Received: 21 December 2024 | Revised: 17 July 2025 | Accepted: 4 August 2025

DOI: 10.1111/1440-1703.70011

REVIEW AND SYNTHESIS

EDITOR'S CHOICE ECOLOGICAL RESEARCH WILEY

National-scale terrestrial biodiversity and ecosystem monitoring with essential biodiversity variables in Japan and Finland

Yayoi Takeuchi[1] | **Lea Végh**[1] | **Hibiki Noda**[2] | **Kristin Böttcher**[3] | **Petteri Vihervaara**[3] | **Jamie M. Kass**[4] | **Ichiro Hama**[5] | **Yusuke Saito**[6]

[1]Biodiversity Division, National Institute for Environmental Studies, Ibaraki, Japan

[2]Earth System Division, National Institute for Environmental Studies, Ibaraki, Japan

[3]Finnish Environment Institute, Helsinki, Finland

[4]Graduate School of Life Sciences, Tohoku University, Sendai, Japan

[5]International Strategy Division, Global Environment Bureau, Ministry of the Environment of Japan, Tokyo, Japan

[6]Biodiversity Strategy Office, Nature Conservation Bureau, Ministry of the Environment of Japan, Tokyo, Japan

Correspondence
Yayoi Takeuchi, Department of Biology, Graduate School of Science, Osaka Metropolitan University, Sugimoto Sumiyoshi-ku, Osaka 558-8585, Japan.
Email: takeuchi.yayoi@omu.ac.jp

Present address
Yayoi Takeuchi, Department of Biology, Graduate School of Science, Osaka Metropolitan University, Osaka, Japan.

Funding information
Climate Change Adaptation Research Program, National Institute for Environmental Studies; Research Council of Finland, FinBIF project, Grant/Award Number: 345733; European Space Agency Living Planet Fellowship Project, Grant/Award Number: 4000135793/21/I-DT-lr; Program on Open Innovation Platform for Industry-academia Co-creation (CO-NEXT) by Japan Science and Technology Agency (JST), Grant/Award Number: JPMJPF2206; Project on Detection of signals of climate change in deciduous broadleaf forests in Japan, National Institute for Environmental

Abstract

Essential biodiversity variables (EBVs) have emerged as a crucial tool for monitoring biodiversity change and provide a framework for standardized and integrated data that align with national and global conservation targets. While EBVs have static definitions, they offer flexibility in data products, allowing regions to develop unique implementation strategies. To guide the development of EBV lists for Japan, we compare data availability with Finland, a country with a similar environment. We review the status of primary data for EBVs in terrestrial ecosystems in these two countries and then compare data for Japan with the Group on Earth Observations Biodiversity Observation Network EBVs and the EBV lists recommended by Europa Biodiversity Observation Network and Finland. Furthermore, we summarize EBVs, remote sensing and modeling applications employed to produce them, and provide ideas for regional EBV priority lists. We found that Japan has medium-to-high data availability across several EBV classes, particularly for species distributions, phenology, and environmental disasters, which include unique datasets. For Japan, we identified data gaps in the EBV classes, *Genetic composition*, *Species traits*, and *Ecosystem structure*. We then discuss how EBVs can contribute to calculating indicators for Japan, such as the "30 by 30," and highlight the remaining data gaps required to realize their implementation. Finally, we provide our perspectives on calculating EBVs at the national scale, focusing on Japan. With several countries and regions developing EBV lists, comparative regional

This manuscript was submitted based on a symposium held on 20 March 2023, at the 71st Annual Meeting of the Ecological Society of Japan in Yokohama, Japan.

Studies; European Union's Horizon Europe research and innovation programme, Grant/Award Number: 101134954

analyses can help elucidate key commonalities and differences to inform more coordinated and effective responses to the global biodiversity crisis.

KEYWORDS

30 by 30, biodiversity data, biodiversity indicators, Kunming-Montreal Global Biodiversity Framework (KMGBF), National Biodiversity Strategies and Action Plans (NBSAPs)

1 | INTRODUCTION

Changes in the Earth system are observable and accelerating due to changes in land use and climate, including extreme weather patterns, pollution, natural resource exploitation, alien species invasions, and extinctions (IPBES, 2019). As these changes affect both biota and the physical environment, they impact not only biodiversity but also the viability and resilience of ecosystems. Such changes directly impact human society through the spread of pathogens and frequency of natural disasters (e.g., pandemics such as COVID-19, droughts, flash floods, and massive fires). In response, global bodies such as the United Nations Framework Convention on Climate Change and the Convention on Biological Diversity (CBD) have committed to halting climate change and biodiversity loss; however, these goals have unfortunately seen little progress (SCBD, 2020). At the 15th meeting of the Conference of the Parties to the CBD (COP15) in 2022, a new global framework called the Kunming-Montreal Global Biodiversity Framework (KMGBF) was adopted. This framework emphasizes the necessity of adapting whole-of-government and whole-of-society approaches to halt and reverse current biodiversity trends and put nature on a path to recovery by 2030. This global consensus highlights the need for timely and accurate reporting of the state and trends in ecosystems and biodiversity. Subsequently, new National Biodiversity Strategies and Action Plans (NBSAPs) have also been adopted or are currently under development in many countries. For instance, Japan revised its NBSAP in 2023, aligning it with the KMGBF and its global targets. As a result, Japan aims to effectively conserve and manage 30% of the land and oceans by 2030 ("30 by 30") and promote nature-based solutions to solve the multidimensional issues of biodiversity through ecosystem-related approaches.

To monitor the progress of these global and national targets and ensure their standardization across the world, mechanisms and methodologies are being developed for reporting the status and trends of biodiversity. The potential contribution of essential biodiversity variables (EBVs) to global and national reports has become a recent topic of interest (Gonzalez et al., 2023). The concept of EBVs, developed by the Group on Earth Observations

BOX 1 What are essential biodiversity variables (EBVs)?

The concept of essential biodiversity variables (EBVs) was first introduced by the Global Biodiversity Observation Network (GEO BON) in 2013 (Pereira et al., 2013) and was inspired by the broader concept of "essential variables" that originated from Earth-observation communities focused on weather and climate (Navarro et al., 2017; Pereira et al., 2013; UNEP/CBD/SBSTTA/17/INF/7, 2013). "Essential variables" are a minimal set of critical measurements designed to harmonize data collection. Aligning biodiversity monitoring efforts with these variables can enhance comparability across spatial and temporal scales, supporting diverse assessments and use cases and fostering greater synergies among different users. Related frameworks include the "Essential Climate Variables" (Bojinski et al., 2014), "Essential Ocean Variables" (Lindstrom et al., 2012), and the newer "Essential Ecosystem Service Variables" (Balvanera et al., 2022). EBVs represent standardized aspects of biodiversity that can be measured (in situ or ex situ) using monitoring data in a flexible manner. The result is an array of integrated information products that are designed to assess trends and changes in biodiversity. Although EBVs reflect the state of biodiversity and ecosystems, they do not primarily address the direct or indirect pressures acting upon them. GEO BON has defined six classes of EBVs (Box Table 1): *Genetic composition*, *Species populations*, *Species traits*, *Community composition*, *Ecosystem structure*, and *Ecosystem function*. The first three classes focus on species, whereas the latter three focus on ecosystems. GEO BON also defined 21 attributes across these 6 classes, with each class comprising 2–5 attributes. EBVs require the integration of different data types (e.g., combining RS data and species occurrence data with model species' geographic potential distributions; Boxes 2 and 3). Core data collected through monitoring efforts are systematically integrated into EBV datasets or data products by combining observations, experimental results, and estimates from modeling data on species, communities, and ecosystems into unified and comprehensive sources of information.

Notably, EBVs are not themselves indicators of biodiversity status; rather, they serve as foundational variables from which indicators are derived. Indicators are direct or indirect measures used to assess global goals and targets and are essential for tracking biodiversity changes and evaluating progress toward conservation objectives. In this context, EBVs function as intermediaries, effectively linking raw biodiversity data to indicators that help achieve specific environmental goals. This dual structure ensures that EBVs play a key role in generating meaningful indicators that accurately reflect the current state and trends of biodiversity.

As such, although GEO BON initially defined EBVs as "generic" variables intended for indicator development, the concept has been adapted to allow for flexible calculation. Some regional groups have developed the EBV framework to align with their biodiversity monitoring schemes and have defined their own variables (here, referred to as "EBV data products" that are typically derived from raw observation data) based on specific taxa or local priorities (e.g., Finland, Europa Biodiversity Observation Network (EuropaBON), Figure 1). Notably, both Finland and EuropaBON have defined their own EBV data products, aligning them with GEO BON's EBV classes. Finland's EBV data products were based on an earlier version of GEO BON's definition of EBV attributes, which at that time included 22 candidate EBVs (UNEP/CBD/SBSTTA/17/INF/7, 2013). In addition, Finland expanded upon the original framework by introducing new data products under *Community composition* and *Ecosystem function* classes (Vihervaara et al., 2017). Defining region-specific EBV data products allows groups to implement effective monitoring of EBVs that are relevant to their needs, reflecting local issues and conservation targets (e.g., Table 4; Junker et al., 2023; Turak et al., 2017). This approach directly contributes to addressing national or regional biodiversity issues, as many challenges are regional in nature, and some EBV attributes may need regional interpretation to align best with regional or local needs, practical costs, or data availability. Consequently, there is a growing emphasis on creating regional EBV workflows to monitor regionally significant targets and issues. In addition, there are challenges associated with achieving global coverage of EBV classes due to spatial and temporal inconsistencies for observational data (Navarro et al., 2017). For example, while some attributes for the *Ecosystem structure* and *Ecosystem function* classes can be monitored efficiently over space and time via RS data, others, like *Genetic composition*, require in situ datasets with typically lower spatial and temporal resolution as well as higher associated costs (Skidmore et al., 2021). Acquiring standardized and frequent in situ observations is difficult due to the lack of global monitoring schemes, difficulties in integrating datasets collected using various methods, and data gaps in taxonomic, geographical, and temporal coverage.

Although public biodiversity datasets exist—such as museum records, field observations and surveys, citizen science, and experimental data—establishing an effective and comprehensive EBV data production workflow remains a key challenge.

Biodiversity Observation Network (GEO BON), an international network of researchers and stakeholders (Navarro et al., 2017; Pereira et al., 2013), provides a standardized classification approach for various kinds of biodiversity data and variables representing key information that reflects the primary dimensions of biodiversity change (Box 1). By defining a minimal set of complementary essential measurements that align with other environmental observation initiatives, the EBV framework standardizes and prioritizes biodiversity monitoring efforts by establishing clear guidelines for observation data (Pereira & Cooper, 2006). There is a need to assess how regions across the world with different climates, geographies, biodiversity patterns, data-sharing cultures, and sociopolitical characteristics can calculate the current EBVs to best characterize their unique environments. It is also important to assess how these regions can produce EBVs that can fill data gaps and effectively report them. Many primary datasets needed to derive EBVs can be accessed through open databases hosting species occurrence and abundance records, community checklists, species traits, and ecosystem or habitat-type extents (Boyd et al., 2023; Jetz et al., 2019; Kissling,

BOX TABLE 1 The six EBV classes and subcategories defined by the Group on Earth Observations Biodiversity Observation Network (GEO BON), Finland, and Europa Biodiversity Observation Network (EuropaBON).

	Entity type (approach)					
	Species (species-focused EBVs)			Ecosystem (ecosystem-focused EBVs)		
EBV class	***Genetic composition***	***Species populations***	***Species traits***	***Community composition***	***Ecosystem structure***	***Ecosystem function***
GEO BON EBV attributes (https://geobon.org/ebvs/what-are-ebvs/)	Genetic diversity; Genetic differentiation; Effective population size; Inbreeding	Species distribution; Species abundance	Morphology; Physiology; Phenology; Movement; Reproduction	Community abundance; Taxonomic/ phylogenetic diversity; Trait diversity; Interaction diversity	Live cover fraction; Ecosystem distribution; Ecosystem vertical profile	Primary productivity; Ecosystem phenology; Ecosystem disturbance
Finland EBV data products (Vihervaara et al., 2017)	Co-Ancestry; Allelic diversity; Population genetic differentiation; Breed and variety diversity	Species distribution; Population abundance; Population structure by age/size class	Phenology; Body mass/ Biomass; Natal dispersal distance; Migratory behavior; Demographic traits; Physiological traits	Taxonomic diversity; Species interactions; Functional diversity	Habitat structure/ condition; Ecosystem extent and fragmentation; Ecosystem composition by functional type	Net primary productivity; Secondary productivity; Decomposition; Nutrient retention; Carbon sequestration; Water filtration and retention; Disturbance regime
EuropaBON EBV data products (Terrestrial Realm, https://github.com/EuropaBON/EBV-Descriptions/wiki/Master-EBV-List)	Genetic diversity of selected terrestrial taxa	Species abundance of: • selected terrestrial bird sp.; • selected terrestrial mammals; • of butterflies; • selected terrestrial animal • disease vectors; • selected terrestrial crop and forest pests Species distribution of: • terrestrial birds;	Phenology of: • fructification of mushrooms; • fructification of wild fruits; • flowering and leaf senescence; • migration of terrestrial birds; • the emergence of butterflies and time of arrival of migratory butterflies	Community biomass of: -selected functional groups of terrestrial arthropods (e.g., predator, decomposer); • soil microbes; Community abundance and taxonomic diversity of pollinator insects; Aerial biomass of: • migrating birds; • migrating bats; • migrating insects Functional composition of soil biota	Vertical structure of vegetation; Ecosystem distribution of terrestrial European nature information system habitats; Connectivity of terrestrial ecosystem habitat types; Standing and lying deadwood	Terrestrial ecosystem productivity; Total bird herbivory; Total mammal herbivory; Rate of decomposition; Fire disturbance regime; Ecosystem disturbance as measured by the human appropriation of net primary production; Terrestrial ecosystem phenology

BOX TABLE 1 (Continued)

	Entity type (approach)					
	Species (species-focused EBVs)			Ecosystem (ecosystem-focused EBVs)		
EBV class	***Genetic composition***	***Species populations***	***Species traits***	***Community composition***	***Ecosystem structure***	***Ecosystem function***
		• all terrestrial mammals; • terrestrial reptiles; • terrestrial priority invertebrates and key pollinators; • selected terrestrial plants; • lichens (as indicators of pollution); • invasive alien terrestrial taxa of European concern				

Note: GEO BON defined 21 essential biodiversity variable (EBV) attributes, while other groups have modified these into EBV data products, applying their own interpretations and adjustments based on expert opinion and data product availability.

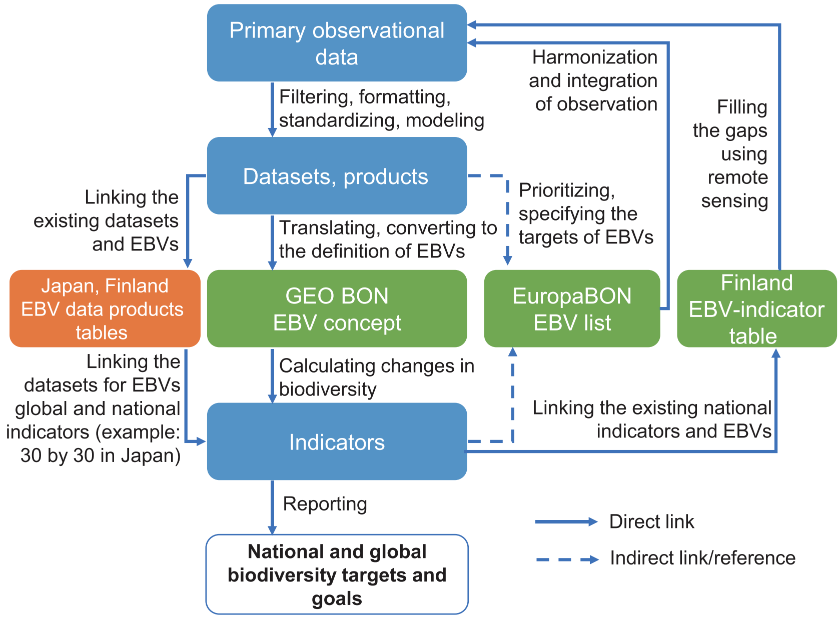

FIGURE 1 The objective of the paper regarding the conceptual information flow of essential biodiversity variables (EBVs) from primary data to indicators, with the ultimate aim of contributing to national and global biodiversity goals. The Group on Earth Observations Biodiversity Observation Network (GEO BON) developed the core EBV concept as an intermediary among primary data, data products, and indicators. EuropaBON created a regional list of EBV data products, or EBV list, based on expert opinion, whereas Finland developed an EBV-indicator table referencing the existing national biodiversity indicators, all aimed at facilitating more practical and efficient monitoring. This study seeks to create EBV dataset tables for Japan and Finland by comparing the GEO BON concept, EuropaBON's EBV list, and Finland's EBV-Indicator table. In addition, we linked the Japanese datasets for EBVs to Japan's 30 by 30 goals.

Ahumada, et al., 2018; Kissling, Walls, et al., 2018), and these datasets are often employed to run models that construct variables (Tehrani et al., 2021). For Japan, many ecological observational datasets published in *Ecological Research* can be used as primary data for EBVs, indicating the significant potential of contributions from ecologists.

Structured national-scale observations are crucial for assessing biodiversity trends at both regional and global scales, as emphasized by Gonzalez et al. (2023), who proposed the establishment of a global system for monitoring and sharing data on biodiversity changes, the Global Biodiversity Observing System (GBiOS). Their approach fosters synergy between local data collection and broad-scale biodiversity insights, effectively bridging the gap between fieldwork and environmental strategies on a national level. Although the implementation of monitoring systems to generate EBVs at the national scale has been limited, research groups in countries like Finland, Australia, New Zealand, and the United Kingdom have explored primary data and methodologies for calculating EBVs within their borders. For instance, Vihervaara et al. (2017) identified mismatches between Finnish biodiversity indicators and EBVs and described potential enhancements using remote sensing (RS) technologies. They highlighted the ability of RS to derive multiple monitoring EBVs as well as Finland's use of RS for tracking shore habitats and water quality to expand national indicators. Turak et al. (2017) outlined a process for prioritizing EBVs at the national scale in Australia that involves prioritization based on ecoregion characteristics and available knowledge. They demonstrated this process in New South Wales by identifying candidate EBVs for tracking biodiversity changes across terrestrial, marine, and freshwater ecosystems. Bellingham et al. (2020) demonstrated the use of extensive biodiversity sampling in New Zealand to implement multiple national-scale EBV measurements at a relatively high spatial resolution. Boyd et al. (2023) outlined an operational workflow to generate annual species occupancy estimates at a national scale for the United Kingdom to detect temporal changes in biodiversity. They produced these annual occupancy estimates for over 5000 species that align with the EBV concept of Species distributions; however, this approach relies on adequate sampling over time and assumptions about species absence. In the United Kingdom, the implementation of forthcoming monitoring systems for EBVs will be aligned with biodiversity indicators, policy goals, and the development of methodologies for generating nationally relevant indicators (POST, 2021). Such examples of employing national datasets to construct EBVs demonstrate the potential for

TABLE 1 Japanese biodiversity datasets, their data providers, and connections to essential biodiversity variables (EBVs).

Provider	Datasets	Format: Tabular	Format: Spatial	Format: Media	Data	Sums of direct/indirect connections
JaLTER*	1	✓			Seed size and weight of tree species	2/1
	2	✓			Leaf phenology	1/-
	3	✓			Urban flowering phenology	2/-
	4	✓			Plant trait database	1/2
	5	✓			Various distribution surveys and censuses	3/5
	6	✓			Fine root dynamics and aboveground/soil environment	1/3
	7	✓			Decomposition rate, microbial community, and soil respiration studies	1/4
	8	✓		✓	Acoustic monitoring of frogs	1/2
	9	✓			Herbivory on broadleaf trees	1/2
	10	✓			Bee occurrence, floral visits	2/2
	11	✓			Biogeochemical Nitrogen content	-/2
	12	✓			Radioactive concentration in small mammals (Fukushima, 2012-)	1/-
	13	✓			Butterfly foraging length	1/2
	14	✓			Butterfly host record (caterpillars included)	1/-
	15	✓			Fungal distribution and functionality	2/-
	16	✓			Forest regeneration after windthrow	1/-
	17			✓	Camera traps of mammals in Fukushima evacuation zone	2/2
	18	✓			Reflectance and transmittance of leaves, shoots, trunks, branches	1/2
BCJ	19	✓	✓		Vegetation maps, surveys, inventory	6/5
	20	✓	✓		Big trees survey	1/3
	21	✓			Animal Distribution Atlas of Japan	1/3
	22	✓	✓		Mammals distribution and habitat survey	1/8
	23	✓			Birds distribution and banding survey	2/3
	24	✓			Amphibian and Reptiles distribution survey	1/3
	25	✓			Insects distribution survey	1/3
	26	✓			Freshwater fishes distribution survey	1/3
	27	✓			Land and freshwater mollusks distribution survey	1/3
	28	✓			Ecosystem monitoring	5/2
	29	✓			Satoyama	2/3
	30	✓			Environmental Indicators (ikimono)	-/5
	31	✓			Regular National Surveys	-/8
	32	✓			Genetic diversity survey	1/2
	33	✓			Monitoring Sites 1000 (2003-)	4/3
	34		✓		Plant community surveys	3/1
	35		✓		Coastline alteration	1/-
NIES	36	✓			Invasive species	1/3
	37	✓			Biodiversity web mapping	2/3
	38	✓			Genome database of endangered species	2/2
	39	✓			DNA barcoding	1/-
	40			✓	Snapshot Japan	2/2
	41			✓	Alpine camera phenological monitoring	2/-
	42	✓			Time-capsule project	1/-
	43		✓		Avian acoustic monitoring	1/1
	44		✓		Avian influenza risk map	2/1
	45		✓		Occurrence maps	1/1
	46		✓		Land Use map	1/1
	47		✓		Traditional landscape diversity	2/1
	48		✓		Satoyama index	1/2
	49		✓		IUCN typology integrated habitat map	1/3
FFPRI	50	✓			Soilmap	1/-
	51	✓	✓		Phytosociological Relevé database	1/2
	52	✓			Genome of forests	1/4
	53	✓			Genome of Cryptomeria japonica	-/3
	54	✓			Longiborn beetles image database	2/1
	55	✓			Trap-nesting bees and wasps	2/3
	56		✓		Forest watersheds	1/1
RED	57	✓	✓		River and reservoir environment and usage map	3/4
	58	✓	✓		River Fish survey	2/4
	59	✓	✓		Benthic fauna survey	2/3
	60	✓	✓		Riverside plant survey	1/2
	61	✓	✓		River birds survey	2/3
	62	✓	✓		Riverside amphibians, reptiles, mammals survey	2/2
	63	✓	✓		Riverside insect survey	2/2
JMA	64	✓			Typhoon	1/-
	65	✓			Landslides	1/-
	66	✓			Earthquakes, volcanic eruptions	1/-
	67	✓			Cherry-blossoming records	2/-
DIAS*	68		✓		Disaster revovery	1/-
	69		✓		Disturbance occurrence	1/-
AIST	70		✓		Anthropogenic heat	1/1
ANEMONE	71	✓			E-DNA metabarcoding	1/2
JAXA	72		✓		Urban roughness	1/2
MSJ	73	✓			Mushrooms	1/1
NARO	74	✓			Genetic resources of vegetation and fruits	2/2
NFI	75	✓			Forest inventory	1/7
NIED	76		✓		Disaster occurrence	1/-
PEN	77		✓	✓	Phenological Eyes Network	2/-
S-NET	78	✓			Specimen records	2/2
Local examples	79	✓			Disaster recovery	1/-
	80	✓			Beach loss due to climate change	1/-
	81	✓			Bumblebees capture data (invasive)	2/-
	82	✓			Disturbance cost (Beach loss)	1/-
	83	✓			Cherry-blossoming records-Kyoto, Tokyo	2/-
	84	✓			Wildlife genetic database	2/3

EBV class	EBV attribute	Sums of direct/indirect connections	Ratio of each class within of total direct/indirect connections
Genetic composition	Genetic diversity	5/2	0.06/0.09
	Genetic differentiation	1/4	
	Effective population size	1/4	
	Inbreeding	1/5	
Species populations	Species distributions	36/5	0.38/0.15
	Species abundances	12/19	
Species traits	Morphology	4/3	0.14/0.14
	Physiology	2/3	
	Phenology	7/4	
	Movement	3/9	
	Reproduction	2/4	
Community composition	Community abundance	6/22	0.12/0.4
	Taxonomic diversity	6/24	
	Trait diversity	2/2	
	Interaction diversity	1/17	
Ecosystem structure	Live cover fraction	3/1	0.11/0.08
	Ecosystem distribution	10/6	
	Ecosystem vertical profile	1/6	
Ecosystem function	Primary productivity	1/7	0.18/0.13
	Ecosystem phenology	5/3	
	Ecosystem disturbances	16/11	
Sums of direct/indirect connections		125/161	

Note: Dark blue indicates a direct connection to an EBV, reflecting the primary objective of the dataset. Light blue indicates a partial connection, representing additional potential uses of the dataset, regardless of its data coverage. Data formats include tabular, media (audio, photo, and video), and spatial (dedicated raster or shapefiles).

Abbreviations of Providers: AIST, National Institute of Advanced Industrial Science and Technology; ANEMONE, All Nippon eDNA Monitoring Network database; BCJ, Biodiversity Center of Japan; DIAS, Data Integration and Analysis System Program; FFPRI, Forestry and Forest Products Research Institute; JaLTER, Japan Long Term Ecological Research Network; JAXA, Japan Aerospace Exploration Agency; JMA, Japan Meteorological Agency; NARO, National Agriculture and Food Research Organization; NFI, National Forest Inventory; NIED, National Research Institute for Earth Science and Disaster Prevention; NIES, National Institute for Environmental Studies; MSJ, The Mycological Society of Japan; PEN, Phenological Eyes Network; RED, River Environmental Database; S-NET, Science Museum Net (connected to the Global and Japanese Biodiversity Information Facility); Local examples, Tohoku University, University of Tokyo, University of Hyogo, Kyoto University.

*Provides access to data from different original sources.

constructing nationwide operational workflows, but they also reveal the challenges involved in developing them effectively. Moreover, they highlight the need to ensure the sustainability of monitoring by involving various stakeholders, especially governmental sectors, and the standardization of basic datasets, such as national statistics and sampling regimes.

Japan has extensive biodiversity data and monitoring activities, thereby having great potential for generating EBVs over time to assess progress toward achieving global biodiversity goals. However, challenges regarding data accessibility and standardization remain to be fully realized. The EBV concept is not widely known or extensively discussed in Japan, although the currently collected data most likely align with EBV definitions. To develop an EBV-based monitoring framework that follows the global concept, the existing datasets should be summarized, and challenges related to data accessibility, gaps, and application must be addressed. Other countries with established nationwide EBV monitoring systems should provide excellent guides for Japan toward realizing this vision. In particular, Finland is a good candidate for a number of reasons. First, it is heavily forested with similar forest types to Japan. Second, it provides a good roadmap for the utilization of RS data to derive EBVs (Vihervaara et al., 2017). Third, Finland is experienced in regional-scale EBV implementation, having calculated some EBVs at the national scale and being involved in the schema for EBV datasets in Europe through Europa Biodiversity Observation Network (EuropaBON) (Table 1).

Here, we review the current status of primary data and datasets for EBVs in Japan and Finland. We compare Japan's data availability with the GEO BON EBVs and the EBV list and table of EuropaBON and Finland, respectively (Figure 1). We then discuss how we can use the lessons learned from these to develop an effective EBV monitoring system at the national scale for Japan. We also establish connections between EBVs and indicators for Japan's NBSAPs using the "30 by 30" conservation target as an example in relation to the KMGBF. Finally, we discuss our perspectives regarding efficient and manageable EBV monitoring, including opportunities for collaborative studies between Japan and Finland to improve biodiversity monitoring and conservation efforts.

2 | CURRENT STATUS OF BIODIVERSITY DATA FOR EBVs IN JAPAN AND FINLAND

Observational biodiversity data are essential for generating national-scale EBVs. Here, we surveyed the existing datasets related to terrestrial biodiversity and ecosystem information in Japan, distinguishing between the primary datasets based on field and RS observations. In Finland, Vihervaara et al. (2017) identified the links and gaps between the existing national biodiversity indicators and EBVs. Following this approach, we first assessed the availability of monitoring, inventory, and processed datasets in Japan and Finland to evaluate the current coverage of biodiversity datasets for EBVs. We then conducted a regional comparison among Japan, Finland, and Europe as a whole. For Europe, we referred to the EuropaBON framework, which lists the group's recommendations for EBV data products (Quoss et al., 2024). Although these products are referred to as "EBVs" in this list, we herein refer to them as "EBV data products." This is because the EBV definitions are meant to be static (Pereira et al., 2013), whereas the specific EBV data products or calculation of their values can be flexible. These lists were developed through consensus among researchers in EuropaBON from various fields during multiple workshops (Hardisty et al., 2019; Lumbierres & Kissling, 2023), making them a prioritized and harmonized set of representative EBV products for Europe.

2.1 | Existing datasets and EBVs in Japan

We assessed the availability of monitoring, inventory, and processed datasets derived from field observations on biodiversity and ecosystems in Japan by reviewing prominent websites and databases focused on nature conservation, biodiversity observation, and forest resource assessments. We primarily targeted datasets with nationwide coverage and local datasets registered in national databases. We also included some local open-access datasets that are maintained by universities and local researchers. Regarding RS datasets, while global data are generally available (Vihervaara et al., 2017), we concentrated on the availability of data specifically from Japanese data providers. Ecosystem monitoring maps for Japan can be accessed via the Japanese Aerospace Exploration Agency (JAXA) data portals and the Data Integration and Analysis System (DIAS) program, which is currently hosted by the Japan Agency for Marine-Earth Science and Technology and operated in collaboration with multiple institutions. However, most of these maps are coarse-resolution Earth-observation products (typically ≥10 m resolution). Higher resolution (3–10 m) observations, such as those from the Advanced Land Observing Satellite mission, are available but with intermittent coverage and revisit times. As the primary focus of this study was to examine the alignment between existing data and EBVs, we did not conduct in-depth analyses of the data itself, such as an assessment of the spatiotemporal or taxonomic coverage. However, when applying these data in practice, it is essential to consider such potential biases.

In total, we identified 16 primary national data providers (Table 1) and summarized their datasets into 65 tabular, 5 media, and 27 spatial datasets (detailed list in Table S1). Existing biodiversity datasets in Japan cover all EBV classes, with at least one direct (dark blue in Table 1) and several indirect (light blue) connections of datasets available for each EBV. Direct connections refer to datasets that can directly describe the EBV, whereas indirect connections refer to datasets with different primary purposes that can be used to calculate the EBV. For example, the purpose of species surveys is to gain information on the distribution and abundance patterns of particular species; therefore, this is directly related to the EBV attributes, Species distributions and Species abundances. However, these data can also be used indirectly to calculate Community abundance if combined with other species surveys or data.

Datasets for the EBV classes, *Species populations*, *Community composition*, and *Ecosystem function* are particularly abundant in Japan. The abundance of these datasets is driven by the need to meet national biodiversity goals and targets. In Japan, another contributing factor is the alignment of these datasets with the research interests of ecologists, although many datasets are still not fully open. In addition, some datasets span multiple EBV classes (e.g., vegetation maps, surveys, inventories, and national surveys), providing valuable linkages among classes. There are also multiple EBV connections in the spatial datasets, such as the "big trees" data to inform species' distributions and morphologies, or tree community data that inform both species and ecosystem distribution EBV attributes. In certain regions and particularly for well-studied species, Japan has relatively abundant data on genetic composition, an EBV class that is often underrepresented in other countries (Hoban et al., 2022). Apart from the nationwide data providers, we identified local data providers, mainly universities, who collect point-scale data related to their research (e.g., the bumblebee's dataset from the University of Tokyo) and often manage experimental forests and areas and their related data. Although their spatial coverage is limited, when combined, they can cover wide latitudinal ranges and serve as valuable resources for describing aspects of biodiversity lacking information in national datasets.

In terms of datasets for RS EBV, the spatial resolution of the identified data is relatively coarse (generally 5 or 10 km), which limits its applicability. Data with resolutions of 1 km or finer are generally preferable for measuring biodiversity and validation efforts at national scales. However, some RS-derived datasets still lack sufficient repeatability, highlighting the need for further efforts to enhance consistency and validation across space and time. Some specific datasets for EBVs, such as the Phenological Eyes Network, a camera-based monitoring system that collects pictures daily during the growing season, are particularly valuable for validating satellite observations of phenological changes. Furthermore, there are Japan-specific datasets for EBVs, such as the Satoyama index (Kadoya & Washitani, 2011). This metric reflects the mosaic nature of land use in Japan's traditional rural landscapes that provide important habitats for many species ("satoyama" in Japanese), and it is calculated based on the diversity of nonurban land uses within a unit area, including farmland. The index aligns with the *Ecosystem structure* class, as it incorporates physical parameters of traditional land use types in rural areas. Given Japan's high frequency of natural disturbances, spatial datasets that observe the impacts and extents of these disturbances are recommended for use in the *Ecosystem function* class. Despite this, we identified data gaps, particularly in certain taxonomic groups and ecosystems. For example, tree species data are abundant in major surveys, whereas grassland ecosystems are less extensively monitored, with only limited continuous monitoring conducted by governmental agencies and academic communities (Noda et al., 2023).

Data providers include not only academic monitoring bodies and projects, such as the Japan Long Term Ecological Research Network (JaLTER), but also national efforts, such as the Monitoring Sites 1000 Project led by the Ministry of the Environment of Japan under a previous NBSAP. Launched in 2003, this project aims to monitor ~1000 sites nationwide covering diverse ecosystems to accumulate long-term data, as outlined in Japan's 2nd NBSAP (MOE, 2002). This project enables the early detection of degradation in Japan's natural environment using both qualitative and quantitative methods. Periodic surveys are conducted by a broad group of researchers, NPOs, and citizen scientists who contribute to the overall quality, quantity, and variety of collected biodiversity data. Such long-term, large-scale, and government-led monitoring efforts are rare in Asia and represent a remarkable advantage for Japan's biodiversity monitoring system.

2.2 | Existing datasets and EBVs in Finland

Following the procedure of compiling datasets and EBVs in Japan, we gathered similar information from Finland

TABLE 2 Finnish biodiversity datasets, their data providers, and connections to Essential Biodiversity Variables (EBVs).

		Format			EBV class	Genetic composition				Species populations		Species traits					Community composition				Ecosystem structure			Ecosystem function			
Provider	Datasets	Tabular	Spatial	Media	Data / EBV attribute	Genetic diversity	Genetic differentiation	Effective population size	Inbreeding	Species distributions	Species abundances	Morphology	Physiology	Phenology	Movement	Reproduction	Community abundance	Taxonomic diversity	Trait diversity	Interaction diversity	Live cover fraction	Ecosystem distribution	Ecosystem vertical profile	Primary productivity	Ecosystem phenology	Ecosystem disturbances	Sums of direct/indirect connections
Luke	1	✓			Genome data for some selected species	○	○	●	○																		1/3
	2	✓			Game mammals					●	●	○			○												2/2
	3	✓			Species distribution of invasive species					●																○	1/1
	4	✓			Phenology of fructification of wild fruits					○	○			●													1/2
	5	✓			Flowering phenology					○	○			●						○							1/3
	6	✓			Leaf phenology							○	○	●							○			○	●		2/4
	7	✓			Pine branch elongation							●	○	●													2/1
	8	✓			Soil microbial and eDNA	○				○			○	○			○	●	○	●				○		○	2/8
	9	✓			Soil microbe community					○							○	●	○	●		○		○		○	2/4
	10	✓			Soil microbe physiology								●											○		○	1/2
	11	✓	✓		Biomass from forest inventory																○			●			1/1
	12	✓			Standing and lying deadwood plot measurements							○									○	●	○			●	2/3
	13		✓		Species distribution of main trees					●	●					○	●	●			○	○	●	○			5/4
	14		✓		Agricultural land use																	○	○	○		●	1/3
	15		✓		Vegetation cover							○									●	●	○	○			2/3
Luontotieto*	16	✓			Genetic diversity monitoring	●	○	○	○																		1/3
	17	✓			Terrestrial birds					●	●			○	○	○	●	○	○	○							3/6
	18	✓			Water birds					●	●			○	○	○	●	○	○	○							3/6
	19	✓			Species monitoring of threatened species (Red Lists)					●	●							○									2/1
	20	✓	✓		Northern Lapland habitat monitoring																○	●	●			●	3/1
	21	✓	✓		Distribution survey of various terrestrial mammals					●	○						○										1/2
	22	✓	✓		Distribution data of terrestrial reptiles					●																	1/-
	23	✓	✓		Monitoring of butterflies and moths					●	●	○		●	○		●	●	○							○	5/4
	24	✓	✓		Species distribution of bumblebees					●	○	○		○	○		○	○	○	○							1/8
	25	✓	✓		Species distribution of terrestrial plants					●	●	○					○	○	○	○		○					2/6
	26	✓	✓		Occurrence of migratory birds					●	●			●	●												4/-
Syke	27	✓			Moth flying periods									●													1/-
	28	✓	✓		Zoonation analysis for forests																	○				●	1/1
	29		✓		Satellite observations**								○	○							●	○	○	●	●	●	4/4
	30		✓		Standing and lying deadwood drone measurements							○									○	●	○			●	2/3
	31	✓	✓		Regional greenhouse net emissions																			●		○	1/1
	32	✓	✓		Butterfly and moth census					●	●	○		●	○	○	●	●	○							○	5/5
	33	✓	✓		Species distribution of bumblebees					●	○	○		○	○		○	○	○	○							1/8
	34		✓		Vegetation height							○									○	○	●				1/3
	35		✓		Land cover map																	●		○			1/1
	36	✓	✓		Habitat types in protected areas																	●				○	1/1
FinBIF	37	✓			DNA barcode of selected species					●																	1/-
	38	✓	✓		Distribution data of terrestrial birds					●	●					●	○	○	○	○							3/4
	39	✓	✓		Distribution data of terrestrial reptiles					●																	1/-
FO	40	✓			Fine root dynamics							●	○						○								1/2
	41	✓			Aboveground/soil environment												○	○				●					1/2
	42	✓			Decomposition rate within study plot																			●	○	○	1/2
Luomus	43	✓	✓		Bird ringing data					●	●	●				●											4/-
	44	✓	✓		Survey of pollinator species					●	○	●								○							2/2
	45	✓	✓		Distribution data of terrestrial reptiles					●																	1/-
FMI	46	✓	✓		Weather radar data of migratory objects						○		○	●	●												2/2
	47			✓	Phenological cameras								○											○	●		1/2
BF	48	✓			Occurrence of migratory birds					●	●			●	●												4/-
CG*	49		✓		Net Ecosystem exchange and gross primary production																			●	●		2/-
FFA	50		✓		Agricultural land use																	○	○	○		●	1/3
FGI	51		✓		Vegetation height by airborne Laser scanning																●	○	●				2/1
FinBOL	52	✓			DNA barcode of selected species					●																	1/-
GSI	53		✓		Soil map																	●					1/-
Sieniatlas	54	✓			Phenology of fructification of mushrooms					○	○	○	○	●				○	○	○							1/7
					Sums of direct/indirect connections	1/2	-/2	1/1	-/2	22/5	12/8	4/12	1/8	11/6	3/7	2/4	5/8	5/9	-/12	2/9	3/7	8/9	4/6	5/9	4/1	7/8	100/135
					Ratio of each class within of total direct/indirect connections	0.02/0.05				0.34/0.10		0.21/0.27					0.12/0.28				0.15/0.16			0.16/0.13			

Note: Dark blue indicates a direct connection to an EBV, reflecting the primary objective of the dataset. Light blue indicates a partial connection, representing additional potential uses of the dataset, regardless of its data coverage. Data formats include tabular, media (audio, photo, and video), and spatial (dedicated raster or shapefiles).

Abbreviations of Providers: BF, Birdlife Finland; CG, Climate Guide; FFA, Finnish Food Authority; FGI, Finnish Geospatial Research Institute; FinBIF, Finnish Biodiversity Information Facility; FinBOL, Finnish Barcode of Life; FMI, Finnish Meteorological Institute; FO, Field Observatory; GSI, Geological Survey of Finland; Luke, Natural Resources Institute Finland; Luomus, Finnish Museum of Natural History; Luontotieto, The Finnish Nature Information Hub; Sieniatlas, Fungi Atlas; Syke, Finnish Environment Institute.

*Provides access to data from different original sources.

**Satellite products from various sources.

to compare the available datasets and their relevance for the EBVs in these two countries. The Finnish Natural Resource Institute (Luke) and Finnish Environment Institute (Syke) are the two major data providers responsible for coordinating national monitoring schemes, synthesizing information for ecosystem and natural resource statistics, and implementing and reporting for environmental policy and legal framework processes. In addition, the Finnish Museum of Natural History coordinates some species monitoring schemes, and the Finnish Biodiversity Information Facility (FinBIF) is the major national data repository for species observations. Moreover, there are numerous individual organizations and research communities that produce valuable biodiversity data, and those that are comparable to Japanese datasets are listed in Table 2. Recently, a new Finnish Nature Information

Hub (Luontotieto) was established to serve as a national gateway for all biodiversity and ecosystem data. This hub provides a search engine for available datasets and their metadata across key data-providing organizations in Finland. It currently offers metadata for available datasets and allows the data to be classified by type or main ecosystem class. Furthermore, the Luontotieto hub provides an overview of all Finnish biodiversity monitoring schemes, indicators, and other information on the state of nature.

To evaluate the usability of each Finnish dataset for calculating EBVs, we classified the datasets by data format in the same manner as the Japanese datasets in Table 1. In total, we listed 54 datasets from 14 primary national data providers in Table 2, and a more detailed list is provided in Table S2. Similar to Japan, there was a trend of more datasets for population abundance (*Species populations*) and habitat structure (comparable with Ecosystem distribution) (Vihervaara et al., 2017). Some EBV datasets had temporal gaps in their monitoring, limitations in spatial coverage to specific regions or sites, or used sampling methods that were not designed to provide comprehensive national data layers or contribute directly to EBVs. Nevertheless, we included them in Table 2, as their methods can be extended to improve their capacity for informing EBVs.

2.3 | Differences and commonalities in existing datasets between Japan and Finland

The number of direct and indirect connections of datasets and EBV, and data providers in Japan and Finland showed interesting similarities and differences (Figure 2). The top data provider in Japan is the Biodiversity Center of Japan (BCJ) under the Ministry of the Environment, whereas that in Finland is the Luke, affiliated with the Ministry of Agriculture and Forestry. This highlights that in both countries, governmental institutions play a central role in securing biodiversity data. Nationwide data hubs hold the second position, with JaLTER in Japan and Luontotieto in Finland, underscoring their importance in ensuring data visibility and dissemination. The third position is occupied by the national environmental research institutions NIES in Japan and Syke in Finland, both providing diverse and mostly interdisciplinary datasets for EBV. In addition, Syke provides marine and freshwater-related data, but these were not included in this evaluation due to our focus on terrestrial data. Interestingly, the top three data providers in both countries contributed more indirect EBV connections than direct ones. This trend was most obvious in the BCJ datasets, which had a higher number of indirect than direct EBV connections. This contributed to enhanced EBV coverage, particularly for the *Community composition* class, compared with its Finnish counterpart, the Luke. We also compared the availability of datasets using direct connections to each EBV attribute between Japan and Finland (Figure S1). Regarding differences, within the *Species populations* class, Japan has more datasets for Species distributions than Finland, as indicated by the asymmetrical node heights in the EBV column. In addition, Japan has a larger amount of data available for Ecosystem disturbances than Finland.

2.4 | Comparative assessment of biodiversity data availability in Japan

Focusing on the terrestrial ecosystems and their descriptions, we compared the availability and coverage of Japanese biodiversity data (Table 1) with the GEO BON EBV attributes and EBV data product lists recommended by EuropaBON and Finland (Box 1). Due to key differences in geography, climate, and biodiversity priorities between Japan and Europe, we assumed that data availability would vary by EBV class and attribute, and also that certain EBV data products might need modifications to best suit Japan's unique environmental and conservation needs.

First, we categorized the existing biodiversity data (the sum of direct connections) in Japan for each EBV class (Table 1) as having "high," "medium," or "low" data availability compared with the GEO BON, EuropaBON (Retrieved on March 30, 2025, from https://github.com/EuropaBON/EBV-Descriptions/wiki/Master-EBV-List), and Finland EBV lists. Japanese data availability for the GEO BON EBVs at the national scale was classified as either "medium," with 4–6 direct connections based on Table 1, or "high," with ≥7 direct connections. In contrast, "low" indicated the lower availability of Japanese national-scale data with ≤3 direct connections. Data coverage for the regional EBV data products was decided based on the type of data available. For example, in the *Species populations* class, EuropaBON has EBV data products related to the distributions and abundances of terrestrial and migratory birds, and these data are also available from the BCJ with adequate point data distribution across the country, so the data availability was classified as "medium." For the EuropaBON flowering and leaf senescence EBV data product in the *Species traits* class, Japan has ample and high-quality related data, so this EBV data product was classified as "high." An example of a "low" EBV data product is the abundance of certain arthropod groups (e.g., other than butterflies and bees)

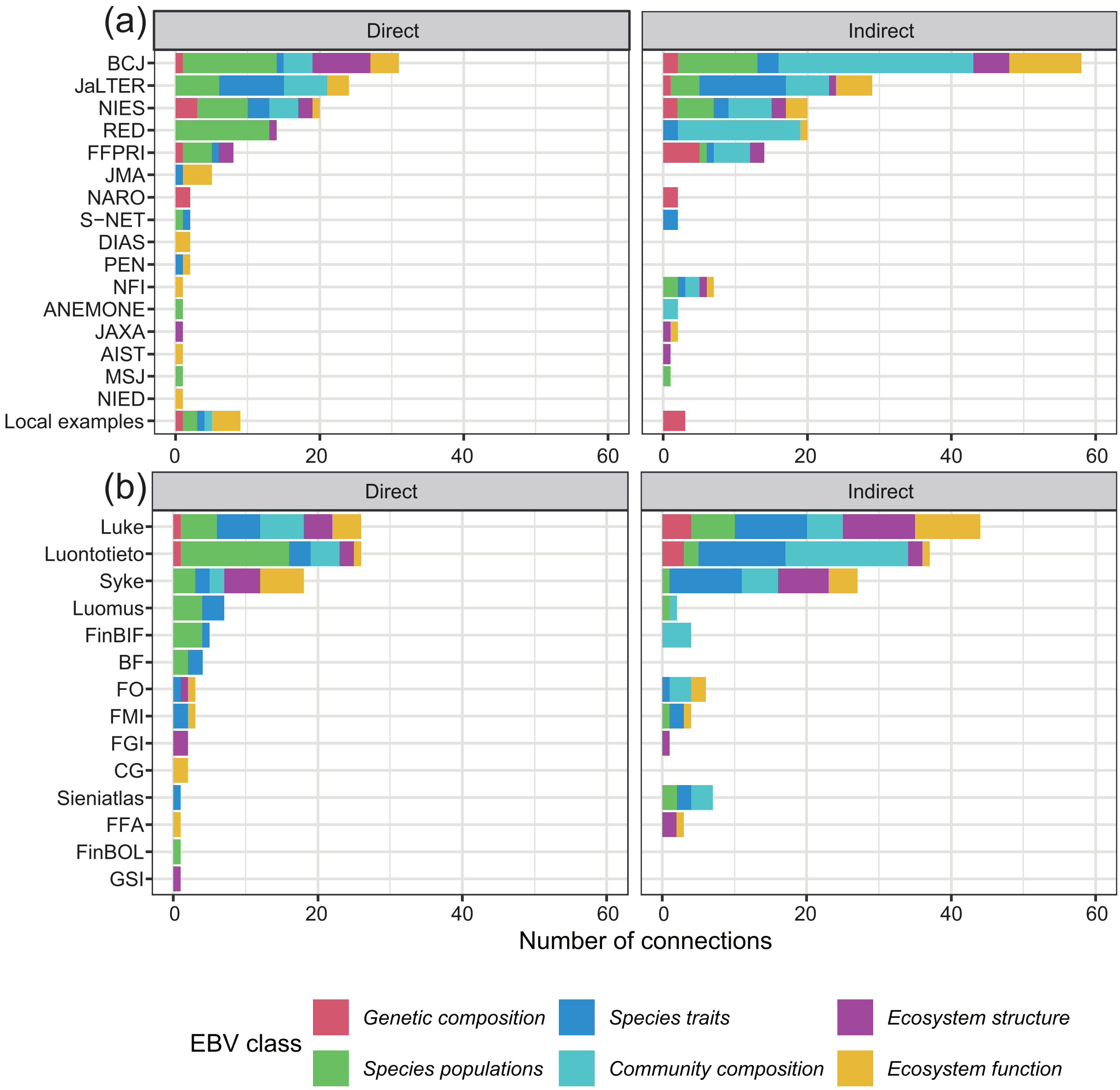

FIGURE 2 Comparison of the number of direct (left) and indirect (right) connections between datasets and essential biodiversity variables (EBVs) by data provider in (a) Japan and (b) Finland, based on Tables 1 and 2. Data providers are ordered by the number of direct connections, followed by total connections (direct + indirect), and then alphabetically. Colors indicate different EBV classes.

with poor data coverage. Although this classification was partially subjective, assessing all datasets in detail was beyond the scope of this study.

The GEO BON EBV attributes and the data products calculated for them by EuropaBON and Finland differed from each other, demonstrating the issues faced when comparing different ecoregions and their data. We found that Japan had adequate or better data for about half or more of the total EBV data products for each entity: 48% for GEO BON (5 "medium" and 5 "high" out of 21 total), 69% for EuropaBON (11 "medium" and 13 "high" out of 35 total, with 1 inapplicable category), and 65% for Finland (9 "medium" and 8 "high" out of 26 total). In addition, we identified 10 unique EBV data products in Japan not included in the lists for EuropaBON or Finland, attributed to the *Species populations*, *Species traits*, or *Ecosystem function* classes (Table 3).

Individual examination of the EBV classes revealed that the *Genetic composition* class had only one EBV data product recommended by EuropaBON and four EBV data products recommended by Finland, reflecting their poor data availability. While Japan has several datasets focusing on the genetic diversity of endangered and agriculturally or economically important species, there is a lack of genetic data on other wild populations. As proposed by Hoban et al. (2022), effective population size

TABLE 3 Biodiversity data quality and availability in Japan compared with the global-focused Group on Earth Observations Biodiversity Observation Network (GEO BON) essential biodiversity variable (EBV) attributes, the regional-focused Europa Biodiversity Observation Network (EuropaBON) EBV list, and Finland's EBV list.

EBV class	GEOBON	EuropaBON	Finland	Additional Japanese data
Genetic composition	Genetic diversity	Genetic diversity of selected taxa	Co-ancestry	
			Allelic diversity	
	Genetic differentiation		Population genetic differentiation	
	Effective population size			
	Inbreeding		Breed and variety diversity	
Species populations	Species distributions	Birds	Species distribution	
		Mammals		
		Reptiles		
		Prior. Invertebrates, key pollinators		Mollusks
		Plants		Selected tree species
		Lichens		
		Alien taxa of concern		
	Species abundances	Birds	Population abundance	Migratory birds
		Mammals		
		Butterflies		
		Disease vectors		
		Crop and forest pests		
			Population structure by age/size class	
Species traits	Morphology		Body mass/Biomass	
	Physiology		Physiological traits	
	Phenology	Fructification of mushrooms and wild fruits		
		Flowering and leaf senescence	Phenology	Cherry blossoming
				Urban flowering
				Leaf flowering
		Migration of terrestrial birds		
		Emergence of butterflies		
		Arrival of migratory butterflies		
	Movement		Migratory behavior	
	Reproduction		Natal dispersal distance	Seed size, weight
			Demographic traits	
Community composition	Community abundance	Comm. biomass of selected functional arthropod groups		
		Community biomass of soil microbes		
		Aerial biomass of migratory birds, bats and insects		
		Abundance of pollinator insects		

(Continues)

TABLE 3 (Continued)

EBV class	GEOBON	EuropaBON	Finland	Additional Japanese data
	Taxonomic/ phylogenetic diversity	Taxonomic diversity of pollinator insects	Taxonomic diversity	
	Trait diversity	Functional composition of soil biota	Functional diversity	
	Interaction diversity		Species interactions	
Ecosystem structure	Live cover fraction	Standing and lying deadwood		
	Ecosystem distribution	Distribution of habitats	Ecosystem extent and fragmentation	
		Connectivity of habitats	Habitat structure/ condition	
	Ecosystem vertical profile	Vertical structure of vegetation		
			Ecosystem composition by functional type	
Ecosystem function	Primary productivity	Ecosystem productivity	Carbon sequestration	
		Rate of decomposition	Decomposition	
			Net primary productivity	
			Secondary productivity	
			Nutrient retention	
			Water filtration and retention	
	Ecosystem phenology	Ecosystem phenology		
	Ecosystem disturbances	Fire disturbance	Disturbance regime	Typhoons
		Disturbance as measured by the human appropriation of net primary production		Earthquakes
		Mammal herbivory		Volcanic eruptions
		Bird herbivory		

Note: Spatial arrangements indicate the correspondence between the EBV classes and GEO BON EBV attributes, and between EBV attributes and data products included in the EuropaBON and Finland EBV lists. Colored cells represent individual EBV data products, and their fill colors indicate data availability in Japan (Blue: High; Green: Medium; Yellow: Low; Gray: Not applicable).

(N_e), a fundamental parameter for genetic biodiversity, can still be estimated even in the absence of direct genetic data. N_e is closely related to census population size (N_c), defined as the number of individuals in a theoretically ideal population, which can be estimated from the Species distributions and Species abundances attributes. The *Species populations* class has the widest data coverage in both Japan and Europe, but data are incomplete for some taxa (Table S1). Data categorized as "high" are most prevalent in the *Species traits* and *Ecosystem function* classes. For the *Species traits* class, Japan has a variety of long-term records of cultural importance, mainly phenological observations of flower blossoming and leaf senescence (Shin et al., 2023). Similar nationwide and long-term phenological observations are rare in Europe; one example is the recording of grapevine budbreaks since 1740 in Kőszeg, Hungary (ICH, 2024). However, there is a lack of direct Japanese datasets related to three of the five GEO BON EBV attributes in this class (Physiology, Movement, and Reproduction). In the *Ecosystem function* class, data categorized as "high" are attributed to the extensive records of environmental disturbances in Japan. Disturbance drivers are quite different between Europe and Japan; fire is the dominant natural disturbance type in Europe, whereas massive fires are rare in Japan. In contrast, the major disturbance drivers affecting Japanese terrestrial biodiversity are biotic, such as herbivory by deer and agricultural pests,

BOX 2 Remote sensing approaches for phenology EBVs

Vegetation phenology, including the timings of flowering, leaf unfolding, and senescence, determines annual photosynthetic production and the seasonal availability of food and habitats for animals. Because of its fundamental role in regulating these ecological processes, phenology is represented by the attributes Phenology and Ecosystem phenology within the EBV classes *Species traits* and *Ecosystem function*, respectively, in the EBV framework. Phenology is also related to the *Species populations* and *Community composition* classes by influencing the availability of food and habitats, and to primary productivity in the *Ecosystem function* class by regulating the seasonal cycle of photosynthesis. This makes phenology a variable that spans several EBV classes, reflecting its broad ecological significance, relevance, and feasibility for RS; it was thus featured in a recent priority list for RS-based EBVs (Skidmore et al., 2021). Here, we focus on phenology as a cross-cutting variable that influences multiple EBV classes, emphasizing the importance of RS techniques to provide accurate, timely data that can inform several biodiversity and ecosystem processes.

Phenological data records the onset of flowering and other seasonal phenomena of interest from both cultural and scientific perspectives, leading to the collection of much data around the world. In Japan, the flowering of cherry trees has great cultural importance and has thus been well recorded since ancient times. Aono and Kazui (2008) published an unprecedented phenological dataset about cherry tree flowering covering >1200 years (812–2021) based on information gathered about full bloom dates from diaries and chronicles written by emperors, aristocrats, governors, and monks. More recent data covers more variables at a wider taxonomic scale: the Japan Meteorological Agency (JMA) observed phenological events for 34 plant and 23 animal species—such as dates of blooming, leaf coloring, and the first songs of birds and insects—using a unified nationwide observation method at 58 weather stations in Japan from 1953 to 2020 (Table 1, No. 60). While the JMA dataset covers a shorter time period compared with Aono and Kazui's dataset, it was collected using systematic methods, making it suitable for understanding long-term trends. This JMA dataset indicates an early blooming and leafing trend for cherry blossoms (advancing by 0.9 days/decade) and a delayed autumn coloration trend for maple leaves (delayed by 3.2 days/decade). Since 2021, these observations have been continued by the National Institute for Environmental Studies (NIES) through citizen science initiatives.

RS techniques, including in situ and satellite observations, are well-suited for phenological monitoring. These techniques are mainly based on time series of vegetation indices (e.g., the Normalized Difference Vegetation Index [NDVI]), calculated from spectrometry data collected over several decades (Duchemin et al., 1999; Schwartz, 1998; White et al., 1997), or from the RGB values of digital camera images (Ide & Oguma, 2010; Peltoniemi et al., 2018; Richardson, 2019; Wingate et al., 2015). The Phenological Eyes Network (PEN), a network for in situ RS, has provided long-term data on canopy-scale camera images and canopy reflectance at ~30 sites worldwide, mainly in Japan (Nasahara & Nagai, 2015). Global datasets derived from satellite sensors with moderate spatial resolution, such as the Moderate Resolution Imaging Spectroradiometer (MODIS) (Ganguly et al., 2010; Gray et al., 2019) and the Visible Infrared Imaging Radiometer Suite (VIIRS) (Moon et al., 2019), have also been widely used. In Finland, information on forest phenology was estimated using MODIS observations with methods adapted for boreal forest ecosystems (Böttcher et al., 2014; Böttcher et al., 2016). In Japan, the RS of phenology has been particularly focused on deciduous forests, and RS-based phenology data have been used to estimate gross primary production (GPP) (Muraoka et al., 2013) and make future predictions under climate change (Hadano et al., 2013). Some limitations include a lack of species-level resolution for observations by MODIS and VIIRS at global and regional scales (Schmeller et al., 2018) and time intervals that, while frequent, may still be insufficient to capture phenological changes in regions with frequent cloud cover or ecosystems where key phenological events occur over short time windows (e.g., flowering and greening in alpine regions). In such cases, a ground-based approach can be particularly useful. Especially in alpine regions where frequent cloud cover limits satellite observations, time-lapse camera monitoring has proven to be an effective method for phenological monitoring (Ide & Oguma, 2013). In the future, analyses of photographs shared by mountain hikers on social media may also offer a promising complementary dataset.

In recent years, high-resolution satellite observations (≤30 m) are available at a suitable temporal frequency (e.g., ~5-day resolution for ESA Sentinel-2 satellites) to describe vegetation phenology, and methods have been developed for these data to estimate vegetation phenological metrics for the global-scale biodiversity assessments made by the European Space Agency GlobDiversity project (Röösli et al., 2020). The higher spatial resolution of Sentinel-2 allows a better link between satellite observations and community phenology compared with MODIS or VIIRS, as the pixel size aligns more closely with the actual patterns of vegetation distribution. In Europe from 2016 onwards, the Copernicus service on High Resolution Phenology and Productivity (HR-VPP) provides phenology and productivity metrics at 10 m spatial resolution calibrated with observations from carbon flux measurement sites, phenological cameras, and phenological databases (Tian et al., 2021). The lower revisit frequency of Sentinel-2 satellites, although relatively frequent, poses a challenge compared with the daily observations of MODIS or VIIRS, particularly in areas with short growing seasons, snow cover, and frequent cloud cover. Hence, observation frequency may limit the accuracy of derived phenological metrics. To further improve observation frequency, fusion of high-frequency information from MODIS/Sentinel-3 and high spatial resolution from Landsat/Sentinel-2 has been proposed (Feng et al., 2006; Wang & Atkinson, 2018). Data fusion can enhance the accuracy of the phenological events detected in heterogeneous landscapes when cloud-free and high-resolution images cannot capture key vegetation phenological stages (Diao et al., 2024; Tian et al., 2024). Recently, the availability of daily PlanetScope imagery with very high spatial resolution (3 m) and near-daily image frequency provides novel opportunities for monitoring the phenology of terrestrial ecosystems. Fine-scale variations (Moon et al., 2021) and flowering events (Dixon et al., 2021) can be captured with these data, opening new avenues for the detection of species-level phenology from space that could inform the *Species traits* class and its Phenology attribute. Recently, geostationary satellite sensors, which observe the same area at short time intervals, have also been available for phenology monitoring. Frequent observation enables monitoring during brief breaks in cloud cover, even in frequently cloudy areas, making more detailed phenology examination possible. An example is the 10-min temporal resolution NDVI data from Himawari-8, which has a relatively coarse spatial resolution of 2 km. These sensors have been used to efficiently monitor the phenology of forests in Japan (Miura et al., 2019) and grasslands in Australia (Tran et al., 2020).

and natural disaster-related, such as typhoons and earthquakes, as well as their secondary impacts, including windthrow, landslides, and tsunamis (Hirayama et al., 2020; Ishihara & Tadono, 2017). In addition, Japan has several active volcanoes, with some erupting frequently every 30–50 years (e.g., Mount Usu in Hokkaido), causing repeated cycles of successional vegetation stages. The differences in the drivers and causes of disturbance suggest that related datasets for EBV data products may need to be specified based on local importance, which may make them inappropriate for inter-regional comparison. Finally, the *Ecosystem structure* class has a balanced number of EBV attributes and data products categorized as "high" and "low," whereas the *Community composition* class is categorized as "low" for some community abundance metrics, as well as trait and interaction diversities. Although there is no direct connection to taxonomic diversity, several datasets in the *Species populations* class can inform this EBV.

The observed commonalities and differences between Japan and Finland may also be attributed to various factors, including the mechanisms related to overuse or underuse of biodiversity, the cultural significance of biodiversity (e.g., tourism and religion), and politically relevant issues, such as invasive species. Fundamentally, data for the *Species populations* class are rich across all regions, reflecting its essential role in producing policy-relevant indicators. However, there are some EBV data products in the *Species traits* and *Ecosystem function* classes that have particular relevance in Japan and perhaps the greater Asia-Pacific region as well, such as phenological events of cultural importance and regional environmental disasters. These EBV data products are necessary to better address specific and regional biodiversity challenges.

In particular, enhancing data availability aligns with the emerging approaches for efficient biodiversity data

BOX 3 Biodiversity modeling approaches for EBVs

Biodiversity modeling has emerged as a powerful, comprehensive, and scalable approach to calculate EBVs across spatial and temporal scales (Boyd et al., 2023; Jetz et al., 2019; Kissling, Walls, et al., 2018; Tehrani et al., 2021). Species distribution models (SDMs) use data on species' occurrences and environmental variables to make predictions of potential geographic distribution (Guisan et al., 2017), including for areas and times without sampled occurrence data (e.g., Tehrani et al., 2021). Predictions of SDMs do not refer to realized distributions of species (i.e., where species actually inhabit) but rather to where they could potentially inhabit given a host of assumptions. Potential distribution information is very useful because it tells us where suitable environments are for the species, but SDM predictions may need post-processing using ancillary data such as expert maps so they can best approximate actual ranges to inform the Species distributions EBV attribute (e.g., Oeser et al., 2024). Workflows for these models can be quite complex, involving preparation and processing of spatial data, cleaning data of spatial and tabular errors, addressing data biases, tuning the complexity of machine learning algorithms used for modeling, and finally exploring and interpreting model outputs (Sillero et al., 2021). Further, there are many potential algorithms used for SDMs, and although top-performing methods have been identified, there is no single "best" solution for all research questions (Valavi et al., 2022). Luckily, there are many open-source programming tools available for SDMs that can help researchers implement methodological best practices (Kass et al., 2024). Additionally, interactive tools that require little to no programming, like *Wallace EcoMod* (Kass et al., 2023) or BON in a Box (Griffith et al., 2024), make these tools available for a broader user base.

To produce accurate model estimates, data of both high quality and quantity are essential. Currently, the wide availability of open datasets for opportunistic species' occurrence data, such as GBIF (https://www.gbif.org/) and the Japanese satellite group JBIF (https://gbif.jp/en/), and OBIS (https://obis.org/), and for climate data such as WorldClim (https://worldclim.org/), CHELSA (https://chelsa-climate.org/), and BIO-Oracle (https://www.bio-oracle.org/), among others, provides valuable resources for SDMs. Expert range maps for some species are available from data providers like the IUCN Red List database (https://www.iucnredlist.org/), but as these may be missing unsampled areas or follow political boundaries, used alone, they may be inappropriate for biodiversity estimates (Orr et al., 2022). Another strategy is to estimate the "area of habitat," which is a correction of an expert map using ancillary data such as elevational limits (Brooks et al., 2019), and these can be used as alternatives to SDMs (though the products are maps with single values instead of continuous prediction surfaces).

Estimates of abundance are much more informative than those for distribution alone because they allow us to make better inferences about biomass, ecosystem function, population dynamics, and extinction risk, for example. However, data on abundance are more difficult to acquire than species occurrences, as they typically require structured sampling designs and significant effort, resulting in a shortage for most taxa (Kissling, Ahumada, et al., 2018). This means it is critical to both gather more abundance data and begin new long-term sampling regimes to build on existing efforts like JaLTER, Monitoring Sites 1000, and the National Forest Inventory (see Table 1). Some national Japanese datasets, such as those for the Monitoring Sites 1000 Project, have abundance data on select species, but these are typically focused on plants and are narrow in taxonomic scope. When the data is available, models that predict species' abundance can be fitted with many of the same methods as for SDMs, and they can estimate environmental drivers and map predicted abundance patterns for different areas and times given future environmental data (Waldock et al., 2022).

SDMs have clear applications for the *Species Populations* class, but they can also be used to make community estimates for the *Community composition* class. Gridded estimates of community composition can be made by overlaying (or "stacking") SDMs from individual species, then optionally correcting assemblage estimates using ancillary data on species interactions to remove improbable co-occurrences (D'Amen et al., 2015). Alternatively, joint SDM approaches can be implemented that model multiple species' distributions simultaneously and account for shared environmental associations (Warton et al., 2015). Community composition estimates from these methods can be used to calculate various biodiversity indices that inform EBV attributes for the *Community composition* class, such as maps of taxonomic richness and turnover (e.g., alpha and beta diversity), as well as similar maps for phylogenetic, functional, abundance, genetic, and interaction diversity when the appropriate datasets are available (Pollock et al., 2020).

In sum, biodiversity models can provide the core data needed to calculate different EBVs, and these can be tailored to priority EBV attribute values for countries, given other diverse data inputs. As more community modeling applications are developed and techniques to integrate different datasets progress, we expect that biodiversity models will continue to grow as key contributors to EBV estimation over time.

acquisition in two key areas: phenology and species distribution. First, phenology is a crosscutting ecological variable represented by the Phenology and Ecosystem phenology attributes within the *Species traits* and *Ecosystem function* classes. It benefits from long-term observational datasets and is suitable for RS-based monitoring (Box 2). Second, the Species distributions EBV attribute can be effectively addressed using modeling-based approaches, such as species distribution models (SDMs), which are widely employed for estimating potential species ranges across spatial and temporal scales (Box 3). Furthermore, joint SDM approaches are expected to contribute to estimating community-level properties, which support the *Community composition* class. Together, the RS- and model-based approaches are increasingly recognized as cost-effective and scalable methods capable of supporting multiple EBV classes and capturing spatiotemporal biodiversity patterns across diverse ecosystems and biomes.

3 | EBVs AND INDICATORS FOR NBSAP TARGETS IN JAPAN

As EBVs capture the distribution, status, and trends of species and ecosystems, they can be applied to calculate indicators that measure the progress for each goal and target, as well as their subcomponents of global and national targets, such as KMGBF and NBSAPs (Kim et al., 2023). Under the CBD definition, indicators can be broken into different categories. Headline indicators are a minimum set of high-level indicators that capture the overall scope of the goals and targets of the KMGBF to be used for planning and tracking progress of the Framework. Complementary and component indicators support or break down headline indicators into more specific components to provide detailed information. For example, the headline indicator recommended for reporting progress on Target 3 (30 by 30) measures the coverage of protected areas, other effective area-based conservation measures (OECMs), and areas not formally designated as protected areas that nonetheless contribute to biodiversity goals; this is a promising metric that can be readily assessed. For Target 3, for example, complementary and component indicators measure species and ecosystem status, evaluating the effectiveness of protected areas and OECMs in ensuring species protection as well as ecosystem health and connectivity (Table 4). Such indicators and their subcomponents can be derived from EBVs, particularly from the classes *Ecosystem structure* and *Species populations*, for which we identified an abundance of available biodiversity data. These indicators reflect key aspects of biodiversity status and trends, such as those related to species distributions, ecosystem distribution, and habitat connectivity, and are essential for assessing the trajectories of different aspects of biodiversity. Monitoring the effectiveness of biodiversity conservation must go beyond simply assessing protected areas, so these indicators should play a crucial role in providing a holistic view of progress. Furthermore, national-scale EBV assessments can support the identification of ecologically important areas that can qualify as OECMs by providing indicator-based insights into biodiversity status and trends. Such data-driven approaches can facilitate the expansion of area-based conservation beyond formally designated protected areas (Shiono et al., 2021).

At the national level, EBVs can also contribute to monitoring biodiversity and establishing a regional system for activities related to the implementation and management of OECMs. In Japan's new NBSAPs (MOE, 2023), one of the key targets is the domestic implementation and delivery of the 30 by 30 target, which involves local stakeholders such as companies, universities, and schools with "green areas" on their campuses or land. To support this, Japan launched the 30 by 30 Roadmap in 2022 (MOE, 2022a). OECMs play a critical role in achieving this target, particularly by engaging local stakeholders in the management of conservation sites. Japan's policy to promote OECMs includes a scheme to certify conserved areas as "Nationally Certified Sustainably Managed Natural Sites." These sites are meant to contribute to biodiversity conservation through the initiatives of private entities and are based on criteria that require

TABLE 4 Proposed components and complementary indicators for Target 3 (as proposed at the 15th meeting of the Conference of the Parties to the Convention on Biological Diversity [SCBD, 2022]), and the criteria for 30 by 30 in Japan (MOE, 2022b), including essential subcomponents of the indicators and their corresponding essential biodiversity variable (EBV) attributes.

Indicator level	Indicators	Subcomponent	Corresponding EBV attributes	Description	No
Complementary indicators	Protected area coverage of Key Biodiversity Areas (KBAs)	KBAs	Species distribution, Ecosystem distribution	KBAs are sites that contribute significantly to the global persistence of biodiversity. They are defined using EBVs such as threatened species, species distribution, and ecological integrity.	1
	Species protection index		Species abundance, Species distribution	The index measures the area-based conservation targets met for species within a country, directly supported by species distribution and species abundance EBVs	2
	Red list of ecosystems connectivity indicator (in development)		Ecosystem distribution	EBVs related to ecosystem extent, ecosystem function, and ecosystem structure could support this indicator by providing data on ecosystem health, connectivity, and resilience.	3
	Protected area connectedness index (PARC-Connectedness)		Ecosystem distribution	EBVs focusing on ecosystem distribution and ecosystem connectivity could contribute to assessing the connectedness of ecosystems across protected areas.	4
	Red list of ecosystems		Ecosystem distribution, Ecosystem disturbance	EBVs such as ecosystem extent and ecosystem function can inform the assessment of ecosystem health and risk of collapse, which are key components of the Red list of ecosystems.	5
Complementary indicators	Status of KBAs	KBAs	Species distribution, Ecosystem distribution	The condition of KBAs, whether favorable or not, can be assessed using species distribution and ecosystem extent.	6
	Protected area isolation index (PAI)		Ecosystem distribution, Species distribution	The index measures the degree of isolation of protected areas and the connectivity of species and ecosystems between them.	7
	Protected areas network metric (ProNet)		Ecosystem distribution	The metric assesses how well protected areas form a cohesive network to maintain biodiversity and ecosystem services, which can be measured by ecosystem connectivity and extent	8
	Coverage of protected areas and Other Effective Area-based Conservation Measures (OECMs) and traditional territories (by governance type)		Ecosystem distribution	This value represents the simple coverage of types of conserved areas, which can be measured using EBVs related to ecosystem distribution.	9

(Continues)

TABLE 4 (Continued)

Indicator level	Indicators	Subcomponent	Corresponding EBV attributes	Description	No
	Proportion of terrestrial, freshwater, and marine ecological regions conserved by protected areas or OECMs	Ecological region (Ecoregion)	Ecosystem distribution	Ecoregions are defined by distinct ecosystem types and can be assessed using EBVs related to ecosystem extent and distribution.	10

monitoring standards that can be supported by EBVs (Table S3).

The validity of a proposed monitoring plan is assessed based on the site's condition and its status in terms of biodiversity conservation value. Several criteria are considered: (1) area boundaries and naming; (2) governance; (3) relevance of biodiversity elements, such as areas, species, or functions important for conservation; and (4) conservation impact of activities, including the use of appropriate monitoring methods and expert involvement. Relevant EBVs can particularly contribute to (3) and (4). In the case of (3), areas with pristine natural ecosystems and species vital for conservation can be identified using the EBV attributes Ecosystem distribution and Species distributions, respectively. For (4), monitoring efforts should ideally involve experts familiar with the site's natural environment and its associated biodiversity. The utility and effectiveness of monitoring activities could be significantly enhanced by sharing results of ecosystem distribution monitoring in real time with experts via a web platform, which would contribute to the assessment and ongoing monitoring of OECM status.

While OECMs are expected to be monitored according to their implementation plans, a key challenge is to enable non-experts, such as local stakeholders, to effectively design and perform these monitoring activities. For example, citizen scientists enhance biodiversity research by surveying under-sampled areas, such as private lands and remote regions, thereby contributing to estimates of species abundance using semistructured sampling as in eBird and analyzing secondary data (e.g., photos and audio) to reveal species interactions and habitat information (Callaghan et al., 2021). Approaches that are both accessible and robust are crucial, especially for participants without extensive scientific expertise. Such participants can contribute valuable insights by assessing the feasibility and practical application of EBV data products produced by scientists to monitor OECMs. The use of indicator species is another way to simplify and enhance the monitoring process. In Japan, abundant insect species associated with particular ecosystems or landscapes have often been used as indicators. For example, the distribution and abundance of rhinoceros beetles and small stag beetles can be considered potential indicators of the health of coppice forests in satoyama areas (MOE, 2024). Furthermore, EBVs for species distributions and functions can be used to identify indicator species for different ecosystem types and conditions.

While high-resolution spatial data are needed for monitoring OECMs, the currently available ecosystem-based EBVs tend to have coarser resolutions, which makes the generation of finer-scale maps of ecosystem processes a priority. To maintain accurate spatial data, field data must be used for verification. Moreover, monitoring data from OECM sites should be systematically archived in data repositories to complement the EBVs and enhance their utility. Such integration would enable local-level monitoring for national-scale assessments, ultimately establishing a feedback loop between OECM implementation and EBV monitoring.

We examined the linkage among biodiversity data, EBV attributes, global indicators, and national criteria for the 30 by 30 targets and identified gaps among them (Figures 3 and S2). The availability of biodiversity data for each EBV class influenced the selection of indicators. For example, data on the Species distributions and Ecosystem distribution attributes were typically available and particularly applicable for the 30 by 30 indicators. In contrast, Community abundance and Taxonomic diversity from the *Community composition* class, as well as all attributes of the *Species traits* class, were largely underutilized for the current suggested indicators. Data on traits such as phenology and taxonomic diversity are available occasionally for Japan and could be effectively incorporated into indicators. This would promote a more balanced utilization of EBVs across different classes, reducing potential biases in biodiversity assessment.

Although each OECM is managed and monitored by its respective stakeholders, the cumulative impacts of the OECM network at the national scale must also be evaluated. The connectivity of ecosystems and the integration of mosaic landscapes with habitats for local biodiversity within the OECM network can exert synergistic effects that are particularly vital for maintaining ecological functions, species migration, and dispersal, allowing genetic exchange across regions. Patchy landscapes with high

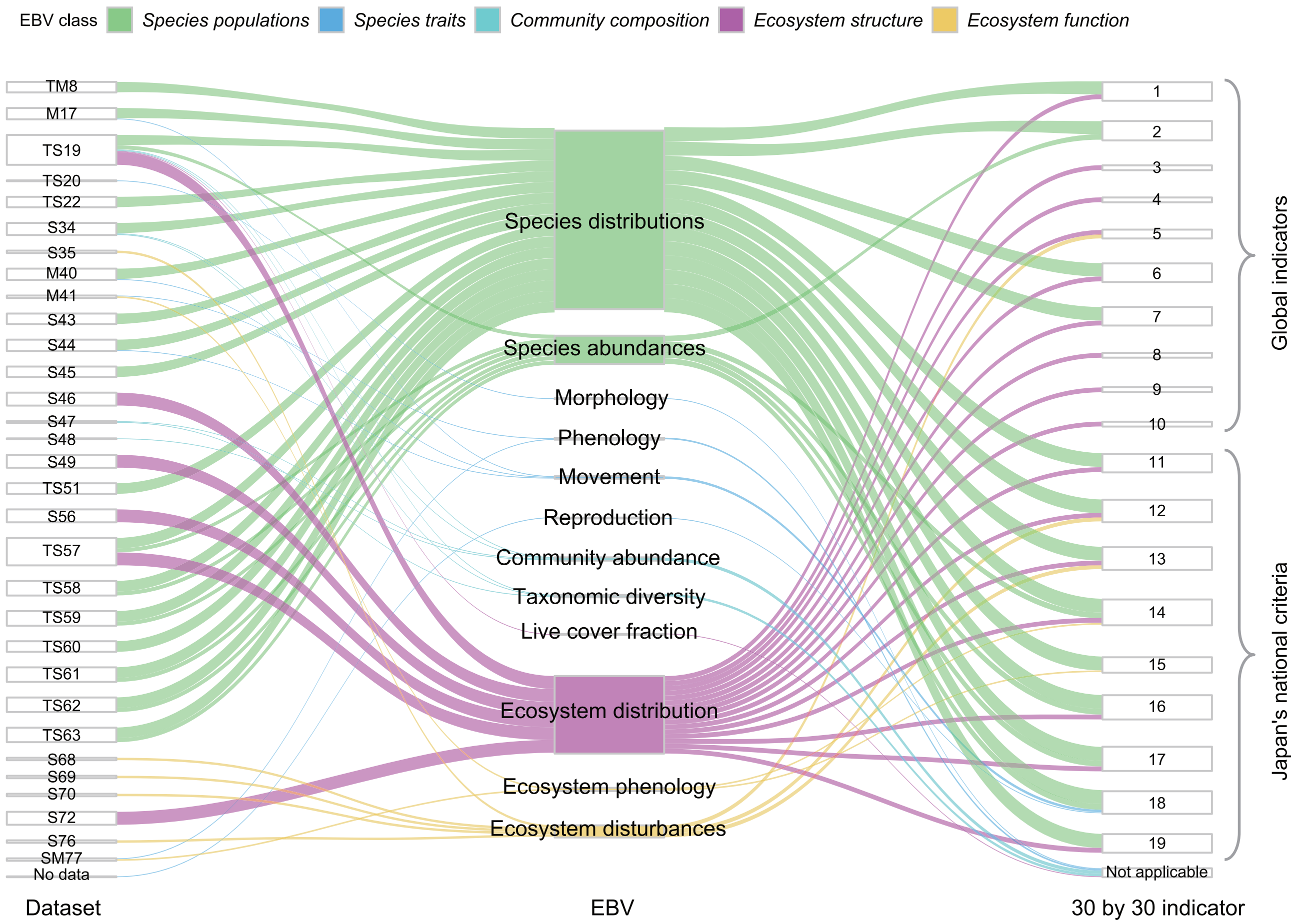

FIGURE 3 The links among biodiversity datasets in Japan, essential biodiversity variable (EBV) attributes, global indicators (as proposed at the 15th meeting of the Conference of the Parties to the Convention on Biological Diversity [SCBD, 2022]), and the criteria for 30 by 30 in Japan (MOE, 2022b). Only direct links to the spatial (S) and media (M) data are shown, listed in Table 1. The number of flows represents the number of datasets (left column) and the number of corresponding indicators or criteria (right column), whereas the height of the middle nodes represents how well connected an EBV is to the datasets and indicators. The codes for the 30 by 30 indicators are listed in Table 4 for global indicators and Table S3 for Japan's national criteria. The figure was modified for a balanced representation; therefore, flow widths are not representative of the data. The links among tabular (T) biodiversity data, indicators, and criteria for 30 by 30 in Japan are shown in Figure S2.

habitat connectivity maintained via traditional agricultural practices, such as satoyama, have harbored high biodiversity over generations. Such landscapes provide essential habitat for animals that depend on heterogeneous environments, such as various species of birds, butterflies, damselflies, amphibians, and fishes, including some species with conservation concern and important ecosystem functions (Katoh et al., 2009). Monitoring the overall connectivity, integrity, and stability of these landscapes is essential to fully capture the broader ecological benefits of the OECM network. EBVs related to ecosystem connectivity and structure can play a vital role in tracking these synergies, ensuring that the OECMs not only maintain the ecological integrity of individual sites but also contribute to larger landscape-level conservation goals.

4 | PERSPECTIVES

4.1 | Suggestions on moving forward toward calculating EBVs at the national scale in Japan

Here, we identified the availability and gaps of datasets for EBVs in Japan and Finland, and we envision the next step is to create a priority list of EBV data products for Japan. High-priority EBVs that align closely with broader biodiversity goals, targets, and local or national management objectives, such as the *Species populations* and *Ecosystem structure* classes, already have high data availability and ongoing monitoring activities. From a policy perspective, this alignment ensures that the data collected are meaningful for decision-making, reporting, and conservation efforts. Aggregating this information at the national scale can provide valuable insights into progress at the regional and global scales (e.g., CBD national reports and Japan Biodiversity Outlook). This process can also aid in addressing key challenges for biodiversity conservation and optimizing the use of limited resources by focusing on the most needed and feasible EBVs. Monitoring all potential EBVs is resource-intensive and often impractical. By prioritizing the most relevant EBVs, resources can be allocated more efficiently, and monitoring efforts can be harmonized across regions and stakeholders (Box 4). In this process, additional EBV data products that are most relevant to evaluate regional and unique environments should also be discussed. For instance, as Japan is a nation of many islands, its biogeography is characterized by frequent isolation, leading to a high number of endemic species, which aligns with the growing global recognition of the importance of island biodiversity (Schrader et al., 2024). In addition, secondary landscapes, such as satoyama, play a crucial role in biodiversity at the landscape level and highlight the current issue of biodiversity underuse (WGCABES, 2021). The Satoyama index can serve as an indicator of this issue, but it needs to consider anthropogenic interventions as key drivers in maintaining biodiversity. EuropaBON selected EBV data products that align with their regional priorities, including specific concerns such as invasive alien species, animal diseases, pests, and pollution indicators (Box 1). Similarly, Japan can select certain EBV data products for conservation and monitoring that reflect its unique national priorities and values, including specific biodiversity disturbance drivers such as typhoons and geological events, as well as secondary landscapes like satoyama, which hold both cultural and ecological significance. Furthermore, Japan's relatively high proportion of urban areas compared with its total land area emphasizes the significance of urban biodiversity and the quality of urban habitats.

On the other hand, data gaps or poor connections between EBV data products and indicators hinder the effective utilization of these products. To fill the data gaps, launching entirely new monitoring activities for EBVs might not be feasible. Thus, as a first measure, efforts should focus on improving data integration and accessibility, as well as opening “hidden” data across both the public and private sectors. Integrating diverse datasets such as citizen science, existing biodiversity databases, and RS datasets (see Box 2 for RS-based phenology) and making these data more accessible are key to facilitating biodiversity monitoring for EBV data products. For example, although Japan is a data-rich country, it faces several challenges regarding data accessibility. For global data users, the foremost challenge is the language barrier, as many of the datasets are only available in Japanese on websites and forms. Metadata are also often not translated into English, and international standards such as the Darwin Core (Wieczorek et al., 2012) and Humboldt Core (Guralnick et al., 2018) are only beginning to appear for deposited data. Thus, in contrast with the European landscape, where data are generally easily accessible in multiple languages and follow common formats, data in Japan are obstructed by language issues and inconsistent metadata. However, efforts are underway to make Japanese data more accessible, such as integrating Japanese vegetation maps with global ecosystem typologies (Keith et al., 2022; Végh et al., 2024) and accumulating standardized biodiversity data through the Japan Initiative for Biodiversity Information (JBIF). Currently, JBIF is working to disseminate biodiversity information globally and promote its use within Japan by adopting the Darwin Core and opening data through GBIF. Such global databases can serve as hubs for integrating the existing data reported in Table 1, facilitating broader access and usage. Furthermore, as Güntsch et al. (2024) discussed, National Biodiversity Data Infrastructures are essential in serving as key providers, facilitators, mediators, and platforms for the effective management, including quality control, integration, and analysis of biodiversity data at the national level (see Section 2.2: Luontotieto in Finland).

In addition, more cost-effective methods should be used to collect and generate primary data for EBV data products. In addition to RS-based monitoring (Box 2) and modeling approaches (Box 3), recent advancements in environmental DNA (eDNA), camera traps, and soundscape recordings provide cost-effective alternatives to conventional field observations and facilitate the collection of standardized biodiversity data. Integrating these advanced methodologies with long-term monitoring schemes can enhance biodiversity monitoring and address the existing gaps of EBVs while contributing to targets 20 and 21 of the KMGBF. Moreover, these approaches can encourage strategic investment in capacity building, development of regional biodiversity observation technologies, and improvement in data collection and management services. While technical challenges exist for these technologies, such as temporal mismatches in available RS data across regions, there are also opportunities, such as sharing open algorithms for calculating RS-based EBV data products through GEO BON's BON in a Box tool (Griffith et al., 2024), for example. Lastly, harmonizing data across various scales and platforms remains a crucial task.

4.2 | Cross-country collaboration can further national EBVs and regional comparisons

The insights presented in this study demonstrate that countries on different sides of the globe with similar ecosystem types likely have related EBV workflows and thus can learn much from each other if joint research initiatives are established. For example, Japan and Finland are heavily forested countries with close to 70% forest cover, and both would benefit from developing multiscale monitoring methods for the early detection of forest ecosystem changes employing RS and long-term observation data. By calculating EBVs related to forest ecosystem structure, phenology, and species composition, joint studies between countries could explore how biodiversity responds to climate, forest management, and conservation practices between global regions. Another opportunity is to take advantage of the extensive long-term phenological data that both Japan and Finland possess to detect changes in forest phenology for EBV production and comparative studies. For example, satellite data with validation via time-lapse cameras can be used to examine the impacts of climate change on leaf flush and fall across latitudinal gradients, with a focus on high-latitude, boreal forests where warming is faster than the global mean (Rantanen et al., 2022). By leveraging the strengths of different nations, such as data availability and advanced monitoring capabilities, and by aligning their research under the EBV framework, countries with environmental similarities like Japan and Finland can work toward more effective, globally integrated biodiversity monitoring and conservation efforts.

This study also highlights the importance of regionally specific EBV data products. In Japan, for instance, we had abundant data on the phenology of cherry blossom trees and disturbance drivers such as deer herbivory, typhoons, and earthquakes that are specific to Japan's unique geography, culture, and environmental concerns. Some of these records are preserved in historical archives, thereby providing valuable opportunities for long-term trend analysis. Similarly, region-specific EBVs can be found in other countries or regions. For example, the EuropaBON's EBV list includes the distributions of invasive alien terrestrial species of European concern, reflecting region-specific priorities. These examples illustrate how the process of developing EBV lists can uncover regional challenges and reveal shared concerns that serve as a basis for collaboration. By aligning such regionally grounded strengths within the EBV framework, countries such as Japan and Finland can contribute to more effective and globally coordinated biodiversity monitoring and conservation efforts.

4.3 | Need for science-policy dialogue

To create a priority list for EBV data products, dialogue with policymakers is crucial to ensure that data collection efforts effectively address policy needs and align with policy priorities. National and regional platforms such as the Japan Biodiversity Observation Network and the Asia-Pacific Biodiversity Observation Network play a critical role in connecting scientific knowledge with policy needs to convene a robust science-policy dialogue (Takeuchi et al., 2021). These platforms bring researchers, policymakers, and social stakeholders, including NGOs and the private sector, together to assess and track the progress of national and global biodiversity goals. Local and regional scientific outcomes and discussions should also be incorporated into global initiatives such as the CBD to facilitate global coordination of biodiversity trends.

Importantly, this study highlights the critical role of governmental institutions as key data providers. For example, the Monitoring Sites 1000 Project (https://www.biodic.go.jp/moni1000/ [in Japanese]) serves as a national model for large-scale biodiversity monitoring. However, Japan faces continuous population decline, which makes maintaining and ensuring sustainable monitoring activities a critical issue. Science plays a key role in guiding the efficient implementation of these activities. For example, integrating advanced technologies, such as RS, with current field-based monitoring approaches can enable more sustainable biodiversity monitoring that requires little human effort. Moreover, scientific reviews and assessments by policymakers are essential to evaluate how EBVs can contribute to addressing policy needs for environmental monitoring. This includes the 30 by 30 initiative and other targets aimed at tracking the progress of national strategies, including initiatives such as the next national biodiversity assessment (JBO4, retrieved on March 30, 2025, https://www.env.go.jp/nature/biodiversity/jbo.html [in Japanese]).

Thus, strengthening the roles of governmental institutions, including biodiversity data collection, can be achieved through robust science-policy dialogue, thereby ensuring that scientific advancements and policy implementation support each other. This would facilitate the collection of effective EBV data products by improving data integration and accessibility, and also by making hidden data more open, as discussed in Section 4.1. In addition, the role of venture companies in biodiversity monitoring and supporting biodiversity impact assessments has gained attention. This involvement can further contribute to promoting a culture of biodiversity appreciation across the private sector and advancing the goal of a nature-positive society.

BOX 4 Schema for establishing a regional EBV priority list

As explained in Box 1, selecting and prioritizing EBVs is a crucial step for implementing effective monitoring that aligns with local needs, conservation targets, and regional priorities. Schemas for prioritizing EBVs have been developed in previous studies. For example, Skidmore et al. (2021) reported a prioritized list of RS-based EBVs. They found that the classes *Ecosystem structure* and *Ecosystem function*, which capture habitat structure and biological effects of disturbance, were the most relevant and feasible for RS and were thus given higher priority than other EBV classes for RS-based approaches. This study underscores the potential of integrating RS into EBV monitoring frameworks to improve biodiversity reporting at global and local scales. More recently, EuropaBON developed a codesign scheme for EBVs conducted through workshops with stakeholders (Lumbierres & Kissling, 2023). This has resulted in two main outcomes: first, knowledge of EBVs has become far more widespread in Europe than in other parts of the world, and second, prioritized EBV data products are aligned with their regional needs of EuropaBON and thus reflect the European landscape and challenges. The EBV workflow was defined based on data gaps, needs, and novel monitoring technologies identified through a survey of experts. This process also facilitated the harmonization of EBV monitoring and enhanced internal collaboration across the EU. Below, we have summarized a multicriteria evaluation scheme for establishing a priority list for EBVs within regional groups.

1. Selection of EBVs: The first step is to start with a broad list of EBVs to be converted from data based on field observation, RS observation, and/or modeling. This long list serves as the basis for further evaluation.
2. Scoring based on key criteria: The criteria for scoring can be flexible, balancing societal needs with practical feasibility. Example criteria include (Skidmore et al., 2021):
   a. Relevancy: Assesses how well each variable supports policy reporting and management needs.
   b. Feasibility: Determines whether scientific methods and technologies are available to monitor the variable.
   c. Suitability: Evaluates how well the variable fits within current research frameworks and data workflows.
3. Expert discussions: Collaboration with experts, including those from scientific policy and monitoring, is essential to gather insights into the definition, feasibility, and policy relevance of each attribute.
4. Scoring, ranking, and review: Once information is collected, each variable is scored based on the criteria. The total score for each attribute is calculated by summing these scores, and this total score is used to rank the variables in terms of priority. Through internal and, if necessary, external review, the list is finalized for implementation, including how resources should be allocated and which policies should be engaged to maximize impact.
5. Management of the list: The priority list is published online, and a final public review is conducted if necessary. The list may be periodically updated to reflect societal needs and advancements in monitoring technologies (i.e., adaptive monitoring).

Establishing an EBV priority list ensures that the most important and actionable EBVs are monitored, significantly contributing to both scientific understanding and policy implementation within the regional context. By following a clear and systematic prioritization process, Japan and Finland can optimize their biodiversity monitoring efforts, ensuring that the most critical biodiversity variables are addressed efficiently and effectively. As the relative importance of EBVs varies among stakeholders, it is crucial to involve policymakers, conservation managers, local communities, and other stakeholders in the process. As the next step, the group will discuss how to implement biodiversity monitoring for the prioritized EBVs, allocate resources effectively, and use cutting-edge biodiversity monitoring technologies to support the implementation process.

5 | CONCLUSION

The results of our comparative analysis of data availability and needs for EBVs highlight the necessity for dual consideration of the benefits of global standardization and the reality of practical implementation at different geopolitical scales. Our comparison of biodiversity data among global, regional, and national scales revealed commonalities and differences, which led us to create a priority list of EBV data products for Japan. This process will help address challenges related to the effective collection and integration of datasets, facilitating global comparisons of biodiversity trends and achievement of targets through initiatives such as GBiOS (Gonzalez et al., 2023). The EBV framework serves as a critical foundation for informing policy, guiding conservation planning, and fostering regional to global collaboration. EBVs not only play a pivotal role in tracking progress toward global and national biodiversity targets but also help identify region-specific environmental characteristics and challenges.

In conclusion, we found that Japan has moderate-to-high data availability across several EBV classes and that these EBVs can support biodiversity indicators, such as those for the 30 by 30 target, although key gaps in the data were revealed, which must be addressed for effective implementation. The EBV framework provides a powerful tool for planning effective biodiversity data collection at the national scale, fostering international collaboration, and facilitating global comparisons. By addressing the challenges of biodiversity conservation, the framework enables significant national progress and meaningful global contributions, helping to ensure more coordinated and impactful efforts toward the CBD's 2050 vision for biodiversity: "lives in harmony with nature."

ACKNOWLEDGMENTS

This review paper was initiated from discussions that began at the symposium "Advancing Terrestrial Ecosystem Assessment with Essential Biodiversity Variables: Insight into Achieving the Global Biodiversity Framework" at the 71st Annual Meeting of the Ecological Society of Japan (ESJ), 2024. This symposium aimed to introduce EBVs to the Japanese ecological community and discuss the potential of EBV frameworks in Japan by referring to existing data, methodologies, and current issues in Japan and Finland. We thank the Ecological Society of Japan for their support in the symposium and for encouraging us to undertake this review. We are also grateful to Dr. Mathieu Basille and two anonymous reviewers for their valuable comments. The study was supported by the Climate Change Adaptation Research Program, National Institute for Environmental Studies (Y.T., L.V.); Project on Detection of signals of climate change in deciduous broadleaf forests in Japan, National Institute for Environmental Studies (Y.T., H.N.); European Space Agency Living Planet Fellowship Project (ESA Contract No. 4000135793/21/I-DT-lr, K.B.); Program on Open Innovation Platform for Industry-academia Co-creation (COI-NEXT) by Japan Science and Technology Agency (JST) (grant no. JPMJPF2206, J.M.K.); European Union's Horizon Europe research and innovation programme (grant agreement No. 101134954, K.B., P.V.); and the Research Council of Finland, FinBIF project (grant number 345733, K.B.).

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

ORCID

Yayoi Takeuchi https://orcid.org/0000-0002-8402-7854
Lea Végh https://orcid.org/0000-0001-7948-480X
Hibiki Noda https://orcid.org/0000-0003-0467-0899
Kristin Böttcher https://orcid.org/0000-0002-2181-5976
Petteri Vihervaara https://orcid.org/0000-0002-5889-8402
Jamie M. Kass https://orcid.org/0000-0002-9432-895X

REFERENCES

Aono, Y., & Kazui, K. (2008). Phenological data series of cherry tree flowering in Kyoto, Japan, and its application to the reconstruction of springtime temperatures since the 9th century. *International Journal of Climatology*, *28*, 905–914. https://doi.org/10.1002/joc.1594

Balvanera, P., Brauman, K. A., Cord, A. F., Drakou, E. G., Geijzendorffer, I. R., Karp, D. S., Martín-López, B., Mwampamba, T. H., & Schröter, M. (2022). Essential ecosystem service variables for monitoring progress towards sustainability. *Current Opinion in Environmental Sustainability*, *54*, 101152. https://doi.org/10.1016/j.cosust.2022.101152

Bellingham, P. J., Richardson, S. J., Gormley, A. M., Allen, R. B., Cook, A., Crisp, P. N., Forsyth, D. M., McGlone, M. S., McKay, M., MacLeod, C. J., Van Dam-Bates, P., & Wright, E. F. (2020). Implementing integrated measurements of essential biodiversity variables at a national scale. *Ecological Solutions and Evidence*, *1*, 12025. https://doi.org/10.1002/2688-8319.12025

Bojinski, S., Verstraete, M., Peterson, T. C., Richter, C., Simmons, A., & Zemp, M. (2014). The concept of essential climate variables in support of climate research, applications, and policy. *Bulletin of the American Meteorological Society*, *95*, 1431–1443. https://doi.org/10.1175/bams-d-13-00047.1

Böttcher, K., Aurela, M., Kervinen, M., Markkanen, T., Mattila, O.-P., Kolari, P., Metsämäki, S., Aalto, T., Arslan, A. N., & Pulliainen, J. (2014). MODIS time-series-derived indicators for the beginning of the growing season in boreal coniferous forest—A comparison with CO_2 flux measurements and phenological observations in Finland. *Remote Sensing of Environment*, *140*, 625–638. https://doi.org/10.1016/j.rse.2013.09.022

Böttcher, K., Markkanen, T., Thum, T., Aalto, T., Aurela, M., Reick, C., Kolari, P., Arslan, A., & Pulliainen, J. (2016). Evaluating biosphere model estimates of the start of the vegetation active season in boreal forests by satellite observations. *Remote Sensing*, *8*, 580. https://doi.org/10.3390/rs8070580

Boyd, R. J., August, T. A., Cooke, R., Logie, M., Mancini, F., Powney, G. D., Roy, D. B., Turvey, K., & Isaac, N. J. B. (2023). An operational workflow for producing periodic estimates of species occupancy at national scales. *Biological Reviews*, *98*, 1492–1508. https://doi.org/10.1111/brv.12961

Brooks, T. M., Pimm, S. L., Akçakaya, H. R., Buchanan, G. M., Butchart, S. H., Foden, W., Butchart, S. H. M., Hilton-Taylor, C., Hoffmann, M., Jenkins, C. N., Joppa, L., Li, B. V., Menon, V., Ocampo-Peñuela, N., & Rondinini, C. (2019). Measuring terrestrial area of habitat (AOH) and its utility for the IUCN Red List. *Trends in Ecology & Evolution*, *34*(11), 977–986.

Callaghan, C. T., Poore, A. G. B., Mesaglio, T., Moles, A. T., Nakagawa, S., Roberts, C., Rowley, J. J. L., Vergés, A., Wilshire, J. H., & Cornwell, W. K. (2021). Three frontiers for the future of biodiversity research using citizen science data. *Bioscience*, *71*(1), 55–63. https://doi.org/10.1093/biosci/biaa131

D'Amen, M., Pradervand, J., & Guisan, A. (2015). Predicting richness and composition in mountain insect communities at high resolution: A new test of the SESAM framework. *Global Ecology and Biogeography*, *24*, 1443–1453. https://doi.org/10.1111/geb.12357

Diao, C., Augspurger, C. K., Zhao, Y., & Salk, C. F. (2024). A satellite-field phenological bridging framework for characterizing community-level spring forest phenology using multi-scale satellite imagery. *ISPRS Journal of Photogrammetry and Remote Sensing*, *211*, 83–103. https://doi.org/10.1016/j.isprsjprs.2024.03.018

Dixon, D. J., Callow, J. N., Duncan, J. M. A., Setterfield, S. A., & Pauli, N. (2021). Satellite prediction of forest flowering phenology. *Remote Sensing of Environment*, *255*, 112197. https://doi.org/10.1016/j.rse.2020.112197

Duchemin, B., Goubier, J., & Courrier, G. (1999). Monitoring phenological key stages and cycle duration of temperate deciduous forest ecosystems with NOAA/AVHRR data. *Remote Sensing of Environment*, *67*, 68–82. https://doi.org/10.1016/s0034-4257(98)00067-4

Feng, G., Masek, J., Schwaller, M., & Hall, F. (2006). On the blending of the Landsat and MODIS surface reflectance: Predicting daily Landsat surface reflectance. *IEEE Transactions on Geoscience and Remote Sensing*, *44*, 2207–2218.

Ganguly, S., Friedl, M. A., Tan, B., Zhang, X., & Verma, M. (2010). Land surface phenology from MODIS: Characterization of the collection 5 global land cover dynamics product. *Remote Sensing of Environment*, *114*, 1805–1816. https://doi.org/10.1016/j.rse.2010.04.005

Gonzalez, A., Vihervaara, P., Balvanera, P., Bates, A. E., Bayraktarov, E., Bellingham, P. J., Bruder, A., Campbell, J., Catchen, M. D., Cavender-Bares, J., Chase, J., Coops, N., Costello, M. J., Czúcz, B., Delavaud, A., Dornelas, M., Dubois, G., Duffy, E. J., Eggermont, H., … Torrelio, C. Z. (2023). A global biodiversity observing system to unite monitoring and guide action. *Nature Ecology & Evolution*, *7*, 1947–1952. https://doi.org/10.1038/s41559-023-02171-0

Gray, J., Sulla-Menashe, D., & Friedl, M. A. (2019). *User guide to collection 6 modis land cover dynamics (MCD12Q2) product*. NASA EOSDIS Land Processes DAAC.

Griffith, J., Lord, J. M., Catchen, M. D., Arce-Plata, M. I., Blanchet, G., Bohorquez, M. F. G., Chandramohan, M., Diaz-Corzo, M. C., Gravel, D., Gonzalez, L. F. U., Gutiérrez, C., Helfenstein, I. S., Hoban, S. M., Kass, J. M., Larocque, G., Laikre, L., Leigh, D. M., Leung, B., Mastretta-Yanes, A., … Gonzalez, A. (2024). BON in a Box: An open and collaborative platform for biodiversity monitoring, indicator calculation, and reporting. *Ecoevorxiv Preprints*. https://doi.org/10.32942/X2M320

Guisan, A., Thuiller, W., & Zimmermann, N. E. (2017). *Habitat suitability and distribution models: With applications in R*. Cambridge University Press.

Güntsch, A., Overmann, J., Ebert, B., Bonn, A., Le Bras, Y., Engel, T., Hovstad, K. A., Lange Canhos, D. A., Newman, P., Van Ommen Kloeke, E., Ratcliffe, S., Le Roux, M., Smith, V. S., Triebel, D., Fichtmueller, D., & Luther, K. (2024). National biodiversity data infrastructures: Ten essential functions for science, policy, and practice. *Bioscience*, *75*, biae109. https://doi.org/10.1093/biosci/biae109

Guralnick, R., Walls, R., & Jetz, W. (2018). Humboldt core – Toward a standardized capture of biological inventories for biodiversity monitoring, modeling and assessment. *Ecography*, *41*, 713–725. https://doi.org/10.1111/ecog.02942

Hadano, M., Nasahara, K. N., Motohka, T., Noda, H. M., Murakami, K., & Hosaka, M. (2013). High-resolution prediction of leaf onset date in Japan in the 21st century under the IPCC A1B scenario. *Ecology and Evolution*, *3*, 1798–1807. https://doi.org/10.1002/ece3.575

Hardisty, A. R., Michener, W. K., Agosti, D., Alonso García, E., Bastin, L., Belbin, L., Bowser, A., Buttigieg, P. L., Canhos, D. A. L., Egloff, W., De Giovanni, R., Figueira, R., Groom, Q., Guralnick, R. P., Hobern, D., Hugo, W., Koureas, D., Ji, L., Los, W., … Kissling, W. D. (2019). The Bari Manifesto: An interoperability framework for essential biodiversity variables. *Ecological Informatics*, *49*, 22–31. https://doi.org/10.1016/j.ecoinf.2018.11.003

Hirayama, H., Tomita, M., & Hara, K. (2020). Quantitative monitoring of changes in forest habitat connectivity following the great eastern Japan earthquake and tsunami. *Landscape Ecology*, *35*, 1519–1530. https://doi.org/10.1007/s10980-020-01034-4

Hoban, S., Archer, F. I., Bertola, L. D., Bragg, J. G., Breed, M. F., Bruford, M. W., Coleman, M. A., Ekblom, R., Funk, W. C., Grueber, C. E., Hand, B. K., Jaffé, R., Jensen, E., Johnson, J. S., Kershaw, F., Liggins, L., Macdonald, A. J., Mergeay, J., Miller, J. M., … Hunter, M. E. (2022). Global genetic diversity status and trends: Towards a suite of essential biodiversity variables (EBVs) for genetic composition. *Biological Reviews*, *97*, 1511–1538. https://doi.org/10.1111/brv.12852

ICH (Intangible Cultural Heritage in Hungary). (2024). Celebration of the 'grapevine bud break'. http://szellemikulturalisorokseg.hu/index0_en.php?name=en_0_szolojoves_unnepe

Ide, R., & Oguma, H. (2010). Use of digital cameras for phenological observations. *Ecological Informatics*, *5*, 339–347. https://doi.org/10.1016/j.ecoinf.2010.07.002

Ide, R., & Oguma, H. (2013). A cost-effective monitoring method using digital time-lapse cameras for detecting temporal and spatial variations of snowmelt and vegetation phenology in alpine ecosystems. *Ecological Informatics*, *16*, 25–34. https://doi.org/10.1016/j.ecoinf.2013.04.003

IPBES. (2019). *Global assessment report of the intergovernmental science-policy platform on biodiversity and ecosystem services*. IPBES Secretariat.

Ishihara, M., & Tadono, T. (2017). Land cover changes induced by the great east Japan earthquake in 2011. *Scientific Reports*, *7*, 45769. https://doi.org/10.1038/srep45769

Jetz, W., McGeoch, M. A., Guralnick, R., Ferrier, S., Beck, J., Costello, M. J., Fernandez, M., Geller, G. N., Keil, P., Merow, C., Meyer, C., Muller-Karger, F. E., Pereira, H. M., Regan, E. C., Schmeller, D. S., & Turak, E. (2019). Essential biodiversity variables for mapping and monitoring species populations. *Nature Ecology & Evolution*, *3*, 539–551. https://doi.org/10.1038/s41559-019-0826-1

Junker, J., Beja, P., Brotons, L., Fernandez, M., Fernández, N., Kissling, W. D., Lumbierres, M., Lyche Solheim, A., Maes, J., Morán-Ordóñez, A., Moreira, F., Musche, M., Santana, J., Valdez, J., & Pereira, H. (2023). D4.1. List and specifications of EBVs and EESVs for a European wide biodiversity observation network. *ARPHA Preprints*. https://doi.org/10.3897/arphapreprints.e102530

Kadoya, T., & Washitani, I. (2011). The Satoyama Index: A biodiversity indicator for agricultural landscapes. *Agriculture, Ecosystems & Environment*, *140*, 20–26. https://doi.org/10.1016/j.agee.2010.11.007

Kass, J. M., Pinilla-Buitrago, G. E., Paz, A., Johnson, B. A., Grisales-Betancur, V., Meenan, S. I., Attali, D., Broennimann, O., Galante, P. J., Maitner, B. S., Owens, H. L., Varela, S., Aiello-Lammens, M. E., Merow, C., Blair, M. E., & Anderson, R. P. (2023). *wallace* 2: A shiny app for modeling species niches and distributions redesigned to facilitate expansion via module contributions. *Ecography*, *2023*, 6547. https://doi.org/10.1111/ecog.06547

Kass, J. M., Smith, A. B., Warren, D. L., Vignali, S., Schmitt, S., Aiello-Lammens, M. E., Arlé, E., Márcia Barbosa, A., Broennimann, O., Cobos, M. E., Guéguen, M., Guisan, A., Merow, C., Naimi, B., Nobis, M. P., Ondo, I., Osorio-Olvera, L., Owens, H. L., Pinilla-Buitrago, G. E., … Zurell, D. (2024). Achieving higher standards in species distribution modeling by leveraging the diversity of available software. *Ecography*, *2025*, e07346.

Katoh, K., Sakai, S., & Takahashi, T. (2009). Factors maintaining species diversity in satoyama, a traditional agricultural landscape of Japan. *Biological Conservation*, *142*, 1930–1936.

Keith, D. A., Ferrer-Paris, J. R., Nicholson, E., Bishop, M. J., Polidoro, B. A., Ramirez-Llodra, E., Tozer, M. G., Nel, J. L., Mac Nally, R., Gregr, E. J., Watermeyer, K. E., Essl, F., Faber-Langendoen, D., Franklin, J., Lehmann, C. E. R., Etter, A., Roux, D. J., Stark, J. S., Rowland, J. A., … Kingsford, R. T. (2022). A function-based typology for Earth's ecosystems. *Nature*, *610*, 513–518. https://doi.org/10.1038/s41586-022-05318-4

Kim, H., Navarro, L., Balvanera, P., Campbell, J., Chaplin-Kramer, R., Child, M., Ferrier, S., Geller, G., Gill, M., Krug, C., Millette, K., Muller-Karger, F., & Pereira, H. (2023). Essential biodiversity variables and essential ecosystem services variables for the implementation of biodiversity conservation and sustainable development goals. *Ecoevorxiv Preprints*. https://doi.org/10.32942/X2130Z

Kissling, W. D., Ahumada, J. A., Bowser, A., Fernandez, M., Fernández, N., García, E. A., Guralnick, R. P., Isaac, N. J. B., Kelling, S., Los, W., Mcrae, L., Mihoub, J., Obst, M., Santamaria, M., Skidmore, A. K., Williams, K. J., Agosti, D., Amariles, D., Arvanitidis, C., … Hardisty, A. R. (2018). Building essential biodiversity variables (EBVs) of species distribution and abundance at a global scale. *Biological Reviews*, *93*, 600–625. https://doi.org/10.1111/brv.12359

Kissling, W. D., Walls, R., Bowser, A., Jones, M. O., Kattge, J., Agosti, D., Amengual, J., Basset, A., Van Bodegom, P. M., Cornelissen, J. H. C., Denny, E. G., Deudero, S., Egloff, W., Elmendorf, S. C., Alonso García, E., Jones, K. D., Jones, O. R., Lavorel, S., Lear, D., … Guralnick, R. P. (2018). Towards global data products of essential biodiversity variables on species traits. *Nature Ecology & Evolution*, *2*, 1531–1540. https://doi.org/10.1038/s41559-018-0667-3

Lindstrom, E., Gunn, J., Fischer, A., McCurdy, A., & Glover, L. K. (2012). *A framework for ocean observing*. UNESCO. https://doi.org/10.5270/oceanobs09-foo

Lumbierres, M., & Kissling, W. D. (2023). Important first steps towards designing the freshwater, marine and terrestrial essential biodiversity variable (EBV) workflows for the European Biodiversity Observation Network. *Research Ideas and Outcomes*, *9*, e109120. https://doi.org/10.3897/rio.9.e109120

Miura, T., Nagai, S., Takeuchi, M., Ichii, K., & Yoshioka, H. (2019). Improved characterisation of vegetation and land surface seasonal dynamics in central Japan with Himawari-8 hypertemporal data. *Scientific Reports*, *9*, 1–12. https://doi.org/10.1038/s41598-019-52076-x

MOE (Ministry of the Environment, Japan). (2002). *Development of the National Biodiversity Strategy of Japan (Revised in 2002) (The "New Biodiversity Strategy")*. MOE. https://faolex.fao.org/docs/pdf/jap158265.pdf

MOE (Ministry of the Environment, Japan). (2022a). *Japan establishes a 30 by 30 roadmap and launches the 30 by 30 alliance for biodiversity*. MOE. https://www.env.go.jp/en/headline/2608.html

MOE (Ministry of the Environment, Japan). (2022b). *The criteria for 30 by 30*. MOE. https://policies.env.go.jp/nature/biodiversity/30by30alliance/documents/30by30site-Identification-criteria.pdf

MOE (Ministry of the Environment, Japan). (2023). *The national biodiversity strategy and action plan of Japan 2023–2030 the roadmap to realizing nature-positive by 2030*. MOE. https://www.env.go.jp/content/000256855.pdf

MOE (Ministry of the Environment, Japan). (2024). *FY 2023, second meeting on 'promotion of the establishment and management of OECMs' agenda, materials, and minutes document 3–5: Monitoring approaches and indicators simplified monitoring methods focusing on insects (in Japanese)*. MOE. https://www.env.go.jp/content/000210249.pdf

Moon, M., Richardson, A. D., & Friedl, M. A. (2021). Multiscale assessment of land surface phenology from harmonized Landsat 8 and Sentinel-2, PlanetScope, and PhenoCam imagery. *Remote Sensing of Environment*, *266*, 112716. https://doi.org/10.1016/j.rse.2021.112716

Moon, M., Zhang, X., Henebry, G. M., Liu, L., Gray, J. M., Melaas, E. K., & Friedl, M. A. (2019). Long-term continuity in land surface phenology measurements: A comparative assessment of the MODIS land cover dynamics and VIIRS land surface phenology products. *Remote Sensing of Environment*, *226*, 74–92. https://doi.org/10.1016/j.rse.2019.03.034

Muraoka, H., Noda, H. M., Nagai, S., Motohka, T., Saitoh, T. M., Nasahara, K. N., & Saigusa, N. (2013). Spectral vegetation indices as the indicator of canopy photosynthetic productivity in a deciduous broadleaf forest. *Journal of Plant Ecology*, *6*, 393–407. https://doi.org/10.1093/jpe/rts037

Nasahara, K. N., & Nagai, S. (2015). Review: Development of an in situ observation network for terrestrial ecological remote sensing: (PEN). *Ecological Research*, *30*, 211–223. https://doi.org/10.1007/s11284-014-1239-x

Navarro, L. M., Fernández, N., Guerra, C., Guralnick, R., Kissling, W. D., Londoño, M. C., Muller-Karger, F., Turak, E., Balvanera, P., Costello, M. J., Delavaud, A., El Serafy, G. Y., Ferrier, S., Geijzendorffer, I., Geller, G. N., Jetz, W., Kim, E.-S., Kim, H., Martin, C. S., … Pereira, H. M. (2017). Monitoring biodiversity change through effective global coordination. *Current Opinion in Environmental Sustainability*, *29*, 158–169. https://doi.org/10.1016/j.cosust.2018.02.005

Noda, A., Ohta, Y., Yokota, H., Inoue, M., Shirakawa, K., Masui, T., Takahashi, Y., & Nishihiro, J. (2023). Database of Japanese semi-natural grassland flora. *Ecological Research*, *38*, 617–623. https://doi.org/10.1111/1440-1703.12388

Oeser, J., Zurell, D., Mayer, F., Çoraman, E., Toshkova, N., Deleva, S., Natradze, I., Benda, P., Ghazaryan, A., Irmak, S., Hasanov, N., Guliyeva, G., Gritsina, M., & Kuemmerle, T. (2024). The best of two worlds: Using stacked generalisation for integrating expert range maps in species distribution models. *Global Ecology and Biogeography*, *33*, 13911. https://doi.org/10.1111/geb.13911

Orr, M. C., Hughes, A. C., Costello, M. J., & Qiao, H. (2022). Biodiversity data synthesis is critical for realizing a functional post-2020 framework. *Biological Conservation*, *274*, 109735. https://doi.org/10.1016/j.biocon.2022.109735

Peltoniemi, M., Aurela, M., Böttcher, K., Kolari, P., Loehr, J., Hokkanen, T., Karhu, J., Linkosalmi, M., Tanis, C. M., Metsämäki, S., Tuovinen, J.-P., Vesala, T., & Arslan, A. N. (2018). Networked web-cameras monitor congruent seasonal development of birches with phenological field observations. *Agricultural and Forest Meteorology*, *249*, 335–347. https://doi.org/10.1016/j.agrformet.2017.10.008

Pereira, H. M., & Cooper, H. D. (2006). Towards the global monitoring of biodiversity change. *Trends in Ecology & Evolution*, *21*, 123–129. https://doi.org/10.1016/j.tree.2005.10.015

Pereira, H. M., Ferrier, S., Walters, M., Geller, G. N., Jongman, R. H. G., Scholes, R. J., Bruford, M. W., Brummitt, N., Butchart, S. H. M., Cardoso, A. C., Coops, N. C., Dulloo, E., Faith, D. P., Freyhof, J., Gregory, R. D., Heip, C., Höft, R., Hurtt, G., Jetz, W., … Wegmann, M. (2013). Essential biodiversity variables. *Science*, *339*, 277–278. https://doi.org/10.1126/science.1229931

Pollock, L. J., O'connor, L. M. J., Mokany, K., Rosauer, D. F., Talluto, L., & Thuiller, W. (2020). Protecting biodiversity (in all its complexity): New models and methods. *Trends in Ecology & Evolution*, *35*, 1119–1128. https://doi.org/10.1016/j.tree.2020.08.015

POST (Parliamentary Office of Science and Technology). (2021). *POSTbrief 41, Biodiversity indicators. Open Parliament Licence v3.0*. UK Parliament. https://doi.org/10.58248/PB41

Quoss, L., Junker, J., & Wendt, E. (2024). *EuropaBON/EBV-descriptions: EuropaBON EBVs list descriptions (v1.0)*. Zenodo. https://doi.org/10.5281/zenodo.12751236

Rantanen, M., Karpechko, A. Y., Lipponen, A., Nordling, K., Hyvärinen, O., Ruosteenoja, K., Vihma, T., & Laaksonen, A. (2022). The arctic has warmed nearly four times faster than the globe since 1979. *Communications Earth & Environment*, *3*, 168. https://doi.org/10.1038/s43247-022-00498-3

Richardson, A. D. (2019). Tracking seasonal rhythms of plants in diverse ecosystems with digital camera imagery. *New Phytologist*, *222*, 1742–1750. https://doi.org/10.1111/nph.15591

Röösli, C., Jong, R., Wingate, V., Marshall, D., Heiden, U., & van de Kerchove, R. (2020). Algorithm theoretical basis document – Land surface phenology. https://eo4society.esa.int/wp-content/uploads/2021/01/GlobDiversity_ATBD_LSP_V3-4_FINAL.pdf

SCBD (Secretariat of the Convention on Biological Diversity). (2020). Global biodiversity outlook 5. https://www.cbd.int/gbo/gbo5/publication/gbo-5-en.pdf

SCBD (Secretariat of the Convention on Biological Diversity). (2022). Decision adopted by the conference of the parties to the convention on biological diversity 15/5. Monitoring framework for the Kunming-Montreal Global Biodiversity Framework, CBD/-COP/DEC/15/5. https://policies.env.go.jp/nature/biodiversity/30by30alliance/documents/30by30site-Identification-criteria.pdf

Schmeller, D. S., Weatherdon, L. V., Loyau, A., Bondeau, A., Brotons, L., Brummitt, N., Geijzendorffer, I. R., Haase, P., Kuemmerlen, M., Martin, C. S., Mihoub, J.-B., Rocchini, D., Saarenmaa, H., Stoll, S., & Regan, E. C. (2018). A suite of essential biodiversity variables for detecting critical biodiversity change. *Biological Reviews*, *93*, 55–71. https://doi.org/10.1111/brv.12332

Schrader, J., Weigelt, P., Cai, L., Westoby, M., Fernández-Palacios, J. M., Cabezas, F. J., Plunkett, G. M., Ranker, T. A., Triantis, K. A., Trigas, P., Kubota, Y., & Kreft, H. (2024). Islands are key for protecting the world's plant endemism. *Nature*, *634*, 868–874. https://doi.org/10.1038/s41586-024-08036-1

Schwartz, M. D. (1998). Green-wave phenology. *Nature*, *394*, 839–840. https://doi.org/10.1038/29670

Shin, N., Saitoh, T. M., Takeuchi, Y., Miura, T., Aiba, M., Kurokawa, H., Onoda, Y., Ichii, K., Nasahara, K. N., Suzuki, R., Nakashizuka, T., & Muraoka, H. (2023). Review: Monitoring of land cover changes and plant phenology by remote-sensing in East Asia. *Ecological Research*, *38*, 111–133. https://doi.org/10.1111/1440-1703.12371

Shiono, T., Kubota, Y., & Kusumoto, B. (2021). Area-based conservation planning in Japan: The importance of OECMs in the post-2020 global biodiversity framework. *Global Ecology and Conservation*, *30*, e01783. https://doi.org/10.1016/j.gecco.2021.e01783

Sillero, N., Arenas-Castro, S., Enriquez-urzelai, U., Vale, C. G., Sousa-Guedes, D., Martínez-Freiría, F., Real, R., & Barbosa, A. M. (2021). Want to model a species niche? A step-by-step guideline on correlative ecological niche modelling. *Ecological Modelling*, *456*, 109671. https://doi.org/10.1016/j.ecolmodel.2021.109671

Skidmore, A. K., Coops, N. C., Neinavaz, E., Ali, A., Schaepman, M. E., Paganini, M., Kissling, W. D., Vihervaara, P., Darvishzadeh, R., Feilhauer, H., Fernandez, M., Fernández, N., Gorelick, N., Geijzendorffer, I., Heiden, U., Heurich, M., Hobern, D., Holzwarth, S., Muller-Karger, F. E., … Wingate, V. (2021). Priority list of biodiversity metrics to observe from space. *Nature Ecology & Evolution*, *5*(7), 896–906. https://doi.org/10.1038/s41559-021-01451-x

Takeuchi, Y., Muraoka, H., Yamakita, T., Kano, Y., Nagai, S., Bunthang, T., Costello, M. J., Darnaedi, D., Diway, B., Ganyai, T., Grudpan, C., Hughes, A., Ishii, R., Lim, P. T., Ma, K., Muslim, A. M., Nakano, S.-I., Nakaoka, M., Nakashizuka, T., … Yahara, T. (2021). The Asia-Pacific biodiversity observation network: 10-year achievements and new strategies to 2030. *Ecological Research*, *36*, 232–257. https://doi.org/10.1111/1440-1703.12212

Tehrani, N. A., Naimi, B., & Jaboyedoff, M. (2021). Modeling current and future species distribution of breeding birds as regional essential biodiversity variables (SD EBVs): A bird perspective in Swiss Alps. *Global Ecology and Conservation*, *27*, e01596. https://doi.org/10.1016/j.gecco.2021.e01596

Tian, F., Cai, Z., Jin, H., Hufkens, K., Scheifinger, H., Tagesson, T., Smets, B., Van Hoolst, R., Bonte, K., Ivits, E., Tong, X., Ardö, J., & Eklundh, L. (2021). Calibrating vegetation phenology from Sentinel-2 using eddy covariance, PhenoCam, and PEP725 networks across Europe. *Remote Sensing of Environment*, *260*, 112456. https://doi.org/10.1016/j.rse.2021.112456

Tian, J., Zhu, X., Shen, M., Chen, J., Cao, R., Qiu, Y., & Xu, Y. N. (2024). Effectiveness of spatiotemporal data fusion in fine-scale land surface phenology monitoring: A simulation study. *Journal of Remote Sensing*, *4*, 0118. https://doi.org/10.34133/remotesensing.0118

Tran, N. N., Huete, A., Nguyen, H., Grant, I., Miura, T., Ma, X., Lyapustin, A., Wang, Y., & Ebert, E. (2020). Seasonal comparisons of Himawari-8 AHI and MODIS vegetation indices over latitudinal Australian grassland sites. *Remote Sensing*, *12*, 2494. https://doi.org/10.3390/rs12152494

Turak, E., Brazill-Boast, J., Cooney, T., Drielsma, M., Delacruz, J., Dunkerley, G., Fernandez, M., Ferrier, S., Gill, M., Jones, H., Koen, T., Leys, J., Mcgeoch, M., Mihoub, J.-B., Scanes, P., Schmeller, D., & Williams, K. (2017). Using the essential biodiversity variables framework to measure biodiversity change at national scale. *Biological Conservation*, *213*, 264–271. https://doi.org/10.1016/j.biocon.2016.08.019

UNEP/CBD/SBSTTA/17/INF/7. (2013). Essential biodiversity variables. Note by the Executive Secretary. https://geobon.org/downloads/policy-support/InfDocs/sbstta-17-inf-07-en.pdf

Valavi, R., Guillera-Arroita, G., Lahoz-Monfort, J. J., & Elith, J. (2022). Predictive performance of presence-only species distribution models: A benchmark study with reproducible code. *Ecological Monographs*, *92*, e01486. https://doi.org/10.1002/ecm.1486

Végh, L., Nishihiro, J., Toyama, H., Ishihama, F., Kudo, H., Tanno, Y., Kadoya, T., & Takeuchi, Y. (2024). High-resolution spatial dataset of ecosystem types in Japan classified within the IUCN global ecosystem typology scheme with new categories at the Regional subgroups level. Authorea. https://doi.org/10.22541/au.173319062.28331883/v1

Vihervaara, P., Auvinen, A.-P., Mononen, L., Törmä, M., Ahlroth, P., Anttila, S., Böttcher, K., Forsius, M., Heino, J., Heliölä, J., Koskelainen, M., Kuussaari, M., Meissner, K., Ojala, O., Tuominen, S., Viitasalo, M., & Virkkala, R. (2017). How essential biodiversity variables and remote sensing can help national biodiversity monitoring. *Global Ecology and Conservation*, *10*, 43–59. https://doi.org/10.1016/j.gecco.2017.01.007

Waldock, C., Stuart-Smith, R. D., Albouy, C., Cheung, W. W. L., Edgar, G. J., Mouillot, D., Tjiputra, J., & Pellissier, L. (2022). A quantitative review of abundance-based species distribution models. *Ecography*, *2022*, 05694. https://doi.org/10.1111/ecog.05694

Wang, Q., & Atkinson, P. M. (2018). Spatio-temporal fusion for daily Sentinel-2 images. *Remote Sensing of Environment*, *204*, 31–42. https://doi.org/10.1016/j.rse.2017.10.046

Warton, D. I., Blanchet, F. G., O'Hara, R. B., Ovaskainen, O., Taskinen, S., Walker, S. C., & Hui, F. K. C. (2015). So many variables: Joint modeling in community ecology. *Trends in Ecology & Evolution*, *30*, 766–779. https://doi.org/10.1016/j.tree.2015.09.007

WGCABES (Working Group for Comprehensive Assessment of Biodiversity and Ecosystem Services, Ministry of the Environment, Japan). (2021). *Summary for policymakers of japan biodiversity outlook 3 (2021 report of comprehensive assessment of biodiversity and ecosystem services in Japan)*. Nature Conservation Bureau, Ministry of the Environment. https://www.biodic.go.jp/biodiversity/activity/policy/jbo3/generaloutline/files/JBO3_pamph_en.pdf

White, M. A., Thornton, P. E., & Running, S. W. (1997). A continental phenology model for monitoring vegetation responses to interannual climatic variability. *Global Biogeochemical Cycles*, *11*, 217–234. https://doi.org/10.1029/97gb00033

Wieczorek, J., Bloom, D., Guralnick, R., Blum, S., Döring, M., Giovanni, R., Robertson, T., & Vieglais, D. (2012). Darwin Core: An evolving community-developed biodiversity data standard. *PLoS One*, *7*, e29715. https://doi.org/10.1371/journal.pone.0029715

Wingate, L., Ogée, J., Cremonese, E., Filippa, G., Mizunuma, T., Migliavacca, M., Moisy, C., Wilkinson, M., Moureaux, C., Wohlfahrt, G., Hammerle, A., Hörtnagl, L., Gimeno, C., Porcar-Castell, A., Galvagno, M., Nakaji, T., Morison, J., Kolle, O., Knohl, A., … Grace, J. (2015). Interpreting canopy development and physiology using a European phenology camera network at flux sites. *Biogeosciences*, *12*, 5995–6015. https://doi.org/10.5194/bg-12-5995-2015

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Takeuchi, Y., Végh, L., Noda, H., Böttcher, K., Vihervaara, P., Kass, J. M., Hama, I., & Saito, Y. (2025). National-scale terrestrial biodiversity and ecosystem monitoring with essential biodiversity variables in Japan and Finland. *Ecological Research*, *40*(6), e70011. https://doi.org/10.1111/1440-1703.70011