EO-based indicators for biodiversity monitoring at national scale in Greece: Framework development for the hELlenic BIOodiversity Information System (EL-BIOS)

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ABSTRACT

Biodiversity is a critical component of Earth's life support systems, influencing ecosystem productivity, resilience, and functionality. Effective monitoring and conservation of biodiversity at a national scale are crucial in the face of global environmental changes. The upcoming biodiversity information system for Greece, namely EL-BIOS, is developing a set of national biodiversity indicators including those based on Earth Observation (EO). The two focus areas of these indicators will be a) state and b) threats, pressures and impacts to biodiversity. The selection of indicators followed a step-by-step procedure, initially involving an exhaustive review of existing frameworks and international initiatives that have developed relevant indicators. These included among others the Biodiversity Indicators Partnership, Intergovernmental Platform for Biodiversity and Ecosystem Services (IPBES), and European Environment Agency (EEA). A thorough analysis of the latest EO technologies and computing advances was also conducted to assess technological feasibility and maturity. Governmental and non-governmental stakeholders were also engaged to ensure their interest in and the adoption of the indicators for biodiversity conservation and monitoring. The final list includes among others nine EO-based indicators that will be ingested in the EL-BIOS EO-data cube related to net primary productivity, seasonality of carbon fluxes, vegetation phenology, plant diversity, vegetation structure, landscape fragmentation, ecosystem type transformations and imperviousness.

Keywords: biodiversity monitoring, remote sensing, EO, data cubes, biodiversity metrics, biodiversity variables, satellite

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1. INTRODUCTION

Inventory and monitoring of biodiversity status, condition and change is a prerequisite for designing and implementing effective conservation and management actions. Existence of such a framework is crucial for halting or reversing biodiversity loss and decline[1], as well as for implementing global agreements and national policies and laws[2].

Biodiversity indicators are essential tools in assessing the health and status of biodiversity, instrumental in effective decision-making and adaptive management of biodiversity, monitor progress, serving as early warning systems for emerging problems, measures of policy success awareness-raising, but also for educational purposes by national and regional governments, media, NGOs, educational institutions, and research bodies[3]. In addition, they facilitate communication between policymakers and scientists by conveying complex biodiversity data in a comprehensible manner, thus acting as science-policy interfaces aiding in the formulation of informed responses to environmental challenges (Biodiversity Indicators Partnership, 2011). Moreover, indicators are pivotal in tracking progress towards global and national biodiversity targets, helping stakeholders understand the status and influencing factors of biodiversity [4].

The wide range of applicability of biodiversity indicators is reflected in the wide range of existing definitions. According to Noss [5] biodiversity indicators are "measurable surrogates for environmental end points such as biodiversity that are assumed to be of value to the public". UNEP–WCMC define biodiversity indicators as "measures based on verifiable data that conveys information about more than itself"[3]. Another definition considers them as "measures of biodiversity that help scientists, managers and politicians understand the condition of biodiversity and the factors that affect it"[6].

Biodiversity indicators range from simple measures to more complex indices, covering not only direct biodiversity metrics, such as species populations and ecosystem extents, but also actions for conservation and sustainable use, and pressures threatening biodiversity, like habitat loss [3,6]. Therefore, biodiversity indicators are purpose-dependent, meaning that the interpretation of the data hinges on the specific issue of concern. For example, data on forest extent can be indicative of various issues including changes in forest resources, conservation progress, threats to forest ecosystems, soil cover changes, carbon sequestration, and the conservation status of species [3].

To ensure the successful adoption and continuous production of indicators, the scientific community agrees on specific selection criteria for indicators including their measurability, cost-efficiency, scientific basis based on reliable and available data, interpretability, and ease of communication [4]. In addition they must be informative but simple, responsive to changing issues, easy to understand, relevant to user needs, and consistently monitored by responsible institutions [6,7].

To monitor biodiversity-change at the global scale, a series of biodiversity monitoring conceptual frameworks and initiatives as the Biodiversity Indicators Partnership have been established to promote delivery and development of biodiversity indicator schemes for use under different conventions and organizations [8]. Driven by similar motives the concept of Essential Biodiversity Variables (EBVs) has emerged as a set of variables, organized in 6 classes, that are linking primary observations and biodiversity indicators that focus on the state of biodiversity metrics [7,9,10].

Despite its limitations for biodiversity monitoring [6,11] satellite remote sensing can provide information to cost-effectively and repeatedly measure and monitor biodiversity indicators for assessments of the state of conservation goals and targets [12]. Satellite remote sensing has many established benefits, providing a cost-effective, systematic, consistent and synoptic view of the Earth's surface, over extended multi-annual periods [12].

According to Turner et al. [13], remote sensing can be utilized for biodiversity estimate in both indirect and direct ways. Studies exploring the usage of satellite remote sensing data and products as predictor variables to extrapolate in-situ observations of species and populations has been the dominant approach employed for biodiversity monitoring [14,15]. Regarding this direct approach, numerous studies have assessed the application of diverse sensors and methodological techniques across various ecosystem settings. Remote sensing can be applied directly to build connections between pixel values and field-measured diversity [16,17] or indirectly to map species distribution [18]. Palmer [17] first proposed the Spectral Variation Hypothesis (SVH), which is closely related to the most popular modeling process between field measured diversity values and remote sensing data. According to Torresani et al. [19], SVH links environmental diversity, which is associated with a greater number of species, to the spectral variety or heterogeneity of the RS data.

Another perspective holds that certain features of biodiversity can be indirectly monitored from space by products and data extracted as surrogate biodiversity indicators from satellite remote sensing measurements [6,20,21]. Following such a paradigm, satellite remote sensing can be used to monitor the distribution, fragmentation, and heterogeneity of ecosystems by providing observations [22] and derived products (such as fractional cover, forest cover, or land cover) [14,23]. Consequently

Remote Sensing of Essential Biodiversity Variables (RS-EBVs) have been defined as the subset of EBVs whose monitoring relies heavily or entirely on the use of RS data [24].

When it comes to national scale the advantages of satellite remote sensing, along with other Earth Observation data sources, makes it very prominent for establishing governmental biodiversity monitoring schemes based on biodiversity indicators [12], that can address the well-known drawbacks of in situ data collection, including restrictions on site accessibility in remote places or regions with specific geographic, meteorological, and socioeconomic characteristics, as well as personnel expenses, time, and logistical support requirements [25]. Furthermore, in-situ biodiversity data collection, especially over extended regional or national scale may result in non-standardization bias associated with the involvement of experts' with various levels of expertise or skills [26].

The recent technological development and advancements in satellite sensors and platforms characteristics [27], along with the availability of open-source data over the past ten years, coincide with rapid progress in computer hardware and software, as well as improvements in satellite data-processing techniques [28]. These factors collectively suggest an increasing potential for satellite remote sensing to directly contribute to biodiversity indicators [12].

The LIFE EL-BIOS project (LIFE20 GIE/GR/001317) "hELlenic BIOodiversity Information System: an innovative tool for biodiversity conservation" aims to create a web-based information system that will collect, integrate, combine, and disseminate existing data on Greece's biodiversity in a comprehensible way. This data will be derived from traditional monitoring methods and multiscale EO data.

A key objective of the project relates to the definition and development of a set of national scale biodiversity indicators that could be used for monitoring and reporting the state and pressures in country’s biodiversity. Within this framework, existing biodiversity monitoring frameworks and indicators at national, European, and international level were explored. Already developed biodiversity indicators, EO data availabilty and methodoloigal maturity were also recorded among others. Following a consultation procedure with public agencies and authorities, and key national stakeholders and groups a final set of national biodiversity indicators was specified.

The aim of this manuscript is to present the workflow followed for the definition and development of EO-based biodiversity indicators for national-scale biodiversity monitoring in Greece. Intermediate steps of the process included i) The review of existing biodiversity indicators proposed and used in various policies and initiatives at national, European, and international levels to build an extensive pool of potential indicators ii) engage key stakeholders from different target groups in a consultation process to ensure that the selected indicators are both scientifically robust and practically relevant, iii) analyze the available approaches for the calculation of the selected EO indicators and identify the optimal algorithms for their estimation.

2. METHODOLOGY

2.1 Methodology outline

The methodology used to define traditional and EO based indicators for biodiversity monitoring at national scale was comprised of three main steps (Figure 1): a) reviewing existing data sources and international initiatives, b) stakeholder engagement and c) the analysis of the current state of EO-platforms and EO-products. After the initial definition of the selected indicators, EO based indicators were developed to be ingested in the EL-BIOS EO-data cube.

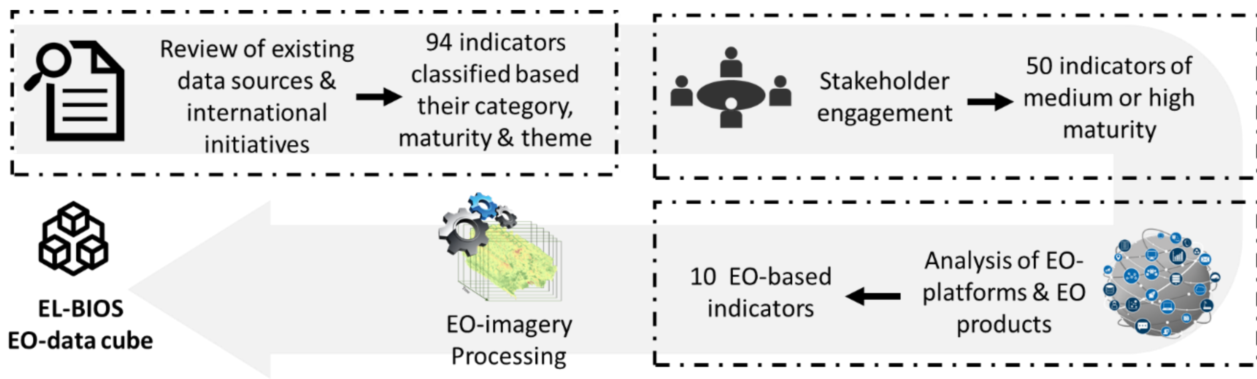

Figure 1 Methodology outline

2.2 Review of existing biodiversity indicators frameworks and international initiatives

A thorough review of biodiversity indicators proposed and used in various policies and initiatives, carried out in order to build an extended pool of candidate indicators for the ELBIOS information system. The main sources were: a) the National Biodiversity Strategy of Greece which covers 13 targets with focus on halting the loss of biodiversity, promoting biodiversity as national capital and intensifying Greece's contribution to the global prevention of biodiversity loss; b) the Aichi Biodiversity Targets, which comprise specific objectives designed to address and mitigate biodiversity loss worldwide, c) the Streamlining European Biodiversity Indicators (SEBI 2020)[29] which has built 26 indicators to monitor biodiversity changes, to examine financial support for biodiversity protection and public awareness of biodiversity issues; d) the European Environment Agency (EEA) indicators which are designed to support policy making focusing on status and trends and on the level of achievement of associated policy objectives; e) the Global Biodiversity Framework for the period after 2020 which includes 23 action-oriented global targets for urgent measures to be taken over the decade leading up to 2030; e) Biodiversity Indicators Partnership (BIP) which is an international effort focused on advancing the creation, dissemination, and utilization of biodiversity indicators; f) the Group on Earth Observation/Biodiversity Observation Network (GEO-BON) that launched a series of global indicators that combine biodiversity observations, remote sensing data, and models to fill significant gaps in our understanding of biodiversity changes at local, national, and global levels These indicators are derived from biodiversity observations, harmonized across various data sources, and standardized to provide a consistent framework for monitoring and adoption of Essential Biodiversity Variables (EBV) including Remote Sensing-EBV[30]; f) the Proposal for a Regulation of the European Parliament and of the Council on nature restoration.

2.3 Engagement of key stakeholders

Key stakeholders from different target groups (Figure 2) were invited in a consultation process, including 57 people from 46 national bodies. Consultation carried out via round table and bilateral discussions and via a questionnaire survey with the aim of ensuring that the selected indicators are both scientifically robust and practically relevant and in order to prioritize a subset of them. Stakeholders were asked to select the 15 most important indicators based on their field of action and expertise, policy requirements, and their needs in practice etc. In addition, the stakeholders engaged in the review of the indicator pool and proposed additional ones (i.e linked to climate change and the new European law for ecosystem restoration) and they were asked to express their interest in indicator calculation (i.e by sharing their datasets).

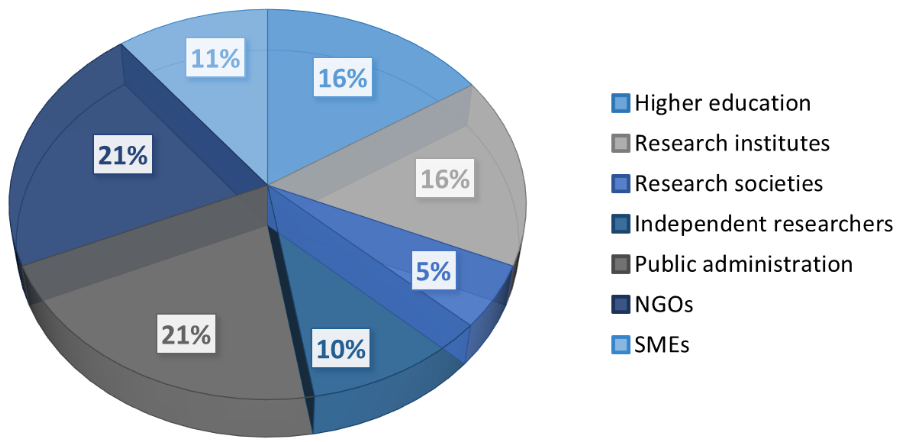

Figure 2: Number of key stakeholders per target group invited to participate in the consultation process.

2.4 Analysis of the current EO technologies and computing advances

Remote sensing has been recognized as a useful tool for biodiversity assessment and is now prominent in biodiversity monitoring [12,13,31]. The current satellite missions provide the requisite data continuity for the effective monitoring of biodiversity, generating petabytes of data accessible at no cost by numerous portals and services. Nevertheless, a significant challenge to integrate EO data into ecological science is to manage Big Earth Data as well as to develop workflows for analysis-ready data, in our case EO based biodiversity indicators.

In the framework of EL BIOS project, data from the Sentinel-1, Sentinel-2, Sentinel-3 and high resolution products (HRL) were evaluated for their spatial, spectral and temporal resolution, Big EO Data cloud computing systems and platforms such as Google Earth Engine (https://developers.google.com/earth-engine/datasets/), Micrososft Planetary Computer (https://planetarycomputer.microsoft.com/), Amazon Web Services (https://aws.amazon.com/) and Copernicus Sentinel Hub (https://docs.sentinel-hub.com/api/) were examined for their ability to serve EL BIOS needs and to develop automated workflows for national-scale products utilizing RS time-series data. Moreover, different algorithms and different levels of data processing were evaluated in order to determine the most accurate and reliable approach for integration into the ELBIOS system.

3. RESULTS

3.1 Initial definition of indicators

The review of policy frameworks and initiatives and the stakeholder consultation process resulted in an extended pool of 94 candidate indicators that potentially could be integrated in the biodiversity information system of Greece. The pool consists a reference basis linking the indicators with the National Biodiversity Strategy Targets, with the potential data provider, and with the relevant policy framework and initiatives (i.e post 2020 biodiversity targets, Aichi Targets 2020 SDGs). The indicators classified in five different biodiversity categories such as species (30 indicators), ecosystems and habitats (12 indicators), protected areas (18 indicators), water (3 indicators), and other aspects such as funding, awareness, education (8 indicators) and related to three general themes; a) state (49 indicators), b) threats, pressures and impacts (20 indicators), and c) responses (25 indicators) (Figure 3). With regard to EO based indicators for monitoring ecosystems and species habitats these related to state (i.e metrics of NDVI) and to pressures (i.e fragmentation).

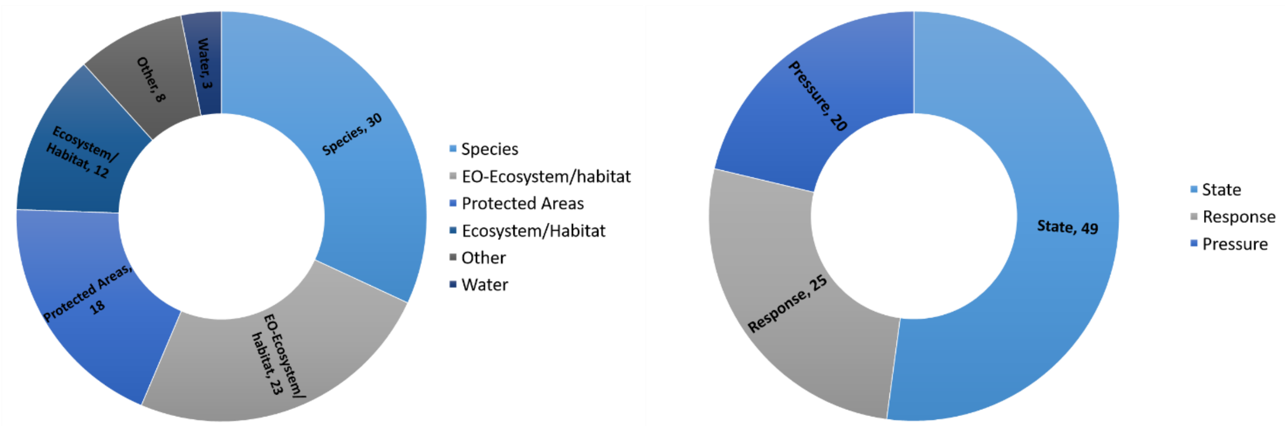

Figure 3: Indicators included in the pool per category (left) and theme (right) (pressure is the simplified term for threats and impacts as well).

As a next step, the indicators ranked according to their maturity for implementation based on the current priorities, needs and available knowledge. Fifty-two (52) of them were considered to have high maturity for implementation, 21 to have medium, and 21 to have low. Specifically, for the EO based biodiversity indicators most of them (16 out of 23) are considered of high maturity whereas few ranked to have medium and low maturity due to their low current interest expressed from the engaged stakeholders (i.e share of agricultural land with high-diversity landscape features, peatland extent and condition.

From the stakeholder consultation, 50 indicators were selected as the subset with higher acceptance.. Fragmentation was the indicator with the highest preference amongst the different interesting bodies, who highlighted the urgency to monitor and assess the growing pressure on biodiversity caused mainly by transport networks. Indicators relevant to land take of natural ecosystems (i.e wetlands) by expansion of urban and agricultural areas received higher acceptance. Also, most of the stakeholders selected indicators relevant to ecosystem condition and expressed the need to explore the potential of EO long time series on vegetation and water, in monitoring biodiversity state. Further, indicators on fires, drought, and sea level rise were selected by many stakeholders denoting the need to respond to the increasing exposure to natural disasters.

The 50 indicators fall in seven focal areas that cover the state and pressures and different types of policy responses (Table 1). Amongst them, 17 EO indicators are included expecting to support the monitoring of biodiversity state and pressures in the country addressing the priorities set in the National Biodiversity Strategy and in other relevant European and global initiatives (Table 2).

Table 1: Number of indicators of higher acceptance per focal area.

Theme	**Focal Area**	**No of indicators**
State	A. State of biodiversity	21 (9 EO based)
Pressure	B. Threats/Pressures/Impacts to biodiversity	13 (8 EO based)
Response	C. Taking up measures and resources for protection of biodiversity	9
Response	D. Taking up measures and resources that mainstream biodiversity protection	1
Response	E. Strengthening of public administration in regard to biodiversity protection	2
Response	F. Public awareness on biodiversity conservation	1
Response	G. Knowledge improvement on biodiversity	3

Table 2: Earth Observation indicators with higher acceptance for biodiversity monitoring in Greece (NBS: relevant National Biodiversity Strategy Targets; Aichi: Relevant Targets Aichi 2020; SDG: Relevant SDGs Targets).

Focal Area	Earth Observation based indicator	NBS	Aichi	SDG
State	Ecosystem coverage changes	2, 3, 5	4, 8, 12, 15	6, 15
	Forest area as a proportion of total land area	2, 3, 5	4, 8, 12, 15	6, 15
	Leaf Area Index	2, 3, 5	15	15
	Normalized Difference Vegetation Index (Functional)	2, 3, 5	15	15
	Plant Phenology Index (PPI)	2, 3, 5	15	15
	Surface Water Occurrence	2, 3, 5	15	6
	Vegetation condition (NDVI, fAPAR2)	2, 3, 5	15	15
	Water and Wetness occurrence	2, 3, 5	15	6, 15
	Change in the extent of wetlands	2.2, 3.1, 13.3	5, 14	6.6
Threats/Pressures/ Impacts	Drought impact on ecosystems in Europe	2, 3, 5	4, 8, 12, 15	15
	Forest fires	2, 3, 5	4, 8, 12, 15	15
	Impact of land use on vegetation productivity in Europe	2, 3, 5	4, 8, 12, 15	15
	Imperviousness and imperviousness change	2, 3, 5	4, 8, 12, 15	15
	Land use/cover changes	2, 3, 5	4, 8, 12, 15	15
	Landscape fragmentation pressure	2, 3, 5	4, 8, 12, 15	15
	Net land take in cities and commuting zones	2, 3, 5	4, 8, 12, 15	15
	Extreme sea levels and coastal flooding	2, 3, 5	10	13, 14, 15

3.2 Earth Observation indicators

Table 3 presents the first indicators that have been implemented in the EL-BIOS Data Cube using high-resolution products (HRL) and Sentinel-2 Level-2A time series (from January 2017 to December 2023) hosted on AWS. They selected, after reviewing current state of EO-platforms and EO products for biodiversity indicator development and considering the indicators that received higher acceptance by stakeholders.

To process and compute the dataset hosted by the EL-BIOS Data Cube, approximately three months and about 5TB of memory space were required

Table 3 Selected EO indicators

Indicator	Update frequency	Spatial analysis	Scale
Annual integral of NDVI	Yearly	10m	national
Intra-annual relative range of NDVI	Yearly	10m	national
Annual maximum of NDVI	Yearly	10m	national
Leaf area index	Monthly	10m	national
Fractional vegetation cover	Quarterly	10m	national
Plant phenology index	Quarterly	10m	national
Imperviousness density	3 years	100m	national
Effective mesh density	3 years	1000m	national
Ecosystem coverage change	6 years	100m	national

Annual integral of NDVI

The annual NDVI integral (NDVI-I) is a linear estimator of the fraction of absorbed photosynthetic active radiation (FAPAR)[32] and thus of the annual net primary production (ANPP)[33]. Many studies in temperate, tropical and Mediterranean forests and shrublands and even in hot deserts [34–36], have demonstrated that NDVI-I values can fully reflect overall vegetation growth status[37] and net primary production (NPP)[38,39].

NDVI-I is calculated, representing the cumulative sum of NDVI (Equation 1)

$$NDVI - I = \sum_{1}^{12} NDVI \tag{1}$$

In general, higher values of NDVI-I indicate more dense vegetation cover and vigorous productivity, which can provide habitat and resources for various species, enhancing biodiversity. Areas with higher NDVI-I values may support a greater variety of plant species, which in turn can support diverse animal populations.

Intra-annual relative range of NDVI

The intra-annual relative range NDVI (IARR-NDVI) has been used as proxy for the seasonality of carbon fluxes[40,41], as well as to characterize vegetation types [42], and to identify functional ecosystem types [36] .

IARR-NDVI is defined as maximum NDVI minus minimum NDVI divided by NDVI-I[36] (Equation 2)

$$\text{IARR\_NDVI} = \frac{NDVI_{max} - NDVI_{min}}{SumNDVI} \tag{2}$$

In general, higher values of IARR-NDVI indicate more pronounced variation in carbon fluxes i.e. changes in vegetation dynamics, phenology and carbon cycle patterns, which may impact ecosystem function and services. Figure 2a represents IARR-NDVI indicator as has been developed using Sentinel 2 Level 2 imagery and implemented in the EL-BIOS Data Cube.

Annual maximum of NDVI

The date of annual maximum NDVI (Dom-NDVI) (Equation 3) [36] usually coincides with the time of maximum vegetation availability [39].

$$Dom - NDVI = argmax(NDVI_{max}[t]) \tag{3}$$

The Dom-NDVI is an effective indicator of vegetation phenology that shows the intra-annual dispersion of the peak photosynthetic activity period [36,35], providing valuable information on the timing of key stages of the annual growth cycle as well as optimal vegetation growth conditions. Dom-NDVI influences ecosystem processes such as carbon sequestration, water recycling, and nutrient cycling, ultimately shaping ecosystem function and productivity. Changes in Dom-NDVI over time may indicate changes in vegetation phenology in response to climate change. Figure 2b represents Dom-NDVI indicator as has been developed using Sentinel 2 Level 2 imagery and implemented in the EL-BIOS Data Cube.

Leaf area index

The Leaf Area Index (LAI) is a measure of foliage and is defined as the amount of leaf area (m^2) per unit of soil area (m^2)[43]. LAI is a key descriptive indicator of vegetation condition [43] and can be used to assess the condition and functions of terrestrial ecosystems [44], to evaluate the photosynthetic capacity of vegetation [45] and biodiversity, modelling and quantifying the role of surface vegetation cover, such as primary productivity and carbon fluxes [46].

The calculation of LAI was based on, the empirical equation (Equation 4) as developed by [47]. LAI values range from 0 (bare ground) to over 10 (dense coniferous forests).

$$\text{LAI} = 3.618 \times \text{EVI} - 0.118 \tag{4}$$

$$\text{Where EVI} = 2.5 \times \frac{NIR - RED}{NIR + 6RED - 7.5BLUE + 1}$$

Figure 2c presents LAI indicator for August as has been developed using Sentinel 2 Level 2 imagery and implemented in the EL-BIOS Data Cube.

Fractional vegetation cover

Fractional Vegetation Cover (FVC) represent the percentage of the surface area occupied by the vertical projection of the vegetation crown. FCover is a key biophysical variable and plays a critical role in carbon cycle studies, agriculture, forestry, monitoring vegetation health, assessing biodiversity and understanding ecosystem dynamics [48,49].

Research has shown strong linea[50] or nonlinear[51] relationships between VIs and FVC in different types of landscapes. Thus, the estimation of FVC was based on NDVI index (Equation 5) [52]and Zeng et al., (2000) [49] approach.

$$FVC = 1 - \left(\frac{NDVI_{median} - NDVI_{max}}{NDVI_S - NDVI_{max}}\right) \quad (5)$$

where $NDVI_{median}$ represents the intermediate value of NDVI for each quarter, $NDVI_S$ denotes bare ground and $NDVI_{max}$ denotes dense green vegetation.

Plant phenology index

The plant phenology index (PPI) tracks the dynamics of canopy green foliage and shows a strong correlation with Gross Primary Productivity (GPP) and provides a functional and efficient approach for plant phenology study [53](Jin et al., 2019). PPI is based on red and NIR reflectance (Equation 6)[55,56], it is approximately linear to the green LAI[55], and has the same unit of measurement as LAI (m^2-m^{-2})..

$$PPI = -K \times \ln\left(\frac{DVI_{max} - DVI}{DVI_{max} - DVI_S}\right) \quad (6)$$

Where DVI=NIR-RED

Figure 2d represent PPI indicator for the third quarter of 2022, as has been developed using Sentinel 2 Level 2 imagery and implemented in the EL-BIOS Data Cube

Imperviousness density

Imperviousness is a well-known ecosystem degradation variable associated with the loss or gain of ecosystem functions, biodiversity, carbon storage and sequestration, soil hydrological properties, ecosystem services and nature conservation. [57,58]. The Imperviousness Density indicator (IMD) reflects the spatial distribution of artificially sealed areas, including the level of soil sealing per unit area. The calculation of the IMD is based on the Copernicus High Resolution Layer Imperviousness Density (HRL-IMD) ready-to-use products, aggregated to a 100m product.

Effective mesh density

At the local, regional, and global levels, landscape fragmentation (LF) is thought to be one of the most significant problems influencing territorial development and negatively affecting biodiversity, ecosystems, and quality of life [59]. Effective Mesh Density (seff) is an indicator of landscape fragmentation, serving as a measure of how much movement is disrupted by Fragmentation Geometries (FGs) when moving between different regions of the landscape is called Effective Mesh Density (seff). Therefore, the greater the seff and consequently the higher the fragmentation, the more FGs there are in the landscape. The seff measure indicator was calculated following Jaeger's Effective Mesh Density (seff) approach (2000) [60] with the use Copernicus High Resolution Layer – (HRL-IMD) product and the Open Street Map (OSM) database.

Ecosystem type change

Ecosystem changes affect biodiversity, ecosystem state and ecosystem services. The ecosystem type change indicator (EC) is particularly relevant for EU and global biodiversity strategies as it is directly related to biodiversity, indicating the extent of available habitats and ecosystems, which is a critical factor for ecosystem health and species conservation. The indicator is particularly important for specialist species and endemic species that depend on specific habitats in the ecosystem and cannot survive in other ecosystems. The EC indicator is based on CORINE Land Cover products for 2012 and 2018 and aggregating CORINE land cover categories to relate to MAES ecosystem types.

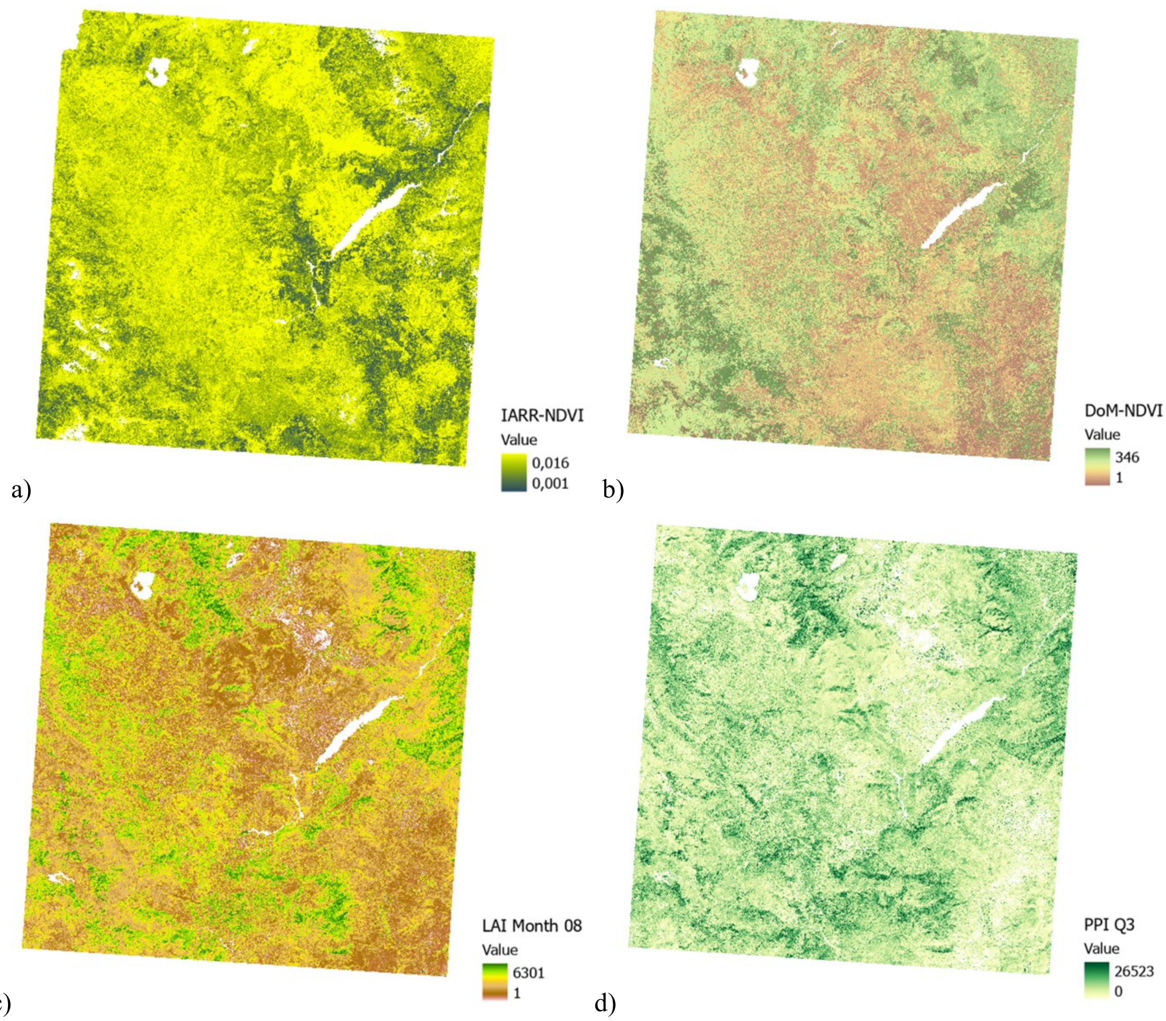

Figure 2 EO indicator as has been developed and implemented in the EL-BIOS Data Cube. A) IARR-NDVI, b) DoM-NDVI, c) monthly LAI, d) quarterly PPI

4. DISCUSSION AND CONCLUSIONS

Biodiversity monitoring is a critical component of environmental conservation and sustainable development. It involves tracking changes in biodiversity over time to understand the health of ecosystems and the effectiveness of conservation measures. EO-based indicators provide a powerful tool for national-scale biodiversity monitoring, integrating data from various sources to offer a holistic view of ecosystem health. Biodiversity Information Systems and biodiversity indicators are integral components of modern conservation efforts and environmental management strategies. These mechanisms play crucial roles in collecting, organizing, analyzing, and disseminating biodiversity data, thereby supporting informed decision-making and effective conservation practices

The LIFE EL-BIOS project aims to support the creation and adaptation of national biodiversity indicators based on conservation and policy needs. This includes incorporating Earth Observation (EO)-based biodiversity indicators, in accordance with the Essential Biodiversity Variables (EBV) Framework and the European Biodiversity Indicators (SEBI) Framework. In this framework of the National Biodiversity Information System of the LIFE EL-BIOS project, qualitative research on biodiversity policy frameworks at national, European and international level was conducted to build a list of biodiversity indicators. Stakeholder engagement led to the identification of initial indicators and finally 10 EO indicators were selected to be implemented in the EL-BIOS Data Cube.

The EL-BIOS Data Cube, the first biodiversity inventory of EO-derived indicators in Greece, offers an extensive archive of comprehensive, consistent, analysis-ready biodiversity indicators at the national level, with data available from 2017 onward. The description of the processing chains and the encoding of scientific methods and know-how for the production of EO biodiversity indicators will allow the assessment of the reproducibility of the results, as well as facilitate their use by users with different levels of expertise and in all geographical areas of Greece and could be reused for objectives other than those for which they were originally developed.

While EO-based indicators offer significant advantages for biodiversity monitoring represent a transformative approach to biodiversity monitoring at the national scale, there are also challenges to their implementation. These include the need for advanced technical expertise, the high cost of EO data and processing, and the complexity of integrating EO data with other biodiversity information. Additionally, there is a need for ongoing research to improve the accuracy and relevance of EO-based indicators and to develop new indicators that can capture more aspects of biodiversity and updated technologies. In the future, as the ELBIOS information system is utilized, its potential integration with the monitoring and evaluation of the National Strategy for Biodiversity should be considered. Collaborative efforts among governments, research institutions, and conservation organizations will be essential for EO-based indicators development as well as for advancing the use of EO-based indicators and ensuring that biodiversity monitoring informs effective conservation and policy actions.

At this point, it must be underlined that the exploitation of technological developments in the field of Earth Observation will be crucial for a more efficient monitoring of biodiversity and natural ecosystems. The rapid development and availability of satellite sensors with improved but diverse characteristics, is shifting the focus to the analysis of multiple remotely sensed measurements, that can capture additional plant functional traits, ecological processes, and ecosystem functions[61]. For example, satellite radar and LiDAR data, such as the one coming from the GEDI (Global Ecosystem Dynamics Investigation) and ICESat (Ice, Cloud, and land Elevation Satellite) missions, could allow the recording of vertical vegetation structure, which can be combined with the recording of spatial distribution from optical data.

The rapid development and availability of cloud-based large spatiotemporal arrays of EO data (i.e. EO data cubes) as the ones developed in the framework of ELBIOS, will also be upgraded and extended with EO data composites from different instruments such as hyperspectral, thermal and LiDAR alongside optical ones[62].

In the future, the development process of EO-based biodiversity indicators will be facilitated by the production and availability of Analysis-Ready Data (ARD), higher level data and standardized products. This advancement will enable users to extract biodiversity-related information without investing time and resources typically required for tasks such as data pre-processing, enhancement, classification etc. Finally, the availability of such homogenized and comprehensively described products will facilitate the expansion of initiatives like ELBIOS to other geographical regions and support the implementation of integrated studies on larger scales.

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REFERENCES

[1] Johnson, C. N., Balmford, A., Brook, B. W., Buettel, J. C., Galetti, M., Guangchun, L. and Wilmshurst, J. M., "Biodiversity losses and conservation responses in the Anthropocene," Science (80-.). **356**(6335), 270 LP – 275 (2017).

[2] Chrysafis, I., Korakis, G., Kyriazopoulos, A. and Mallinis, G., "Predicting Tree Species Diversity Using Geodiversity and Sentinel-2 Multi-Seasonal Spectral Information," Sustainability **12**(21) (2020).

[3] Biodiversity Indicators Partnership., "Guidance for national biodiversity indicator development and use," Cambridge, UK (2011).

[4] McQuatters-Gollop, A., Mitchell, I., Vina-Herbon, C., Bedford, J., Addison, P. F. E., Lynam, C. P., Geetha, P. N., Vermeulan, E. A., Smit, K., Bayley, D. T. I., Morris-Webb, E., Niner, H. J. and Otto, S. A., "From Science to Evidence – How Biodiversity Indicators Can Be Used for Effective Marine Conservation Policy and Management ," Front. Mar. Sci. **6** (2019).

[5] Noss, R. F., "Indicators for Monitoring Biodiversity: A Hierarchical Approach," Conserv. Biol. **4**(4), 355–364 (1990).

[6] Pettorelli, N., Wegmann, M., Skidmore, A., Mücher, S., Dawson, T. P., Fernandez, M., Lucas, R., Schaepman, M. E., Wang, T., O'Connor, B., Jongman, R. H. G., Kempeneers, P., Sonnenschein, R., Leidner, A. K., Böhm, M., He, K. S., Nagendra, H., Dubois, G., Fatoyinbo, T., et al., "Framing the concept of satellite remote sensing essential biodiversity variables: challenges and future directions," Remote Sens. Ecol. Conserv. **2**(3), 122–131 (2016).

[7] 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., et al., "Essential Biodiversity Variables," Science (80-.). **339**(6117), 277 LP – 278 (2013).

[8] Secretariat of the Convention on Biological Diversity., "Briefing note on scientific and technical issues related to the global monitoring of biodiversity" (2022).

[9] Schmeller, D. S., Mihoub, J.-B., Bowser, A., Arvanitidis, C., Costello, M. J., Fernandez, M., Geller, G. N., Hobern, D., Kissling, W. D., Regan, E., Saarenmaa, H., Turak, E. and Isaac, N. J. B., "An operational definition of essential biodiversity variables," Biodivers. Conserv. **26**(12), 2967–2972 (2017).

[10] Pettorelli, N., Owen, H. J. F. and Duncan, C., "How do we want Satellite Remote Sensing to support biodiversity conservation globally?," Methods Ecol. Evol. **7**(6), R. Freckleton, Ed., 656–665 (2016).

[11] Paganini, M., Leidner, A. K., Geller, G., Turner, W. and Wegmann, M., "The role of space agencies in remotely sensed essential biodiversity variables," Remote Sens. Ecol. Conserv. **2**(3), 132–140 (2016).

[12] 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. and Virkkala, R., "How Essential Biodiversity Variables and remote sensing can help national biodiversity monitoring," Glob. Ecol. Conserv. **10**, 43–59 (2017).

[13] Turner, W., Spector, S., Gardiner, N., Fladeland, M., Sterling, E. and Steininger, M., "Remote sensing for biodiversity science and conservation," Trends Ecol. Evol. **18**(6), 306–314 (2003).

[14] Timmermans, J. and Daniel Kissling, W., "Advancing terrestrial biodiversity monitoring with satellite remote sensing in the context of the Kunming-Montreal global biodiversity framework," Ecol. Indic. **154**, 110773 (2023).

[15] Randin, C. F., Ashcroft, M. B., Bolliger, J., Cavender-Bares, J., Coops, N. C., Dullinger, S., Dirnböck, T., Eckert, S., Ellis, E., Fernández, N., Giuliani, G., Guisan, A., Jetz, W., Joost, S., Karger, D., Lembrechts, J., Lenoir, J., Luoto, M., Morin, X., et al., "Monitoring biodiversity in the Anthropocene using remote sensing in species distribution models," Remote Sens. Environ. **239**(January), 111626 (2020).

[16] Rocchini, D., Hernández-Stefanoni, J. L. and He, K. S., "Advancing species diversity estimate by remotely sensed proxies: A conceptual review," Ecol. Inform. **25**, 22–28 (2015).

[17] Palmer, M. W., Earls, P. G., Hoagland, B. W., White, P. S. and Wohlgemuth, T., "Quantitative tools for perfecting species lists," Environmetrics **13**(2), 121–137 (2002).

[18] Gillespie, T. W., Foody, G. M., Rocchini, D., Giorgi, A. P. and Saatchi, S., "Measuring and modelling biodiversity from space," Prog. Phys. Geogr. **32**(2), 203–221 (2008).

[19] Torresani, M., Rocchini, D., Sonnenschein, R., Zebisch, M., Marcantonio, M., Ricotta, C. and Tonon, G., "Estimating tree species diversity from space in an alpine conifer forest: The Rao's Q diversity index meets the spectral variation hypothesis," Ecol. Inform. **52**(February), 26–34 (2019).

[20] Alleaume, S., Dusseux, P., Thierion, V., Commagnac, L., Laventure, S., Lang, M., Féret, J.-B., Hubert-Moy, L. and Luque, S., "A generic remote sensing approach to derive operational essential biodiversity variables (EBVs) for conservation planning," Methods Ecol. Evol. **9**(8), 1822–1836 (2018).

[21] 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., et al., "Priority list of biodiversity metrics to observe from space," Nat. Ecol. Evol. **5**(7), 896–906 (2021).

[22] Koskikala, J., Kukkonen, M. and Käyhkö, N., "Mapping Natural Forest Remnants with Multi-Source and Multi-Temporal Remote Sensing Data for More Informed Management of Global Biodiversity Hotspots," Remote Sens. **12**(9) (2020).

[23] Lock, M., van Duren, I., Skidmore, A. K. and Saintilan, N., "Harmonizing Forest Conservation Policies with Essential Biodiversity Variables Incorporating Remote Sensing and Environmental DNA Technologies," Forests **13**(3) (2022).

[24] Pettorelli, N., Wegmann, M., Skidmore, A., Mücher, S., Dawson, T. P., Fernandez, M., Lucas, R., Schaepman, M. E., Wang, T., O'Connor, B., Jongman, R. H. G., Kempeneers, P., Sonnenschein, R., Leidner, A. K., Böhm, M., He, K. S., Nagendra, H., Dubois, G., Fatoyinbo, T., et al., "Framing the concept of satellite remote sensing essential biodiversity variables: challenges and future directions," Remote Sens. Ecol. Conserv. **2**(3), 122–131 (2016).

[25] Mallinis, G., Chrysafis, I., Korakis, G. and Pana, E., "A Random Forest Modelling Procedure for a Multi-Sensor Assessment of Tree Species Diversity," Remote Sens. (2020).

[26] Lõhmus, A., Lõhmus, P. and Runnel, K., "A simple survey protocol for assessing terrestrial biodiversity in a broad range of ecosystems," PLoS One **13**(12), e0208535 (2018).

[27] Briottet, X., Bajjouk, T., Chami, M., Delacourt, C., Feret, J.-B., Jacquemoud, S., Minghelli, A., Sheeren, D., Weber, C., Fabre, S., Adeline, K., Vaudour, E., Luque, S., Deville, Y., Soudani, K. and Verpooter, C., "BIODIVERSITY – Une Nouvelle Mission Spatiale Pour Le Suivi Des Ecosystèmes A Une Echelle Fine," Rev. Française Photogrammétrie Télédétection **224**(1 SE-Numéro Spécial Imagerie Hyperspectrale), 33–58 (2022).

[28] Verde, N., Kokkoris, I. P., Georgiadis, C., Kaimaris, D., Dimopoulos, P., Mitsopoulos, I. and Mallinis, G., "National scale land cover classification for ecosystem services mapping and assessment, using multitemporal copernicus EO data and google earth engine," Remote Sens. **12**(20) (2020).

[29] European Environment Agency., [Streamlining European biodiversity indicators 2020: Building a future on lessons learnt from the SEBI 2010 process] (2012).

[30] GEO BON., "Strategy for development of Essential Biodiversity Variables, Version 2.0" (2017).

[31] O'Connor, B., Secades, C., Penner, J., Sonnenschein, R., Skidmore, A., Burgess, N. D. and Hutton, J. M., "Earth observation as a tool for tracking progress towards the Aichi Biodiversity Targets," Remote Sens. Ecol. Conserv. **1**(1), 19–28 (2015).

[32] Sellers, P. J., Randall, D. A., Collatz, G. J., Berry, J. A., Field, C. B., Dazlich, D. A., Zhang, C., Collelo, G. D. and Bounoua, L., "A Revised Land Surface Parameterization (SiB2) for Atmospheric GCMS. Part I: Model Formulation," J. Clim. **9**(4), 676–705 (1996).

[33] Paruelo, J. M., Epstein, H. E., Lauenroth, W. K. and Burke, I. C., "ANPP Estimates from NDVI for the Central Grassland Region of the United States," Ecology **78**(3), 953 (1997).

[34] Stoms, D. M. and Hargrove, W. W., "Potential NDVI as a baseline for monitoring ecosystem functioning," Int. J. Remote Sens. **21**(2), 401–407 (2000).

[35] Hoare, D. and Frost, P., "Phenological Description of Natural Vegetation in Southern Africa Using Remotely-Sensed Vegetation Data," Appl. Veg. Sci. **7**(1), 19–28 (2004).

[36] Alcaraz, D., Paruelo, J. and Cabello, J., "Identification of current ecosystem functional types in the Iberian Peninsula," Glob. Ecol. Biogeogr. **15**(2), 200–212 (2006).

[37] Ma, C., Guo, Z. Z., Zhang, X. K. and Han, R. M., "Annual integral changes of time serial NDVI in mining subsidence area," Trans. Nonferrous Met. Soc. China (English Ed. **21**(SUPPL. 3) (2011).

[38] Goward, S. N., Tucker, C. J. and Dye, D. G., "North American vegetation patterns observed with the NOAA-7 advanced very high resolution radiometer," Vegetatio **64**(1), 3–14 (1985).

[39] Pettorelli, N., Vik, J. O., Mysterud, A., Gaillard, J.-M., Tucker, C. J. and Stenseth, N. C., "Using the satellite-derived NDVI to assess ecological responses to environmental change," Trends Ecol. Evol. **20**(9), 503–510 (2005).

[40] Guerschman, J. P., Paruelo, J. M. and Burke, I. C., "Land use impacts on the normalized difference vegetation index in temperate Argentina," Ecol. Appl. **13**(3), 616–628 (2003).

[41] Cabello, J., Fernández, N., Alcaraz-Segura, D., Oyonarte, C., Piñeiro, G., Altesor, A., Delibes, M. and Paruelo, J. M., "The ecosystem functioning dimension in conservation: Insights from remote sensing," Biodivers. Conserv. **21**(13), 3287–3305 (2012).

[42] Alcaraz-Segura, D., Cabello, J. and Paruelo, J., "Baseline characterization of major Iberian vegetation types based on the NDVI dynamics," Plant Ecol. **202**(1), 13–29 (2009).

[43] Asner, G. P., Scurlock, J. M. O. and Hicke, J. a., "Global synthesis of leaf area index observations :," Glob. Ecol. Biogeogr. **12**(2003), 191–205 (2003).

[44] Dash, J. and Ogutu, B. O., "Recent advances in space-borne optical remote sensing systems for monitoring global terrestrial ecosystems," Prog. Phys. Geogr. Earth Environ. **40**(2), 322–351 (2016).

[45] Brede, B., Verrelst, J., Gastellu-Etchegorry, J.-P., Clevers, J. G. P. W., Goudzwaard, L., den Ouden, J., Verbesselt, J. and Herold, M., "Assessment of Workflow Feature Selection on Forest LAI Prediction with Sentinel-2A MSI, Landsat 7 ETM+ and Landsat 8 OLI," Remote Sens. **12**(6) (2020).

[46] Meyer, L. H., Heurich, M., Beudert, B., Premier, J. and Pflugmacher, D., "Comparison of Landsat-8 and Sentinel-2 Data for Estimation of Leaf Area Index in Temperate Forests," Remote Sens. **11**(10) (2019).

[47] Boegh, E., Soegaard, H., Broge, N., Schelde, K., Thomsen, A., Hasager, C. B. and Jensen, N. O., "Airborne multispectral data for quantifying leaf area index, nitrogen concentration, and photosynthetic efficiency in agriculture," Remote Sens. Environ. **81**(2–3), 179–193 (2002).

[48] Gutman, G. and Ignatov, A., "The derivation of the green vegetation fraction from NOAA/AVHRR data for use in numerical weather prediction models," Int. J. Remote Sens. **19**(8), 1533–1543 (1998).

[49] Zeng, X., Dickinson, R. E., Walker, A., Shaikh, M., DeFries, R. S. and Qi, J., "Derivation and Evaluation of Global 1-km Fractional Vegetation Cover Data for Land Modeling," J. Appl. Meteorol. **39**(6), 826–839 (2000).

[50] Ormsby, J. P., Choudhury, B. J. and Owe, M., "Vegetation spatial variability and its effect on vegetation indices," Int. J. Remote Sens. **8**(9), 1301–1306 (1987).

[51] Li, F., Kustas, W. P., Prueger, J. H., Neale, C. M. U. and Jackson, T. J., "Utility of Remote Sensing–Based Two-Source Energy Balance Model under Low- and High-Vegetation Cover Conditions," J. Hydrometeorol. **6**(6), 878–891 (2005).

[52] Baret, F., Clevers, J. G. P. W. and Steven, M. D., "The robustness of canopy gap fraction estimates from red and near-infrared reflectances: A comparison of approaches," Remote Sens. Environ. **54**(2), 141–151 (1995).

[53] Jin, H., Jönsson, A. M., Bolmgren, K., Langvall, O. and Eklundh, L., "Disentangling remotely-sensed plant phenology and snow seasonality at northern Europe using MODIS and the plant phenology index," Remote Sens. Environ. **198**, 203–212 (2017).

[54] Jin, H., Jönsson, A. M., Olsson, C., Lindström, J., Jönsson, P. and Eklundh, L., "New satellite-based estimates show significant trends in spring phenology and complex sensitivities to temperature and precipitation at northern European latitudes," Int. J. Biometeorol. **63**(6), 763–775 (2019).

[55] Jin, H. and Eklundh, L., "A physically based vegetation index for improved monitoring of plant phenology," Remote Sens. Environ. **152**, 512–525 (2014).

[56] European Environment Agency (EEA)., "Copernicus Land Monitoring Service User Manual - HIGH RESOLUTION VEGETATINO PHENOLOGY AND PRODUCTIVITY (HR-VPP), Seasonal Trajectories and VPP Parameters," Eur. Environ. Agency (2020).

[57] Marando, F., Heris, M. P., Zulian, G., Udías, A., Mentaschi, L., Chrysoulakis, N., Parastatidis, D. and Maes, J., "Urban heat island mitigation by green infrastructure in European Functional Urban Areas," Sustain. Cities Soc. **77**, 103564 (2022).

[58] Vallecillo, S., Maes, J., Teller, A., Babí Almenar, J., Barredo, J. ., Trombetti, M., Abdul Malak, D., Paracchini, M., Carré, A., Addamo, A., Czúcz, B., Zulian, G., Marando, F., Erhard, M., Liquete, C., Romao, C., Polce, C., Pardo Valle, A., Jones, A., et al., [EU- wide methodology to map and assess ecosystem condition: Towards a common approach consistent with a global statistical standard] (2022).

[59] Ibáñez, I., Katz, D. S. W., Peltier, D., Wolf, S. M. and Connor Barrie, B. T., "Assessing the integrated effects of landscape fragmentation on plants and plant communities: the challenge of multiprocess–multiresponse dynamics," J. Ecol. **102**(4), C. Lortie, Ed., 882–895 (2014).

[60] Jaeger, J. A. G., "Landscape division, splitting index, and effective mesh size: New measures of landscape fragmentation," Landsc. Ecol. **15**(2), 115–130 (2000).

[61] Ustin, S. L. and Middleton, E. M., "Current and near-term advances in Earth observation for ecological applications," Ecol. Process. **10**(1), 1 (2021).

[62] Chatenoux, B., Richard, J.-P., Small, D., Roeoesli, C., Wingate, V., Poussin, C., Rodila, D., Peduzzi, P., Steinmeier, C., Ginzler, C., Psomas, A., Schaepman, M. E. and Giuliani, G., "The Swiss data cube, analysis ready data archive using earth observations of Switzerland," Sci. Data **8**(1), 295 (2021).