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DISCLAIMER

This report provides the view on the potential of EO in ecosystem accounting and its use in policies from the project team. It has not passed a review by the ecosystem accounting community and therefore can't represent an official statement from this community.

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1 Executive Summary

The Pioneering Earth Observation Applications for the Environment – Ecosystem Accounting (PEOPLE-EA) project targets to study and demonstrate the relevance of Earth Observation (EO) for ecosystem accounting in terrestrial and freshwater ecosystems. Ecosystem accounting is the process of measuring the contributions of ecosystems to economic activities and human well-being. By using ecosystem accounts, researchers and policymakers can collect information about the distribution, extent, and health of ecosystems, as well as for the services they provide, such as climate regulation, wood provision, crop pollination, water filtration, and recreation.

Ecosystem accounts are inherently spatially related accounts, with the implication that they strongly depend on the availability of spatially explicit datasets. Earth Observation (EO) refers to the use of remote sensing technologies to monitor land, marine and atmosphere. This report shows the potential that EO can provide to generate ecosystem accounts, building further on the pioneering work of several projects and initiatives.

The approval of chapters 1 to 7 of the System of Environmental-Economic Accounting – Ecosystem Accounting (SEEA EA), as a United Nations Statistics Division (UNSD) standard in 2021, has accelerated the experiences gained in this field as seen by the number of research papers raising quickly.

In Europe, there is a strong focus to 'stop the loss of biodiversity and restore ecosystems' through the EU Biodiversity Strategy 2030 and its related pledge processes. Member States have made good progress on ecosystem assessments and are in the transition phase to extend their assessments with accounts. These ecosystem accounts provide information based on existing reporting initiatives such as the Habitats Directive, Water Framework Directive, Forest Strategy, etc. and complement through adding spatial details or cover larger areas to existing information or even potentially add new spatial datasets from the advance in remote sensing platforms to support the new Biodiversity Strategy.

Several projects and initiatives are advancing in gaining experiences with ecosystem accounting and try to harmonize and standardize the data flows and models. Despite the good progress and opportunity to further build on these experiences, there are still several important obstacles to take in all core ecosystem accounts: extent, condition and services and assets.

An in-depth literature review of 113 scientific papers has shown that EO data streams[1] can be integrated to accelerate ecosystem account reporting. Classification algorithms based on EO and Machine Learning are already operationalized for Land Cover and Land Cover Change mapping. Such classifications can act as the backbone of ecosystem extent accounts, however, typically provide only information at the upper ecosystem level. These workflows need to be further extended to delineate ecosystems conform the SEEA EA methodology and to add ecological relevant data such as species composition or other ecological processes. New Artificial Intelligence (AI) techniques require massive training datasets, which require highly

[1] Ecosystem accounts require regular consistent reporting and therefore the focus of this report is on the use of satellite recurring data, providing wall-to-wall coverage at national level regularly, typically in a free and open manner. However it does not limit to complement these with other remotely sensed (e.g. airborne) data, these latter datasets mostly do not provide the same characteristics as described above.

qualified in-situ reference data (e.g., at lower EUNIS levels) to be collected according to a standardized, comprehensive, context dependent, and cost-efficient protocol. EO provides wall-to-wall monitoring and hence can contribute to provide reliable and consistent metrics on ecosystem condition also outside protected areas. The contribution is mainly identified for ecosystem structure, functions and composition indices, and probably their distance from a reference condition if not set too far back in time. However, the use of EO data for ecosystem services is still marginal, despite the well-established conceptual framework. Flows of ecosystem services require the aggregation of different diverse datasets, spatial and non-spatial, with modelling tools and platforms. There is a large need on practical methodological guidelines, operational examples and adequate infrastructure to further exploit the use of EO data, following the FAIR principles.

To conclude, this report shows that ecosystem accounting under the standardized SEEA EA framework is considered as an important new tool. On one hand it can provide relevant information for new legislative reports and could potentially complement to ongoing monitoring and reporting obligations for EU policies. EO provides a cost-effective way to collect large amounts of data in a standardized form with consistency in space and time and hence provide an important input for spatial-explicit ecosystem accounting.

However, some challenges are to be overcome that requires further research. Main challenges include:

- *Data availability and Processing capacity*: While there is a wealth of Earth Observation data available, it can be difficult to obtain, access, and process for use in ecosystem accounts. Additionally, there may be gaps in coverage or inconsistencies in data quality that need to be addressed. Providing tools to generate Account Ready Data stacks (AccoRD) to simplify earth observation data streams for statistical accounting can be a solution.
- *Sensor specifications and Data quality*: The quality and reliability of EO data can vary depending on the type of sensor used, atmospheric conditions, and other factors. This can make it difficult to compare data from different sources and ensure accuracy in ecosystem accounting. The elaboration of harmonized datasets, accompanied with quality data on the estimates of uncertainties can be a solution.
- *Modelling tools and platforms*: Ecosystems are complex systems and require practical guidelines with operational examples, adequate IT infrastructures (following the FAIR principles) to use the wealth of EO and other data streams at appropriate scales. Creating a roadmap to foster further investments in research and innovation to promote novel solutions (such as Infrastructure-as-a-Service) can be the way forward.
- *Interpretation and validation*: Earth observation data often require interpretation and validation to ensure that they accurately represent real-world conditions. This can be challenging, particularly when dealing with complex ecosystems, immature observation approaches or areas with limited ground-based data.
- *Multi-disciplinary teams*: Earth observation in statistical accounts requires the expertise of many disciplines including, statisticians, ecologists, national mapping agencies, geospatial and EO experts. Further collaboration and knowledge sharing platforms can be a solution.

Overall, Earth Observation has the potential to provide valuable information for ecosystem accounting, but it is important to address the challenges associated with data availability, resolution, and interpretation to ensure that the data is accurate and reliable. While there is no option to wait for an 'obstacle-free environment' in the use of EO data for ecosystem accounting, further investments in research remain required to overcome the challenges as outlined above.

2 Introduction

Decision- and policy- making often involve macroeconomic assessments, that use the national accounts. To date, national accounts produced under United Nations System of National Accounts (SNA) (United Nations, 2009), do not incorporate information about ecosystems, their extent and/or their condition, and how ecosystems contribute to economic activity (Comte et al. 2022). The economic consequences of ecosystem degradation are therefore not reflected in indicators produced with the national accounts, such as GDP.

The first seven chapters of the System of Environmental-Economic Accounting—Ecosystem Accounting (SEEA EA) (United Nations et al., 2021), have been adopted by the United Nations Statistical Commission in 2021, as an international statistical standard (Edens et al., 2022). More specifically, SEEA EA is a statistical framework which unifies spatially explicit data to measure ecosystem extent and condition and associated ecosystem service flows and how these interact with our economy and contribute to our well-being. It extends the traditional System of National Accounts to include ecosystem services and natural capital.

However, ecosystem accounting requires a reliable and standardized measurement of the different ecosystem types' of extent and as well as of ecosystem condition attributes (stock) and the ecosystem services they deliver (flow) in spatial and temporal terms (UNEP-WCMC/EEA, 2020).

Earth observation has become an essential element in assessing and addressing challenges at local to global scale, providing synoptic overviews which can be used for situation assessment and change detection. Earth Observation (EO) data and EO products (e.g., land cover/land use and vegetation, above ground biomass, climatic indices maps, etc.) can provide important information about the current state, as well as for changes of ecosystems and their services, in spatial and temporal terms. Subsequently, this information can be used to quantify and monitor changes and identify trends of the related ecosystem services. By this, the integration of EO data and EO products into the SEEA EA is considered a valuable tool to be combined with other socio-economic and ground truth ecosystem reference datasets to generate information that considers both economic and environmental aspects in the decision-making process.

Recent outcomes of the Group on Earth Observations (GEO) – Earth Observations for Ecosystem Accounting Initiative (EO4EA) point out the importance of EO data and products in ecosystem accounting, e.g., the Copernicus land monitoring services can provide long-term support to ecosystem accounting in Europe, mainly via the Corine Land Cover products. Moreover, EO enables much of the approach, feasibility, and options for standardization of ecosystem accounting.

The aim of this report is to (a) provide a policy analysis on drivers in ecosystems and their services assessment and accounting, (b) identify EO integration in EU monitoring and reporting obligations, (c) provide an overview of EO relevant major ongoing projects and networks and (d) identify and assess EO data integration into ecosystem accounting via a literature review.

2.1 Concepts and Terminology

The table below shows the major concepts and terminology used throughout the document.

Table 1: Terminology

Concept/Term	Abbrev.	Description
Aries for SEEA Explorer		An integrated, open-source modelling platform for environmental sustainability, used to produced rapid, standardized, scalable and customizable ecosystem accounts consistent with SEEA EA
Cultural services		Experiential and intangible ecosystems services related to the perceived or actual qualities of ecosystems whose existence and functioning contributes to a range of cultural benefits.
Ecosystem		A dynamic complex of plant, animal and microorganism communities and the abiotic environment, interacting as a functional unit
Ecosystem Accounting	EA	An integrated and comprehensive statistical framework to organize data on habitats and landscapes, measure ecosystem services, tracking changes in ecosystem assets and link this information to economic and other human activity.
Ecosystem Assessment		The interpretation of scientific results/evidence in non-monetary terms and other form of information that is intelligible and meaningful for policy and decision making.
Ecosystem assets	EAs	Contiguous spaces of a specific ecosystem type characterized by a distinct set of biotic and abiotic components and their interactions.
Ecosystem Type	ET	Recurrent classified discrete units (e.g., deciduous forests) that represent complexes of organisms and their associated physical environment within an area, baed on one or more dominant features (Keith et al., 2015, based on Tansley, 1935).
Ecosystem extent		The size of an ecosystem asset in terms of spatial area.
Ecosystem condition		The quality of an ecosystem measured in terms of its biotic (e.g., structural, functional and composition) and abiotic characteristics (e.g., chemical and physical)
Ecosystem condition typology	ECT	A hierarchical typology for organizing data on ecosystem condition characteristics
Ecosystem services	ESs	The contributions of ecosystems to benefits used in economic and human activity.
Findable, Accessible, Interoperable and Reusable	FAIR	The FAIR principles emphasize machine-actionability. The first step in (re)using data is to find them. Once found, they need to know how to access it. The data usually needs to interoperate with workflows. The goal is to optimize the reuse of data and models.
Mapping and Assessment of Ecosystems and their Services	MAES	A conceptual framework for Mapping and Assessment of Ecosystems and their Services (MAES), developed to steer a more harmonized approach to ecosystem and ecosystem services assessments across EU Member States.

Concept/Term	Abbrev.	Description
Integrated Natural Capital Accounting	INCA	A project implemented at EU level compliant with the SEEA EA to build ecosystem accounts.
Natural Capital Accounting	NCA	A process of quantifying and valuing the stocks and flows of natural resources and ecosystem services in economic terms. It is a broader concept that encompasses the valuation of all natural resources.
Open Earth Observation	OPENEO	An interface that targets the processing and analysis of Earth Observation (EO) data in the context of open-source software (Apache 2.0)
Provisioning services		Those ecosystem services representing the contributions to benefits that are extracted or harvested from ecosystems.
Regulating services		Those ecosystem services resulting from the ability of ecosystems to regulate biological processes and to influence climate, hydrological and biochemical cycles and thereby maintain environmental conditions beneficial to individuals and society

More information can be found at https://seea.un.org/sites/seea.un.org/files/documents/EEA/Revision/3_seea_eea_draft_glossary_v4_july2020.pdf.

3 Policy analysis

Ecosystem services are public goods and most of them are not currently priced on markets and, consequently, are often not considered in economic decisions. This has had often significant negative consequences for nature and natural processes, and in turn, for society. Ecosystem accounting has adopted the language and guiding principles of economic accounts (System of National Accounts) that will enable ecosystems and their services to be properly incorporated into standard accounting frameworks, and thus allow for the value of nature to be included in decision making. This chapter identifies the main policy drivers that ecosystem accounting and ecosystem services assessment could inform at EU level. Focus is mainly dedicated to the recent development with some insight into the close history of the development of ESs concept, assessment, and accounting.

3.1 Brief history of the policy drivers in ecosystems and their services assessment and accounting

The EU became one of the leaders of the research and implementation of the ecosystem services concept. The adoption of the EU biodiversity strategy 2020 in 2011 did formally start Action 5 of the strategy, better known as the *Mapping and Assessment of Ecosystems and their Services* (MAES[2]). The introduction of this strategy emphasized the importance of biodiversity as part of natural capital in terms of ES provision and the overall standard of living (quality of life) of people. The strategy aimed to reverse the loss of biodiversity and accelerate the EU's transition to a resource-efficient green economy. The main goal by 2020 was to stop the loss of biodiversity and ES degradation within the EU and fully restore it where possible, while increasing the EU's contribution to preventing global biodiversity loss. The EU 2020 biodiversity strategy consisted of 6 targets and 20 actions focused on halting biodiversity loss and the degradation of ecosystem services. ESs were included in target no. 2, "*Maintaining and enhancing ecosystems and their services*", which specified "*By 2020, ecosystems and their services are maintained and enhanced by establishing green infrastructure and restoring at least 15% of degraded ecosystems*" (European Commission 2011). Special emphasis on ES has been transferred into action no. 5, "*Member States, with the assistance of the Commission, will map and assess the state of ecosystems and their services in their national territory by 2014, assess the economic value of such services, and promote the integration of these values into accounting and reporting systems at EU and national level by 2020*" (European Commission 2011).

However, the goals to stop the loss of biodiversity and restore ecosystems were not reached. The goal to assess the ecosystem services by MS was reached partially. Based on the initial experience, a new and very ambitious strategy started to be developed stop the loss of biodiversity. In order to support this goal, the European Commission has initiated the creation of an expert group on MAES. A coherent analytical framework as well as common typologies of ecosystems for mapping and a typology of ecosystem services for accounting, have been developed to be applied by the EU and its Member States to ensure consistent approaches. Its implementation has resulted in a first technical report (Maes et al. 2013). It contributed to the sub-global assessments of ecosystems and ecosystem services under the Intergovernmental Platform for Biodiversity and Ecosystem Services (IPBES). A second report (Maes et al. 2014) proposed an initial set of indicators that could be used at the European and

[2] Available online at https://biodiversity.europa.eu/ecosystems/maes

Member State level to map and assess biodiversity, ecosystem condition and ecosystem services. The third report (Erhard et al. 2016) is taking stock of the available information to map and assess the condition of European ecosystems. The fourth report describes the methodology for mapping and assessment of urban ecosystems and their services (Maes et al. 2016), while the fifth report provides an integrated analytical framework and set of indicators for mapping and assessing the condition of ecosystems in the EU (Maes et al. 2018). Based on these reports, an ecosystem assessment covering the total land area of the EU as well as the EU marine regions was carried out (Maes et al. 2020). The assessment report shows that the pressures on ecosystems are increasing and the potential of ecosystems to deliver services was equal to or lower than the baseline value of one decade ago. More efforts are needed to bend the curve of biodiversity loss and ecosystem degradation and to put ecosystems on the path to recovery.

For ecosystem services accounting the publication of this *EU wide Ecosystem Assessment* in October 2020 was an important policy milestone, showing opposite trends between the ecosystem service potential and demand. While the number of services that ecosystems can offer was stable or decreasing, society showed a growing demand for most services which explains the negative trend. Despite the crucial role of ecosystems and their services for society, there is no established and regular measurement of ecosystem extent, condition and their changes over time, nor of the quantity of services these ecosystems supply. The ecosystem accounting framework addresses this major gap. For instance, new work showed that, based on 2012 data, *EU's ecosystems generated an annual flow of selected seven ecosystem services* - crop pollination, crop provision, timber provision, water purification, flood control, carbon sequestration and recreation in high-value natural areas - at the value of € 172 billion (Vyšná et al, 2021). The report also shows the importance of making ecosystem accounts operational, including the data foundation, developing an accounting infrastructure, rolling out at Member States and the involvement of the research community. Data underpins the modelling of ecosystem services flow; however *many data gaps* were seen especially the availability and use of geospatial datasets. For example, it was found that EU datasets to underpin ecosystem condition indicators were collected regularly for only 50% of the accounts.

3.2 Recent policy drivers in ecosystems and their services assessment and accounting

In Europe, the *European Green Deal* and the newly adopted *EU Biodiversity Strategy for 2030* recognize the value of ecosystem accounting in the development of a comprehensive Natural Capital Accounting in Europe. The vision of EU biodiversity policy by 2050 is the protection, valuation, and adequate restoration of biodiversity and ecosystem services (natural capital) it provides. The main reason is the intrinsic value of biodiversity and its fundamental contribution to the standard of living and economic prosperity. The European Green Deal (EC 2019) recognizes that *ecosystems provide essential services* such as food, fresh water and clean air, and shelter. They mitigate natural disasters, pests and diseases and help regulate the climate. This specific action aims to provide a knowledge base on ecosystems and their services in Europe.

The European Commission, under the coordination of Eurostat, has proposed a new regulation – *an amendment to the EU Regulation No 691/2011* – that among other things requires member states to compile ecosystem accounts and report them to Eurostat. In support of this regulation, the Commission with the member states is developing detailed guidelines for countries on how to produce accounts[3]. These guidelines are compliant to the recently (March 2021) adopted new international statistical standard (SEEA-EA[4]). The SEEA-EA was developed to elicit the value of ecosystems for the economy and people in the context of a range of policy demands. The mandatory reporting stimulates countries to use a common set of rules and methods to track changes in ecosystem assets (ecosystem extent and conditions) and flows (ecosystem services), and to link ecosystem information to economic and development activities. It can also be used to underpin the development of ecosystem-related indicators from other international agreements such as UNFCC, UNCCD, UNCBD. In the process of preparation of the accounts, EO data has a high potential to fill some (key) data gaps. EO data can be used as baseline not only for the preparation of spatial data sets (i.e., ecosystem types, ecosystem condition) but also for the identification of changes in time periods as well (i.e., land cover changes).

3.2.1 Recent activities in mapping and assessing ecosystems and their services

All EU Member States are recently actively involved in *mapping and assessing the state of ecosystems and their services* in their national territory (Mederly & Černecký 2020, pages 21-22). In order to deliver Action 5 of the 2020 Biodiversity Strategy, members of the MAES Working Group provide updates on progress in their countries twice a year and a barometer is updated accordingly (see Figure 1). According to this assessment, nine European countries (UK, the Netherlands, Ireland, Hungary, France, Finland, Estonia, Bulgaria and Greece) have already achieved full implementation, not only the ecosystem and ES assessment but also their integration in national policies. Other countries are approaching this objective (Germany, Italy, Romania, Lithuania) while others (Greece, Estonia, Norway, Cyprus and Lithuania) have made large progress.

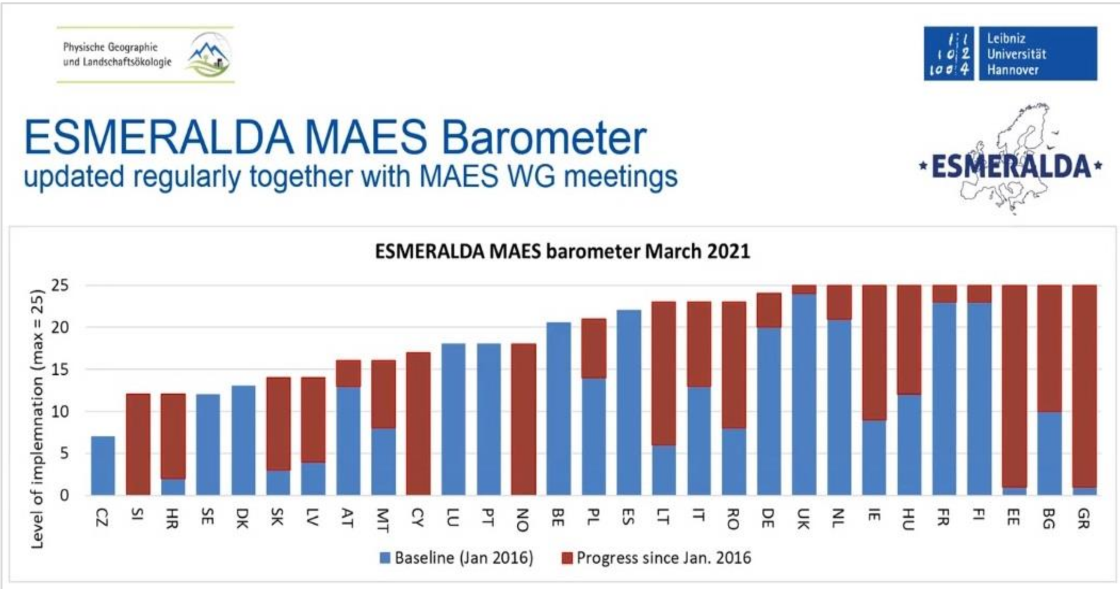

Figure 1 The ESMERALDA MAES barometer: Development in evaluation and application of ecosystem services approach of EU Member States in the period 01/2016 - 03/2021 (Source: https://biodiversity.europa.eu/ecosystems).

[3] See https://ec.europa.eu/environment/nature/capital_accounting/

[4] See https://seea.un.org/sites/seea.un.org/files/documents/EA/seea_ea_white_cover_final.pdf

Mederly et al. (2020) analyzed EU Member States *evaluations of ecosystems services with further development into ecosystem accounting.* The number of assessed ESs in individual countries varies significantly but is on average 15 – 20 ESs, ranging from 3 – 6 ESs (CZ) to 26 – 28 ESs (UK, NL, GR). The ratio of ES representation by main groups largely varies. Some countries have over-represented provisioning ESs (FI, LT, UK), while others focus more on cultural ESs (DK, IE, SP). Regulating and supporting ESs are strongly represented in almost all countries. Ecosystem maps were used as an important basis for the ES assessment for most countries. Some countries (LT) used simpler land use maps or the European Corine Land Cover maps, some other - national land cover classification (GR). ES assessment methods vary significantly across countries. Complex ES mapping and assessment involving many indicators and statistical data evaluation were for example presented in studies of BE, NL, UK, RO, SP. Biophysical models have been used in different countries - DK, FI, GE, IE, IT, LU. Economic valuation in the form of a benefit transfer method was used by CZ, IT, UK, FI, SP. Most of the studies focus on the current status and trends related to ESs value but some also offer future development scenarios (UK, PT, SP). Most of the studies address not only these *ESs capacities*, but also the *demand and current ESs flows* (actual use) and compare them in different ways. The most common methods include statistical evaluation of relationships between these categories for administrative units or regions (e.g., DK, GE) (Mederly & Černecký 2020).

3.2.2 Biodiversity for 2030

The new EU Biodiversity Strategy for 2030 recognizes that natural capital investment, including restoration of carbon-rich habitats and climate-friendly agriculture, are among the five most important fiscal recovery policies, which offer high economic multipliers and positive climate impact. Over the last 30 years, the EU has put in place a solid *legislative framework to protect and restore its natural capital*. However, recent evaluations (Považan et al., 2021) show that although legislation is fit for purpose, implementation on the ground is lagging. This is having dramatic consequences on biodiversity and comes with a substantial economic cost. The full implementation and enforcement of EU environmental legislation is therefore at the heart of this strategy, for which political support and financial and human resources will need to be prioritized.

3.2.3 8th Environment Action Programme

The 8th Environment Action Programme[5], as shown in Figure 2, will guide European environment policy until 2030, builds on the EU Green Deal to speed up the transition to a climate-neutral, resource-efficient economy recognizing that human wellbeing and prosperity depend on healthy ecosystems. It forms the EU basis for achieving the United Nation's 2030 Agenda and its Sustainable Development Goals. On 26 July 2022, the Commission presented a list of headline indicators for monitoring progress towards the EU's environment and climate goals to 2030, as well as 2050 long-term vision to 'live well, within planetary boundaries. These indicators will be monitored from 2023 onwards by this 8th Environment Action Program and two in-depth assessments in 2024 and 2029.

[5] See https://environment.ec.europa.eu/strategy/environment-action-programme-2030_en

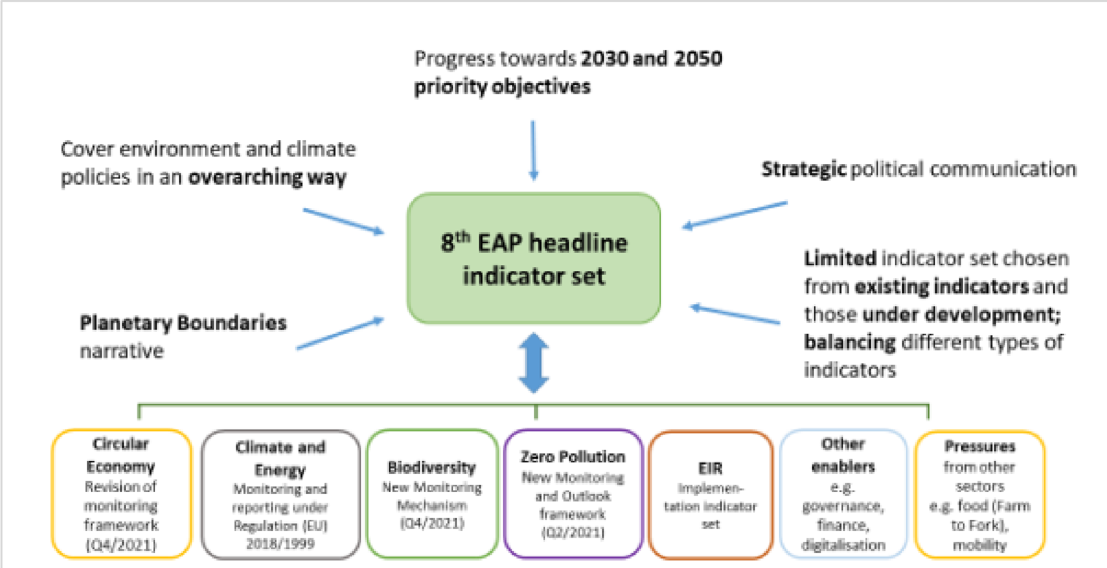

Figure 2. European 8th Environment Activity Program.

In this European 8th Environment Activity Program rule 31 mentions[6] "*Natural capital accounting, a tool that aims to measure the changes in the stock of natural capital at a variety of scales and to integrate the value of ecosystem services into accounting and reporting systems,* should support measuring progress towards ambitious targets and measures to reduce greenhouse gas emissions and protect and restore biodiversity, which it cannot replace".

Article 3 defines the enabling conditions to attain the priority objectives, with item (w) "ensuring that environment policies and action at Union, national, regional and local level are based on the best available scientific knowledge and technologies, and strengthening the environmental knowledge base, including indigenous and local knowledge, and its uptake, including through research, innovation, fostering green skills, training and retraining, *and further building up environmental and ecosystem accounting.*"

3.3 EO for monitoring and reporting obligations

Earth Observation (EO) datasets provide new opportunities to fill certain data gaps for environmental reporting. This chapter analyses the current use and potential of EO data in ecosystem accounts that could be further explored to fill these gaps in EU regulations/directives.

3.3.1 Regulation for Environmental economic accounts

Environmental accounts are a multipurpose data system encompassing a conceptual framework and tables which describes the interrelations between the economy and the environment in a way that is consistent with the national accounts. One of the most important features of the environmental accounts is their capacity to organize and present coherently

[6] See https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32022D0591

information in both physical terms (often for the environment) and monetary terms (often for the economy). The European environmental accounts are established in Regulation (EU) 691/2011. The Regulation[7] provides a legal framework for a harmonized collection of comparable data from all EU Member States and EFTA countries. The European environmental accounts are consistent with the SEEA 2012 Central Framework and are structured in six modules: air emissions accounts, environmentally related taxes by economic activity, economy-wide material flow accounts, environmental protection expenditure accounts, environmental goods and services sector accounts, and physical energy flow accounts. Next to the above modules, an amendment[8] to the Regulation (EU) 691/2011 has been proposed in July 2022 to introduce three new environmental economic accounts modules: forest accounts, ecosystem accounts, and environmental subsidies and similar transfers accounts. The main objective of the proposal is to extend the scope of the European environmental economic accounts to provide better information for the European Green Deal.

The European Commission supported the UN in the development of the ecosystem accounting (SEEA EA, UNSD 2021) framework through generating EU accounts through the Knowledge Innovation Project on Integrated Natural Capital Accounting (KIP-INCA) (Vysna et al., 2021). A feature of accounting frameworks is their organization of data from multiple sources and the potential to support the derivation of more coherent and consistent indicators to support EU Green Deal, Biodiversity strategy and its 8th Environment Action Program.

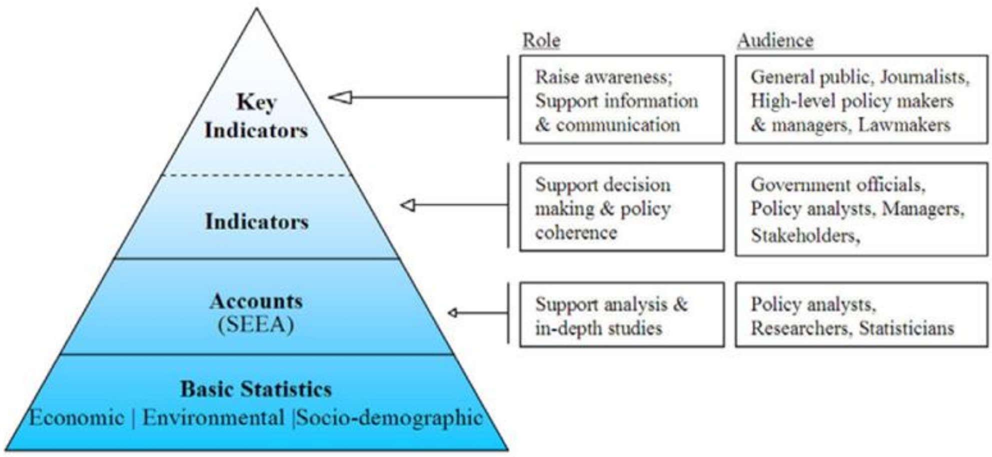

Figure 5. Information pyramid (from Eurostat Environmental accounts[9]).

KIP-INCA[10] provides ecosystem accounts, in both physical and monetary terms, for nine ecosystem services for the period 2000 to 2012. These accounts are established through a set of models, developed by the Joint Research Centre (La Notte, 2022), in which the ecosystem service flow is determined by the interaction between an ecosystem component and a socio-economic component based on the SEEA EA accounting framework. The use of spatial models

[7] http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32011R0691:EN:NOT
[8] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2022:329:FIN
[9] See https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Environmental_accounts_-_establishing_the_links_between_the_environment_and_the_economy#Policy_relevance_and_uses_of_environmental_account
[10] https://ecosystem-accounts.jrc.ec.europa.eu/

to quantify the ecosystem service actual flow is based on the assessment of the 'Potential', which is the service that ecosystems can potentially provide depending on their type, extent and condition; and on the assessment of 'Demand', which is considered as the need for a given ecosystem service by the socio-economic system (La Notte, Vallecillo et al., 2019). Supply-Use tables is a well-known technique in statistical accounting and hence has been extended to support ecosystem accounts to be kept compatible and ease integration within National Accounts. The nine Ecosystem Service accounts were comprised of two provisioning services (wood and crop), six regulating & maintenance services (carbon sequestration, crop pollination, soil retention, flood control, water purification, [11] and species maintenance￼), and one cultural service (nature-based recreation). Earth Observation (EO) data represents in average less than 20% of the data used to generate the physical ecosystem accounts. EO data is mostly used as a proxy (indirect use) for spatial disaggregation of tabular statistics, and accounts for flood control and partially soil retention and crop pollination are directly generated usingEO data at least as equal importance of tabular statistical input. The main EO datasets used are Copernicus Digital Elevation Model, Copernicus Imperviousness, Copernicus Riparian zones, Copernicus Biomass Productivity and Global Human Settlement. Note that some data inputs (Corine Accounting Layer, MAES classification or LUCAS nitrogen) were not counted as direct EO inputs whereas Corine accounting layers and MAES classification are derived from EO data.

The new proposed regulation on ecosystem accounting includes the mandatory reporting of ecosystem extent and condition accounts every three years, plus annual ecosystem service accounts for seven services: wood provision, crop provision, crop pollination, global climate regulation (carbon sequestration and carbon retention), local climate regulation, air filtration, tourism-based recreation. It is assumed that next to these mandatory reporting, in the coming years additional accounts will be added for voluntary reporting. The potential to use EO data for most of these (and other) services, as well as for ecosystem extent and condition, is high to provide more spatial and temporal details and ease the generation of regular accounts, hence bring the accounting framework in operations. In some cases, the Guidance Notes under development already indicate where and how EO data can be used. For example, assessing the local climate regulation service requires as input data Land Surface Temperature, which can be derived from EO data (MODIS, VIIRS, Sentinel 3, Landsat). However, further work is needed to explore all options to feed ecosystem accounts compilation as per the EU legal proposal with EO data and the links to the standard environmental reporting already in place.

3.3.2 Habitats Directive

The Habitats Directive targets the conservation of a wide range of rare, threatened or endemic animal and plant species. In accordance with Art. 17 of the Habitats Directive, the mapping of the occurrence Annex 1 habitats is important. Individual Annex 1 habitats cannot be identified with EO alone, but EO data can be used as supporting data set in addition to the field mapping data so delineation for ecosystem extent. It is important to stress that EO data is complementary to field mapping surveys and we should strive to combine them to achieve the best possible boundaries mapping with least uncertainties. For example, the EO data in

[11] This account is not made publicly available.

combination with Machine Learning (ML) techniques can be used for the further precision of habitat boundaries, which are often imprecise due to as the impression of field data. This approach was used, for example, in Slovakia, where data from LPIS created by photo-interpretation based on aerial Orto imagery were applied to the field mapping data in order to better capture the boundaries of Annex 1 habitat data collected by field mapping. This approach was applied on a national scale; the physical field maps by field workers was changed into LPIS boundaries derived from Earth Observation, and the final area for Art. 17 for selected Annex 1 habitat types was calculated. Similarly, ecosystem extension data, especially boundaries of ecosystems, can be used in combination with field mapping data to reach better precision of habitat borders (Figure 3).

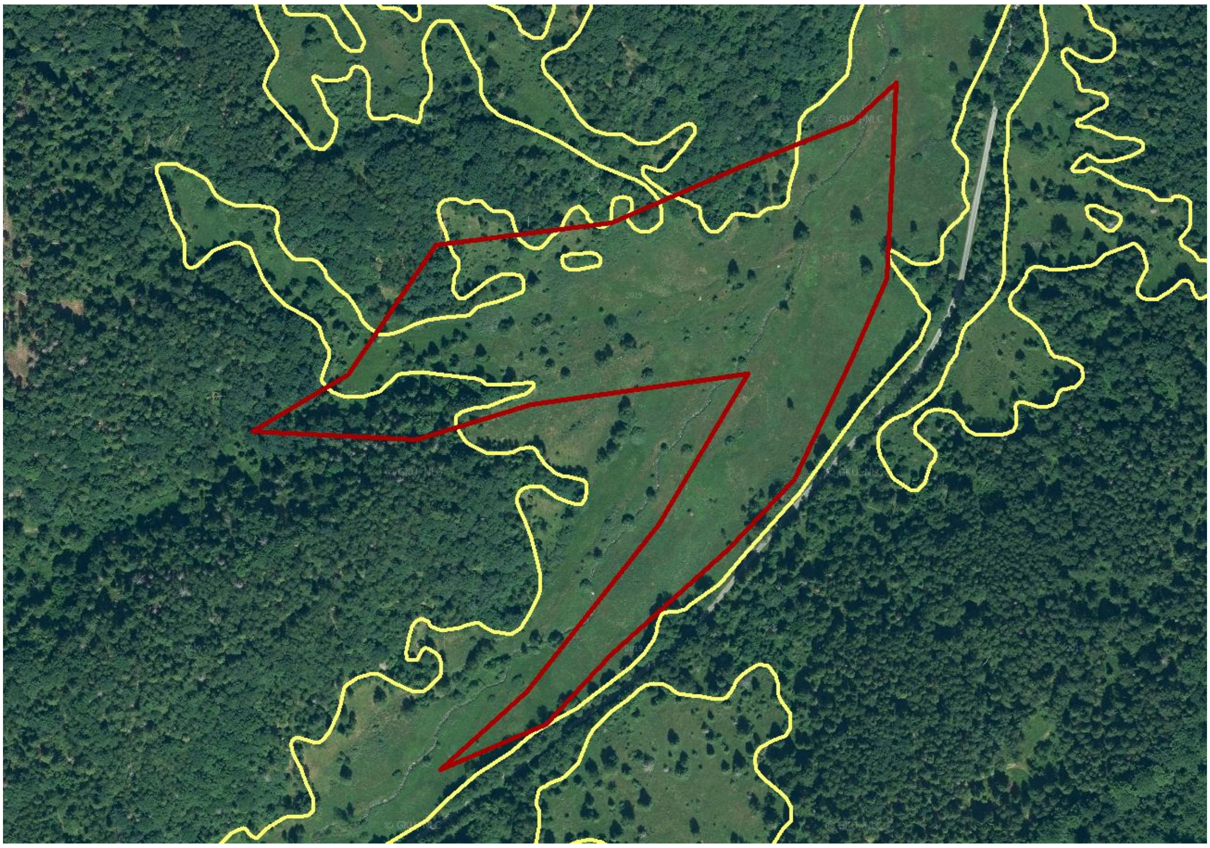

Figure 3. Example of field mapping data precision created by experts in the past based on physical maps of 1:50000 (in red), compared to LPIS borders prepared recently by EO data (in yellow)

To your question, the red line is the past field mapping, where only physical maps were available for field workers with a precision of 1:50 000; no EO was used. Therefore, the outputs from the field mapping were very rough, with rather low precision for the borders of ecosystems captured. Aerial images were not available at that time or were not used as an input source for practical mapping, which created such a big difference in precision. Yellow is the border prepared as an output of LPIS for the purpose of agricultural schemes produced on the basis of EO. Therefore, we used the method of transposing the old data into a more precise new data set by overlapping these two data sets by specific rules and transposing the attributes of the previously mapped ecosystem into new, more precise borders prepared by EO.

EO data can be useful for the verification of classification of the individual habitat types but with limited results. There have been recent activities dedicated to the development of software tools for identification, monitoring, and evaluation of habitats by remote sensing techniques, i.e., Mikula et al. (2021). By using specific approaches and tools, the team created a baseline for the identification of a few Annex 1 habitats, with the best positive results in the identification of 91E0 Alluvial forests with Alnus glutinous and Fraxinus excelsior and a 91F0 Riparian mixed forest of Quercus robur, Ulmus laevis, Ulmus minor, Fraxinus excelsior, or Fraxinus angustifolia, along the great rivers, so far. However, the tool is still in development, and it requires quite a lot of calibration and some manual inputs by using a semiautomatic approach. Due to these circumstances, it is difficult to use it on a broader scale; however, the technique will probably develop and advance over time. The typology of Annex-I habitat types require to apply a single AI/ML model, and hence its use is limited to prepare models that extrapolate field mapping data. By using EO, it is also possible to correct coarser mapping of habitat extent, by more accurate delineation of forest and non-forest parts, identifying smaller areas of water habitats, etc.

Reporting according to Art. 17 also requires an assessment of the conservation status, and thus the ecosystem condition data derived from EO could support this process. Conservation status defined by this reporting obligation requires to assess favorable reference values, structure and functions. Future prospects, range and surface area of the particular habitats and important parameters for which the EO data can be highly relevant.

The Habitats Directive in addition to the reporting obligations also defines the requirement regarding the implementation of regular monitoring of habitats and species of European importance, specifically Art. 12 of the Habitats Directive deals with this. The EO data could be relevant also for this part as complementary source of information.

The updated reference information system named European Nature Information System (EUNIS) is prepared for the habitat types listed in Annex I of the EU Habitats Directive, the habitat types in Resolution 4 of the Bern Convention and of the European Red List of habitats (https://eunis.eea.europa.eu/). Its purpose is to contribute to the knowledge base for implementing the Biodiversity Strategy for 2030. This typology uses a hierarchical scheme and as such specific ML/AI models can be trained per level and per habitat to generate an ensemble to create more accurate maps, at least for the levels 1 to 3. Several projects and Member States are exploring to use these techniques to create high-spatial habitat maps. These experiences could also guide and optimize the ground-truth data collection as well as to identify which habitats can be monitorable using EO. Upcoming new EO datasets (e.g. hyperspectral) could further improve these models.

3.3.3 Birds Directive

The Birds Directive aims to protect all of the 500 wild bird species naturally occurring in the European Union. Similarly to the Habitats Directive, the Birds Directive also requires Member States to report every 6 years detailed information on the status of all EU wild living birds. Through the preparation of ecosystem extent and ecosystem condition data, the EO data could indirectly provide supportive information i.e. for the identification of suitable species habitats for the purposes of preparing maps of nesting distribution as well as the quality of species habitats (Article 10).

3.3.4 Water Framework Directive

The Water Framework Directive is about getting polluted waters clean again and ensuring clean waters are kept clean. As such it requires important data collection for water quality monitoring and, like previous directives, requires detailed data at the national level. In-situ networks are set in place to provide such information and are prime use to support this Directive. EO data could complement this information i.e., to refine the boundaries of surface water ecosystems through data provided for ecosystem extent, where Copernicus data sets and some other offer excellent basis for identification of ecosystem boundaries. Ecosystem condition accounts include some indices that could reveal the water quality at full spatial coverage, which can be derived from EO data (i.e., turbidity).

3.4 New initiatives in the field of biodiversityPledge process

As part of the EU Biodiversity Strategy, Member States are expected to submit to the Commission a list of pledges, closely linked to the reporting under Article 17 Habitats Directive and Article 12 Birds Directive:

- a list of habitats and species that should at least show a strong positive trend by 2030;
- an explanation of the criteria used for selecting these habitats and species;
- an additional list of habitats and species for which further measures should be taken to achieve non-deterioration by 2030;
- an explanation of the measures need to achieve the desired positive/ stable trends by 2030;
- If relevant, an explanation of why certain habitats and species are not expected to achieve the target, despite all possible measures taken; and a list of these habitats and species:
- If relevant, an explanation of measures that will be taken to improve the quality of monitoring.

EO data, in combination with in-situ data and ground truth measurements, could support many new requirements resulting from the newly established goals in the field of biodiversity at EU and Member State level. It is highly relevant to mention the preparation of detailed lists of existing and newly proposed protected areas for achieving goals related to the protection of 30% of the EU territory, of which 10% (the so-called pledge process) should have a strict protection regime. For this, EO data can contribute, specifically the parts related to the mapping (extent account) of ecosystems, but also assessment of their condition by various parameters/indicators. For instance, the data on the state of forest ecosystems can significantly help in the identification of areas by Member States that will be classified as new protected or strictly protected areas.

Another part of this process is also the definition of 30% of habitats and of species for which the Member States should demonstrate an improvement of conservation status by 2030. EO data provides a continuous stream of observations and can become highly relevant. The preparation of ecosystem extent account with spatial dataset can contribute to localization and identification of boundaries for habitats and EO data could contribute to planning of the practical management measures in particular sites.

3.4.2 Nature Restoration law

The upcoming legal framework for the restoration of ecosystems, habitats and species defines the requirements for the commitment of Member States to restore degraded ecosystems in a certain period in order to:

- enable the long-term and sustained recovery of biodiverse and resilient nature;
- contribute to achieving the EU's climate mitigation and climate adaptation objectives;
- meet international commitments.

The proposal contains the following specific targets:

- targets based on existing legislation (for wetlands, forests, grasslands, river and lakes, heath & scrub, rocky habitats and dunes) - improving and re-establishing biodiverse habitats on a large scale, and bringing back adversely affected species populations by improving and enlarging their habitats;
- pollinating insects – reversing the decline of pollinator populations by 2030, and achieve thereafter an increasing trend of pollinator populations, measured every three years after 2030, until satisfactory levels are achieved;
- forest ecosystems – achieving an increasing trend for standing and lying deadwood, uneven aged forests, forest connectivity, abundance of common forest birds and stock of organic carbon;
- urban ecosystems – no net loss of green urban space by 2030, an increase in the total area covered by green urban space by 2040 and 2050, and a minimum level of tree canopy cover by 2050;
- agricultural ecosystems – increasing grassland butterflies and farmland birds, the stock of organic carbon in cropland mineral soils, and the share of agricultural land with high-diverse landscape features; restoring drained peatlands under agricultural use;
- marine ecosystems – restoring marine habitats such as seagrass beds or sediment bottoms that deliver significant benefits, including for climate change mitigation, and restoring the habitats of iconic marine species such as dolphins and porpoises, sharks and seabirds;
- river connectivity – identifying and removing barriers that prevent the connectivity of surface waters, so that at least 25 000 km of rivers are restored to a free-flowing state by 2030.

As an example, ecosystem accounts for pollination can become an important tool for supporting the EU pollinators initiative to identify places with significant demand for crop-pollination, where there is a lack of this service. These places are therefore a high priority to contribute to the future restoration of habitats for pollinators, and hence can benefit from the use of geospatial EO data.

3.5 Policy Traceability Matrix

The Policy Traceability Matrix is a table to link ecosystem accounts to different EU policies.

Table 2 below is a summary of links between ecosystem accounts and its relevance for monitoring and reporting to the EU policies. The *matrix was prepared based on a joint evaluation of selected experts working in the project*, especially early adopters representing Member States. Each expert evaluated the relevance of ecosystem accounts in general to the policy and the contribution of EO to the introduction of ecosystem accounting and more particularly for ecosystem extent, ecosystem condition and ecosystem services. The values reported by expert estimates were subsequently summarized and averaged and rounded to a whole number. *The values expressed through the score are given on a scale from 1 to 5, with a value of 1 - indicating low relevance and a value of 5 - high relevanc*e. **They only tend to present a general overview by few experts on the applicability of ecosystem accounting and the relevance of Earth Observation data therein and by no means represent a full view on the European continent. The latter would require a follow-up study with surveys to all Member States which is out of scope for this project**.

Table 2. Policy Traceability Matrix.

	Ecosystem accounting								
	Ecosystem extent			**Ecosystem condition**			**Ecosystem services**		
Policy	Relevance of use of EO data	Possible contribution to monitoring obligation	Possible contribution to reporting obligation	Relevance of use of EO data	Possible contribution to monitoring obligation	Possible contribution to reporting obligation	Relevance of use of EO data	Possible contribution to monitoring obligation	Possible contribution to reporting obligation
EU legislation on environmental ecosystem accounting (SEEA EA)	5	x	x	5	x	x	5	x	x
Habitats Directive	4	x	x	4	x	x	2		
Birds Directive	3	x	x	3	x	x	2		
Water Framework Directive	4	x	x	3	x	x	2		
Monitoring EU progress towards sustainable development goals	2			2			3		x
8th EAP / biodiversity (post-2020 global biodiversity framework)	4		x	4		x	4		x
Pledge process - 30% protected land, 10 % strictly protected	3	x (expected)	x (expected)	2	x (expected)	x (expected)	3		
Pledge process - 30% habitats or species improved conservation status	4	x (expected)	x (expected)	3	x (expected)	x (expected)	2		
8th EAP / circular economy	1			3			4		
8th EAP / climate and energy	3	x	x	3			4	x	x
8th EAP / Zero pollution	3			3			3	x	x
Nature Restoration Law	4	x (expected)	x (expected)	5	x (expected)	x (expected)	4		
Mapping and Assessment ecosystems process	5	x	x	5	x	x	5	x	x
Common Agricultural Policy (CAP), high nature value (HNV) farmlands and forests	4	x	x	4	x	x	4	x	x
Forest strategy	4	x	x	4	x	x	3		
EU Pollinators Initiative	3	x	x	4	x	x	4	x	x

As **Table *2*** above shows, ecosystem accounting can contribute to several policies, mainly on EU legislation on environmental ecosystem accounting and the policies related to ecosystem reporting (MAES, CAP and Forest strategy) but also to the new processes as is the Nature Restoration Law and the pledge processes, as part of the 8th Environment Action Programme. Earth Observation is (or can be) of major importance (score 4 or higher) in about 50 - 60% of all ecosystem accounts, almost equally spread across extent, condition and services.

Policy key messages

- An important part of the new EU biodiversity strategy for 2030 is the restoration of degraded ecosystems, the assessment of the value of ecosystem services as well as the gradually increased interest in ecosystem accounting.

- The MAES process at the EU level significantly contributed to the progress towards the introduction of ecosystem accounting. The EU wide Ecosystem Assessment prepared in 2020 is an important milestone for this introduction at EU level and at MS level, next to the adoption of the SEEA-EA standard.

- EU member states are gradually finalizing their pilot national ecosystem assessments, on the basis of which they will subsequently test and introduce ecosystem accounts.

- EO becomes an important tool for the preparation of reporting not only in the field of ecosystem accounting, but also in other biodiversity protection policies at the EU level.

- To take full benefit of EO in this reporting, sufficient investment in harmonization, interoperability, collection and sharing of ground-truth and other in-situ data at MS level is required.

- Ecosystem accounting could contribute by complementing through its geospatial nature the monitoring and reporting obligations defined in the Habitats Directive (art. 12 and art. 17), the Birds Directive (art. 11 and art. 12), the Water Framework Directive, Forest Strategy, etc.

- New and upcoming initiatives in the field of biodiversity such as the so-called pledge process (30% of the EU territory, of which 10% strict protection regime, 30% of biotopes and species reach an improved conservation status) or upcoming Nature Restoration Law provide significant opportunities for the use of EO data.

4 International networks and projects

The number of projects and initiatives dealing with ecosystem accounting has increased quickly since the adoption of the SEEA EA standard in 2021. This chapter analyses six key projects or initiatives: INCA, MAIA, EuropaBON, EO4EA, SEEA for ARIES, and Open Earth Monitor. Many more projects could be analyzed, especially those part of the many national initiatives, however the authors have selected these projects due to its relevance at European continent scale.

4.1 INCA

The INCA project was set up under the 7th Environment Action Programme – Living well, within the limits of our planet (2014 – 2020)) which called for the EU to establish a sound method for natural capital accounting with a strong focus on ecosystems and the services they provide. This objective was reiterated in the EU Biodiversity Strategy to 2030.

INCA stands for Integrated system of Natural Capital and ecosystem services Accounting for the European Union and is a project launched by the European Commission (DG ENV, RTD, JRC and ESTAT) and the European Environment Agency to develop and publish a set of European ecosystem accounts that assess the status and trends of Europe's ecosystems and the contributions of natural capital to people and the economy. INCA developed a set of ecosystem accounts for the whole of the EU (La Notte et al., 2017; Vallecillo et al., 2018; Vallecillo et al., 2019; Petersen et al., 2020, Vysna et al., 2021).

The experience gained in the early phases of INCA provided valuable input into global developments in ecosystem accounting that led to the publication by the UN of the first ever international handbook on ecosystem accounting, SEEA – Experimental ecosystem accounting (SEEA EEA), in 2014. This publication sparked interest among researchers, economists and accountants in several countries and an extensive testing of proposed concepts and methods have followed, bringing together ecological and economic information to produce internationally comparable statistics. INCA was one of the projects that used the SEEA EEA as working guidance and thus tested its concepts and recommendations in practice. The experience gained had resulted in the definition of an architecture to calculate the Potential and Demand of a service and derive the Flow from this. Such concept was also proposed as input into the revised handbook SEEA – Ecosystem Accounting, adopted at the UN level in March 2021. The large geographic scope and the international aspect of the INCA project, combined with the wide range of different accounts the project produced, made the INCA an important test case of the original SEEA EEA handbook and a substantial source of experience for its revised version.

In parallel, based on the testing done in the initial phases of the INCA project, the European Commission could adopt the amended EU Regulation No 691/2011 introducing ecosystem services accounts.

The INCA project consists of three phases:

Phase 1 (2014-2015) aimed at setting the conceptual basis and collaboration among services of the European Commission and the EEA.

Phase 2 (2016-2020) aimed at developing biophysical models and monetary valuation of 9 ecosystem services for Europe.

Phase 3 (2021-2023) aimed at making available knowledge and tools for MS statistical officers and practitioners to calculate national accounts for the EU Member States.

During Phase 3 an ad-hoc project was established, led by VITO, to support Eurostat in operationalizing the ecosystem accounting and hence contribute to the implementation of the proposed amendment of the EU Regulation 691/2011 on ecosystem accounting. Initially, seven of the nine ecosystem services models which were created by the Joint Research Centre for 2000 to 2012 (La Notte et al., 2017; Vallecillo et al., 2018; Vallecillo et al., 2019; La Notte et al., 2021). Two additional models on air filtration and local climate regulation were created for 2018 (Babi et al., 2023)., These models were refactored according to the FAIR principles (findable, accessible, interoperable and reusable), and used to generate the 2018 accounts (Buchhorn et al., 2022).

The project provides guidelines on how to report the ecosystem accounts in line with the legislation, and hence explains how to implement the SEEA EA using European datasets to generate these accounts (/indicators) for the EU27 member states. The guidance note covers the ecosystem extent, condition and seven services as described in the legislation. The refactored KIP-INCA ecosystem service models are made compliant to these guidance notes and integrated as public plug-in in QGIS to run locally. The project also provides support to Eurostat in developing validation workflows and the use of the accounts in EU policies.

The following ecosystem service models are provided, based on the underpinning INCA models based on the provided literature:

- Provisioning services: wood and crop provision (Vallecillo et al., 2019; La Notte, 2022)
- Regulating and maintenance services: pollination, global climate regulation (both sequestration and retention), local climate regulation (Marando et al., 2022), air filtration (Babi et al., 2023 in press) and (not in the Legislation) soil retention, as well as flood control (Vallecillo et al., 2020)
- Cultural services: tourism recreation (Zulian et al., 2022)

Based on these models, a new European wide account series of nine service accounts, covering 2000 to 2021, will be generated and published around end of 2023. These accounts will be based on the EU extent typology; however, no tool is being developed to generate extent or condition accounts. The QGIS INCA plug-in tool is developed to generate service accounts at national scale, however can also be applied at sub-national scale. The tool runs locally and hence all data is to be mapped (stored) locally to be run. This implies that all Earth Observation pre-processing is done prior to the generation of the accounts. Currently EO data is mainly used as a geospatial proxy to distribute tabular statistics. The following EO datasets are used:

- Land cover: Corine Land Cover Accounting Layers
- Vegetation indices: Leaf Area Index, Fraction of Vegetation Cover
- Biomass productivity: Dry Matter Productivity
- Digital Elevation Model, Imperviousness and Riparian zones
- Particular Matter (PM2.5 and PM10)

The current legislation does not mandate to report geospatial maps, so the Member States need to report only the tabular accounts. Geospatial maps can be provided on voluntary basis;

hence several guidance notes describe a simple default model (limited use of geospatial data) and an advanced model (more use of geospatial inputs).

Some of the key lessons learned related to ecosystem accounting and use of Earth Observation from the INCA 2021-2023 project include:

- The importance of ecosystem account time-series: Ecosystem accounts are an important piece of information since it helps policymakers to address questions. Consistent time-series of ecosystem accounts are key to assess these questions and measure sustainability improvements of policies;
- The need for guidelines to implement a standard: Applying the SEEA EA standard in a uniform way across EU Member States is not straightforward and required clear and detailed guidelines. This is important for ensuring comparability of results and facilitating the exchange of information between different users;
- Tools and the simplicity of models: Ecosystem service accounts represent a simplification of a complex network of socio-ecological processes. A tool can facilitate the generation of these account; however, default (EU continental) datasets should be provided to ease the generation as well as the flexibility for countries to ingest more accurate national datasets;
- The level of expert knowledge to integrate EO: The use of EO datasets is still limited and mainly used in an indirect manner (i.e., spatial distribution of statistics) for the generation of accounts. Pre-processing of EO datasets require extensive expert knowledge, including linking the data with relevant phenomena on the ground, and a good quantification of the uncertainties, which limits the ability to integrate more EO in accounts.

Overall, the INCA project demonstrated that operationalization to generate ecosystem account at a regular and consistent manner is feasible, but also that there still exist large gaps to integrate Earth Observation (EO) within the current tools and platforms. It also shows that more research is required to model the ecological complex networks and further improve the accuracy and reduce uncertainty of accounting results.

4.2 ESMERALDA, MAIA and SELINA

Two successive, flagship H2020 projects ESMERALDA[12] (Enhancing ecoSysteM sERvices mApping for poLicy and Decision mAking) and MAIA[13] (Mapping and Assessment for Integrated ecosystem Accounting) have been completed during the past six years, overcoming bottlenecks, creating capacity and producing baseline information and data for the mapping and assessment of ecosystems, their services and natural capital accounting.

Based on the findings of the ESMERALDA database, it is concluded that remote sensing and EO can be used also indirectly to get derivatives for ecosystem services. Examples of such measurements are, for instance, NDVI, land cover and surface temperature. Alone they are not directly reflecting to ecosystem services, but they can be used as important indirect proxies for them, or they can also feed in the models. Additionally, the role of novel EO techniques and data sets is becoming increasingly important in environmental monitoring, both for biodiversity (Vihervaara et al. 2017b), and for ecosystem services (Cord et al. 2017).

[12] http://www.esmeralda-project.eu/
[13] https://maiaportal.eu/

Satellite Earth observation as well as airborne and drone observations have huge potential to improve quantification, mapping and assessment of ecosystems and their services. Optical, radar and LiDAR data can be used for direct measurements, or to gather information that feed in the models.

The MAIA project, led by Wageningen University from 2018 to 2020, aimed to promote the mainstreaming of natural capital accounting in some EU Member States and Norway. The project focused on testing and implementing in participating countries the ecosystem accounting methodology (SEEA-EA). The project comprised several WPs, that aimed at community engagement, knowledge build-up, testing and development of methods for SEEA EA, and in-country implementation of SEEA EA accounts. Amongst others, it led to some 15 scientific publications as well as over 20 pilot SEEA EA accounts in all participating countries. On the MAIA website (maiaportal.eu) a series of webinars on ecosystem accounting can be found. Additionally, the accounting-oriented MAIA project, provides some state-of-the art outcomes highlighting how EO data can be integrating for ecosystem extent accounting, in combination with national and local datasets. Such examples are highlighted by Grunewald et al. (2020), providing an ecosystem extent account for Germany, and by Bruzón et al. (2022), showcasing a national-level accounting approach and application for ecosystem flows, from 1970 to 2015, in Spain.

The SELINA project (Science for Evidence-based and sustainable decisions about Natural capital) is coordinated by Leibniz University Hannover (LUH), started on 1 July 2022 and includes all 27 EU member states, Norway, Switzerland, Israel and the United Kingdom. SELINA is underpinned by the EU Biodiversity Strategy 2030. The SELINA project aims to develop and test in a series of case studies a framework to consolidate findings on ecosystems together with their services, to support sustainable decision-making within the public and private sectors. SELINA intends to establish practical recommendations for decision-making based on scientific evidence. The project also aims to foster social changes necessary to protect and use the environment sustainably. It builds further on ESMERALDA, which aimed to map and evaluate ecosystems, their resources and potential ecosystem services. However, SELINA focuses on implementation. It will apply methods and data on ecosystem services developed in recent years across Europe in 15 individual projects in practice and in examples at different spatial levels. Commercial partners such as soft-drink manufacturer Coca-Cola, Norwegian financial services company Storebrand and regional water suppliers are also involved. Subsequently, findings should serve as a model, which provides support in future commercial and political decision-making processes.

Some of the key lessons learned related to ecosystem accounting and use of Earth Observation from the MAIA project include:

- The importance of stakeholder engagement: The project involved extensive stakeholder engagement, including consultations with policymakers, researchers, and representatives from civil society organizations;
- The need for harmonized and standardized methodologies: The project developed new methodologies for ecosystem accounting that were designed to be harmonized and standardized across different regions and countries;
- The value of integrating different types of data: The project demonstrated the value of integrating different types of data, including satellite data, ground-based

measurements, and socio-economic data, to improve the accuracy and relevance of ecosystem accounting;

- The challenges of data availability and quality: The project highlighted the challenges of data availability and quality, particularly in countries where data may be scarce or unreliable. The project highlighted the use of new methods for using alternative data sources, such as remote sensing data, to fill data gaps.

Overall, the MAIA project demonstrated the potential of ecosystem accounting as a tool for informing policy and decision-making, but also highlighted the need for continued research and development in this area to overcome challenges related to data availability and quality, harmonization and standardization, and stakeholder engagement.

4.3 EUROPABON

The H2020 EUROPABON Coordination and support action, led by iDiv in Germany from 2019 to 2023, designs an European monitoring framework for biodiversity and ecosystem services. The objective is to provide solutions to produce relevant biodiversity indicators for policy and management assessment and scenarios, in co-design with stakeholders at different scales (regional, national and European). Workflows are designed through integrating data streams with models, with focus on Essential Biodiversity Variables (EBV) and to a lesser extent on Essential Ecosystem Service Variables (EESV).

EBV's can become important inputs for the extent and condition accounts, while EESV's have a clear link with service accounts. The following 70 variables are under design:

- Terrestrial EBV: 4 genetic composition, 12 species population, 3 species traits, 6 community composition, 3 ecosystem structure, 5 ecosystem function
- Terrestrial freshwater EBV: 8 species population, 6 community composition, 3 ecosystem structure and 5 ecosystem function variables
- EESV: an initial list of ecosystem services (i.e., belowground carbon content, economic value of pollination and seed dispersal, public visitation rates to protected areas, etc.) was created but their ranking was lower than EBVs and hence not further addressed in the gap analysis and design of workflows.

The gap analysis did mainly focus on data integration from field observation networks and taxonomic groups. The use of remote sensing programs which generate data flows for some EBVs was found hard to evaluate in the proposed bottlenecks framework. The workflow design is currently still in progress and the number of variables that use Earth Observation data is not yet finalized. Some first results however show the importance of EO data especially for ecosystem structure and function variables.

The project focuses on designing the system and does not implement the system at this stage. However, five demonstrators are being developed to prove the feasibility of such system to support different EU policies: Birds Directive, Habitat Directive, Freshwater Directive, Soil Restoration and Climate, Bioeconomy strategy.

Some of the key lessons learned related to ecosystem accounting and use of Earth Observation from the EuropaBON project include:

- Partial or full bottlenecks were found in the generation of 74% of the proposed variables;
- EBVs can provide important inputs for ecosystem condition accounts;
- The highest potential to use Earth Observation data is seen in ecosystem structure and function variables, however there is also potential in the other EBV classes across all realms (Terrestrial, Freshwater and Marine);
- EESVs seem to be ranked with lower priority by the policy makers than EBVs.

In conclusion, EuropaBON can provide valuable input for biodiversity related ecosystem condition variables. The use of EO data is mainly seen in the ecosystem-related variables, and ecosystem service variables are not prioritized (yet) within the project.

4.4 GEO EO4EA

Earth Observation for Ecosystem Accounting (EO4EA) is an initiative within the Group on Earth Observation (GEO). The main objective of EO4EA initiative is the facilitation of development and usage of EO data in natural capital accounting consistent with the standards and guidelines of the SEEA-EA. The EO4EA working groups are open for all participants and combines therefore the knowledge of EO and EA communities of various entities, i.e., public sector, private sector, academia, and NGO's. The main goal is to develop, pioneer, and test the methods and tools that will allow Earth observation technology to enable the widespread adoption of ecosystem accounting.

The EO4EA working group has four major work streams:

- Case Studies and Synthesis – currently over 80 countries have already generated SEEA accounts in some extent. The working group compiles a state-of-the-art review of these accounts explicit with the goal to identify the EO usage and facilitate the gained knowledge;
- Ecosystem extent and condition – this working group develop and tests methods for the generation of extent and condition accounts. It focuses on the technical application of EO data to support the account generation.
- Identification, measurement and monitoring of ecosystem services – this working group explore the approaches and tools to use EO data in service account generation.
- Implementation and capacity building – this working group tasks the capacity building, pilot testing and implementation of ecosystem accounting at the sub-national and national scale.

The central point of entry is the webpage under: https://www.eo4ea.org/. Several workshops and meetings inform over the initiative and efforts of the working groups as well as aim to support knowledge transfer. The webpage provides several case studies and examples for the implementation of EO in the SEEA-EA compliant account generation.

Some of the key lessons learned related to ecosystem accounting and use of Earth Observation from the EO4EA initiative include:

- Enhance the availability and accessibility of EO data: GEO EO4EA can promote the development and dissemination of EO data and tools that are relevant to ecosystem accounting. This can help to address data gaps and inconsistencies in ecosystem accounting.

- Improve the quality and accuracy of ecosystem accounts: GEO EO4EA can provide technical support and capacity building to countries and organizations to improve the quality and accuracy of ecosystem accounts. This can help to ensure that ecosystem accounts are consistent, comparable, and reliable.
- Foster collaboration and partnerships: GEO EO4EA can bring together stakeholders from different sectors and regions to collaborate on ecosystem accounting. This can help to build trust and credibility and increase the adoption and impact of ecosystem accounting.
- Promote innovation and research: GEO EO4EA can support innovation and research in the use of EO data for ecosystem accounting. This can help to identify new and more accurate ways of measuring ecosystem services and provide evidence to inform policies and decision-making.
- Raise awareness and advocacy: GEO EO4EA can raise awareness and advocacy for ecosystem accounting and the use of EO data. This can help to increase the demand for ecosystem accounts and the adoption of EO data for ecosystem accounting.

In conclusion, GEO EO4EA can contribute to ecosystem accounting by enhancing the availability and accessibility of EO data, improving the quality and accuracy of ecosystem accounts, fostering collaboration and partnerships, promoting innovation and research, and raising awareness and advocacy.

4.5 ARIES for SEEA

Approaches such as ARIES (Artificial Intelligence for Ecosystem Services) have demonstrated how to maximize data and model reusability and interoperability (FAIR principle) when assessing ecosystem services and, more generally, in modelling complex human-nature interactions and their consequences. Notably, ARIES has been applied to the SEEA-EA: the ARIES for SEEA Explorer was released in April 2021, and it is accessible at https://seea.un.org/content/aries-for-seea.

Through a web browser interface, the application can generate ecosystem accounts for any user- specified terrestrial area in the world (such as a country, administrative region, or watershed), by using freely available global remote-sensing derived data and models, computing these accounts online, and returning results back to the user. The current Explorer functionalities are restricted to assessing 1. ecosystem extent, based on the IUCN Global Ecosystem Typology, 2. ecosystem condition, currently limited to forest ecosystem types, and 3. selected ecosystem services (Villa et al. 2021)

ARIES provides a common platform to make data and models interoperable and improve the ability of National Statistical Offices to automate the compilation of environmental-economic accounts and related indicators. ARIES for SEEA thus demonstrates a path forward for better synthesizing the information required to monitor complex linked social-ecological systems through indicators such as the Sustainable Development Goals (Balbi et al. 2022).

Some of the key lessons learned related to ecosystem accounting and use of Earth Observation with ARIES for SEEA include:

- The combination of ARIES and SEEA can provide a more comprehensive understanding of the linkages between the environment and the economy, which can inform policies and decision-making;
- ARIES can be customized to address specific needs and priorities of individual countries, which can enhance its relevance and applicability;
- ARIES can use EO data to generate high-resolution maps of ecosystem services, which can improve the accuracy of ecosystem accounting;
- The use of ARIES for ecosystem accounting requires significant capacity-building and training for stakeholders, including government officials, private sector, and civil society organizations;
- Technical and institutional barriers to integrate ARIES for SEEA and Earth Observation into existing environmental and economic accounting systems need to be addressed through examples;
- ARIES, as any other solution, may not capture all the complexities of ecosystems, and the selection of ecosystem services to be included in the analysis may be subjective.

In conclusion, the combination of ARIES, SEEA, and EO can provide a promising approach to ecosystem accounting. However, there are significant challenges that need to be addressed to ensure the successful integration of these approaches into existing environmental and economic accounting systems.

4.6 Open Earth Monitor

The Horizon-Europe Open-Earth-Monitor (OEMC) project, led by the OpenGeoHub in Wageningen from 2022 to 2026, aims to build a FAIR-compliant cyberinfrastructure to accelerate the uptake of environmental information and help build user communities at European and global levels. Its objective is to provide operational solutions and decision-making tools for European and global initiatives such as DestinE, Digital Twin Initiative, Fit for 55, UN sustainable development goals and more. Based on stakeholder consultation, the OEMC project will build a range of tools serving EU citizens and governance needs via easy-to-use data portals and apps. The project will also consider and address global governance needs for spatial data and develop a single landing page to find all environmental information produced by the project, track the state of our planet, and develop solutions for environmental and climatic challenges.

Some of the key lessons learned related to ecosystem accounting and use of Earth Observation with Open Earth Monitor include:

- Citizen science can be a valuable tool for collecting environmental data: The Open Earth Monitor project relies on volunteers to collect data on the environment, such as water quality, air pollution, and biodiversity. Citizen science can be a cost-effective way of gathering data, especially in areas where data collection by national administrations is limited or expensive.
- Standardization and data quality are essential: To ensure the accuracy and reliability of data collected through the Open Earth Monitor project, standardization of data collection protocols and quality control measures are necessary, to integrate with other data sources.

- Technology needs to be user-friendly and accessible: The use of low-cost and easy-to-use sensors and open-source software enables volunteers to collect and analyze data without significant technical expertise.
- Collaboration and partnerships are crucial: The collaboration and partnerships with local communities, non-governmental organizations, and academic institutions can help to build trust and credibility, as well as to increase the reach and impact of the project.
- Data needs to be integrated into decision-making: The Open Earth Monitor project has the potential to provide valuable data for ecosystem accounting. However, for the data to be useful, it needs to be integrated into decision-making processes and policies.

In conclusion, the Open Earth Monitor project will provide valuable lessons that can be applied to ecosystem accounting. These include the importance of citizen science, standardization, user-friendly technology, collaboration, and data integration into decision-making. It also has the potential to support ecosystem accounting by providing data on the state and trends of ecosystems.

Table 3. Overview of ecosystem accounts for selected projects and initiatives

Project/ Initiative	***Timeframe***	***Extent account***	***Condition account***	***Services account***	***FAIR principle***	***Use of EO***
INCA	2014-2023	X (MAES)	X (6 ET)	X (9 services)	YES (svc)	YES, but limited
MAIA/ SELINA	2018-2027	X	X	X	NO	YES, national showcases
EUROPABON	2019-2023	- (habitat)	- (EBV)	-	NO	YES, for EBV
GEO EO4EA	n.a.	X WG1	X WG1	X WG2	NO	YES, evidence?
ARIES4SEEA	2021-…	X (EFG)	X (forest)	X (4 services)	YES	YES, link to SDG
OpenEarthM	2022-2026	-	X (potentially indicators related to forest condition, these indicators are not yet specified)	X (only global climate regulation service)	YES	YES, link to destinE, digitalTwin

Key lessons learned from the running Initiatives and Projects

- Ecosystem accounting provides a more comprehensive understanding of the linkages between the environment and the economy, can inform policies and decision-making however requires regular reporting in a consistent manner.

- There is a need to harmonize and standardize methodologies to implement the SEEA-EA standard.

- Progress should be made to overcome the challenges of data availability and quality when integrating different types of data. Citizen science can be a valuable tool for collecting environmental ground truth data. Earth Observation data provides the geospatial coverage and detail to generate high-resolution maps of ecosystem services, which can improve the accuracy of ecosystem accounting.

- Ecosystem service accounts do typically not include information on the uncertainty of the account, which make them more difficult to use as a basis for decision making.

- The availability and accessibility of EO data for ecosystem accounting to users with no specific IT skills or EO expert knowledge needs to be enhanced to increase the EO data uptake. Essential Biodiversity Variables can provide important inputs for ecosystem condition accounts, especially for the ecosystem structure and function classes.

- Innovation and research should be promoted, first to make the models reproducible (FAIR principle) and then to better capture the complexities of ecosystems. The technology needs to become user-friendly and accessible.

- There is a need to foster collaboration and partnerships involving all multi-disciplinary stakeholders and raise awareness and advocacy through significant capacity-building, training and knowledge sharing.

5 Review on EO data integration into ecosystem accounting

5.1 Introduction

Despite several literature reviews (Compte et al., 2022) have been done on assessing the scientific developments and future challenges on ecosystem accounting, none had a specific focus on the integration of Earth Observation data for ecosystem accounting. We have conducted a systematic literature review on the use and potential of integrating Earth Observation (EO) datasets in SEEA-EA ecosystem accounting with focus on Europe. The results of this review were published in a scientific paper (Kokkoris et al., 2024). This chapter provides a summary of the results, the reader is referred to the scientific paper to find more details.

5.2 Material and methods

Literature relevant to EO data used for accounting purposes regarding ecosystem extent, condition and ecosystem services, was gathered through a Scopus[14] database search, under combined search terms, following the best practice guide for a systematic review as proposed by Siddaway et al. (2019). The results provided a list of scientific publications that was assessed, by creating a relevant spreadsheet matrix, including a set of queries (see Supplementary Materials).

The data analysis deals with descriptive characteristics of the publication pool, in terms of year of publication, journal name, type of assessment and relevance to EO data and accounting. More precisely, the matrix used for this analysis included thirty-five (35) queries. This matrix was distributed among the participating partners of the PEOPLE project, while additional papers were also welcomed and integrated in this phase based on the experts' knowledge of the relevant literature, in case that the Scopus query string has not included them or were not indexed in the Scopus database. All papers were initially assessed against queries (1), (2), (3) and (4). Papers published prior 2006 and/or are with no relevance to satellite and/or EO data, have been excluded from the further analysis.

5.3 Results

The initial search results provided 391 publications, covering a time period from 1995 to 2022. This number of publications was reduced to 113 papers after filtering publications, (a) published in 2006 or after, (b) include EO data modelling or use of EO products.

A clear **tendance** was seen with an increase from 2020 onwards, going from on average 5 papers prior to 2020 to around 25 relevant papers per year after 2020. publications consider applied approaches, including case-studies and applied science.

Most (86%) of the reviewed publications are directly or indirectly providing input for ecosystem accounting, i.e., compatible indicators and methods, with the **SEEA EA framework**. Most papers did include information on ecosystem extent (66%) and ecosystem condition (39%). Ecosystem services were primarily focused on regulating and maintenance services (46%), followed by provisioning services (30%) and by cultural services (18%). Less than 20% of the papers did include monetary valuation.

[14] https://www.scopus.com/search/form.uri?display=advanced

Related to **ecosystem types**, woodland and forest ecosystems (65%) were mainly addressed, followed by urban, cropland and grassland papers. Most studies did not follow a standardized ecosystem typology (e.g., MAES levels) and mostly correspond to generalized categories.

Most approaches and models were defined as scalable, hence applicable at different tiers, however most studies (76%) did deal with local/regional (tier 3) assessments, followed (18%) with national (tier 2) and only 10% global (tier 1) assessments.

Most studies (75%) are based on Landsat **missions' sensors**, while less than 8% did include data from aerial cameras. Some (6%) studies did exploit Lidar data and only 2% did use very high resolution images (i.e., QuickBird, Geoeye-2).

A variety of **methods and models** were addressed for EO data and/or EO products integration and exploitation with focus on random forest algorithm and classifications based on band ratios. Moreover, indices such as NDVI, NDWI combined with computer-assisted photointerpretation are also used in many studies to identify mostly the different ecosystem types / vegetation categories. For ecosystem services related assessment, many different methods and models are used (e.g. hydrological models). In most cases even multiple models were used to generate the final accounts.

Regarding the **platforms** used for the analyses, GIS platforms (ArcGIS, QGIS) prevail, followed by Google Earth Engine, R and Python interfaces for script development. The use of new advanced platforms and tools (e.g. InVEST and ARIES) was still very limited (5%).

Additionally, an **uncertainty analysis**, or accuracy assessment is present in about half of the papers. Most methods are based on existing models and algorithms, that have been modified for each respective case study, or tested with local scale data and validated with field assessments and surveys. It is worth mentioning that rather few of these models are publicly available in a transparent and reproducible form (FAIR principles) or described in detail, allowing the adoption and transfer of the model to other areas as well.

5.4 Discussion

Most studies are based on **ecosystem extent** assessment and use this as the baseline for ecosystem services quantification or provide time-series with land use changes among different years (see Ramirez-Reyes at al. 2019). The development of EO based workflows and pipelines specifically for ecosystem extent mapping and monitoring (e.g., Verde et al 2020) based on standardized class schemes would be beneficial for the wider uptake of such approaches. Several studies rely on dense time-series analysis for the quantification of changes in ecosystem extent and the accounting reports (i.e., Nguyen et al 2021, Lee et al. 2021a, Lee et al. 2021b). In these cases, medium and/or low spatial resolution data are used.

Key messages and main challenges for EO based ecosystem extent accounting.

- EO data and products include available time-series with land use changes among different years to support ecosystem extent accounts.
- Limitations are noted for EO use to create extent accounts, related to: (a) the use of diverse input data, (b) accuracy variability over different areas and different classes, (c) coarse update intervals and outdatedness in comparison to the real world.
- The development of EO based workflows and pipelines specifically for ecosystem extent mapping and monitoring, based on standardized class schemes (i.e., EUNIS or IUCN GET) would be beneficial for the wider uptake of such approaches.

Most studies do not focus on **ecosystem condition** assessment as part of a particular framework (e.g., MAES, SEEA-EA), however they provide valuable input for assessing ecosystem condition parameters such as ecosystem extent, extent change and biodiversity proxies. The review study of Schulte to Bühne and Pettorelli (2017) includes a table with a detailed overview of current applications of multispectral-radar SRS data fusion for species and ecosystem monitoring, as well as biodiversity threat detection via (a) image fusion (pixel-based fusion, object-based fusion) or (b) decision-level data fusion (integration) (see Table 4 in Annex II). From this table we conclude that there is a variety of options for assessing biodiversity and ecosystem attributes, relevant with the SEEA ecosystem condition accounting framework (SEEA Ecosystem Condition Typology classes and indicators). Additionally, the 'EU-wide methodology to map and assess ecosystem condition' JRC Science for Policy Report (Vallecillo et al. 2022), highlights the importance of remote sensing and EO data (e.g., Copernicus products) integration. However, it also mentioned that Copernicus data may not provide input for a large percentage of ecosystem condition indicators, but are important in terms of spatial resolution, coverage and frequency of temporal updates (e.g. tree cover density is only available at 3-yearly interval).

A major challenge in SEEA EA framework and in particular for the variables used to support accounting for each SEEA Ecosystem condition typology class, is setting the reference levels. An example of developing a forest condition index in Greece (see Vallecillo et al. 2022, Table 16) highlights that EO data can be used to support accounting for indicators describing land cover and land use characteristics, such as tree layer cover, occurrence of forest strata, forest fragmentation and could provide information for setting threshold levels among different forest types and/or identify reference areas.

Key messages and main challenges for EO based ecosystem condition accounting.

- Ecosystem condition assessments should follow a particular framework (e.g., MAES, SEEA-EA).
- Earth observation data and products can be used to support ecosystem condition indicators assessment for indicators corresponding to land use, land cover characteristics (e.g., vegetation cover, forest structure, fragmentation, land use, land cover, landscape characteristics).
- There is a variety of options for assessing biodiversity and ecosystem attributes, relevant to the SEEA ecosystem condition accounting framework.
- Setting mapping specifications for the relevant ecosystem condition accounting indicators, emerges as a necessity for standardized accounting for each Tier (local, regional, national, global).
- EU wide models for different ecosystem parameters based on EO data are useful for ecosystem condition accounting upon validation with in-situ or field data (ground-truth in-situ).

Regarding **ecosystem services** assessment and accounting, the outcomes of this study propose that the focus must be on specific studies that highlight how EO data and products can be used and integrated into the ecosystem services framework, including identification, mapping, assessment, monitoring and for accounting purposes (e.g., see Braun et al. 2018, Comte et al. 2022, Bruzón at al. 2022) in order to comply with SEEA EA requirements. Two recent papers (Capriolo et al. 2022, Boschetto et al 2023) demonstrate the use of ARIES in national accounting by adapting the internal models and data with national parameters and data. Spatial and temporal changes, and their dependencies to ecosystem extent maps, are highlighted as important to identify trade-offs and synergies of ecosystem services supply and flow (see Braun et al. 2018). Another issue is that most studies do not follow a standardized approach, e.g., a classification scheme such as the Common International Classification of Ecosystem Services – CICES (Haines-Young and Potschin-Young, 2018; Czúcz et al. 2018). Increasingly, however, studies are referring to the ecosystem services classification of the SEEA EA, which is the follow-up to CICES. Finally, in the majority of the studies, local citizens', stakeholders' and decision-makers' opinion (or public participation) is missing, a fact that can lead to a misinterpretation of each studies outcome regarding ecosystem services use and demand.

Key messages and main challenges for EO based ecosystem services accounting.

- Ecosystem extent assessment derived from EO data and products provides the baseline for ecosystem services quantification.
- Scale and detail of EO data and products affects accordingly the corresponding ecosystem services accounts.
- Field data integration is crucial for robust elaboration of ecosystem services accounts.
- Earth observation data and products can be used to support public participation approaches on mapping and assessment of ecosystem services, in order to elaborate real world accounts.

Operationalization of EO data and products for ecosystem accounting is not a straightforward task and consists of different steps of data collection and handling, modelling approaches and interpretation. Moreover, integration of EO outcomes into a common, standardized accounting scheme, such as SEEA EA, sets challenges to be tackled in terms of accuracy, uncertainty, harmonization, methods used and synthesis. Accuracy of ecosystem accounts are dependent on factors as landscape characteristics, classification algorithms, complementary geospatial data, thematic resolution and correspondence among datasets.

Most studies are based on desktop GIS and remote sensing software (e.g., ArcGIS, QGIS, ENVI, ERDAS, eCognition) in order to map and assess ecosystems and provide spatio-temporal relationships among studied attributes. Ready-to-use plugins and open-source algorithms are also available to analyze and interpret EO source data, such as satellite or aerial multispectral imagery, facilitated by the existence of online platform such as OpenEO, ESA's Thematic Exploitation Platforms, Sentinel Hub, Google Earth Engine etc. Specialized platforms and plugins (e.g., InVest, ARIES, INCA-tool) are also available and developed for ecosystem services assessment and account drafting; however, their use is considered as limited and should be further incorporated in ecosystem accounting studies.

Key messages and main challenges for EO based ecosystem accounting.

- Scale influences the analysis (i.e., cell-based vs administrative based units).
- Differences in the thematic resolution and correspondence among various datasets might also trigger uncertainties.
- Complementary geospatial data integration issues.
- Classification algorithm issues.
- Technical processing issues (i.e., rasterization of vector data).
- A variety of tools is available to support EO integration in ecosystem accounting, including GIS platforms and specialized software and tools (e.g., InVest, INCA-tool, ARIES), that should be always considered when operationalize accounting.

6 Conclusion

This technical report shows that EO has the potential to support scientifically based accounting under the SEEA EA framework and thus, EO data and technologies should be integrated into natural capital accounting in EU Member-States and worldwide. The current dominant EU framework, outlined by the EU Biodiversity Strategy for 2030, the European Green Deal, and the proposed Nature Restoration Law, supported by recently finished and ongoing EU-wide projects, such as MAIA and SELINA H2020 projects, provides an, at least, adequate environment to proceed with the EO integration into natural capital accounting across Member States, and the standardization of procedures, methodologies, indicators, data requirements and specifications.

Earth observation (EO) can support ecosystem accounting by providing accurate and timely data on ecosystem variables such as land use, land cover, biomass, carbon storage, and biodiversity, in this way supporting extent, condition and physical ecosystem services accounting. Relevant EO data can be derived from a range of sensor constellations and sensors including but not limited to Sentinel, Landsat, VIIRS, etc, that all provide free and open access data. The availability of data will be even larger in the future, especially after launch of the NISAR satellite that will provide L-band data essential for mapping biomass. However, various processing steps are needed to convert EO data into account-ready data including image pre-processing, processing, interpretation and modelling. Models based on EO data require sufficient ground-truth in-situ datasets, both to train as well as to calibrate/validate the models. Furthermore, providing easy access to account ready data to users is crucial. It should involve selecting a data platform, developing a viewer, and training ecosystem accountants in using these datasets.

A variety of data and tools is available to support EO integration in ecosystem accounting, including GIS platforms and specialized software and applications. However, there are challenges that need to be overcome for operational EO integration into ecosystem accounting drafting. Main challenges include data availability, data processing capacity, data standardisation in terms of quality, spatial and temporal resolution, as well as technical issues e.g., related to algorithm development and availability.

Moreover, EO provides the most cost-effective way to collect large amounts of data in a standardised form, with consistency in terms of quality, spatial and temporal resolution throughout the globe, while simultaneously combined with and validated by field survey's datasets to improve and maximise accuracy. Additionally, EO data and products can be used to support public participation approaches on mapping and assessment of ecosystems and their services, in order to draft real world accounts with geospatial information.

Concluding, there is no option (or need) to wait for an 'obstacle-free environment' for EO use and integration. We should immediately proceed building on best available knowledge, practices, and data, given the urgent demand for better data from ecosystem accounting projects world-wide and the proposed legislation on ecosystem accounting in the EU, and by this timely support the development of ecosystem accounts, towards scientifically informed reporting, decision and policy making. We should also continue to invest in research to take benefit of the newest datasets, technologies, and models to further improve the accuracy of ecosystem accounts and quantify and further reduce their uncertainties.

Supplementary material: Summary of selected papers for the literature review: *Type of Publication, Year of Publication, Authors, Publication Title, DOI, Journal name, Abstract*.

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Annex I- Overview of selected papers

* meta-papers, + conference-papers

[1] Christain et al. (2006)	[42] Corner et al. (2020)
[2] Bontemps et al. (2009) +	[43] del Rio-Mena et al. (2020)
[3] Silvero et al. (2009)	[44] del Rio-Mena et al. (2020)
[4] Ode et al. (2010)	[45] Fitoka et al. (2020)
[5] Pileri et al. (2010)	[46] Grenier et al. (2020)
[6] Mallinis et al. (2010)	[47] Havinga et al. (2020)
[7] Roerink et al. (2011) +	[48] Heris et al. (2020)
[8] Vačkář et al. (2011)	[49] Huang et al. (2020)
[9] Varela et al. (2011)	[50] Lai et al. (2020)
[10] Franke et al. (2012)	[51] Lebedev et al. (2020)
[11] Mori et al. (2012) *	[52] Paulin et al. (2020)
[12] Li et al. (2014)	[53] Puzachenko et al. (2020)
[13] Mallinis et al. (2014)	[54] Roces-Diaz et al. (2020)
[14] Karp et al. (2015)	[55] Sannigrahi et al. (2020)
[15] Martinez-Harms et al. (2016)	[56] Shi et al. (2020)
[16] Robert S. (2016)	[57] Sumarga et al. (2020)
[17] Simons et al. (2016)	[58] Talukdar et al. (2020)
[18] Locher-Krause et al. (2017)	[59] Venter et al. (2020)
[19] Blasi et al. (2017)	[60] Venter et al. (2020)
[20] Braun et al. (2017)	[61] Venter et al. (2020)
[21] Chrysafis et al. (2017)	[62] Žoncová et al. (2020)
[22] Cochran et al. (2017)	[63] Verde et al. (2020)
[23] Robinson et al. (2017)	[64] Baker et al. (2021)
[24] Rodriguez-Rodriguez et al. (2017)	[65] Bindajam et al. (2021)
[25] Shulte et al. (2017)	[66] Castro-Magnani et al. (2021)
[26] Yuan et al. (2017)	[67] Che et al. (2021)
[27] Braun et al. (2018)	[68] Coffin et al. (2021)
[28] Ligate et al. (2018)	[69] Fang et al. (2021)
[29] Panpeng et al. (2018)	[70] Gomiz-Pascual et al. (2021)
[30] Willemen et al. (2018)	[71] Hanssen et al. (2021)
[31] Zhao et al. (2018)	[72] Heris et al. (2021)
[32] Braun et al. (2019)	[73] Huang et al. (2021)
[33] Giordano et al. (2019)	[74] Julian et al. (2021)
[34] Hu et al. (2019)	[75] Kundu et al. (2021)
[35] Hunt et al. (2019)	[76] Lee et al. (2021)
[36] Kucsicsa et al. (2019)	[77] Lee et al. (2021)
[37] Mariathasan et al. (2019)	[78] Li et al. (2021)
[38] Ramirez-Reyes et al. (2019)	[79] Mba et al. (2021)
[39] Rioux et al. (2019)	[80] Mesquita et al. (2021)
[40] Akubia et al. (2020)	[81] Ngyen et al. (2021)
[41] Capriolo et al. (2020)	[82] Stritih et al. (2021)

[83] Tanács et al. (2021)	[99] Liu et al. (2022)
[84] Turpie et al. (2021)	[100] Mandal et al. (2022)
[85] Ye et al. (2021)	[101] Marando et al. (2022)
[86] Zhu et al. (2021)	[102] Mokany et al. (2022)
[87] Abdullah et al. (2022)	[103] Nikwanana et al. (2022)
[88] Comte et al. (2022) *	[104] Normyle et al. (2022)
[89] Bruzon et al. (2022)	[105] Rodríguez-Puerta et al. (2022)
[90] Buchhorn et al. (2022)	[106] Sakellariou et al. (2022)
[91] Cimburova et al. (2022)	[107] Song et al. (2022)
[92] Codemo et al. (2022)	[108] Traganos et al. (2022)
[93] Deng et al. (2022)	[109] Traganos et al. (2022)
[94] Vallecillo et al. (2022)	[110] Wang et al. (2022)
[95] Ghorbanpour et al. (2022)	[111] Wang et al. (2022)
[96] Ibsen et al. (2022)	[113] Wang et al. (2022)
[97] Izakovičová et al. (2022)	[113] Yang et al. (2022)
[98] Kumar et al. (2022)	

Supplementary material: Summary of selected papers for the literature review: *Type of Publication, Year of Publication, Authors, Publication Title, DOI, Journal name, Abstract*.

Annex II - Overview of current applications of multispectral-radar SRS data fusion for species and ecosystem monitoring, as well as biodiversity threat detection

Table 4. Overview of current applications of multispectral-radar SRS data fusion for species and ecosystem monitoring, as well as biodiversity threat detection via (A) image fusion (P = pixel-based fusion; O = object-based fusion) or (B) decision-level data fusion (integration) (Source: Schulte to Bühne and Pettorelli, 2017).

	Variable	Proxy	Multispectral sensor (spatial resolution)	Radar sensor (wavelength; spatial resolution)	Spatial scale	Reference	Type of data fusion
(A)							
Species-level biodiversity	Species distribution	Distribution of alfalfa stands (*Medicago salvatica*)	MODIS (250 m)	RADARSAT-2 (C-band; 50 m)	50,000 km2	Hong et al. (2014)a	P
	Community composition	Relative basal area of 10 tree species and 2 tree genera	Landsat 5 TM (30 m), SPOT 5 (10 m)	Radarsat-1 (C-band, *c.* 27 m), ALOS PALSAR (L-band, *c.* 12.5 m)	360 km2	Wolter and Townsend (2011)a	P
Ecosystem-level biodiversity	Ecosystem distribution	Distribution of different forest types, including different successional stages	Landsat 5 TM (30 m)	RADARSAT-2 (C-band, 8 m), ALOS PALSAR (L-band, 12.5 m)	3,100 km2	Lu et al. (2011)a	P
			Landsat 5 TM (30 m)	ALOS PALSAR (L-band, 12.5 m)	3,000 km2	Lu et al. (2014)a	P
			Landsat 5 TM and Landsat 7 ETM+ (30 m)	ALOS PALSAR (25 m)	*c.* 370,000 km2	Lucas et al. (2014)	O
		Distribution of vegetation and/or geomorphology types in a wetland ecosystem	Landsat 7 ETM+(15 m and 30 m)	JERS-1 (L-band, 100 m), SRTM (C-band, *c.* 90 m)	31,000 km2	Hamilton et al. (2007)	O
			Landsat 5 TM (30 m)	RADARSAT-1 (C-band, 33 × 27 m)	1,600 km2	Souza-Filho et al. (2009)	P

	Variable	Proxy	Multispectral sensor (spatial resolution)	Radar sensor (wavelength; spatial resolution)	Spatial scale	Reference	Type of data fusion
			Landsat 5 TM (30 m)	ALOS PALSAR (L-band, 20 m), ERS-1/2 (C-band, 30 m)	250 km2/34,000 km2	Bourgeau-Chavez et al. (2009, 2016)	O
			GF-1 (2 m and 8 m)	ALOS PALSAR (L-band, 14 m), RADARSAT-2 (C-band, 6.3 m × 5.2 m)	250 km2	Fu et al. (2017)a	P/O
	Vertical ecosystem structure	Canopy height	Landsat 5 TM and Landsat 7 ETM+ (30 m)	SRTM (C-band, *c.* 30 m)	62,000 km2	Walker et al. (2007)a	O
			Landsat 7 ETM+ (30 m)	SRTM (C-band, *c.* 30 m)	110,000 km2	Kellndorfer et al. (2010)	O
		Above-ground biomass	Landsat 7 ETM+ (30 m)	ALOS PALSAR (L-band, 16 m resampled)	31, 000 km2	Basuki et al. (2013)	P
Threats to biodiversity	Deforestation	Historic deforestation events	Landsat 7 ETM+ (30 m)	ALOS PALSAR (L-band, 25 m)	30 km2	Reiche et al. (2015a)a	P
(B)							
Species-level biodiversity	Species distribution	Bird species	NLCD (from Landsat TM; 30 m)	SIR-C (both L and C band, 25 m)	*c.* 1,200 km2	Bergen et al. (2007)a	Genetic Algorithm For Rule Set Production
			MODIS–derived LAI and Vegetation Continuous Fields (500 m)	QuickScat (X-band, 1 km)	17.8 million km2	Buermann et al. (2008)	Species Distribution Model
		Subcanopy plant species	Landsat 5 TM and 7 ETM+ (30 m), GeoEye-1 (1.64 m), IKONOS (4 m)	RADARSAT-2 (L-band, 8 m), ALOS PALSAR (L-band, 12.5 m)	22.3 km2	Ghulam et al. (2014)	Decision tree algorithm
		Tropical tree species	MODIS-derived NDVI, LAI, Vegetation continuous fields (500 m)	QuickScat (X-band, 1 km)	*c.* 7.5 million km2	Prates-Clark et al. (2008)	Species Distribution Model

	Variable	Proxy	Multispectral sensor (spatial resolution)	Radar sensor (wavelength; spatial resolution)	Spatial scale	Reference	Type of data fusion
			MODIS –derived LAI and Vegetation Continuous Fields (500 m)	QuickScat (X-band, 2.25 km), SRTM (C-band, *c.* 30 m)	17.8 million km2	Buermann et al. (2008)	Species Distribution Model
Ecosystem-level biodiversity	Ecosystem distribution	Wetland vegetation types	Landsat TM and ETM+ (57 m)	JERS-1 (L-band, 100 m), SRTM (C-band, 30 m)	1.2 million km2	Bwangoy et al. (2010)	Classification trees
			GF-1 (2 m and 8 m)	ALOS PALSAR (L-band, 14 m), RADARSAT-2 (C-band, 6.3 m × 5.2 m)	250 km2	Fu et al. (2017)a	Random forest
		Forest types	Landsat TM (30 m), AVNIR-2 (10 m)	ALOS PALSAR (L-band, 15 m)	7,750 km2	Laurin et al. (2013)	Maximum Likelihood & Neural Networks Classifiers
			SPOT 1 or 2 (20 m)	ERS (C-band, 12.6 m)	Not reported	Hégarat-Mascle et al. (1998)	Dempster-Shafner fusion
			Landsat TM (30 m)	SIR-C (C and L-band, 12.5 m)	*c.* 520 km2	Rignot et al. (1997)a	Rule-based classification
	Horizontal ecosystem structure	Forest stem density	MODIS vegetation continuous field product (500 m)	ERS1-2 (C-band, 25 m or 50 m depending on location)	1.5 million km2	Cartus et al. (2011)	Exponential SIBERIA model, semi-empirical Interferometric Water Cloud Model
		Woody canopy cover	Landsat TM (30 m)	ALOS PALSAR (L-band, 12.5 m)	*c.* 31,000 km2	Naidoo et al. (2016)a	Random Forest
		Sediment grain size	Landsat TM (30 m)	ERS-1 and 2 (C-band, 12.5 m)	*c.* 100 km2	van der Wal and Herman (2007)a	Multiple least-squares regression
		Soil density, composition	Sentinel-2, Landsat, MODIS (rescaled to 100 m)	Sentinel-1 (C-band, rescaled to 100 m)	*c.* 78,000 km2	Poggio and Gimona (2017)a	Generalised additive model

	Variable	Proxy	Multispectral sensor (spatial resolution)	Radar sensor (wavelength; spatial resolution)	Spatial scale	Reference	Type of data fusion
		Soil moisture	Landsat 5 TM (30 m)	ERS-2 (C-band, not reported)	400 km2	Wang et al. (2004)	Quantitative modelling
	Vertical ecosystem structure	Biomass	JERS VNIR (18 m)	JERS-1 SAR (L-band, 60 m)	6,700 km2	Wang and Qi (2008)	Quantitative modelling
			Landsat 7 ETM+ (30 m)	ALOS PALSAR (L-band, resampled to 30 m)	107 km2	Attarchi and Gloaguen (2014)a	Linear regression
			SPOT-5 (5 m)	ALOS PALSAR (L-band, 25 m)	1,090 km2	Hamdan et al. (2014)a	Linear regression
		Timber volume	SPOT-4 (resampled to 100 m)	ALOS PALSAR (L-band, resampled to 100 m)	*c.* 360 km2	Ismail et al. (2015)	Linear regression
	Ecosystem function	Fire dynamics extent of burned areas	Landsat 5 TM (30 m)	Envisat ASAR (C-band, 60 m × 80 m)	*c.* 90,000 km2	Stroppiana et al. (2015)a	Fuzzy decision algorithm
		Wetland inundation dynamics	Landsat 5TM (30 m)	ALOS PALSAR (L-band, 100 m)	*c.* 3,400 km2	Ward et al. (2014)a	Classification tree modelling
			Landsat 7 ETM+ (30 m)	RADARSAT-1 (C-band, 12.5 m)	*c.* 15 km2	Gala and Melesse (2012)	Post-classification combination
Threats to biodiversity	Eutrophication	Chlorophyll-α, Secchi disk depth, suspended sediment concentration, turbidity	Landsat 5 TM (30 m)	ERS-2 (C-band, 12.5 m)	*c.* 29,600 km2	Zhang et al. (2002)a	Artificial neural networks
		Inorganic nitrogen concentration	HJ-1 (30 m)	RADARSAT-2 (C-band, 12 × 8 m)	*c.* 2,500 km2	Liu et al. (2014)a	Random Forest

	Variable	Proxy	Multispectral sensor (spatial resolution)	Radar sensor (wavelength; spatial resolution)	Spatial scale	Reference	Type of data fusion
	Forest degradation	Degradation of palm swamp	Landsat 5 TM (30 m)	ALOS PALSAR (L-band, 12.5 m)	3,500 km2	Hergoualc'h et al. (2017)	Random Forest
	Deforestation	Plantation expansion	Landsat TM and ETM+ (30 m)	ALOS PALSAR (L-band, 50 m)	3,400 km2	Dong et al. (2013)	Post-classification combination
		Deforestation events	Landsat TM (30 m)	SIR-C (L and C-band, 12.5 m), JERS-1 (L-band, 12.5 m)	*c.* 520 km2	Rignot et al. (1997)a	Rule-based classification
			Landsat 5 and 7 (30 m)	ALOS PALSAR (L-band, 25 m)	*c.* 7,800 km2	Reiche et al. (2013)a	Rule-based classification
			Landsat 7 ETM+ (30 m)	ALOS PALSAR (L-band, 25 m)	*c.* 96 km2	Reiche et al. (2015b)a	Bayesian time series modeling
			Landsat MSS/TM/ETM+ (30 m)	ALOS PALSAR (L-band; 25 m)	3,300 km2		