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NewLife4Drylands
LIFE20 PRE/IT/000007

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Executive summary

The present document is a "Report on ecosystem services assessment tools". The document describes the state of the art on ecosystem services assessment and mapping, mentioning the contributions of EU projects funded under different programs. The document presents the methods and principles of the MAES analytical framework and provide a brief description of the different available tools for ecosystem services assessment and mapping. In addition, the document presents an example of application of the collaborative and open-source platform for interoperable models and data ARIES for ecosystem services assessment and mapping in one of the NewLife4Dryland study area, the Alta Murgia National Park. ARIES application has access to all information (data and models) available on a web-based Integrated Modelling network and provides a dedicated user interface to compile accounts within the UN System of Environmental-Economic Accounting (SEEA). The SEEA Ecosystem Accounting (SEEA-EA) constitutes an integrated and comprehensive statistical framework for organizing data about habitats and landscapes, measuring the ecosystem services, tracking changes in ecosystem assets, and linking this information to economic and other human activity.



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1. Introduction

NewLife4Drylands deals with land degradation processes, of which desertification is one aspect, and considers restoration as a process. Both processes must be monitored resorting to status and trend indicators and time thresholds in order to ensure that ecosystems achieve or maintain a healthy state or a good condition, which is key requirement to secure the sustainability of human activities and human well-being.

To this goal, in 2011 the European Union adopted a Biodiversity Strategy to 2020 (European Commission, 2011) aiming to stop by 2020 the loss of biodiversity and the decline of ecosystem services provision in the EU. The adoption of the strategy reflected the commitments taken by the EU in 2010, within the international Convention on Biological Diversity (CBD).

The Biodiversity Strategy stated that by 2020, ecosystems and their services would be "maintained and enhanced by establishing green infrastructure and restoring at least 15% of degraded ecosystems". Therefore, EU's sustainable growth will be secured along with increased mitigation and adaptation to the effects of climate change, promotion of economic, territorial and social cohesion, and protection of cultural heritage.

In addition, according the Strategy, by 2020 each Member States, with the assistance of the Commission, would "map and assess the state of ecosystems and their services in their national territory, assess the economic value of such services, and promote the integration of these values into accounting and reporting systems at EU and national level". These efforts were identified in the Action 5 of Target 2 the Strategy, better known as Mapping and Assessment of Ecosystems and their Services (MAES).

Over the years, MAES delivered a number of relevant outcomes such as an agreed analytical framework with standards and indicators for mapping ecosystem status and ecosystem services. The conceptual framework links socio-economic systems with ecosystems via the flow of ecosystem services, and is used as a common integrated ecosystem service assessment framework at EU scale (Maes et al., 2020).

Other frameworks, widely used in performing ecosystems assessments at different scales, are those provided by the Millennium Ecosystem Assessment (MEA, 2005), and the Economics of Ecosystem and Biodiversity (TEEB, 2010). Other initiatives, such as the Intergovernmental Science-Policy Platform of Ecosystems and Biodiversity (IPBS), founded in 2012, and research projects, such as the EU FP7 OpenNESS (Potschin et al., 2016) and the H2020 ESERALDA (Burkhard et al., 2018) provided further relevant methodological contributions and case studies for ecosystem services assessment.

At the end of 2019 the European Commission put at the core of its European Green Deal (European Commission, 2019) the preservation and restoration of ecosystems, setting the path towards climate neutrality by 2050 through a number of strategic actions. Among these, the EU Biodiversity Strategy for 2030 (European Commission, 2020) considers ecosystems as solutions, not only to protect biodiversity, but also to enhance carbon uptake and contribute to climate mitigation, as well as to deliver essential benefits to people, agriculture and the economy (Maes



and Jacobs, 2017). The 2020 EU Ecosystem Assessment (Maes et al., 2020) highlights that also human dominated ecosystems such as agricultural lands and urban green areas are important providers of provisioning, regulating and cultural ecosystem services, and that these ecosystems should be properly considered when looking for solutions to halt biodiversity loss (Mace et al., 2018).

Given the necessity to adopt a common reference framework for ecosystem services assessment in LIFE projects, a guide for beneficiaries has been released in 2018 (Project administration LIFE, 2014-2020). The guide provides an easy method to implement ecosystem services assessment according to the analytical framework developed under the MAES initiative, introducing key concepts and methodology.

The present document introduces briefly the MEAS analytical framework and its implementation to assess and map ecosystem services in LIFE projects and, given the necessity to operate practically at context-appropriate scales that are different from the EU one, focuses on the application of a modelling framework of the quantitative assessment of ecosystem services in the NewLife4Drylands case study areas.

2. Ecosystem services: definitions and classifications

The concept of ecosystem service (ES) is relatively new. It appeared in the last decade of the 20th century, when the first publications on this topic appeared in the scientific literature. An important milestone in ecosystem service evaluation was de Groot's publication "Functions of Nature" (1992), followed by Costanza et al. (1997) and Daily (1997), who further developed and promoted the concept in a global context.

The acknowledgement of the concept of ESs by policy makers followed the publication of United Nations "Millennium Ecosystem Assessment" (MEA) in 2005. The work on the MEA started in 2001 and involved over 1300 international experts, providing a global and comprehensive assessment of human impacts on ecosystems and their services. The key finding of the MEA was that over 60 per cent of the ecosystem services evaluated are being degraded or used unsustainably.

The MEA initiative was followed by a second international initiative, The Economics of Ecosystems and Biodiversity (TEEB), carried out between 2007 and 2010. TEEB was launched by the European Commission and the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety, responding to proposal of environment ministers from the G8+5 countries meeting in Potsdam, Germany, in March 2007. TEEB contributed greatly to bring the economic perspective of the ES in the policy debate, highlighting the economic value of biodiversity as well as the costs arising from biodiversity loss and ecosystem degradation.

In 2012, four UN entities, i.e. UNEP, UNESCO, FAO and UNDP, established the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) aiming at strengthening "the science-policy interface for biodiversity and ecosystem services as well as for the conservation and sustainable use of biodiversity, long-term human well-being and sustainable development".

Different definitions of ESs have been provided over the years. De Groot et al., (2002) defined ecosystem services as "the capacity of natural processes and components to provide goods and services that satisfy human needs, directly or indirectly". According to MEA (2005) ecosystem services are the "benefits people obtain from ecosystems", while TEEB define them as the contributions provided by ecosystems to benefits stemming from economic, social, cultural and other human activities (TEEB 2010, SEEE-EEA, 2012). The quality and quantity of such contributions depends on ecosystem structure and functions in combination with other inputs.

Any attempt to assess, measure, value or map ecosystem services should be preceded by their categorization, which also allows to communicate results in a clear way (Burkhard and Maes (Eds.), 2017). A number of different typologies or ways of classifying ES are available, for example those provided by the Millennium Ecosystem Assessment (MEA) and The Economics of Ecosystems and Biodiversity (TEEB), or national assessments, such as those used in the UK, Germany and Spain. As the approach to classification differs, addressing different scale and using different definitions, they are not always easy to compare. In order to try to overcome this 'translation problem', the Common International Classification of Ecosystem Services (CICES) was proposed in 2009 and revised in 2013 (V4.3), and again in 2016-2017 (V5.1). The CICES developed from the work on environmental accounting undertaken by the European

Environment Agency (EEA). It supports their contribution to the revision of the System of Environmental-Economic Accounting (SEEA), which is currently being led by the United Nations Statistical Division (UNSD).

The MEA classification system proposed four main ES categories: 1) Provisioning services – food, materials and energy, which are directly used by people; 2) Regulating services – those that cover the way ecosystems regulate other environmental media or processes; 3) Cultural services – those related to the cultural or spiritual needs of people; and 4) Supporting services – ecosystem processes and functions that underpin other three types of services. Figure 1 provides examples of services under each of the four MEA categories and their relationship to different components of human well-being.

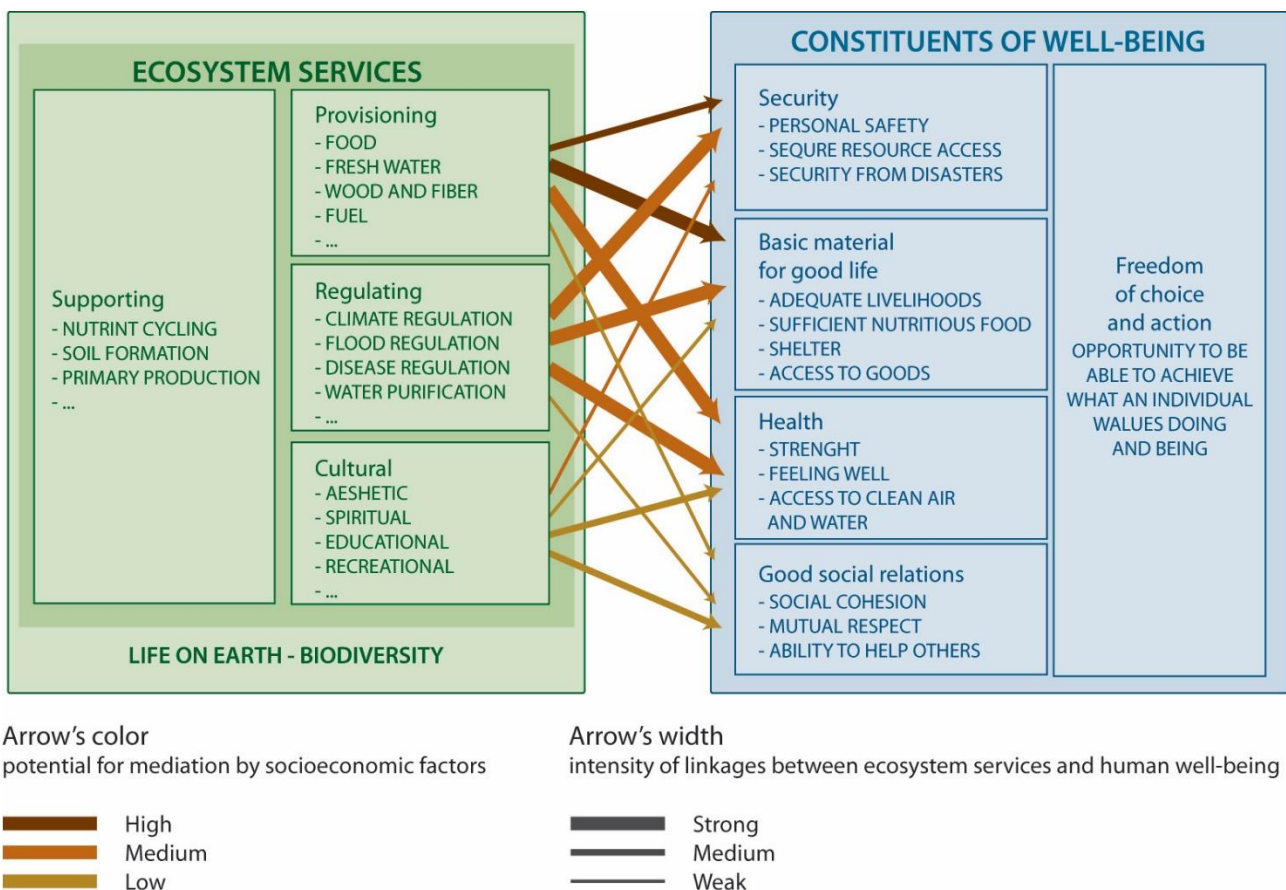


Figure 1. The links between ecosystem services and human well-being as described by MEA classification system (Source: MEA, 2005).

The TEEB approach to ESs classification is very similar, with three categories overlapping, i.e. provisioning, regulating and cultural, and a fourth category defined "habitat or supporting services" including habitats for species and maintenance of genetic diversity.

The CICES approach to ESs classification differs from the other as it is structured in a hierarchical way with five levels. At the higher hierarchical level, it recognizes three major "sections" of ES: provisioning, regulating and cultural. These are defined as in the MEA and

TEEB classifications. The CICES does not cover the so-called 'supporting services' originally defined in the MEA. Rather these supporting services are treated as part of the underlying structures, process and functions that characterise ecosystems. The following levels in a descending hierarchy are "divisions", "groups", "classes" and "class type" (Figure 2). Within each section, specific divisions identify main types of output or process provided by a given ecosystem (nutrition, materials, energy, etc.). The group level splits divisions by biological, physical or cultural type or process. Classes and class types provide a further level of detail.

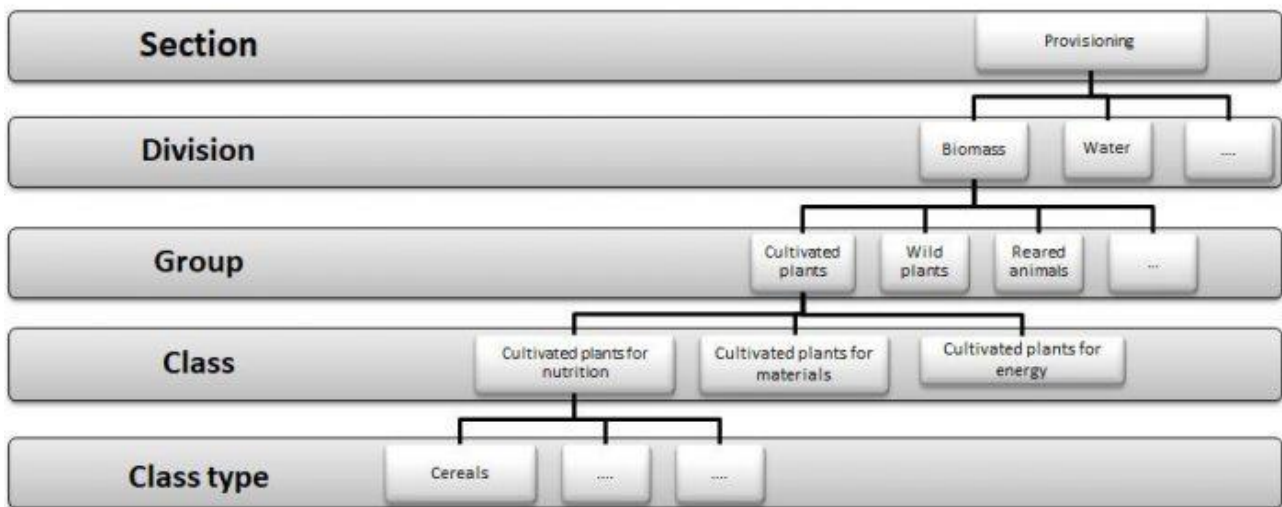


Figure 2. The hierarchical structure of CICES, illustrated with reference to a provisioning service (cultivated plants- cereals) (Source: CICES, 2021).

The first four levels can be used for ecosystem accounting, without reducing the value of the classification for different uses, such as mapping that may need more detailed categories at local scales. The new aggregation of provisioning services in Version 5.1 also considers accounting situations in which, for example, the end-use of a crop is unknown. Where this occurs, the output can be recorded at Group level (e.g. Cultivated terrestrial plants for nutrition, materials or energy). Furthermore, Version 5.1 was extended to more formally cover abiotic ecosystem outputs

The hierarchical structure is also designed to address issues of scale and accommodate geographical differences in what kinds of ecosystem output are recognised as a service. Thus the more aggregated Groups and Division categories may be used for reporting at broader spatial scales, where a number of the more specific classes are combined. At finer geographical scales, the specific classes that make sense at the local level might represent these broader categories of service.

As with the previous version of CICES, the hierarchical structure of V5.1 allows further classes and class types to be added as new applications emerge. The structure is therefore not intended to be exhaustive below class level. Rather it is meant as a framework that can develop and be adapted over time.

3. Ecosystem services assessment: methods and principles of the MAES analytical framework

The MAES conceptual framework adopts the typology of ESs as defined in CICES, ensuring comparability of results among LIFE projects and facilitating the reporting on ecosystem services in the LIFE KPI Webtool.

The MAES framework links socio-economic system with ecosystems via the flow of ecosystem services, and through external drivers affecting ecosystem directly, as impacts from human activities, or as consequence of using the services (Figure 3)

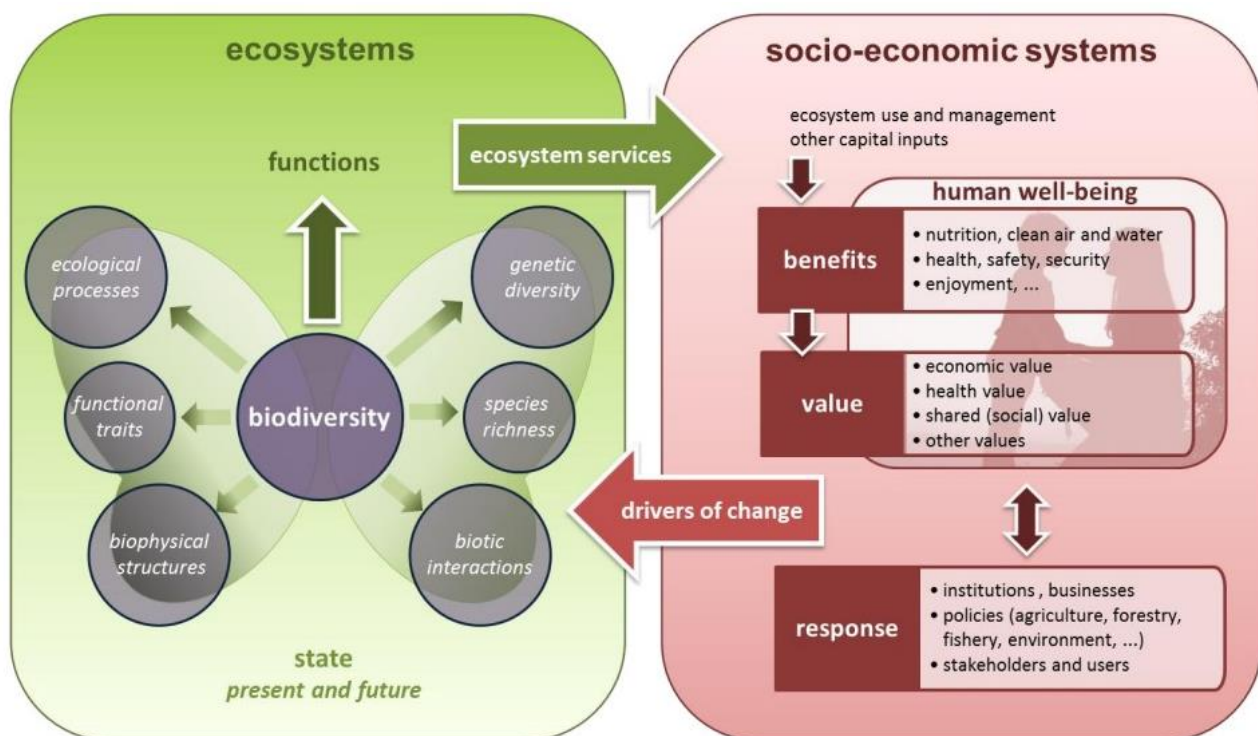


Figure 3. The MAES framework (source: EU, 2013). In the framework ecosystems state is synonym of ecosystem condition. Pressures refers to processes affecting the condition of ecosystems.

Based on Corine Land Cover classification and on bathymetry data, MEAS identify 12 types of aggregated ecosystem types: seven terrestrial, one freshwater and four marine types. Terrestrial types are urban, grassland, cropland, forest and woodland, heathland and shrub, sparsely vegetated land, and wetland. In the framework MAES identify the following six main classes of pressures: 1. Habitat conversion and degradation (land conversion); 2. Introductions of invasive alien species; 3. Pollution and nutrient enrichment; 4. Over-exploitation; 5. Climate change; and 6. Other pressures.

In assessing ecosystem conditions, the framework distinguishes between indicators of **environmental quality**, expressing the physical and chemical quality of ecosystems (e.g. concentration of air pollutants in urban ecosystem type, or fragmentation of the other six terrestrial ecosystem types), and **ecosystem attributes**, expressing the biological quality of

ecosystems. Ecosystem attributes are further subdivided in **structural ecosystem attributes** and **functional ecosystem attributes**. For the different ecosystem type, a core set of indicators is provided (Table 1). Indicators were selected in agreement with key stakeholders. Structural ecosystem attributes are divided in the following four groups:

1. General structural ecosystem attributes (seven indicators)
2. Structural ecosystem attributes based on species diversity and abundance (two indicators)
3. Structural ecosystem attributes monitored under the EU nature directives (four indicators)
4. Structural soil indicators (one indicators)

Condition class	Indicator	U	C	G	F	H	S	W	RL
Environmental quality	Percentage of population exposed to noise	●							
	Percentage of population exposed to air pollution above the standards	●							
	Concentration of air pollutants	●							
	Percentage of population connected to urban waste water collection and treatment plants	●							
	Fragmentation		●	●	●	●	●	●	
	Tropospheric ozone (ground level ozone) concentration				●				
	Concentration of nitrogen, sulphate, sulphur, calcium and magnesium				●				
	Percentage of forest under management plan or equivalent				●				
	Nutrient and BOD concentration in surface water	●							●
	Water Exploitation Index								●
Structural ecosystem attributes (general)	Percentage area of ecosystem	●			●				
	Share of High Nature Value farmland in agricultural area		●	●					
	Share of organic farming in UAA		●	●					
	Livestock density		●	●					
	Deadwood				●				
	Biomass volume (growing stock)				●				
Structural ecosystem attributes based on species diversity and abundance	Ecological Status								●
	Farmland Bird Indicator		●	●					
Structural ecosystem attributes monitored under the EU nature directives	Abundance and distribution of common forest birds				●				
	Percentage covered by Natura 2000 or by Nationally Designated Areas	●	●	●	●	●	●	●	●
	Conservation status and trends of species of Community interest	●	●	●	●	●	●	●	●
	Conservation status and trends of habitats of Community interest	●	●	●	●	●	●	●	●
Structural soil indicator	Population status and trends of bird species of Community interest	●	●	●	●	●	●	●	●
	Soil organic carbon	●	●	●	●	●	●	●	

Table 1. Core set of indicators for terrestrial and freshwaters MAES ecosystem types (U: Urban; C: Cropland; G: Grassland; F: Woodland and forest; H: heathland and shrub; S: sparsely vegetated land; W: Wetlands; RL: Rivers and lakes; ● : Key indicator for the ecosystem type).

Additional indicators for ecosystem types are presented in the 5th MES report on mapping and assessment of ecosystem condition (EC, 2018). For example, in case of agricultural land uses, which include cropland and grassland ecosystems, structural soil attributes include four additional indicators, i.e. soil pH, soil erodibility (K factor, tonne ha h/MJ mm), bulk density (Mg m⁻³), and soil biodiversity, expressed as DNA-based richness and abundance (Table 2). Furthermore, two functional soil attributes are introduced, i.e. available water capacity and soil nutrients availability (N and P, mg kg⁻¹). The same set of structural and functional soil indicators apply also for forest ecosystems, while general and specific structural ecosystem attributes differ greatly (Table 3).

	Ecosystem condition	Cropland	Grassland
Environmental quality	Nitrogen concentration in surface and groundwater in Nitrogen Vulnerable Zones (mg/l)	Y	Y
	Heavy metal concentrations in soil (mg/kg)	Y	Y
Ecosystem attributes			
Structural ecosystem attributes (general)	Grassland habitat fragmentation (meshes/1000 km ²)	NA	Y
	Landscape fragmentation index (index)	Y	Y
	Crop diversity/ 10 km×10 km (number)	Y	NA
	Crop rotation (functional crop groups) (number)	Y	NA
	Density of semi-natural elements (%/ha)	Y	Y
	Connectivity of semi-natural elements (index)	Y	Y
	Share of fallow land in UAA (%)		Y
	Share of High Nature Value farmland in agricultural area (%) (SEBI 020) (AEI23)	Y	Y
	Share of organic farming in UAA (%) (SEBI 020) (AEI4)		Y
Livestock density (LU/ha)		Y	
Structural ecosystem attributes based on species diversity and abundance	Farmland Bird Indicator (index) (SEBI 001) (AEI2.4.1)		Y
	Grassland Butterfly Indicator (index) (SEBI 001)	NA	Y
	Mammals, amphibians, reptiles impacted by changes in agriculture (Red List index)	N	N
	Wild pollinators (where available) (species richness)		Y
Structural ecosystem attributes monitored under the EU nature directives	Conservation status and trends of habitats of Community interest associated to grassland (%)	NA	Y
	Percentage of agroecosystems covered by Natura 2000 (%)	Y	Y
	EU Population status and trends of bird species associated to cropland and grassland (%)	Y	Y
	Conservation status and trends of species of Community interest associated to cropland and grassland (%)	Y	Y
Structural soil attributes	Soil organic carbon (SOC) (% or g/kg)	Y	Y
	Soil pH (pH)	Y	Y
	Soil erodibility [K-factor (tonne ha h/MJ mm)]	Y	Y
	Bulk density (kg/m ³)	Y	Y
	Soil biodiversity (DNA-based richness and abundance)	Y	Y
Functional ecosystem attributes (general)	Water availability (m ³ /ha/year)		Y
	Gross primary production (kJ/ha/year)	Y	Y
Functional soil attributes	Available water capacity (index)	Y	Y
	Soil nutrients availability (nitrogen & phosphorus) (mg/kg)	Y	Y

Table 2. Ecosystem services indicators for agricultural lands. Y = available indicator, either individually for each of the two considered ecosystem types, or as one indicator (Y across the two columns) to be further split into cropland and grassland i.e. by masking on the basis of Corine Land Cover; N: Not available (these indicators are also printed in red, see section 3.4.3); NA: Not Applicable; UUA: Utilized Agricultural Area; SEBI: Indicator of Streamlining European Biodiversity Indicators; AEI: Agri-Environment Indicator; Indicators printed in **bold** are key indicators (see also section 4.2.1). *This indicator can only be assessed at level 1 of the MAES ecosystem typology (for all terrestrial ecosystems combined). Source: 5th MES report on mapping and assessment of ecosystem condition (EC, 2018).

Ecosystem condition	
Environmental quality	Percentage of forest designated as "protective forests" (soil, water, other functions and infrastructure and managed resources) (%)
	Percentage of forest under management plan or equivalent instruments (%)
	Tropospheric ozone (ground level ozone) concentration (ppb)
	Concentration of nitrogen, sulphate, sulphur, calcium and magnesium (kg/ha)
Ecosystem attributes	
Structural ecosystem attributes (general)	Deadwood (m3/ha) (SEBI 018)
	Plant functional types (typology)
	Forest types (typology)
	Forest age structure (% of forest in age categories)
	Seral diversity (typology)
	Defoliation (% of trees)
	Discolouration (% of trees)
	Tree height (m)
	Tree cover density (%)
	Tree crown size (diameter, m)
	Forest fragmentation and connectivity (index) (SEBI 013) (CI)
	Biomass volume (growing stock) (m3/ha) (SEBI 017)
	Carbon stock (tonne/ha)
	Forest area (km2)
	Forest structural heterogeneity (index from remote sensing)
	Forest structural homogeneity (index from remote sensing)
	Canopy volume (from remote sensing) (m3)
	Naturalness (index or typology)
	Invasive alien species (number or richness) (number of species/area unit)
	Leaf-related indicators (see note 3)
	Pigment content (chlorophyll, carotene xanthophyll) (µg/g)
	Content of: nitrogen, phosphorous, carbon, lignin, cellulose, phenole, plant water content, wax, starch, sugar (%)
Structural ecosystem attributes based on species diversity and abundance	Species diversity, richness (number and abundance of species, including vascular plants, vertebrates, etc.) (number of species, indexes)
	Phylogenetic diversity (index)
	Forest tree species (number of species or species richness), tree sp. composition (index)
	Genetic variability (index; % of forest managed for the conservation and utilization of forest tree genetic resources)
	Threatened forest species (red list index) (SEBI 002) (CI)
	Understorey vegetation (species richness) (index)
	Rove and ground beetles (species richness) (index)
	Bryophyte, moss, liverwort, lichen and fungal species richness (index)
Structural ecosystem attributes monitored under the EU nature directives	Percentage of forest covered by Natura 2000 (%)
	Percentage of forest covered by Nationally Designated Areas (%)
	Threatened forests related habitats (Red List index) (% , number, area) (CI)
	Conservation status and trends of habitats of Community interest associated to forest (%) (SEBI 005)
	Abundance and distribution of common forest birds (index) (SEBI 001) (CI)
	Conservation status and trends of species of Community interest associated to forest (%)
	EU Population status and trends of bird species of Community interest associated to forest (%)
Structural soil attributes	Soil biodiversity (DNA-based richness and abundance)
	Soil pH (pH)
	Soil organic carbon (SOC) (% or g/kg)
	Soil moisture (water stress) (index)
	Bulk density (kg/m3)
	Soil erodibility (K-factor) (tonne ha h/MJ mm)

Functional ecosystem attributes (general)	Photosynthesis (e.g. indexes: NDVI (Normalized Difference Vegetation Index), VCI Copernicus (Vegetation Condition Index), fPAR (Fraction of Photosynthetically active radiation), LAI (Leaf Area Index)) (CI)
	Chlorophyll fluorescence (remote sensing proxies)
	Carbon sequestration (Dry matter productivity Copernicus) (tonne/ha/year)
	Plant productivity (NPP) (tonne/ha/year)
	Evapotranspiration (l/ha/day)
	Leaf respiration (net ecosystem-atmosphere CO2 exchange)
	Leaf phenology type, leaf age, leaf development (measures according to annual cycles)
	Plant and canopy phenology (measures according to annual cycles)
	Carbon dioxide exchange and carbon balance (net ecosystem-atmosphere CO2 exchange)
	Greening response (remote sensing proxies)
Functional soil attributes	Available water capacity (index)
	Nutrient availability (nitrogen and phosphorus) (mg/kg)

Table 3. Ecosystem services indicators for forest ecosystems. According to the EU Forest Strategy (COM(2013) 659 final) sustainable forest management means using forests and forest land in a way, and at a rate, that maintains their biodiversity, productivity, regeneration capacity, vitality and their potential to fulfil, now and in the future, relevant ecological, economic and social functions, at local, national, and global levels, and that does not cause damage to other ecosystems. For the purpose of MAES the notion of 'over-exploitation' comprises all forest management practices with adverse effects on these objectives, and which can be assessed by an array of indicators embracing relevant aspects of forest condition and forestry practices. 2 The indicator should be measured as long-term average (ideally taking into consideration information on annual fellings and net annual increment for the whole rotation period or more) and it should be interpreted carefully, taking into account complementary information and other indicators. For instance, large areas of older stands may have large potential for harvesting and relatively small mean net annual increments. Another example is the use of fast-growing non-native species or fertilisation which may contribute to an increase in growing stock, but may be detrimental to biodiversity (see: <https://www.eea.europa.eu/data-and-maps/indicators/forest-growing-stock-increment-and-fellings/forestgrowing-stock-increment-and-4>). 3 Leaf-related indicators: size (mm), form (typology), type (typology), anatomy (typology), optical properties (reflectance measurements), wettability traits (g/m²), dry matter content (%), specific leaf area (m²/kg), mass per area (g/m²), carbon content (%), nitrogen content (%), phosphorus content (%), pigment content (%), water content (%). CI: Composite Indicator; Indicators printed in **bold** are key indicators; SEBI: Indicator of Streamlining European Biodiversity Indicators; *This indicator can only be assessed at level 1 of the MAES ecosystem typology (for all terrestrial ecosystems combined). Source: 5th MES report on mapping and assessment of ecosystem condition (EC, 2018).

Within the MAES framework, the indicators are used to evaluate the changes of ecosystems conditions and ESs provisions over the short and the long term. Short-term trends analyse changes relative to 2010 (e.g. 2010 to 2018) which is the baseline year for this assessment. Long-term trends analyse changes relative to a year preceding 2010, usually 2000 or 1990, but others years can be selected depending on data availability. The baseline year 2010 marked the starting point of the EU Biodiversity Strategy to 2020 whose targets were under evaluation.

Both short- and long-term trends are assessed as percentage change per decade of each considered indicator. According to the framework, as the CORINE land cover data are the reference data set, the assessment of ecosystem services considers a maximum of three steps related to the reference years of the CORINE land cover data sets (2000, 2006, 2012, and 2018). For example, the overall trends at EU level was first assessed between 2000 and 2012 as the rate of change per decade of each indicator, but a more detailed analysis also described the

changes occurred between 2000 - 2006 and 2006 - 2012. For both short- and long-term trends assessment, four outcomes are possible:

- i. **No change:** the change is not significantly different from 0% per decade, the condition of the ecosystem remain the same;
- ii. **Improvement:** significant downward trend of pressure indicators or upward trend of condition indicators; change to a higher state of ecosystem conditions due to natural regeneration or restoration;
- iii. **Degradation:** significant upward trend of pressure indicators or downward trend of condition indicators; change to a lower state of ecosystem condition due to pressures;
- iv. **Unresolved:** the direction of the trend cannot be defined. This include also the cases in which only one point in time is available for the considered indicator(s) or lack of data.

As stated above, the baseline year for ecosystem assessment is 2010, and indicators data for 2010 represents the baseline data for the calculation. In case data for 2010 are not available, linear interpolation can be used to estimate them taking the values for years that comprise 2010 (e.g. 2008 and 2012).

In order to calculate the baseline value of an indicator between two years T_1 and T_2 for which the indicators values are respectively Y_1 and Y_2 , the following formula applies:

$$\text{Indicator value at baseline}_{2010} = [(Y_2 - Y_1) / (T_2 - T_1)] \times (2010 - T_1) + Y_1$$

For all the indicators based on CORINE land cover the datasets for 2006 and 2012 are used to calculate the baseline value for 2010.

The assessment define trends as the percentage of change per decade. Its calculation can be based on the values of the indicator X in the first and in the last year, as follows:

$$\% \text{ change per decade} = 100 \times [(X_{\text{last year}} - X_{\text{first year}}) / (X_{\text{first year}})] \times 10 / (\text{last year} - \text{first year})$$

If the values of the indicator are measure on an absolute scale (e.g. percentage or proportion) the change is simply given by the difference between the last and the first year, corrected by the number of years in between:

$$\% \text{ change per decade} = (X_{\text{last year}}(\%) - X_{\text{first year}}(\%)) \times 10 / (\text{last year} - \text{first year})$$

In case of multiple indicators values, the calculation is based on the intercept and slope of linear regression

$$\% \text{ change per decade} = 100 \times [(Slope \times 10) / (Intercept + Slope \times 2010)]$$

Policy relevance and statistical significance are the two criteria guiding the interpretation of results. Based on a precautionary principle, a change is considered as significant in case the percentage change per decade is higher than or equal to +5% or lower than -5%, i.e. $\pm 0.50\%$ per year. This holds for both short- and long-term trends and regardless statistical testing. A change outside this interval is then considered always of political relevance and must be reported. Depending on the sign and the interpretation of the indicator, this change is an improvement

or a degradation, i.e. improvement if conditions increase or degradation if pressures increase. If the change falls within the $\pm 5\%$ interval per decade, no change is assumed, but a statistical test to assess significance is advisable, and in case of statistical significance, the trend may be reclassified.

According to IPBES (2019), global indicators of ecosystem extent and condition have shown a 47% average decrease of their natural baselines, with a continuous decline of at least 4% per year affecting many of them. For these reason, the MAES framework adopted a reference threshold of 5% per decade to report a significant loss ecosystem conditions. It is worth to note that the reference threshold adopted by Eurostat is actually much higher, i.e. 1% per year as cut off level to detect significant changes in the Sustainable Development Goals (SDG) indicators (Eurostat, 2019). Given that the response of ecosystem to pressures is often slower than the actual change in pressure, the adoption of this higher threshold would imply the risk of overlooking ecologically relevant change in ecosystem conditions.

In practice within the framework of LIFE projects, it is suggested to adopt the following steps:

- i. Identification and characterisation of the relevant ecosystem types and assessment of their conditions;
- ii. Analyse the human-environment systems to identify pressures;
- iii. Selection and quantification of the relevant ecosystem services;
- iv. Normalization of ecosystem service values and their inclusion in an assessment matrix; this can in turn be linked to spatial units.

Although the production of maps is not mandatory in LIFE projects, maps are indeed a valuable tool to support decision-making and to formulate recommendations for ecosystems management and monitoring. The choice of how to measure and map ecosystem service indicators depends on four main criteria: i) the overall purpose of the ecosystem service assessment; ii) the availability of data; iii) the type of measurement needed to quantify the indicators; and iv) the availability of human and financial resources. The adoption of these criteria results in a 3-tiered approach to ecosystem assessment and mapping, which is summarized in the following table.

	Tier-1	Tier-2	Tier-3
Purpose	Advocacy/awareness raising and communication	Assessment not implying any decision	Assessment needed to support decision making
Data availability	Largely available (look-up tables, expert knowledge and participatory mapping)	Available, also as proxy, and/or possible to get by combining existing data (for composite indicators)	Not immediately available, not harmonised at EU level, need to work on a large number of data
Measurement methods	Direct measurement	Direct measurement and indirect measurement	Modelling
Resources (skills and budget)	Basic/any skills Low budget	Average/some skills (e.g. GIS) Medium budget	High skills High budget

Table 4. Choice criteria in a tiered approach to ecosystem services mapping.



Once data (or their proxies) have been collected to assess the indicators for the target ecosystem services, they are generally 'normalised' or 'standardised'. By using standardised values, it is possible to compare, and possibly map, different services or the same services across regions or over time. In the MAES framework indicator values are normalized resorting to relative scales. These, for example, might range from 0 to 1 or from 0 to 5, where 0 represents no relevant ecosystem service supply. Lack of relevance does not mean that a given ecosystem service is not provided but rather that although the service is provided to some extent, it is not perceived as a benefit or its level of supply is relatively the lowest with respect to the service provided by other spatial units within a given ecosystem. At the other end of the scale, 1 or 5 represent the maximum level of ecosystem service supplied by a given ecosystem type.

4. Mapping ecosystem services: approaches and tools

Many of the indicators considered in the MAES framework refer to spatially explicit data, and can therefore be mapped. Maps with data for different points in time can then be used to generate maps of change at the level of the mapping units. Possible mapping units include both raster and vector-based geometries, such as grids at different resolutions (usually between 100 m and 25km), catchments, river basins, soil mapping units, land use classes, ecosystem types, or administrative units (e.g. NUTS regions, or provinces). An increasing number of modelling tools is available to assess and map ecosystem services and their indicators (Bagstad et al., 2013). The following figure synthesizes some of the existing typologies of assessment tools in terms of approach, and data and expertise requirements.

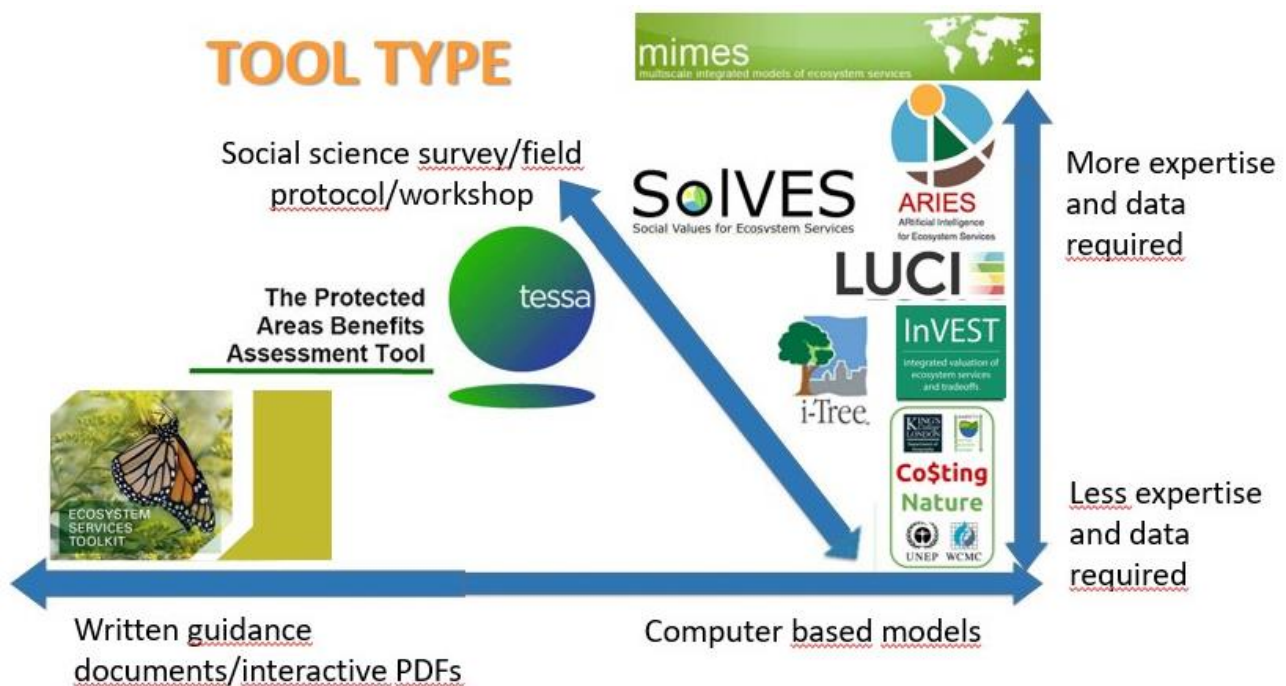


Figure 4. Example of modelling tools to assess and map ecosystem services.

A short description of some popular ecosystem services modelling and mapping tools is given below.

ARIES (ARTificial Intelligence for Environment & Sustainability, <https://aries.integratedmodelling.org/>) is a collaborative and open-source platform for interoperable models and data, based on the Knowledge Laboratory (k.LAB) technology, an artificial intelligence (AI)-powered and digital software for rapid ecosystem services assessment and valuation (Villa et al., 2014). It gives equal emphasis to ecosystem service supply, demand and flow in order to quantify actual services provision and uses by society (as opposed to

quantifying potential service benefits). Besides ecosystem services, ARIES also tackles natural capital accounting, food security, marine spatial planning, and renewable energy.

ARIES uses artificial intelligence to pair ES models with spatial data in order to quantify ES flows for a study area. The software will prioritize specific process-based models and revert to simpler models where required. It is based on the k.LAB technology, which allows users to contribute models and scientific data that simulate and integrate environmental and socioeconomic systems. Collaborative information is hosted on a network and when provided with a user query, ARIES automatically builds all the agents involved in the nature/society interaction, connects them into a flow network and creates the best models for each agent and connection.

The system to be analyzed is defined by selecting a spatial context (i.e., bounding box, administrative boundaries, watershed and more) on the map and setting the spatial and temporal resolution. This allows for a detailed and dynamic assessment of how nature provides benefits to people.

ARIES has global models for carbon storage, sediment regulation, pollination, crop production, nature-based tourism, outdoor recreation, and monetary valuation of forest ecosystem services through spatially explicit meta-analysis; with models of riverine flood regulation and water supply in advanced prototype and regional models for western Europe available for additional services like timber supply and forage production. ARIES prototypes are currently available for experienced modellers (training is recommended), and a web-based ARIES Explorer (k.Explorer) suitable for non-technical users was released in 2018.

Co\$ting Nature (<http://www.policysupport.org/costingnature>) Co\$ting Nature V.3 is a web based policy-support tool for natural capital accounting and analysis of the ecosystem services provided by natural environments. The focus is on costing nature (understanding the resource, e.g. the land area, and the opportunity cost of protecting nature to produce ecosystem services) as opposed to valuing nature (i.e. how much someone is willing to pay for it), though the tool does support economic valuation and has the necessary tools for this goal.

The tool estimates the current provision of 18 different ecosystem services including Timber (softwood, hardwood), Fuelwood (softwood, hardwood), Grazing/fodder, non-wood forest products, water provisioning (quantity, quality), fish catch, carbon, natural hazard mitigation (flood, drought, landslide, coastal inundation), culture-based tourism, nature-based tourism services, environmental and aesthetic quality services, wildlife services (pollination, pest control), wildlife dis-services (crop raiding, pests).

The tool can identify the beneficiaries, and then analyse current human pressures on the land, future threats and levels of biodiversity. It derives conservation priority from these factors. Users can also apply scenarios for land-use or land management change, and examine the impacts on ecosystem services and the implications for beneficiaries. The tool can be used to assess the impacts of human interventions for conservation prioritization and planning. It also calculated Nature's contributions to the Sustainable Development Goals (SDGs).

Model inputs are global spatial data (GIS, remote sensing) at 1 km² or 1 ha resolution, which are provided by the tool globally. Users can also provide their own datasets. Users can run the tool



at local scale, or for major basins or countries. For those requiring a simpler tool Co\$tingNatureMap provides access to baseline and scenario runs of Co\$tingNature globally and regionally and allows comparison between sites where conservation or development investments are planned.

INVEST (Integrated Valuation of Ecosystem Services and Trade-offs, <https://naturalcapitalproject.stanford.edu/software/invest>) InVEST is a suite of free, open-source software models used to map and value the goods and services from nature that sustain and fulfill human life. The multi-service, modular design of InVEST provides an effective tool for balancing environmental and economic goals. InVEST enables decision makers to assess quantified trade-offs associated with alternative management choices, and to identify areas where investment in natural capital can enhance human development and conservation.

The toolset includes distinct ecosystem service models designed for terrestrial, freshwater, marine, and coastal ecosystems, as well as a number of "helper tools" to assist with locating and processing input data and with understanding and visualizing outputs. InVEST models are spatially-explicit, using maps (raster and vector formats) as information sources and producing maps as outputs. InVEST returns results in either biophysical terms (e.g., tons of carbon sequestered) or economic terms (e.g., net present value of that sequestered carbon). The spatial resolution of analyses is also flexible, allowing users to address questions at local, regional, or global scales.

InVEST models are based on production functions that define how changes in an ecosystem's structure and function are likely to affect the flows and values of ecosystem services across a land- or a seascape. The models account for both service supply (e.g., living habitats as buffers for storm waves) and the location and activities of people who benefit from services (e.g., location of people and infrastructure potentially affected by coastal storms). InVEST models are distributed as a standalone application that is independent of a GIS software. A mapping software such as QGIS or ArcGIS is needed to view results. Running InVEST effectively does not require knowledge of Python programming, but it does require basic to intermediate skills in GIS software.

The tool is modular in the sense that you do not have to model all the ecosystem services listed, but rather can select only those of interest. The current available modules are: Carbon storage and sequestration (aboveground living biomass, belowground living biomass, soil, and dead organic matter), Coastal blue carbon, Coastal vulnerability, Crop pollination, Crop production, Habitat quality, Habitat risk assessment, Offshore wind energy, Recreation, Seasonal water yield, Scenic quality, Sediment retention, Urban cooling, Urban flood risk mitigation, Water purification, and Wave energy.

i-TREE Eco (www.itreetools.org) is a software application designed for urban forest assessment. It uses field data from complete inventories or randomly located sample plots, along with hourly air pollution and meteorological data. It quantifies the structure and environmental effects of urban forests (for trees and shrubs) and calculates their value to communities. Since 2006, i-Tree has been a cooperative effort between the USDA Forest Service, Davey Tree Expert

Company, The Arbor Day Foundation, Society of Municipal Arborists, International Society of Arboriculture, Casey Trees, and SUNY College of Environmental Science and Forestry.

i-Tree Eco is one of a suite of i-Tree products developed in the US. i-Tree Eco allows users to collect data on the urban forest and estimate the quantity and economic value of multiple ecosystem services that it provides for the community. This includes information on urban forest structure, air pollution removal, rainfall interception, carbon sequestration and storage, and resource value. Tree data are collected and entered into the software. A series of scientific algorithms calculate structural and functional information about the value of each tree (if 100% of trees are sampled i.e. a 'full inventory') or an estimate for the total tree population (if a 'sample inventory' is conducted using plots randomly located throughout the study area).

i-Tree Eco is a stand alone program no other software required but Microsoft Excel, QGIS, ArcGIS Desktop with Spatial Analyst Extension (optional) will help with results analysis and reporting. More specifically, i-Tree Eco provides extensive forest and individual tree analyses including the following:

- i) Functional Analyses: Pollution removal and human health impacts; Carbon sequestration and storage; Hydrology effects (avoided run-off, interception, transpiration); Building energy effects; Tree bio-emissions; Avian habitat suitability (plot-based projects; limited to 9 bird species); Avian Habitat Suitability; and Ultraviolet radiation (UV) tree effects;
- ii) Structure and composition analyses: Species condition and distribution; Leaf area and biomass; Species importance values; Diversity indices and relative performance;
- iii) Forecasting modeling options including: Tree planting inputs; Extreme event impacts for weather and pests; Annual mortality adjustments;
- iv) Management information including: Pest risk analysis; User defined optional fields; Cost benefit analysis.

LUCI (<https://www.lucitools.org/>) is an ecosystem services modelling tool, which illustrates the impacts of land use on various ecosystem services (Jackson et al., 2013; Sharps et al., 2017). It runs at fine spatial scales and compares the current services provided by the landscape with estimates of their potential capability. LUCI uses this information to identify areas where land use change might be beneficial, and where maintenance of the status quo might be desirable. LUCI is relevant for a range of users at multiple scales and levels of decision-making. It can be applied for applications around sustainable development, conservation, sustainable tourism, restoration, and policy-making. The ecosystem services that LUCI models include: Agricultural production; Erosion risk and sediment delivery; Carbon sequestration; Flood mitigation; Habitat provision; Water quality (Nitrogen and Phosphorus).

LUCI functions at sub-field to national scale simultaneously. It uses readily available national data that is easily supplemented with local knowledge. To date, LUCI has been applied in several countries, but most extensively in the United Kingdom and New Zealand.

LUCI is a spatially explicit decision support tool. The landscape's spatial configuration is important, as LUCI "values" features and potential interventions by area modified and the area

affected by these modifications. LUCI's built-in trade-off tool allows the user to compare multiple ecosystem services at once. Its output identifies locations in the landscape where trade-offs or co-benefits/synergies in ecosystem services exist. Trade-offs are areas where one service would benefit from management interventions but lead to the degradation of a different service being provided by the same area. Co-benefits and synergies are areas where multiple services might benefit from interventions.

Mimes (Multi-scale Integrated Models of Ecosystem Services, <http://www.afordablefutures.com/>) is an analytical framework designed to assess the dynamics associated with ecosystem service function and human activities (Boumans et al., 2015). MIMES integrate diverse types of knowledge and elucidate how benefits from ecosystem services are gained and lost. In MIMES, users formalize how materials are transformed between natural, human, built, and social capitals. This information is synthesized within a systems model to forecast ecosystem services and human-use dynamics under alternative scenarios.

The MIMES requires that multiple ecological and human dynamics are specified, and that outputs may be understood through different temporal and spatial scales to assess the effects of different actions in the short and long term and at different spatial scales. MIMES case studies rely on georeferenced datasets as well as knowledge of ecological, economic, and social processes. These diverse information sources are synthesized as systems models within a computational environment that analyzes and forecasts ecosystem service and human-use dynamics over space and time.

The framework is supported by a growing library of modules that are nested within modeled ecosystems. MIMES is also supported by developing theory on the dynamics of coupled human and natural systems (CHANS). When appropriate, new case studies benefit from previous work by adapting available modules through a collaborative dialogue with stakeholders for plug-and-play utility. The MIMES framework has the ability to consider multiple ecosystem goods and services simultaneously and calculate their responses to multiple interacting environmental and human drivers at a range of spatial and temporal scales. MIMES is both spatially and temporally explicit, allowing users to understand the long-term sustainability of ecosystem services under different scenarios of human action.

SoLVES (Social Values for Ecosystem Services; https://www.usgs.gov/centers/gecsc/science/social-values-ecosystem-services-solves?qt-science_center_objects=0#qt-science_center_objects) is a geographic information system tool developed to incorporate quantified and spatially explicit measures of social values into ecosystem service assessments (Sherrouse and Semmens, 2020). SoLVES 4.0 provides an open-source version of SoLVES, which was designed to assess, map, and quantify the social values of ecosystem services in a variety of biophysical and social contexts including mountain, forest, coastal, riparian, agricultural, and urban environments around the globe.

Social values, i.e. the perceived, nonmarket values the public ascribes to ecosystem services, particularly cultural services, such as aesthetics and recreation, can be evaluated for various

stakeholder groups. These groups are distinguishable by factors such as their attitudes and preferences regarding public uses (for example, motorized recreation and logging).

As with previous versions, SolVES 4.0 derives a quantitative 10-point, social-values metric (the value index) from a combination of spatial and nonspatial responses to public value and preference surveys. The tool also calculates metrics characterizing the underlying environment, such as average distance to water and dominant landcover.

SolVES 4.0 has been developed with Python using a QGIS user interface and a PostgreSQL database for required data. SolVES is integrated with Maxent maximum entropy modeling software to generate more complete social-value maps and offer robust statistical models describing the relation between the value index and explanatory environmental variables. A model's goodness of fit to a primary study area and its potential performance in transferring social values to similar areas using value-transfer methods can be evaluated.

SolVES 4.0 provides an improved open-source, public-domain tool for decision makers and researchers to evaluate the social values of ecosystem services and to facilitate discussions among diverse stakeholders regarding the tradeoffs among ecosystem services

The **TESSA** toolkit (<http://tessa.tools/>) is an easy-to-use workbook that leads the user through the steps needed to assess the ecosystem services provided at a particular site. It is built around a comparison of the site in two alternative states, e.g. before and after restoration or conversion, and encourages a high level of stakeholder engagement.

The toolkit was initially developed for conservation practitioners but can be used by anyone, including the private sector and those with no prior knowledge of ecosystem services. It includes an introduction to the concepts of ecosystem services and natural capital, guidance on how to conduct a preliminary scoping appraisal to identify important services and beneficiaries, decision trees to identify the best methods to use for each service, and links to a set of simple low-cost methods for measuring ecosystem services either qualitatively or quantitatively. Worked examples are provided, as well as instructions for collecting site-specific data where appropriate (including field surveys and stakeholder input). There is also guidance on how to communicate results to decision-makers. The tool is not constrained to specific land use types.

TESSA is built around a comparison of two alternative states of the site, e.g. before and after restoration or degradation, the toolkit is based on an interactive pdf document which leads the user through a step by step approach to assess the main ecosystem services provided by the site under consideration (typically 100 – 100,000 ha). Preliminary guidance helps the user to select a suitable site, define the exact questions to be addressed (e.g., threats, pressures, drivers of change; what to implement), engage the relevant stakeholders and find out about the local political, environmental and socio-economic context.

The first step is then a scoping appraisal to identify which are the most important services provided by the site. For each of these services, there is a choice of several assessment methods, including manual calculations using published data, stakeholder mapping, field surveys or modelling tools (options include use of the WaterWorld and Co\$tingNature models). A decision tree for each service assessment helps the user to choose the most suitable method,



given the available data and resources. Hypertext links take the user to separate short pdfs, which describe how to apply each method, and there are also links to additional guidance documents and case studies.

5. ARIES: a collaborative and open-source platform for interoperable models and data

In order to capture the complexity and the specificity of the land degradation phenomena identified in the in the New Life 4 Drylands case study areas (Table 7), specific indicators may be necessary. The selection of reliable indicators should consider the following characteristics: (a) objectively and scientifically measurable, (b) preferentially quantitative, (c) easy and cost-effective to be measured, (d) sensitive to environmental changes, (e) simple in concepts, and (f) able to support policy decisions (DESIRE, 2008)

The tool selected for this purpose is ARIES, a web-based application built on a first prototype Integrated Modelling Platform known as k.LAB (Knowledge LABORatory, <https://integratedmodelling.org/getting-started/>), and then implemented on a second prototype end users' model, called k.Explorer (<https://aries.integratedmodelling.org/>).

Knowledge Laboratory (k.LAB) is the open-source software powering ARIES. Thanks to k.LAB interface, users can freely explore the observation space by querying the knowledge base. k.LAB is designed to integrate models via the use of well-defined scientific concepts. The software gives access to an integrated network of web-accessible models, cataloged, and related across scientific disciplines through semantics. k.LAB provides a user-friendly means to query the network, seeking information about a concept of interest. The system links natural science (e.g., process-based models) and human behavior (e.g., agent-based models) effortlessly and resolves differences in units or scale automatically, enabling outputs to support complex, interdisciplinary decisions. Behind the scenes, an artificially intelligent engine assembles the best possible workflow to compute outputs that describe the concept of interest to the modeller or decision maker. This deductive process builds a decision tree to resolve the principal concept to the most suitable data or model, and in turn resolves any other concepts required by the data or models chosen at each step, seamlessly linking models to provide holistic outputs that support real-world decision making. Specific, detailed models are chosen over more general, coarser alternatives if data exist to support them. To properly match models to contexts, k.LAB uses a sophisticated, multiple criteria ranking algorithm that can mix objective criteria (such as spatio-temporal resolution) with user-provided rankings of data or model reliability and quality.

The most visible application of k.LAB is the ARIES project, a suite of state-of-the-art ecosystem services models aimed at supporting science-based decision-making. ARIES stands out as a tool for social-environmental systems modeling, using knowledge and models built independently by many actors and endorsed by the scientific community to produce holistic outputs, making evidence-based environmental decision making easier and more effective.

ARIES has been in development since 2007 and in use since 2008 in various releases of increasing sophistications. It chooses ecological processes models where appropriate and turns to simpler models where process models do not exist or are inadequate. Based on a simple user query, ARIES builds all the agents involved in the nature/society interaction, connects them into a flow network and creates the best possible models for each agent and connection. The result is a detailed, adaptive, and dynamic assessment of how nature provides benefits to people.

ARIES for SEEA Explorer has been developed by the Statistic Division of the UN Department of Economic and Social Affairs (UN DESA) and the UN Environment Program (UNEP), in collaboration with the international research and innovation platform Artificial Intelligence for Environment & Sustainability (ARIES) at the Basque Centre for Climate Change (BC3).

5.1 ARIES functioning

ARIES application has access to all information (data and models) available on the Integrated Modelling network and provides a dedicated user interface to easily compile accounts within the UN System of Environmental-Economic Accounting (SEEA). ARIES for SEEA can also be accessed via software download (for recurrent users), for better performance in terms of speed and computation capacity (<https://aries.integratedmodelling.org/aries-for-seea-documentation/>).

There are seven different ecosystem services modules, developed by ARIES team: (a) Carbon sequestration and storage; (b) Flood regulation, (c) Coastal flood regulation; (d) Aesthetic views and open space proximity; (e) Freshwater supply; (f) Sediment regulation; (g) Subsistence fisheries and recreation.

5.1.1 Setting the spatial and temporal context of the analysis

The user interface contains a menu in which it is possible to specify the geographic area, the temporal, and the spatial scale of interest. There are three options to select an analysis context by zooming and panning on the map: (1) map boundaries, in which the entire visible area on the screen is the analysis context; (2) administrative regions, in which the larger administrative entity (e.g. country or subnational unit) is identified, according to the M49 standard endorsed by the UN; (3) river basin, in which it is possible to select an area of land draining to a specific water body based on FAO Hydrological Basins (<https://www.fao.org/aquastat/en/countries-and-basins/>); (4) Alternatively, the user can also directly type the name of geographical context (i.e., country, region, city, or other geographic entities) in the ARIES for SEEA search bar. These names are queried from the OpenStreetMap (OSM) database.

5.1.2 Spatial and temporal resolution

The user can select the spatial resolution for analysis, choosing between metres and kilometres. If an input data chosen resolution is not available (i.e. too high), ARIES will compile accounts at the resolution of the finest grained available data.

As for temporal resolution, there are two different possibilities: (1) single year analysis; (2) multi-year analysis. If data are missing for a specific year of interest, ARIES automatically fills the gaps using the closest available year's data.

5.1.3 Study setup

Each account contains a drop-down menu (three horizontal dots), from which the user can select the different accounts to compile (Figs. 5 and 6):

- (1) Extent Accounts, measure the extent of the IUCN Global Ecosystem Typology, or land cover, present in the context in km². The different types of accounts provide different levels of detail in summarizing ecosystem/land cover extent and its change over the selected time period;
- (2) Condition Accounts, measure ecosystem condition. Currently, only forest ecosystem condition accounts are supported, but condition accounts for other ecosystem types will be added soon (beginning with grasslands);
- (3) Ecosystem services accounts (physical terms), measure the biophysical quantities of services provided by ecosystems and used by economic units;
- (4) Ecosystem Services Accounts (monetary terms), measure the monetary value of the selected ecosystem services, applying SEEA EA-compliant valuation method. In the current version, three ecosystem services are available (Crop provisioning: value of ecosystem contribution, Crop provisioning: value of pollination contribution, Global climate regulation: value of change in C storage);
- (5) Spatial and temporal aggregation, in which the user can select how the account results are aggregated in accounting tables. Currently only the first option is available (Primary only – no subdivisions), where there is a single table summarizing results for the entire spatial context identified by the user;
- (6) Temporal Accounting, when a multiple-years analysis is selected.

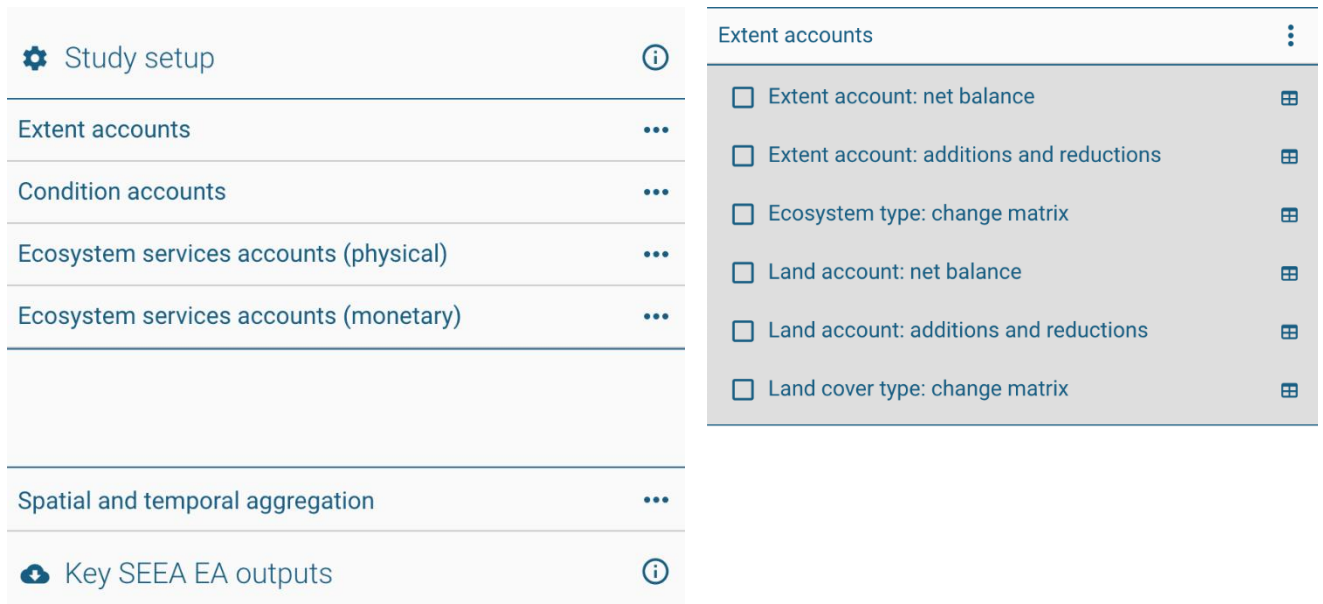


Figure 5. ARIES study set-up interfaces: spatial and temporal aggregation and extent account options.

Condition accounts	⋮	Ecosystem services accounts (physical)	⋮
Metrics (choose one or more)	👤	<input type="checkbox"/> Crop provisioning: ecosystem contribution	🗃️
▶ <input type="checkbox"/> Forest condition metrics		<input type="checkbox"/> Crop provisioning: pollination contribution	🗃️
Output tables		<input type="checkbox"/> Global climate regulation: C storage	🗃️
<input type="checkbox"/> Ecosystem condition variable account	🗃️	<input type="checkbox"/> Sediment regulation: soil erosion control	🗃️
<input type="checkbox"/> Ecosystem condition indicator account	🗃️	<input type="checkbox"/> Recreation: nature-based tourism	🗃️
<input type="checkbox"/> Ecosystem condition index (simplified)	🗃️	Spatial and temporal aggregation	⋮
Ecosystem services accounts (monetary)	⋮	🔗 Ecosystem accounting areas	📘
<input type="checkbox"/> Crop provisioning: value of ecosystem contribution	🗃️	<input checked="" type="checkbox"/> Primary only (no subdivisions)	
<input type="checkbox"/> Crop provisioning: value of pollination contribution	🗃️	<input type="checkbox"/> Administrative subregions	
<input type="checkbox"/> Global climate regulation: value of change in C storage	🗃️	<input type="checkbox"/> Protected areas	
		<input type="checkbox"/> River basins	
		📅 Temporal accounting	📘
		<input checked="" type="checkbox"/> Start and end years	
		<input type="checkbox"/> All years in time series	

Figure 6. ARIES study set-up interfaces: condition and ecosystem services accounts options, spatial and temporal aggregation options.

5.1.4 Key outputs and observations

This section shows the most relevant spatial inputs and outputs in the account(s) selected by the user (e.g., in the case of climate regulation, the most relevant outputs are carbon storage in soil and in vegetation and the total storage). The last section stores all tables and maps produced in that session, so that the user can download them in a zipped file (in Excel spreadsheets and in GeoTIFF raster format).

5.1.5 Run an accounting model

When ARIES have computed a model input or intermediate output, it is listed and can be explored individually, by selecting the specific layer (e.g., aridity). When a main output of the model is computed, this is listed (in the darker section) above the other inputs/intermediate outputs (Fig. 7). In case the model is dynamic (i.e., is calculated for more than a year), the progress bar at the bottom of the search bar/results box progresses as the computation continues. In the right upper corner of the app, there are three tabs available: (1) Data view (always available); (2) Documentation view; (3) Data flow view (Fig.7).

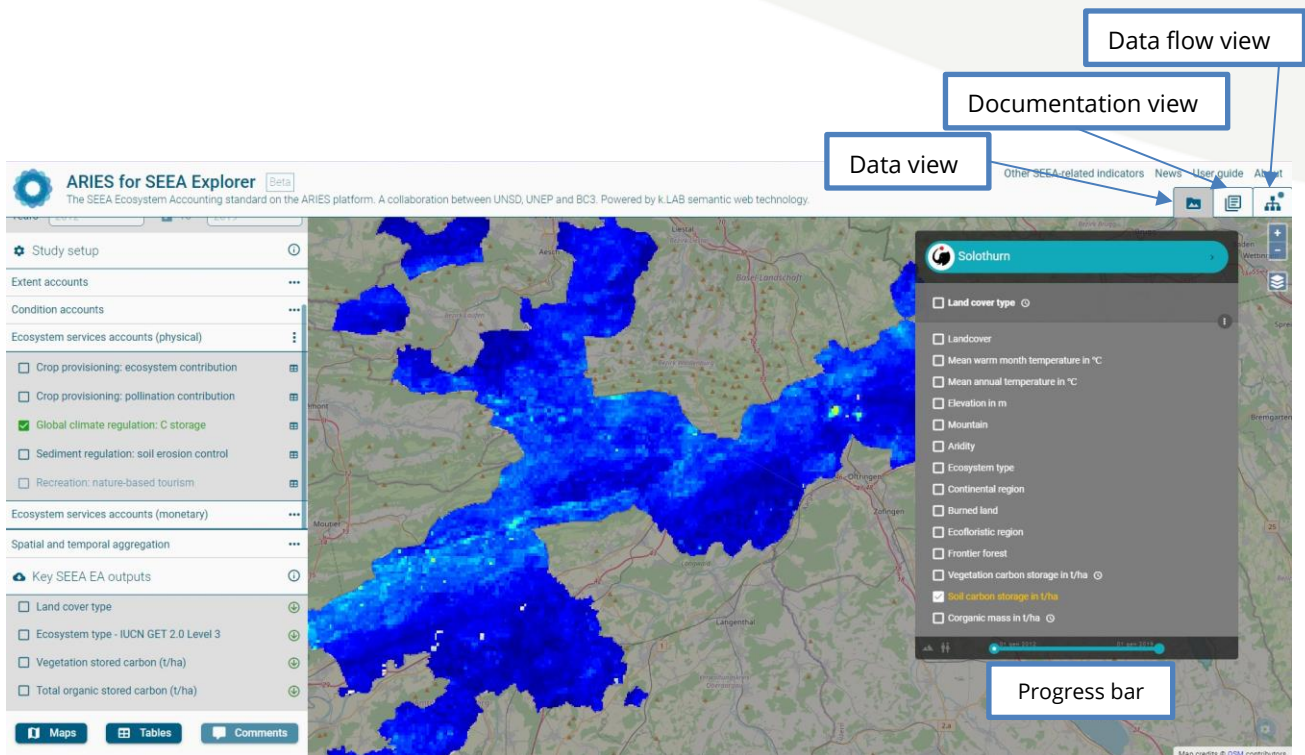


Figure 7. Example of ARIES ecosystem services physical accounts results: global climate regulation, soil carbon storage t/ha (100 m resolution).

5.1.6 The report

A tree-menu facilitates navigation of the information reported; it includes: (1) a general introduction to the model(s); (2) information on the SEEA framework or any other more general modeling frameworks (when part of a larger models set); (3) the applied methods; (4) a summary of the main results; (5) caveats or other considerations in model result interpretation; (6) reference(s) for data and method(s) used.

Images section: Figures and maps generated during the computation are listed and explored in this section individually. In case results come from multi-year models, the maps are interactive and show changes over time.

Resources section: This section lists all the resources used in the computations, to provide full-transparency in the final output. Each of the data resource can be explored individually.

Dataflow section: The section shows a list containing a visual summary of each model component and how these were combined to obtain the results. Once the model has run, the dataflow view shows a diagram that visually summarize each model component and how those were combined to obtain the results.

Search and knowledge bar: This box is used to call models, select the context, modify default settings and show the help page. Note that the general ARIES Explorer search bar is case sensitive. In this section there is the possibility to: (1) reset a previously used context; (2) Draw a new context, using the cursor; (3) adjust the spatial and/or temporal resolution of the analysis; (4) Activate the interactive mode to add input manually, adjusting parameter values; (5)

Remember the last context selected; (6) Show the help tutorial; and (7) Show the coordinates of the cursor.

5.2 ARIES output and background

The ARIES platform offers consistent hosting of data and models, naming conventions and quality assurance rules. All data are ensured to be FAIR – Findable, Accessible, Interoperable and Reusable by all.

Thanks to ARIES technology, the ARIES for SEEA Explorer application allows users to produce standardized, scalable, and customizable ecosystem accounts for the area of interest that are consistent with the SEEA Ecosystem Accounting framework (United Nations et al., 2021). This spatially explicit accounting framework is indeed coherent with the MAES approach described in the previous chapters, which provides a higher-level reference framework.

The current Explorer functionalities are restricted to assessing ecosystem (1) **extent** (based on the IUCN Global Ecosystem Typology), (2) **condition** (for forest ecosystem types), and (3) selected ecosystem **services** in physical and monetary units using basic models as a starting point. The outcomes can be analyzed and downloaded to further explore the results (with a GIS software).

Considering the IUCN Global Typology (table 5), an "Ecological Typology" is defined as a classification of land or water intended to represent variation in the expression of multiple ecological features. Traditional approaches to ecological classification have been based on biogeography or biophysical attributes, with approaches differing between terrestrial, freshwater, and marine disciplines. Ecosystem classifications are specific kinds of ecological typologies based on units that conform to the definition of ecosystems (e.g., ecological units that comprise a biotic complex, an abiotic complex, the interactions between and within them, and occupy a finite physical space; Keith et al., 2013).

Six design criteria for a global ecosystem typology were developed to serve the dual needs for conservation and sustainability of ecosystem services (table 5). Critically, an ecosystem typology must represent both ecosystem functions and the biota engaged in them. In addition, for application across the globe's diverse ecosystems, users, and scales of analysis, it must be conceptually consistent throughout the biosphere, have a scalable structure, spatially explicit units and avoid superfluous complexity (Keith, D.A., et al., 2020).

	PRINCIPLE	DESCRIPTION	RATIONALE
1	Representation of ecological processes	Groupings reflect major ecological processes, shaping ecosystem assembly and maintaining their defining characteristics and traits.	Enables generalisations and predictions about ecosystem functions and dynamics; responses to environmental change and management actions. Major ecosystem components, drivers, states and transitions should be consistent within a group.
2	Representation of biota	Within groups, ecosystems distinguishable through differences in the identity (composition) of their biota.	Enables generalisations and predictions about biodiversity for conservation and management applications. Units reflect not only functions, but the identity of engaged biota.
3	Conceptual consistency throughout the biosphere	The typology should encompass all components of the biosphere within a single theoretical framework.	Promotes comprehensive coverage of ecosystems from all environments, logical consistency, robust ecosystem identification and comparison between units.
4	Scalable structure	Groupings should be arranged in a hierarchical or nested structure to reflect the nature and magnitude of their similarities.	Enables representation of different features at particular hierarchical levels and facilitates applications across a range of spatial and organisational scales.
5	Spatially explicit units	Distributions of units should be mappable through any practical combination of ground observation, remote sensing and spatial modelling.	Enables comparative spatial analyses and time series analyses of ecosystem extent and distribution for monitoring and reporting.
6	Parsimony & utility	The typology should be no more complex than required to achieve other specifications and should use simple, accessible and clearly defined terminology.	Facilitates wide usage among people with varied objectives, skills and backgrounds.

Table 5. Design principles for a global ecosystem typology, IUCN Global Ecosystem Typology 2.0 (Keith, D.A., et al., 2020).

5.2.1 SEEA – System of Environmental Economic Accounting

The SEEA Ecosystem Accounting (SEEA EA) constitutes an integrated and comprehensive statistical framework for organizing data about habitats and landscapes, measuring the ecosystem services, tracking changes in ecosystem assets, and linking this information to economic and other human activity. The United Nations Statistical Commission adopted the SEEA Ecosystem Accounting at its 52nd session in March 2021. This adoption follows a comprehensive and inclusive process of detail testing, consultation, and revision.

The SEEA EA is built on five core accounts. These accounts are compiled using spatially explicit data and information about the functions of ecosystem assets and the ecosystem services they produce. The five ecosystem accounts are:

- (1) ecosystem extent accounts record the area of each ecosystem, classified by type within a specified area (ecosystem accounting area);
- (2) ecosystem condition accounts record the condition of ecosystem assets in term of selected characteristics at specific points in time;
- (3, 4) ecosystem services flow accounts (physical and monetary) record the supply of ecosystem services by ecosystem assets and the use of those services by economics units, including households;

(5) monetary ecosystem asset accounts record information on stocks and changes in stocks (addition and reductions) of ecosystem assets. This includes accounting for ecosystem degradation and enhancement.

The SEEA EA also supports 'thematic accounting', which organizes data around specific policy-relevant environmental themes, such as biodiversity, climate change, oceans and urban areas. Other important thematic accounts would include accounting for protected areas, wetlands and forests.

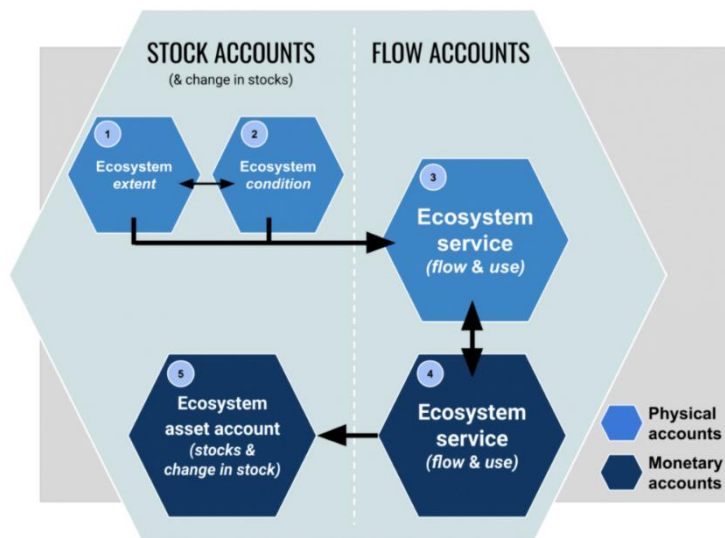


Figure 8. Ecosystem accounts and how they relate to each other, source: <https://seea.un.org/ecosystem-accounting>

The SEEA EA takes a spatial approach to accounting as the benefits a society receives from ecosystems depend on where those assets are in the landscape in relation to the beneficiaries. This spatial focus identifies the location and size of ecosystem assets, the ecosystem services provided, and the location of beneficiaries. For example, the beneficiaries of water filtration ecosystem services are likely located downstream of the ecosystem asset that provides that benefit (Fig. 9).

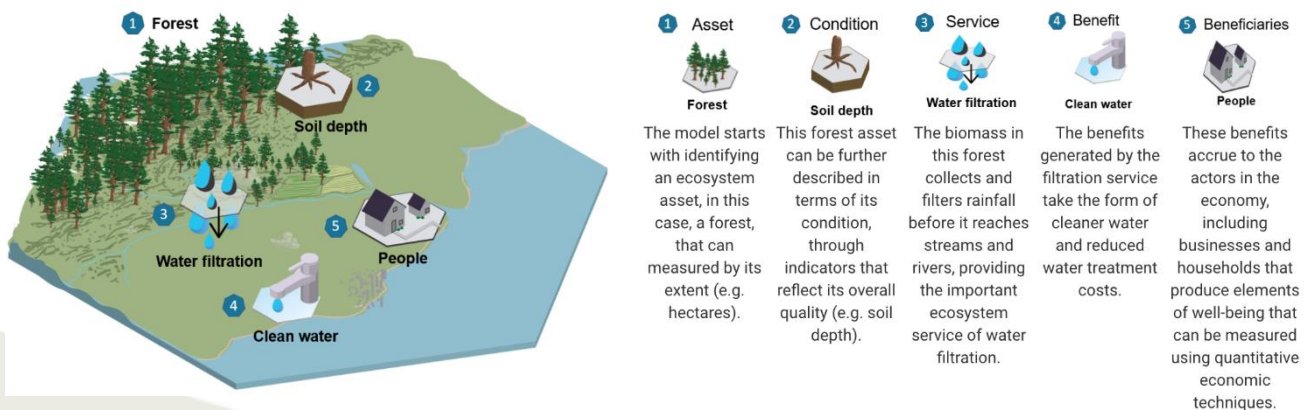


Figure 9: How ecosystem assets generate ecosystem services to beneficiaries in a spatial relationship, and from asset to final beneficiaries points description; source: <https://seea.un.org/ecosystem-accounting>.

5.2.2 ARIES - Extent account

The ecosystem Extent Account is the first SEEA EA account. It records the total area of each ecosystem, classified by type within a specified ecosystem accounting area (e.g., Nation, Province, river basin, protected area). Ecosystem extent accounts are measured over time in ecosystem accounting areas by ecosystem type, thus illustrating the changes in extent from one ecosystem type to another over the accounting period.

A full ecosystem extent account includes gross changes (addition and reductions), as well as net change between opening and closing years among individual ecosystem assets of the same ecosystem type and for each accounting period. Each change can be classified into managed expansion/reduction (changes due to direct human activity, such as forest clearing for agricultural land) or natural expansion/regression (changes resulting from natural processes, such as forest succession). Finally, ecosystem extent can be recorded as a change matrix that quantifies the specific change of each ecosystem type into another ecosystem type between an opening and closing year.

Keith et al., (2020) recognize 25 Level 2 biomes: four marine, three freshwater, seven terrestrial, two subterranean, and nine in transitional realms. These are further subdivided into 108 Level 3 Ecosystem Functional Groups (EFGs). ARIES currently enables the modelling of 29 "Level 2.5" ecosystem types that are a mix of Level 2 biomes and Level 3 EFGs. These include 21 terrestrial biomes and EFGs, seven wetland EFGs, plus the open water biome. Additional conceptual work is needed to determine how to best spatial data to map the remaining biomes and EFGs, particularly in freshwater and marine ecosystems using global time-series data.

The methods for mapping Level 2.5 ecosystems generally follow Sayre et al. (2020) temperature domains, landform, and elevation data, with aridity domains from United Nations (2017), combined with land cover data in a lookup table. This enables the mapping of ecosystems change overtime using the best available data.

The outcome can be compared across years to evaluate change in ecosystems extent over time, through the .xlsx net balance file (Table 6).

	Coastal saltmarsh reedbed	Cropland	Urban industrial ecosystem
Extent at start of 2012 (km²)	87.19218201986583	16300.114640400048	950.9513298592648
Extent at start of 2019 (km²)	93.49970157023918	15813.322543336779	1051.87164266525
Net change	6.307519550373357	-486.79209706326947	100.92031280598519
	Temperate woodland	Temperate subhumid grassland	Rocky pavement lavaflow scree
Extent at start of 2012 (km²)	108.3409240417059	216.68184808340956	7.049580673946576
Extent at start of 2019 (km²)	61.59107325658578	433.36369616681543	79.02950966055913
Net change	-46.749850785120124	216.68184808340587	71.97992898661255
	Seasonally dry temperate heath shrubland	Temperate forest	Other desert semidesert
Extent at start of 2012 (km²)	207.40608403874322	1104.1869518771762	453.0283159415081
Extent at start of 2019 (km²)	244.13810965562195	1277.45822423157	361.3837671802046
Net change	36.73202561687873	173.2712723543939	-91.6445487613035
	Episodic arid floodplain	Aquatic	Total
Extent at start of 2012 (km²)	5.93648898858659	216.3108175216229	19657.19916344587
Extent at start of 2019 (km²)	5.565458426799928	219.6500925777028	19640.87381872813
Net change	-0.3710305617866618	3.3392750560798845	-16.32534471775032

Table 6. Example of ecosystem extent accounts – LULC change net balance, from ARIES estimation.

The ecosystem extent accounting by ARIES encompasses the delivery of several different intermediate outputs:

- *July average temperature and annual average temperature*

The July average temperature data derive from the WorldClim (WorldClim2.1), representing the mean temperature (degrees °C), in the average of time period 1970 – 2000 for July at 30-second spatial resolution (<https://www.worldclim.org/data/worldclim21.html>). The mean annual temperature (from WorldClim – WorldClim2) represents the 1970 – 2000 average in degrees (°C), measured with 30-second spatial resolution (<http://worldclim.org/version2>).

- *Global elevation data*

This resource is provided by NCEAS Environment and Organisms (ENO) Working Group. EarthEnv creates a 90 m DEM compatible with a previous product (SRTM digital elevation models - DEMs) that has problems in running elevation and slop-dependent models in the northern polar regions (<https://www.earthenv.org/DEM>).

- *Global Aridity Index*

The Aridity index represents the ratio between precipitation and ET₀, thus rainfall over vegetation water demand (aggregated on annual basis). Under this formulation, the index values increase for more humid conditions, and decrease with more arid conditions. Data resolution is in 30 arc seconds or 1 km at the equator. This resource is provided by CGIAR-CSI (<https://cgiarcsi.community/data/global-aridity-and-pet-database/>).

- *Corine Land Cover (CLC) 2012, Version 2018 20*

Ecosystem extent accountings are based on Corine Land Cover (CLC) data at two points in time, i.e., for the reference year 2012 and 2018. The CLC European database is based on standard methodology and nomenclature with the following base parameters: (1) 44 classes in the hierarchical 3-level Corine nomenclature; (2) minimum mapping unit (MMU) for status layers is 25 hectares; (3) minimum width of linear elements is 100 m; (4) minimum mapping unit (MMU) for Land Cover Changes (LCC) for change layers is 5 hectares.

The CLC programme provides important data sets supporting the implementation of key priority areas of the Environment Action Programmes of the European Community as protecting ecosystems, halting the loss of biological diversity, tracking the impacts of climate change, assessing developments in agriculture, and implementing the EU Water Framework Directive. The CLC programme is also a part of the Copernicus Land Monitoring Service (<https://land.copernicus.eu/>) initiative, run by the European Commission and the European Environment Agency, which will provide environmental information from a combination of air- and space-based observation systems and in-situ monitoring (<https://land.copernicus.eu/pan-european/corine-land-cover/clc-2012>).

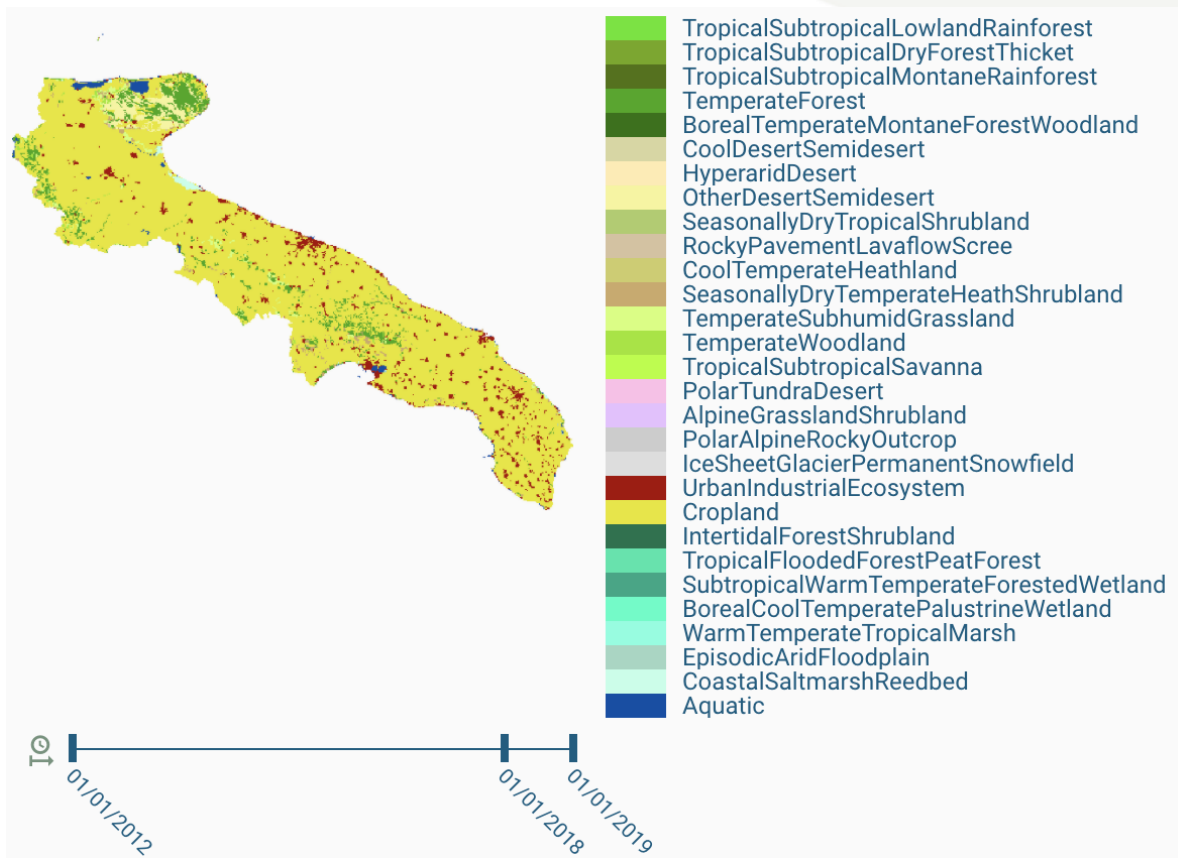


Figure 10. Example of CLC map, retrieved by ARIES.

5.2.3 ARIES: Ecosystem Condition accounts and condition metrics

The Ecosystem Condition Account tracks changes in ecosystem assets' condition over time, which is central to assessing the changing capacity of ecosystems to supply ecosystem services. Ecosystem condition is defined in the SEEA EA as the quality of an ecosystem measured in terms of its abiotic and biotic characteristics. Given the variation between ecosystem types (ETs), different indicators must be considered to characterize their most important ecological and non-ecological attributes within condition accounts.

The SEEA EA ecosystem condition typology (ECT) organizes data on ecosystem condition characteristics, grouping ecosystem condition indicators into three groups and six classes:

- i) *Abiotic ecosystem characteristics*: (1) Physical state (e.g., soil structure, water availability); (2) Chemical state (e.g., soil nutrient level, water quality, air quality);
- ii) *Biotic ecosystem characteristics*: (3) Compositional state (biological diversity); (4) Structural state (including vegetation, biomass, food chains); (5) Functional state (including ecosystem processes, disturbance regimes);
- iii) *Landscape level characteristics*: (6) Landscape and seascape characteristics (including landscape diversity, connectivity, fragmentation, embedded semi-natural elements in farmland).

ARIES provides as complete an ecosystem condition account as possible; ideally including information for all six ECT classes. However, doing so requires global time series data, which are not available for all ECT classes. The initial forest condition account can include up to six user-selected metrics belonging to four ECT classes, as shown below with global data sources (which are automatically replaced by local data in case of availability).

ECT class	Condition variable
Physical state	Self-calibrating Palmer Drought Severity Index (scPDSI)
Structural state	Burned area
Structural state	Normalized Difference Vegetation Index (NDVI)
Structural state	Leaf Area Index (LAI)
Functional state	Net Primary Production (NPP)
Landscape characteristics	Relative magnitude of forest fragmentation (FF)

Table 7: the SEEA EA ecosystem condition typology (ECT classes) and the relative condition variables, from ARIES documentation.

Most of the global time series data available for these metrics begin around the year 2000. The user can choose to report data on an annual basis or using 3-years average values, which smooth out inter-annual variations in weather (as recommended when accounting periods span multiple years). To obtain meaningful ecosystem condition indicators, data must often be adapted from their originally collected temporal resolution (multi-daily, weekly, monthly, etc.) and aggregated into annual observations. Depending on the indicator, this has been done before data were stored on the ARIES network, by calculating the average (e.g., drought severity index DS, NDVI, LAI), sum (NPP), or maximum (burned area) value from remote sensing observations over the course of the year. Table 8-10 summarize the results on terms of indicators values and their changes between 2012 and 2019. ARIES-SSEA provides also an overall indicator for ecosystem conditions, built on the 0-1 interval normalization of the sum of five normalized indicators, i.e. DS, NDVI, LAI, NPP and FF.

Indicators	Opening value	Closing value	Change
NPP	8.802	8.802	0.000
FF	0.235	0.235	0.000
DS	1.260	0.000	-1.260
NDVI	0.612	0.612	0.000
LAI	1.919	1.919	0.000

Table 8: Example of Ecosystem condition variable account, from ARIES estimation. NPP, net primary productivity ($t\ ha^{-1}$); FF, forest fragmentation indicator; DS, drought severity index; NDVI, normalized difference vegetation index indicator (-); LAI, leaf area index (m^2m^{-2}).

Indicator	Opening value	Closing value	Ref. opening value	Ref. closing value	Indicator opening value	Indicator closing value
NPP	8.802	8.802	9.317	9.317	0.853	0.853
FF	0.235	0.235	0.185	0.185	0.716	0.716
DS	1.260	0.000	1.427	0.000	0.766	0.000
NDVI	0.612	0.612	0.684	0.684	0.846	0.846
LAI	1.919	1.919	2.642	2.642	0.680	0.680

Table 9: Ecosystem condition indicator account, from ARIES estimation. NPP, net primary productivity (t ha⁻¹); FF, forest fragmentation indicator; DS, drought severity index; NDVI, normalized difference vegetation index indicator (-); LAI, leaf area index (m²m⁻²).

Ecosystem condition index	
Index at start of 2012	0.922
Index at start of 2019	0.918
Net change	-0.004

Table 10: Ecosystem condition index (simplified), from ARIES estimation.

Details on some selected ecosystem conditions derived from the accounting performed by ARIES-SSA are given below.

Relative Magnitude of Fragmentation (RMF)

This output, provided by the University of Helsinki, represents a global remote-sensing data product (i.e. the 27-year annual ESA CCI land cover maps which can be categorized as an EBV 'Ecosystem Distribution') to derive an annual (27 years) time-series of the Relative Magnitude of Fragmentation (RMF) at a global scale and with a spatial resolution of 300 m. From this derived EBV data product, it is possible to calculate a RMF indicator of ecosystem degradation, i.e. the change, and rate of change, in fragmentation of ecosystems (e.g. forests) over the last 27 years (<https://portal.geobon.org/ebv-detail?id=4>).

Copernicus Land Service LAI 1km V2

The Leaf Area Index, from Copernicus Global Land Service, is defined as half the total area of green elements of the canopy per unit horizontal ground area. The satellite-derived value corresponds to the total green LAI of all the canopy layers, including the understory which may represent a very significant contribution, particularly for forests. Practically, the LAI quantifies the thickness of the vegetation cover. Aries team calculated the annual mean value of LAI data from Copernicus 1km NDVI data (<https://land.copernicus.eu/global/products/lai>).

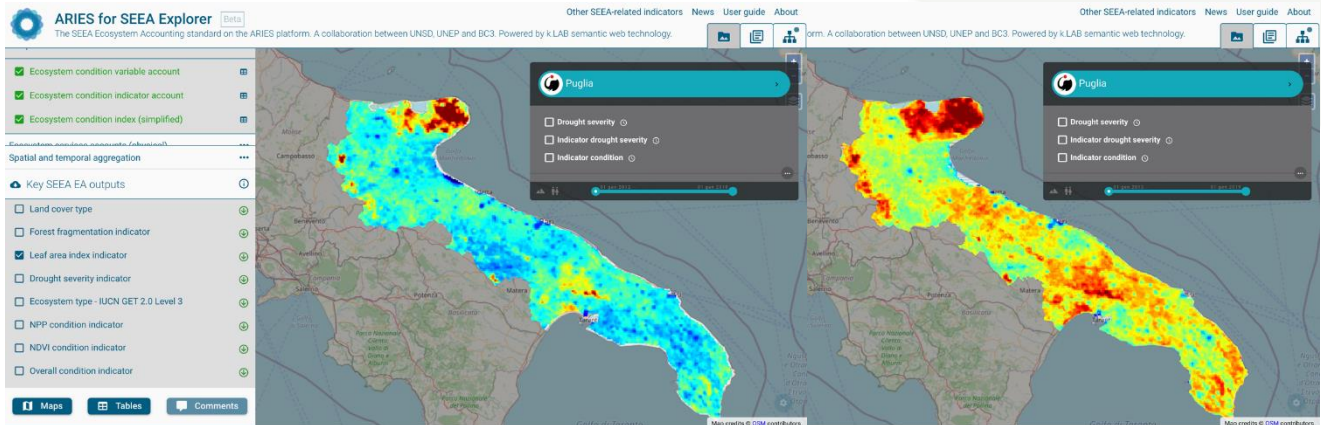


Figure 11: Leaf Area Index – LAI map (left) and NDVI (right), retrieved by ARIES-SSEA.

Copernicus Lands Service NDVI 1km V2

The Normalized Difference Vegetation Index (NDVI), from Copernicus Global Land Service, is an indicator of the greenness of the biomes. As such, it is closely linked to the FAPAR (Fraction of Absorbed Photosynthetically Active Radiation). Even though it is not a physical property of the vegetation cover, it has a very simple formulation:

$$NDVI = (REF_{nir} - REF_{red}) / (REF_{nir} + REF_{red})$$

where REF_{nir} and REF_{red} are the spectral reflectances measured in the near infrared and red wavebands respectively, makes it widely used for ecosystems monitoring. Aries team calculated the annual mean value of NDVI data from Copernicus 1km NDVI data (<https://land.copernicus.eu/global/products/ndvi>).

Self-Calibrating Palmer Drought Severity Index (scPDSI)

The scPDSI metric, by UK NERC-NCAS, was introduced by Wells et al. (2004), who gives detailed information about its calculation. The scPDSI is a variant on the original PDSI of Palmer (1965), with the aim to make results from different climate regimes more comparable. As with the PDSI, the scPDSI is calculated from time series of precipitation and temperature, together with fixed parameters related to the soil/surface characteristics at each location. Aries team calculated the annual mean value of scPDSI data from scPDSI monthly data (<https://crudata.uea.ac.uk/cru/data/drought/#global>).

Forest Fragmentation Index

Time-series Forest fragmentation data have been developed by Naimi, based on global European Space Agency-Climate Change Initiative (ESA-CCI) land cover data. Naimi (2020) define the 'forest' class by aggregating all 14 tree-cover related land cover types from the ESA CCI product into one class. Eight non-forest classes are defined (agriculture, grassland, wetland, settlement, sparse vegetation, bare area, water, permanent snow and ice) that are used as

multinomial categorical data, or as binary categorical data (to define forest vs. non-forest). Those classes follow the reclassification used by Mousivand & Arsanjani (2019).

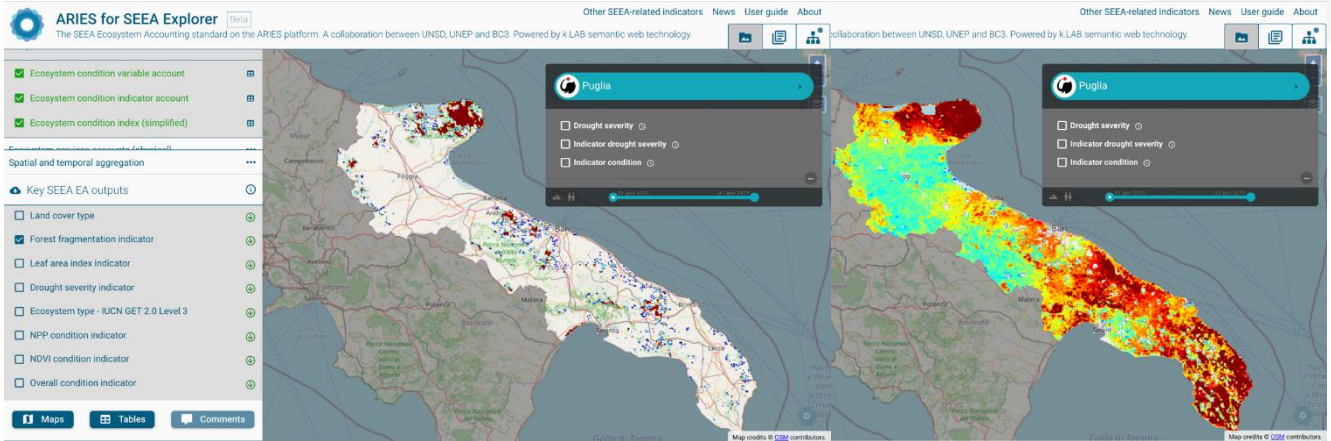


Figure 12: Forest fragmentation index (left) and NPP indicator maps, from ARIES estimation.

MODIS/Aqua Net Primary Production Gap-Filled Yearly L4 Global

The MYD17A3HGF Version 6 product provides information about annual Net Primary Production (NPP) at 500 m pixel resolution, by the U.S. National Aeronautics and Space Administration (NASA). Annual NPP is derived from the sum of all 8-day Net Photosynthesis (PSN) products (MYD17A2H) from the given year. The NPP value is the difference of the Gross Primary Productivity (GPP) and the Maintenance Respiration (MR).

The MYD17A3HGF is generated at the end of each year when the entire yearly 8-day MYD15A2H is available. Hence, the gap-filled MYD17A3HGF is the improved MYD17, which has cleaned the poor-quality inputs from 8-day Leaf Area Index and Fraction of Photosynthetically Active Radiation (FPAR/LAI) based on the Quality Control (QC) label for every pixel. If any LAI/FPAR pixel did not meet the quality screening criteria, its value is determined through linear interpolation. However, users cannot get MYD17A3HGF in near-real time because it will be generated only at the end of a given year (<https://lpdaac.usgs.gov/products/myd17a3hgf006/>).

5.2.4 ARIES: Ecosystem services accounts (physical)

The ecosystem services physical accounts provided by ARIES-SSEA include the following four ecosystem services: i) crop provisioning, ii) pollination, iii) climate regulation via C storage, and iv) soil erosion control (Figure 13). A fifth one, nature-based tourism, is in its final stages of development and will be made available in a future ARIES for SEEA release.

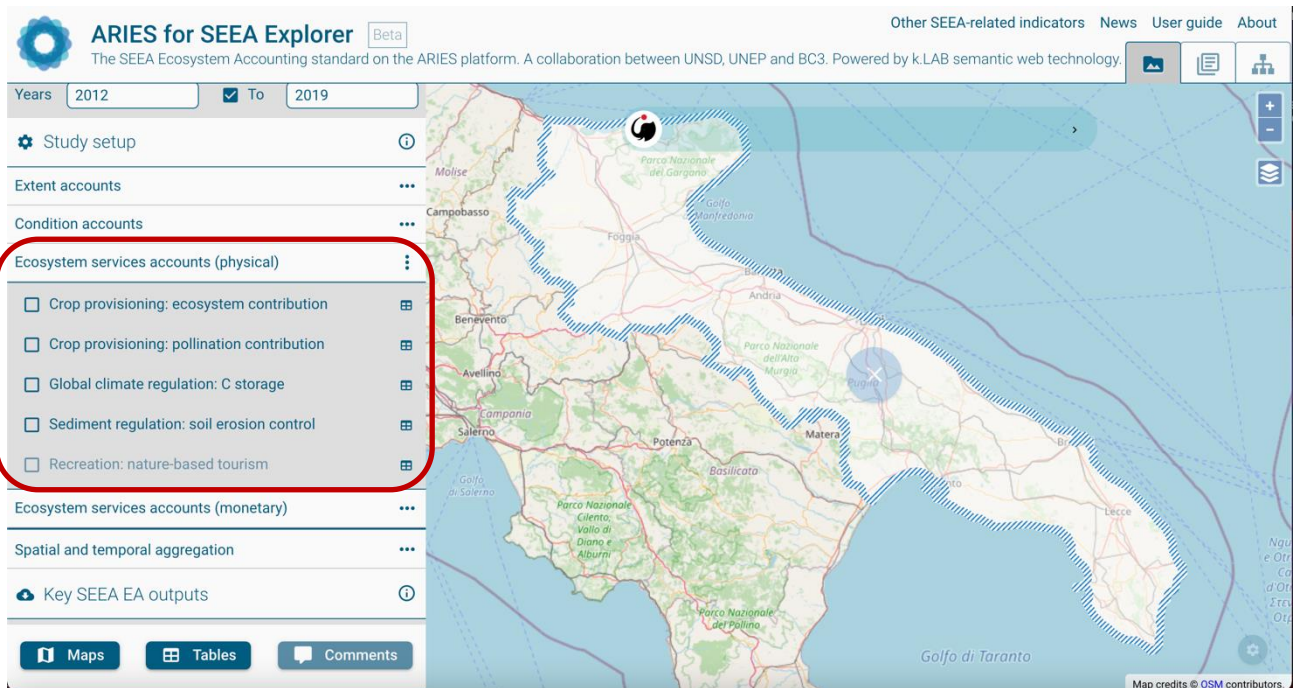


Figure 13: Ecosystem services accounts (physical) provided by ARIES

5.2.4.1 Crop provisioning

As defined in the SEEA EA and by UNDESA (ARIES documentation), crop provisioning services are "the ecosystem contributions to the growth of cultivated plants that are harvested by economic units for various uses including food and fiber production, fodder and energy."

The initial models focus on twelve globally important crops used as staples, feed, bioenergy, and for other key products: rice, maize, soybeans, wheat, barley, oil palm, potato, rapeseed, rye, sugar beet, sugar cane, and sunflower. Lacking subnational time series agricultural statistical data needed to produce credible spatially disaggregated crop production data (Joglekar et al., 2019), ARIES relies on crop production data from the Spatial Production Allocation Model (SPAM) for 2010, replaced by national data where available (SPAM, 2020).

To account for changes in crop production over time, ARIES adjusts cell-level production values upward or downward based on yearly changes in crop production from FAOSTAT (2020). This dataset was created for pollinators-dependent crops and using the World Bank official exchange rate for conversion in 2015.

The final dataset combines information, by crop and by country, for the time series 1992-2018 on: (1) the biophysical volume of production, expressed in tons of production (product quantity), and (2) the prices, expressed in USD at 2015 constant price per ton. The global dataset

of country boundaries combining products comes from OpenStreetMaps, GADM and FAO. Improving spatial understanding of crop production systems allows policymakers and donors to better target agricultural and rural development policies and investments, increasing food security and growth with minimal environmental impacts.

ARIES follows Vallecillo et al. (2019) in estimating the ecosystems contribution to crop production (EcoConCrop) as the ratio of natural inputs to natural plus human inputs, in energetic terms. These accounts measure in biophysical terms the services provided by ecosystems and are then transformed in economic units. The calculation of monetary values is done using crop-specific producer prices available from FAO as a proxy for SEEA-compatible resource rent valuation estimates. Further adjustment to produce basic price estimates (i.e., by adjusting for taxes and subsidies on products) would give a more accurate SEEA-compatible price estimate, but this adjustment should be done on a country-by-country basis.

In ARIES, tabular national statistical data requires spatialization and aggregation through spatial modelling. For crop provisioning, this approach assumes crop extent to be constant (based on spatial data for the reference year), with only crop yield (tons produced per hectare) to change over time. Increases or decreases in production are thus spread across the whole country, rather than for that specific (but unknown) areas.

5.2.4.2 Climate regulation service: Carbon storage

As defined in the SEEA EA, "Global climate regulation services are the ecosystem contributions to the regulation of the chemical composition of the atmosphere and oceans that affect global climate through the accumulation and retention of carbon and other GHG (e.g., methane) in ecosystems and the ability of ecosystems to remove carbon from the atmosphere".

The carbon models currently include: (1) Global lookup tables for vegetation carbon storage from Ruesch et al. (2008); (2) Spatially explicit global soil carbon storage data by ISRIC- World Soil Information (<https://www.isric.org/explore/soilgrids>). Valuation can be done on the change in carbon storage between an opening and closing year.

In assessing the climate regulation service, ARIES-SSEA delivers a number of intermediate layers (all available for download as GEOTiff raster files) which are integrated in the assessment of total carbon storage for the spatial extent selected by the user: land cover type, mean warm month temperature (°C), mean annual temperature (°C), elevation (m a.s.l.), aridity index, vegetation carbon storage (Mg ha⁻¹) and soil carbon storage (Mg ha⁻¹).

Vegetation carbon storage

Vegetation Carbon storage is quantified as the sum of aboveground and below ground biomass carbon storage, using a lookup table based on: (1) land cover type; (2) ecofloristic region according to FAO classification; (3) continental region; (4) the presence of frontier forests (a proxy for the degree of forest degradation), and (5) the recent occurrence of fires. The method and the look-up table used were first published in FAOSTAT (2020).

ARIES also provides the user with the option to value changes in carbon storage with a user-supplied Social Cost of Carbon (SCC), expressed in 2015 USD. SCC estimates vary widely based on underlying assumptions used to generate them, including discount rates and time horizon applied (Wang, P., et al., 2019). Additionally, country-specific SCCs can be generated, reflecting differential impacts of climate change, which are greater in countries at higher risk (Tol, R.S.J., 2019).

As a starting point, Nordhaus et al., (2017) provide a value of \$33.70 USD for a ton of carbon emitted in the year 2015. This cost can be adjusted upward or downward based on the year emissions were recorded (i.e., emissions in earlier years, where atmospheric CO₂ concentrations were lower, have a lower SCC, and vice versa). For example, a baseline set of assumptions used in ecosystem accounts for South Africa adjust it upward or downward by 3% in each year before or after 2015 and annualize costs using a 3.66% discount rate and 100-year time horizon. The SCC method applied here is generally viewed as a conservative estimate, and the user has the option to adjust the SCC from this starting point to reflect country-specific climate policy. Critically, valuation is applied to changes in the stock of carbon (through carbon sequestration and land-use change), not to carbon storage.

The results of the amount of carbon stored in vegetation (aboveground and belowground biomass) are summarized in a table available for download; unit is in tons per hectare.

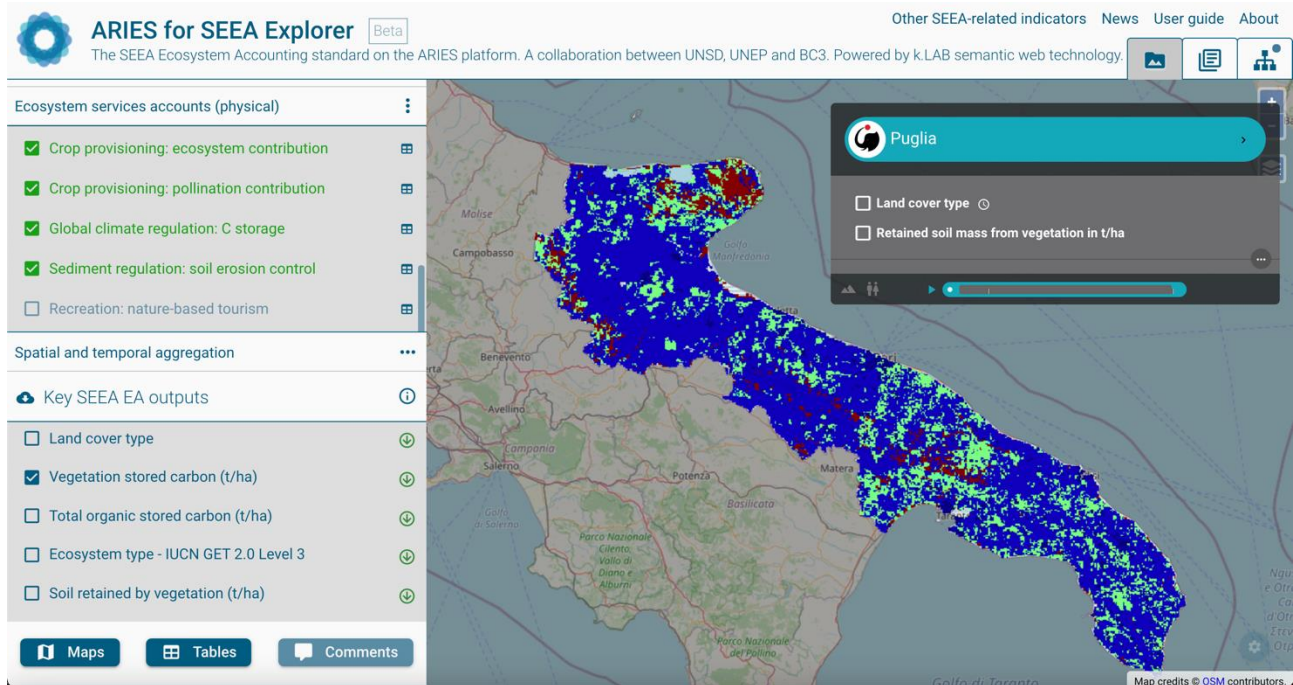


Figure 14: Ecosystem services accounts (physical), Key SEEA EA output: Vegetation stored carbon (t ha⁻¹) map, from ARIES estimation.

Soil organic carbon storage

Soil organic carbon maps, expressed in $t\ ha^{-1}$ for a 0-200 cm depth are derived from SoilGrids (version 2017). SoilGrids is a system for automated soil mapping based on state-of-the-art spatial predictions methods. SoilGrids predictions are based on globally fitted models using soil profile and environmental covariate data (Hengl et al., 2017). Currently, SoilGrids.org serves a collection of updatable soil property and class maps of the world at 250 m spatial resolutions produced using automated soil mapping based on machine learning algorithms. SoilGrids data are available publicly under the Open Database License. For the most up to date version of SoilGrids refer to <https://www.isric.org/explore/soilgrids>.

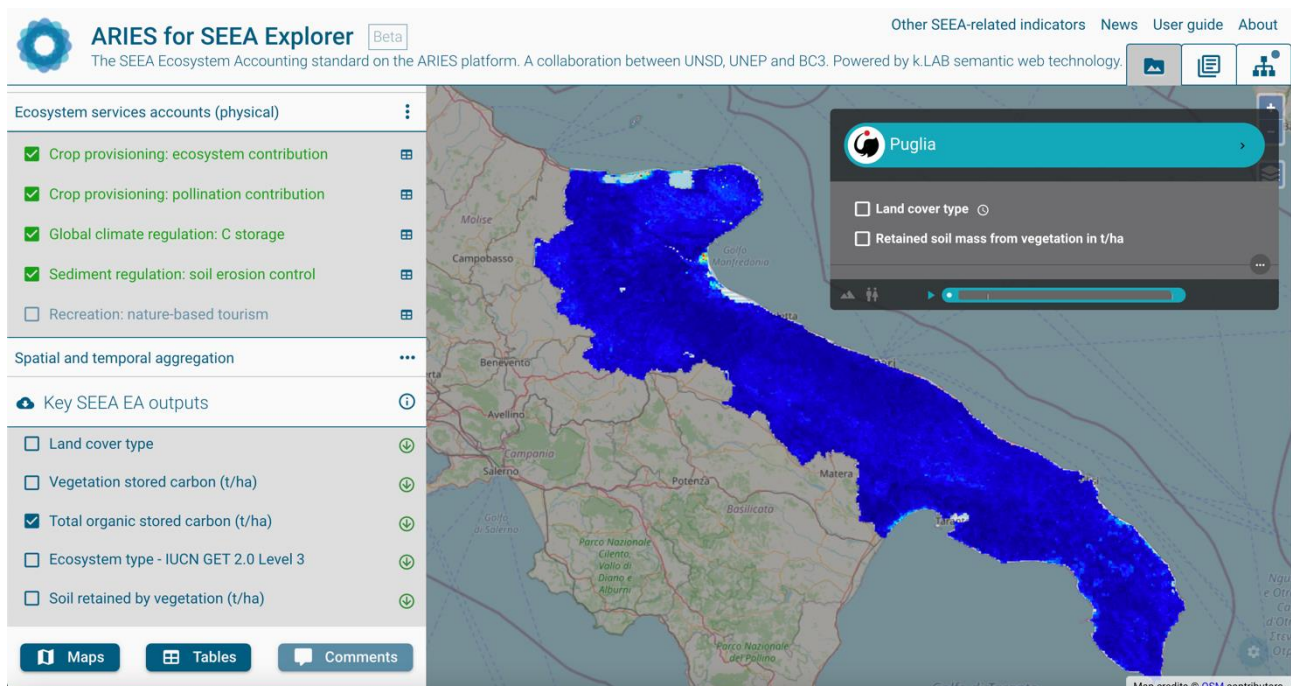


Figure 15: Ecosystem services accounts (physical), Key SEEA EA output: Total organic carbon storage ($t\ ha^{-1}$) map, from ARIES estimation.

Total ecosystem carbon storage is eventually computed as the sum of the carbon mass stored in aboveground and belowground vegetation, plus the amount of carbon stored in the first 200cm of soil (Fig. 15).

5.2.4.3 Sediment regulation: soil erosion control

An example of carbon models is the sediment regulation model, implemented by the Revised Universal Soil Loss Equation (RUSLE) according to Renard et al. (1997) and provides biophysical estimates of soil loss and retention by vegetation (in tons of sediment per hectare per year). The potential value (supply) of sediment regulation ecosystem service is computed by calculating RUSLE twice, first using the best land cover data available, then changing all land cover to bare soil and differentiating the results to estimate the avoided soil erosion attributable to vegetation.

As defined by the SEEA EA, "Soil erosion control services are the ecosystem contributions, particularly the stabilizing effects of vegetation, which reduce the loss of soil (and sediment) and support use of the environment (e.g., agricultural activity, water supply). This may be recorded as a final or intermediate service." This account reports the level soil erosion model produced by the Revised Universal Soil Loss Equation (RUSLE) model (Renard et al., 1997) and provides biophysical estimates of the prevention of soil loss by vegetation (in tons of sediment per hectare per year):

$$A = R * K * LS * C * P$$

where A represents soil loss ($Mg\ ha^{-1}\ y^{-1}$), R rainfall runoff erosivity ($MJ\ mm\ ha^{-1}\ h^{-1}\ yr^{-1}$), K soil erodibility ($t\ ha\ h\ ha^{-1}\ MJ^{-1}\ mm^{-1}$), LS slope steepness and length, C cover management (-), and P conservation practice (-). Soil erosion control as an ecosystem service is modeled as the difference between erosion with vegetation present vs. with bare soil, to estimate the contribution of vegetation (ecosystems) to soil erosion control. This implementation of RUSLE uses methods from Desmet and Govers (1996) to calculate the LS factor, based on contributing area, grid cell size, aspect, and slope length exponents (Sharp et al., 2015; Williams, 1995), and to calculate the K factor, based on soil organic matter and clay, sand, and silt fractions, and global studies for C and P factors based on land cover type (Borelli et al., 2017; D.Yang et al., 2003). The RUSLE equation used by this sediment regulation model has several well-known limitations; most notably, it applies only to rill erosion, and does not estimate gully, streambank, or mass erosion. RUSLE was originally developed for agricultural lands in the U.S., though it has since been applied in a wide variety of settings, including ES assessment and global applications. In order to estimate the soil erodibility factor K ($t\ ha\ h\ ha^{-1}\ MJ^{-1}\ mm^{-1}$, Figure 16), ARIES derives the required input from SoilGrids 205m (ISRIC); soil data refer to the uppermost soil layer (0-5 cm) and include percent silt, sand and clay fractions and soil organic carbon content (%). All these are available as downloadable raster layers (GEOtiff format).

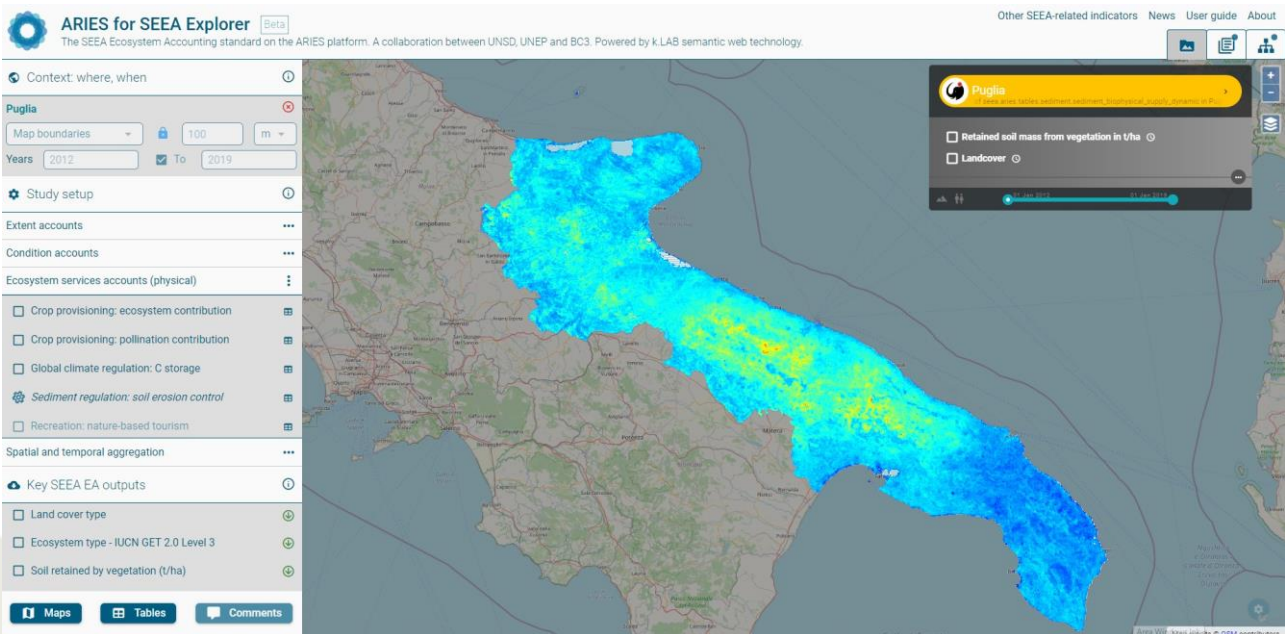


Figure 16. Ecosystem services accounts (physical), Key SEEA EA output: K factor ($t\ ha\ h\ ha^{-1}\ MJ^{-1}\ mm^{-1}$) map, from ARIES estimation.



The LS factor is derived from the EarthEnv 90 m DEM, compatible with previous SRTM (Shuttle Radar Topography Mission) data and covering latitudes between 83 degrees N-S. The Basque Centre for Climate Change used EarthEnv DEM data to produce a seamless aspect and slope layers. Global aspect and slope data are in degrees (<https://www.earthenv.org/DEM>).

The Contributing area (km²) required for the calculation of the LS factor is derived from HydroSHEDS flow accumulation data. The flow accumulation maps distributed with HydroSHEDS define the amount of upstream area (in number of cells) draining into each cell. The drainage direction layer is used to define which cells flow into the target cell. The number of accumulated cells is essentially a measure of the upstream catchment area. However, since the cell size of the HydroSHEDS data set depends on latitude, the cell accumulation value cannot directly be translated into drainage areas in square kilometers. A flow accumulation map reflecting true catchment areas is in preparation. Values range from 1 at topographic highs (river sources) to very large numbers (on the order of millions of cells) at the mouths of large rivers (<https://www.hydrosheds.org/>).

ARIES derives the rainfall erosivity factor R (MJ mm ha⁻¹ h⁻¹ yr⁻¹) the Global Rainfall Erosivity Database (GloREDA) which contains 3,625 precipitation stations from 63 countries in the Globe with temporal resolutions of 1 to 60 minutes. The R-factor values calculated from precipitation data of different temporal resolutions are normalized to R-factor values with temporal resolutions of 30 minutes using linear regression functions. Precipitation time series ranged from a minimum of 5 years to maximum of 52 years. The average time series per precipitation station is around 16.8 years, the most datasets including the first decade of the 21st century. Gaussian Process Regression (GPR) has been used to interpolate the R-factor station values to a European rainfall erosivity map at 30 arc-seconds (~1 km at the Equator). The global rainfall erosivity map is publicly available and can be used by other research groups to perform national, continental, and global soil erosion modelling (JRC 2017).

6. Examples of ARIES-SEEA applications to NL4DL study areas

One of the advantages of the ARIES-SEEA integrated platform is the possibility the user has to set the spatial extent of the assessment and retrieving all at once spatially explicit updated information and data. These can be used for a preliminary ecosystem service assessment even in absence of measured ground data and observations. Furthermore, it allows the integration of data from additional sources, such as regional web-based geoportals, and geospatial data provided by national and supranational agencies.

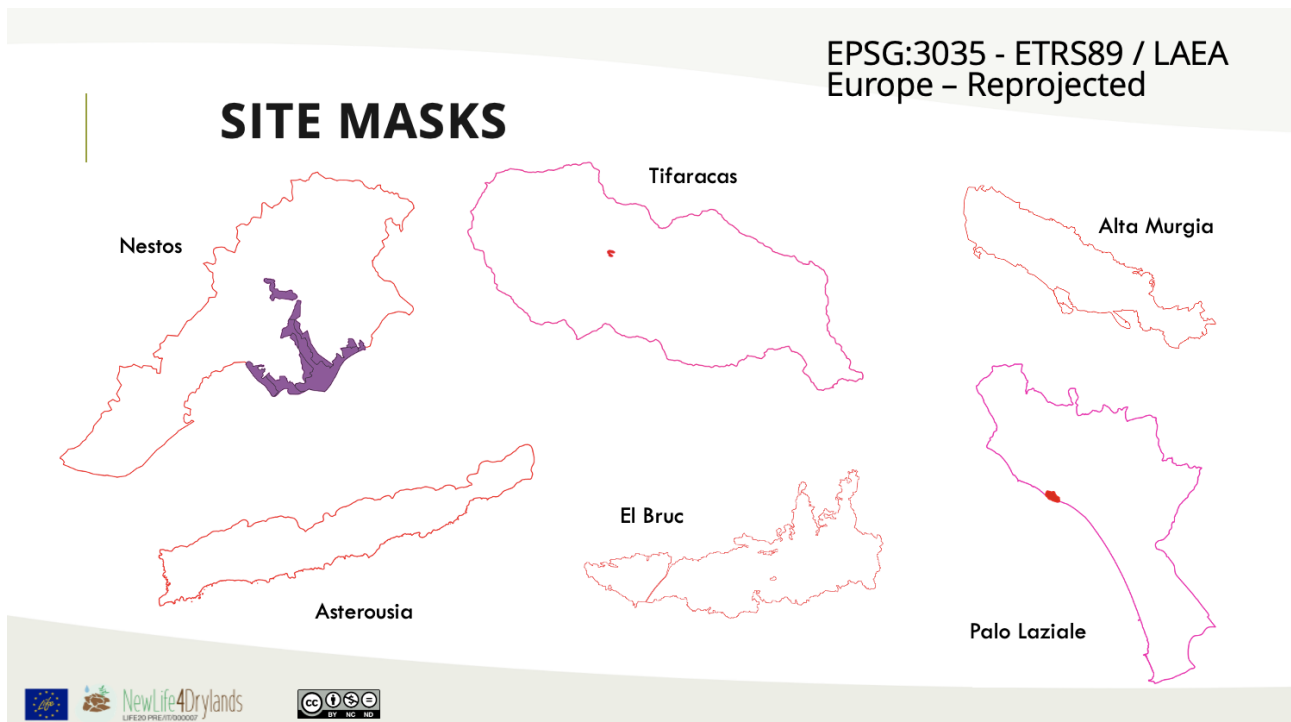


Figure 17. Site areas masks considered for ARIES-SEEA assessment. In some cases, (Nestos, Tifaracas and Palo Laziale) the study area is much smaller than the mask used for estimations.

6.1 Elevation data

Elevation data are provided by NASA-USGS (AppEEARS, <https://urs.earthdata.nasa.gov/>) in raster format (GeoTiff), with a 30 meters resolution data in the period 2000–2021. The reference system of downloadable rasters is WGS84 (EPSG: 4326).

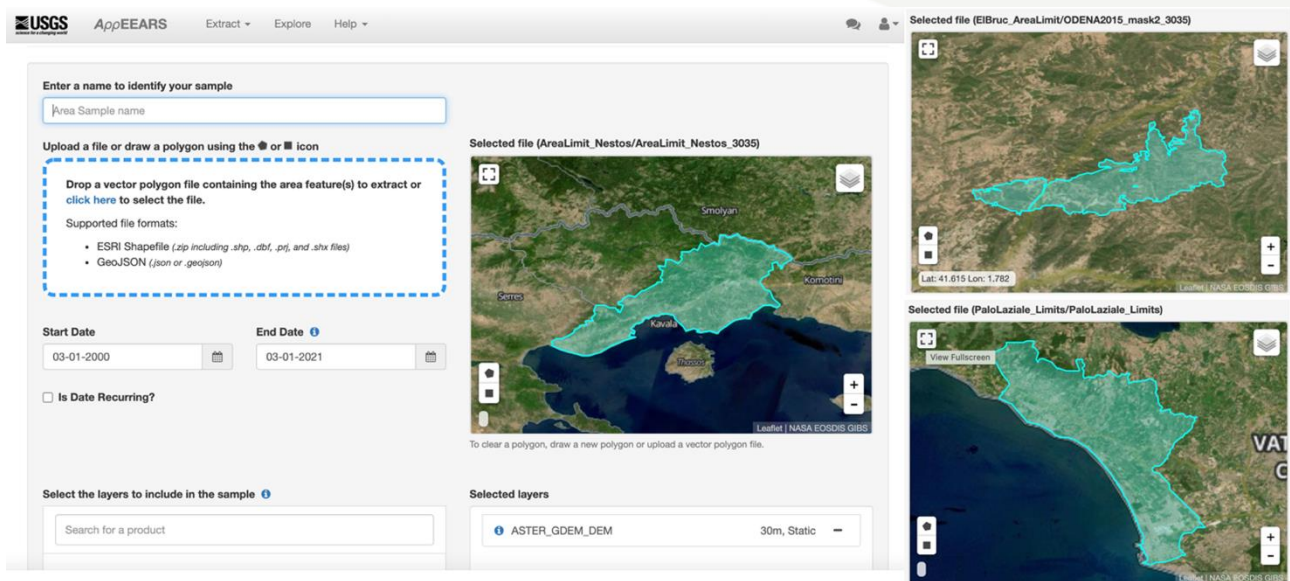


Figure 18: Digital Elevation Model (DEM) from USGS (appEARS). Examples of three NL4D study sites and relative layout from the NASA webpage service (<https://lpdaacsvc.cr.usgs.gov/>).

6.2 Soil data from SoilGrids

Thematic maps related to soil properties such as textural fractions and bulk density were downloaded from SoilGrids, 2017 (ISRIC). The webGIS application allows to download different thematic layers; for each layers different depths are available for selection by the user (e.g. 0-5 cm, 5-15 cm, 15-30 cm, etc.).



Figure 19. Example of soil data retrieved from SoilGrids, 2017: Bulk density (0–5 cm depth).

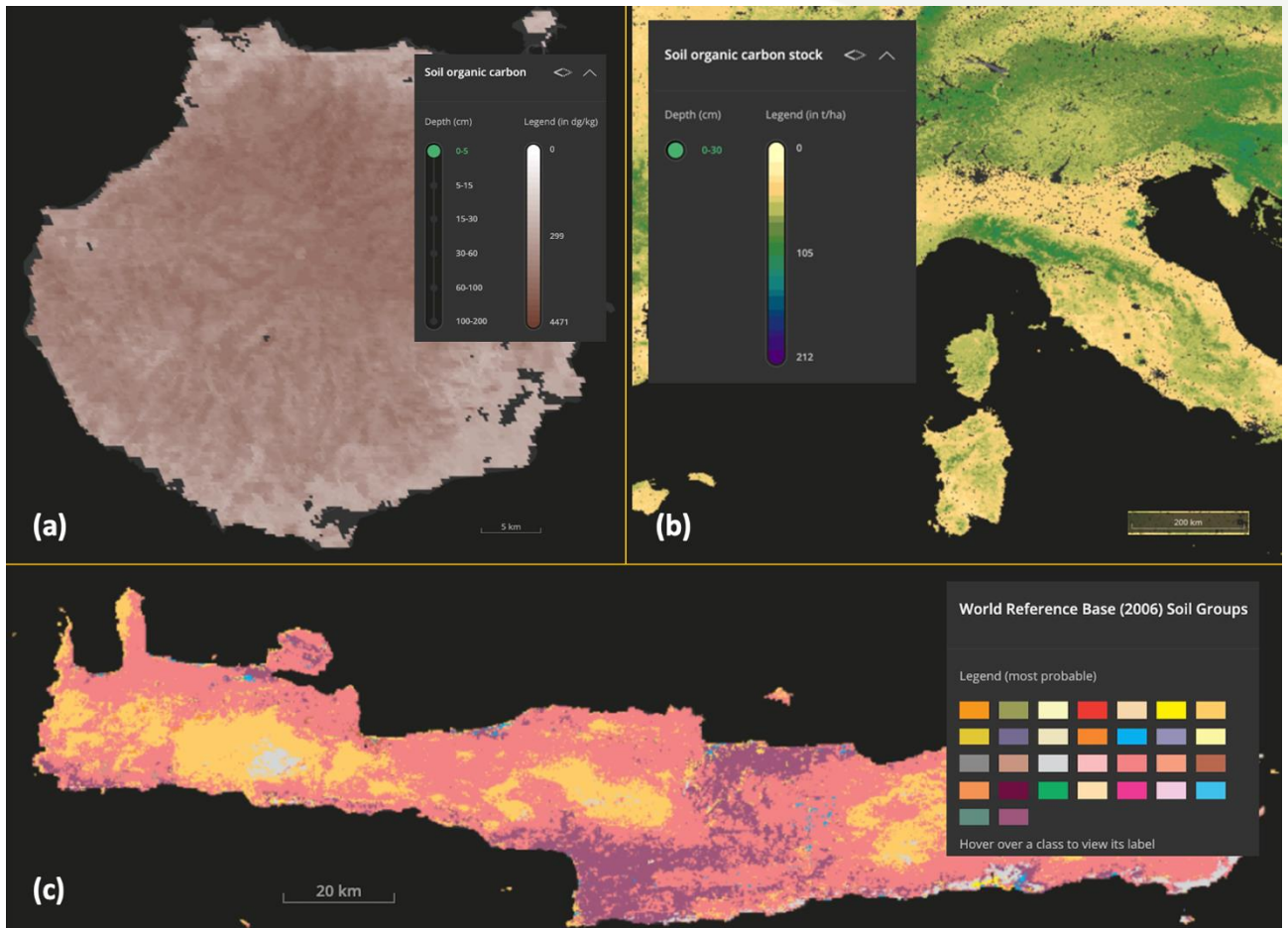


Figure 20. Different layout outputs by SoilGrids (2017): (a) Soil organic carbon (0 – 5 cm, %) in Gran Canaria island; (b) Soil organic carbon stock (0 – 30 cm, Mg ha⁻¹), and (c) World reference base (2006) soil groups in Crete island (<https://soilgrids.org/>).

In the SoilGrid user's interface It is possible to select zones within a spatial range of 2 degree in latitude and longitude. The following layers were retrieved: (1) bulk density map, (2) Topsoil soil organic carbon 0 – 5 cm and 0 – 30 cm depth intervals, and (3) soil groups. In this case the raster resolution is 250 m.

6.3 Other thematic maps from regional or national Geoportals

As for maps related to surface hydrology, geology and geographical features, these were retrieved from the regional geoportals wherever available. This type of data is of interest in helping to further defining the ecosystem conditions for each case-study area. An example for Apulia is given in figures 21 and 22. Within the Regional Geoportal there is a section in which it is possible to explore and download different thematic layers thanks to a dedicated webGIS service.

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Cartografia CTR, DTM, Ortofoto, UDS e Carte Idrogeomorfologiche

Seleziona foglio: 454 - Altamura

Layer code

Riepilogo situazione 454 - Altamura

10 Records per pagina

Tipologia	Numero File	Dettaglio
Aggiornamento al 2011 dell'Urbanizzato	1	Vai al dettaglio
Aggiornamento al 2011 dell'Uso del Suolo 2006	1	Vai al dettaglio
Carta Tecnica Regionale formato PDF	64	Vai al dettaglio
Carta Tecnica Regionale formato Shape	64	Vai al dettaglio
Carte Idrogeomorfologiche formato PDF	1	Vai al dettaglio
Carte Idrogeomorfologiche formato Shape	1	Vai al dettaglio
Digital Terrain Model	64	Vai al dettaglio
Ortofoto	64	Vai al dettaglio
Reti Pianoaltimetriche	105	Vai al dettaglio
Uso Del Suolo 2006	64	Vai al dettaglio

Layer records list

Cartografie Tecniche e Tematiche

- Documenti
- Legende, Vestizioni e Manuali
- Date dei Voti Regionali
- Volo 2006
- Volo 2015
- Cartografie Tecniche
- Carta Tecnica 1:5.000
- Reti Geodetiche
- Grigliati
- Carta Idrogeomorfologica
- DBT Multiscala 2006 - Copertura Topologica
- DBT Multiscala 2006 - Viabilità
- Cartografie Tematiche
- Modello Digitale del Terreno
- Uso del Suolo
- Mobilità
- Osservatorio Regionale Biodiversità
- Rotte Caretta caretta 2013
- Carta Glaciologica
- WMS
- Download
- Cartografie
- Cartografie Storiche
- FAQ

Figure 21: Regional Geoportal of Apulia Region. Download Section (http://www.sit.puglia.it/portal/portale_cartografie_tecniche_tematiche/Download/Cartografie)

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Background maps and tools

Zoom and other instruments

Scale and coordinate

Scala: 2000000
X: 821.477,43629
Y: 4.583.886,73440

Regione Puglia - Aree Politiche per la mobilità e qualità urbana - Servizio Assetto del Territorio

Cofinanziato da:
Unione Europea - Asse I - Linea di Intervento 1.5 - Azione 1.5.1 - "Completamento e ampliamento delle iniziative ITC finanziate nell'ambito del POR Puglia 2000-2006"
Sviluppo di Servizi, Contenuti e Portali regionali
Piano di Azione e Coesione - Asse I - "Promozione, valorizzazione e diffusione della ricerca e dell'innovazione per la competitività"

Figure 22: WebGIS section in Apulia Region Geoportal (<http://www.sit.puglia.it/>).

6.4 Example of ARIES-SEEA application: Alta Murgia National Park

6.4.1 The study area

The study area is in the Mediterranean basin in Apulia Region, Southern Italy. The study site is a Natura 2000 protected area (IT9120007). This is a community importance site and in addition a Special Protection Area that has been included in a National Park since 2004 (Fazzini, P., et al., 2021). This area is considered of crucial importance for the conservation wildlife and priority species (Council Directive 2009/147/EC).

6.4.2 ARIES-SEEA outputs

For each case study area, the following five thematic modules were considered, according to ARIES: 1) Terrain; 2) Climate Regulation; 3) Soil Erosion, 4) Soil Characteristic; 5) Land Use Land Cover. Details are presented in the following figures, showing raster maps related to each module for a number of .

Module	Thematism	Description	Unit	Resolution (m)	EPSG
Terrain	DEM	Elevation, meters	m	30	3035
	Slope	Slope, degree	°	100	3035
	Aspect	Aspect, degree	°	100	3035

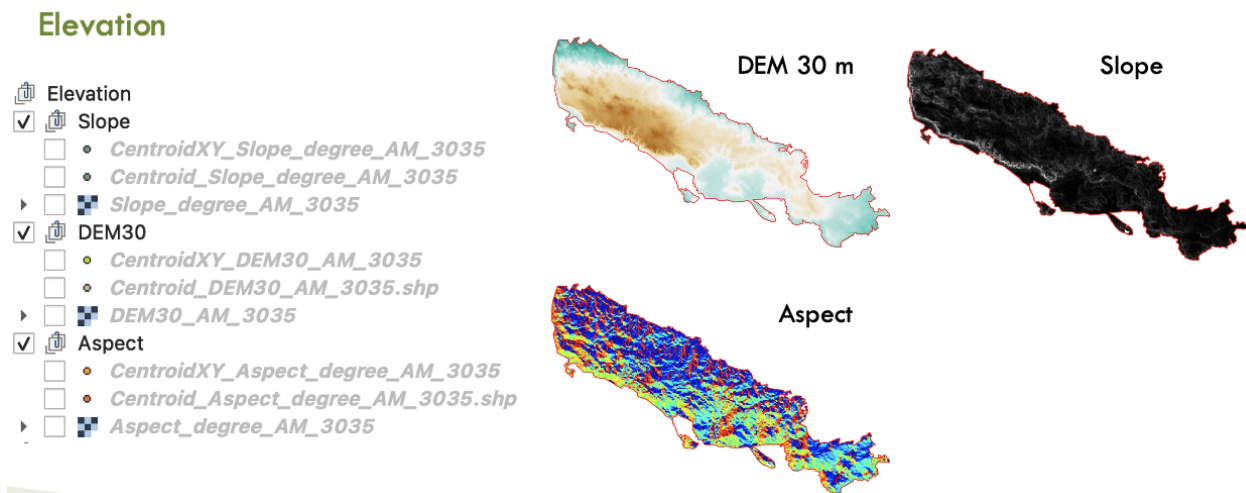


Figure 18. Alta Murgia case study: ARIES-SEEA terrain module outputs.

Module	Thematism	Description	Unit	Resolution	EPSG
Climate Regulation	Wildfires	Annual burned areas	boolean	100	3035
	Mean T warmest month	July average temperature	°C	100	3035
	Mean annual temperature	Yearly average temperature	°C	100	3035
	Aridity	Ratio between precipitation and ET ₀	(-)	100	3035

Climate Regulation

- ClimateRegulation
 - BurnedLand_AM_3035
 - Aridity
 - CentroidXY_Aridity_AM_3035
 - Centroid_Aridity_AM_3035
 - Aridity_AM_3035
 - MeanWarmMonthTemperature
 - CentroidXY_MeanWarmMonthTemp_C_AM_3035
 - Centroid_MeanWarmMonthTemp_C_AM_3035
 - MeanWarmMonthTemp_C_AM_3035
 - MeanAnnualTemperature
 - CentroidXY_MeanAnnualTemp_AM_3035
 - Centroid_MeanAnnualTemp_AM_3035
 - MeanAnnualTemp_AM_3035

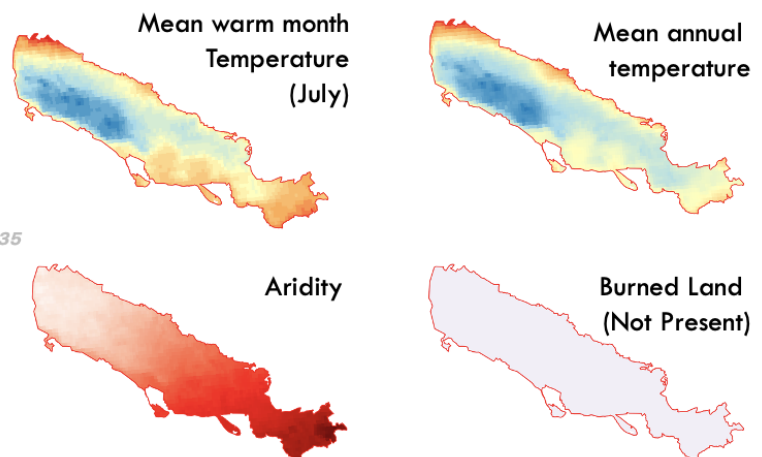


Figure 19. Alta Murgia case study: ARIES-SEEA climate regulation module outputs.

Module	Thematism	Description	Unit	Resolution (m)	EPSG
Soil erosion	Ls factor	RUSLE Ls factorm Slope Length and Steeness factor	(-)	100	3035
	K factor	RUSLE K factor, soil erodibility	t ha h ha ⁻¹ MJ ⁻¹ mm ⁻¹	100	3035
	C factor	RUSLE C factor	(-)	100	3035
	C factor unvegetated	RUSLE C factor unvegetated	(-)	100	3035
	Soil retained mass caused by vegetation		t ha ⁻¹ y ⁻¹	100	3035
	Soil mass potential removed by erosion	Potential soil erosion	t ha ⁻¹ y ⁻¹	100	3035

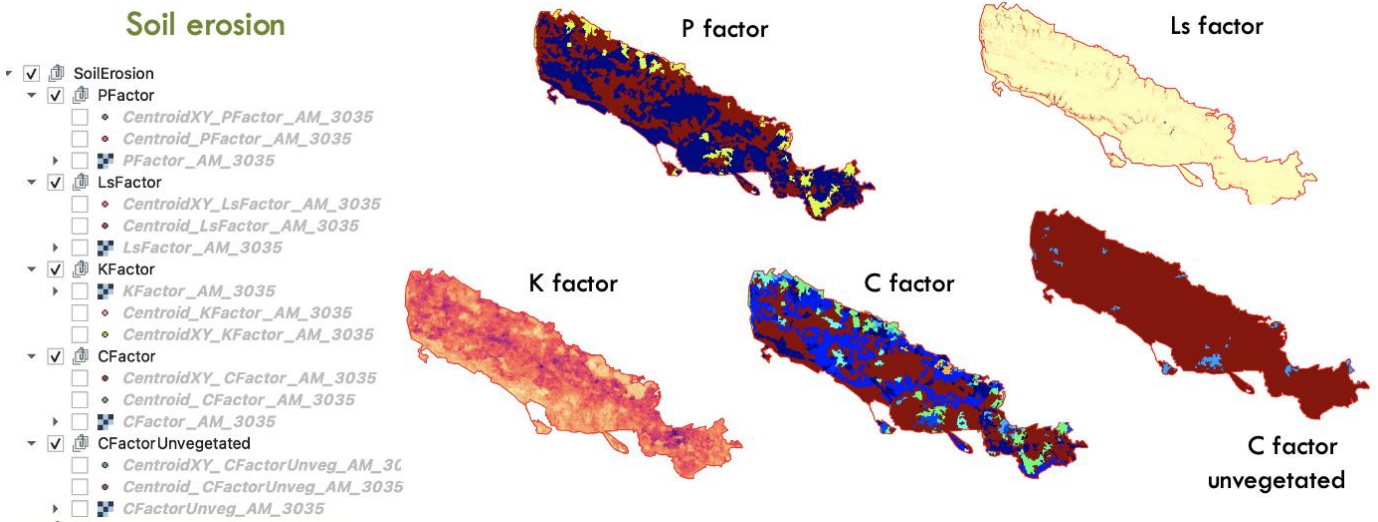


Figure 20. Alta Murgia case study: ARIES-SEEA soil erosion module outputs.

Module	Thematism	Description	Unit	Resolution (m)	EPSG
Soil characteristics	Sand	Topsoil (0-5 cm) sand fraction, USDA limit	$g\ kg^{-1}$	100	3035
	Silt	Topsoil (0-5 cm) silt fraction, USDA limit	$g\ kg^{-1}$	100	3035
	Clay	Topsoil (0-5 cm) clay fraction, USDA limit	$g\ kg^{-1}$	100	3035
	BD	Topsoil (0-5 cm) Bulk density	$cg\ cm^{-3}$	100	3035
	SOM	Topsoil (0-5 cm) - soil organic MATTER	$dg\ kg^{-1}$	100	3035
	TOC storage	Total organic carbon stock	$t\ ha^{-1}$	100	3035
	SOC storage	Soil organic carbon stock 0-200 cm	$t\ ha^{-1}$	100	3035
	VOC storage	Vegetation carbon stock	$t\ ha^{-1}$	100	3035

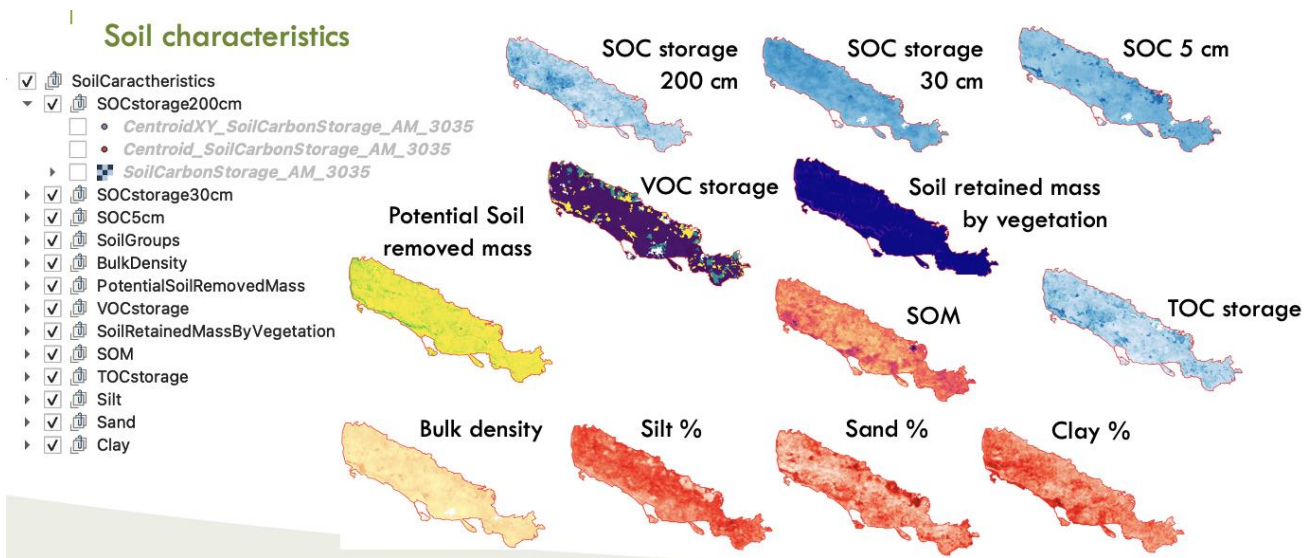


Figure 21. Alta Murgia case study: ARIES-SEEA soil characteristics module outputs.

Module	Thematism	Description	Unit	Resolution (m)	EPSG
LULC	Land cover type	CORINE land cover 2012	class	100	3035
LULC	Land cover type	CORINE land cover 2018	class	100	3035

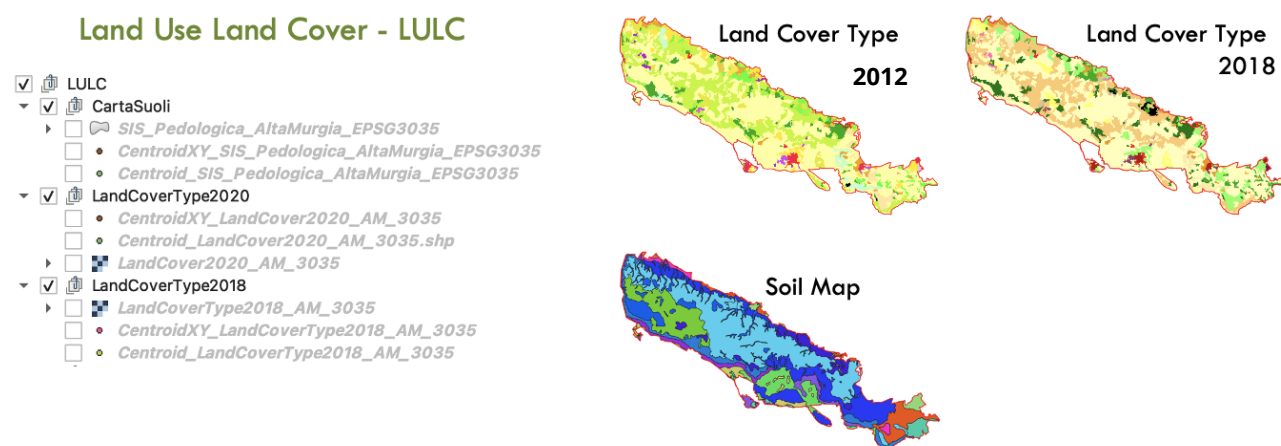


Figure 22. Alta Murgia case study: ARIES-SEEA land use/land cover module outputs.

6.4.3 Post-processing of raster data

The following table lists all the thematic layers produced for the Alta Murgia case study area. After importing the original maps, each layer was re-projected in the EPSG 3035 reference system, useful for the homogeneous representation of sites within the European borders. Each map is renamed with the following syntax: map name (e.g., MeanAnnualTemp), study area code (e.g., AM - Alta Murgia), and EPSG reference system (e.g., 3035).

Thematism	File Name	Source	URL
slope	Slope_degree_AM_3035		https://integratedmodelling.org/
DEM	DEM30_AM_3035	Aster DEM	https://urs.earthdata.nasa.gov/
aspect	Aspect_degree_AM_3035		https://integratedmodelling.org/
Wildfires	BurnedLand_AM_3035	Annual burned area, 2011, derived from MODIS MCD64A1 version 6	https://lpdaac.usgs.gov/products/mcd64a1v006/
Mean T warmest month	MeanWarmMonthTemp_C_AM_3035	July average temperature, WorldClim 2.1	https://integratedmodelling.org/
Mean annual temperature	MeanAnnualTemp_AM_3035	Yearly average temperature, WorldClim 2	https://integratedmodelling.org/
Aridity	Aridity_AM_3035	The Global Aridity Index, CGIAR-CSI	https://cgiarcsi.community/data/global-aridity-and-pet-database/
P factor	Pfactor_AM_3035		https://integratedmodelling.org/
Ls factor	LsFactor_AM_3035		https://integratedmodelling.org/
K factor	Kfactor_AM_3035		https://integratedmodelling.org/
C factor	Cfactor_AM_3035		https://integratedmodelling.org/
C factor unvegetated	CFactorUnveg_AM_3035		https://integratedmodelling.org/
Soil retained mass caused by vegetation	SoilRetainedMassByVegetation_AM_3035	ARIES estimation	https://land.copernicus.eu/pan-european/corine-land-cover/clc-2012

Soil mass potential removed by erosion	PotSoilRemovedMass_ tha_AM_3035	ARIES estimation	
Sand	Sand_percentage_AM_3035	Percent sand, 0 cm (soil surface), SoilGrids 250m, 2017 version	https://www.isric.org/explore/soilgrids
Silt	Silt_percentage_AM_3035	Percent silt, 0 cm (soil surface), SoilGrids 250m, 2017 version	https://www.isric.org/explore/soilgrids
Clay	Clay_percentage_AM_3035	Percent clay, 0 cm (soil surface), SoilGrids 250m, 2017 version	https://www.isric.org/explore/soilgrids
BD	BulkDensity_AM_3035		https://www.isric.org/explore/soilgrids
SOM	Soil_organic_matter_percentage_AM_3035	Percent soil organic matter, 0 cm (soil surface), SoilGrids 250m, 2017 version	https://www.isric.org/explore/soilgrids
TOC storage	OrganicCarbonMass_ tha_AM_3035	ARIES estimation	https://integratedmodelling.org/
VOC storage	VegCarbonStorage_ tha_AM_3035	ARIES estimation	https://integratedmodelling.org/
SOC storage200	SoilCarbonStorage_ tha_AM_3035	ARIES estimation	
SOC storage30	SoilOrganicCarbonStoc k0_30cm_AM_3035		https://www.isric.org/explore/soilgrids
Sgroups	SoilGroups_AM_3035		https://www.isric.org/explore/soilgrids
Ecofloristic Region	EcofloristicRegion_AM_3035		https://integratedmodelling.org/
Ecosystem type	EcosystemType_AM_3035	Ecosystem type - IUCN GEY 2.0 Level 3	https://integratedmodelling.org/
Land Cover type	LandCoverType_AM_3035	Corine Land Cover (CLC) 2012, Version 2018 20	https://integratedmodelling.org/
UDS11	UDS2011_merged_AM_3035		http://www.sit.puglia.it/
quarry	cave_merged_AM_3035		http://www.sit.puglia.it/
fold	pieghe_merged_AM_3035	Carta Geologica d'Italia (II Edizione)	http://www.sit.puglia.it/
fault	faglie_merged_AM_3035	Carta Geologica d'Italia (II Edizione)	http://www.sit.puglia.it/
disposition	giaciture_strati_merger d_AM_3035	Carta Geologica d'Italia (II Edizione)	http://www.sit.puglia.it/
sinkhole	doline_merged_AM_3035		http://www.sit.puglia.it/
orli	orli_TerrazzoMorfologico_merged_AM_3035		http://www.sit.puglia.it/
lithology	litologia_merged_AM_3035		http://www.sit.puglia.it/
top	vette_merged_AM_3035		http://www.sit.puglia.it/
summit points	PuntiSommitali_merger d_AM_3035	Estrazione da DTM in dotazione da Regione Puglia	http://www.sit.puglia.it/
water basin	bacini_idrici_merged_ AM_3035	Piano di Tutela delle Acque Regione Puglia	http://www.sit.puglia.it/
bank	ripe_ErosioneFluviale_ merged_AM_3035	Carta Tecnica Regionale Puglia	http://www.sit.puglia.it/
river edge	cigli_SpondaFluviale_ merged_AM_3035	Carta Tecnica Regionale Puglia	http://www.sit.puglia.it/
reticolo	reticolo_merged_AM_3035	Piano di Tutela delle Acque Regione Puglia	http://www.sit.puglia.it/

Table 11. Thematic layers produced for the Alta Murgia case study area.

To allow the statistical analysis of raster data, every map was sampled resorting to two different QGIS sampling methods: 1) Point Sampling Tool, and 2) pixel to points. Both sampling methods allow to identify the value of each pixel of the map as the value of the pixel centroid at a given resolution (100 m grid cells). The result of this process is a vector map containing numerical values of centroids for each cell of the grid (Fig. 26).



Figure 26. Raster sampling tool on a 100 x 100m regular grid.

After sampling all the raster layers, an R script was compiled to compile a single table containing all the variables of interest for the calculation of standardized indicators of potential provision of ecosystem services (Fig. 27).

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	xcoord	ycoord	Aridity	JulyAvgTemp	AnnualAvgTemp	DEM	Aspect	Slope	Cfactor	CfactorUnveg	Kfactor	LaFactor	LandCoverType	ID	ClayPerc
2	4832728.734	2020232.827	0.32960001	23.2999924	14.49166679	308	282.72437	2,04794288	0.25	0.34999999	0.0225924	54.38001251		22	27
3	4832728.734	2020331.476	0.32960001	23.2999924	14.49166679	307	244.85521	3.4852972	0.25	0.34999999	0.0225924	226.6237946		22	27
4	4832728.734	2020430.125	0.32960001	23.2999924	14.49166679	318	258.69006	2.95587325	0.25	0.34999999	0.0225924	195.4448768		22	27
5	4832728.734	2020528.775	0.32960001	23.2999924	14.49166679	304	272.86243	2.58018374	0.25	0.34999999	0.02244029	71.12155914		35	30
6	4832728.734	2020627.424	0.3292	23.3999962	14.60000038	302	264.28943	2.58980417	0.25	0.34999999	0.02244029	8.08405399		22	29
7	4832728.734	2020726.073	0.3292	23.3999962	14.60000038	314	270	2.57696891	0.25	0.34999999	0.02283578	8.34239674		22	27
8	4832728.734	2020824.722	0.3292	23.3999962	14.60000038	320	296.56506	2.88065338	0.25	0.34999999	0.02283578	15.80617905		22	27
9	4832728.734	2020923.371	0.3292	23.3999962	14.60000038	317	303.36636	3.16161919	0.25	0.34999999	0.02284414	16.99227524		22	28
10	4832728.734	2021022.02	0.3292	23.3999962	14.60000038	314	293.19861	2.94323659	0.25	0.34999999	0.02284414	39.85826874		22	28
11	4832728.734	2021120.67	0.3152	23.10000038	14.26666641	305	287.65015	2.97403073	0.25	0.34999999	0.02274017	37.57295609		35	28
12	4832728.734	2021219.319	0.3152	23.10000038	14.26666641	308	280.7843	2.75420046	0.25	0.34999999	0.02326616	15.85736752		35	27
13	4832728.734	2021317.968	0.3152	23.10000038	14.26666641	309	265.03027	2.97403073	0.25	0.34999999	0.02326616	40.46731949		35	27
14	4832728.734	2021416.617	0.3152	23.10000038	14.26666641	310	266.87787	3.54645801	0.25	0.34999999	0.02287377	48.52618027		35	30
15	4832728.734	2021515.266	0.31650001	23.20000076	14.40833282	310	271.12329	3.28488064	0.25	0.34999999	0.02287377	20.54178238		35	30
16	4832728.734	2021613.916	0.31650001	23.20000076	14.40833282	316	286.1134	3.01688552	0.25	0.34999999	0.02299279	17.18948364		35	32
17	4832728.734	2021712.565	0.31650001	23.20000076	14.40833282	311	309.09387	2.65616679	0.25	0.34999999	0.02299279	7.48846531		35	32
18	4832728.734	2021811.214	0.31650001	23.20000076	14.40833282	306	315	2.18704343	0.25	0.34999999	0.02299279	6.22806883		35	32
19	4832728.734	2021909.863	0.31650001	23.20000076	14.40833282	306	323.53076	1.84318507	0.25	0.34999999	0.02292227	2.78071284		35	31
20	4832728.734	2022008.512	0.31650001	23.20000076	14.40833282	302	334.44003	1.64315963	0.25	0.34999999	0.02292227	4.73173952		35	31
21	4832728.734	2022107.162	0.31650001	23.20000076	14.40833282	301	336.80139	1.47258973	0.25	0.34999999	0.02254456	4.30402136		35	31
22	4832728.734	2022205.811	0.31650001	23.20000076	14.40833282	288	288.43494	1.22300279	0.25	0.34999999	0.02254456	3.68690228		35	31
23	4832728.734	2022304.46	0.31650001	23.20000076	14.40833282	290	288.43494	1.22300279	0.25	0.34999999	0.02254456	3.68690228		35	31
24	4832728.734	2022403.109	0.31650001	23.20000076	14.40833282	291	279.46234	1.56817508	0.25	0.34999999	0.02287379	4.73999739		35	30
25	4832728.734	2022501.758	0.31639999	23.2999924	14.52500057	288	263.29016	2.20592785	0.25	0.34999999	0.02287379	12.02503204		35	30
26	4832728.734	2022600.408	0.31639999	23.2999924	14.52500057	289	264.80557	3.54645932	0.25	0.34999999	0.02287379	15.4083252		35	30
27	4832728.734	2022699.057	0.31639999	23.2999924	14.52500057	301	262.5686	2.98792267	0.25	0.34999999	0.02313126	35.7371788		35	32
28	4832728.734	2022797.706	0.31639999	23.2999924	14.52500057	290	261.8699	2.7035798	0.25	0.34999999	0.02313126	14.59151936		35	32
29	4832728.734	2022896.355	0.31639999	23.2999924	14.52500057	277	277.30576	2.53316689	0.25	0.34999999	0.02305266	13.64339828		35	31
30	4832728.734	2022995.004	0.31639999	23.2999924	14.52500057	283	291.25049	2.48859	0.25	0.34999999	0.02305266	11.28439426		35	31
31	4832728.734	2023093.653	0.31639999	23.2999924	14.52500057	287	294.77515	1.8454355	0.25	0.34999999	0.02246736	3.52816401		35	29
32	4832827.383	2020134.178	0.32030001	23.10000038	14.23333359	316	270	1.28913641	0.25	0.34999999	0.02253558	2.2441387		22	129
33	4832827.383	2020232.827	0.32030001	23.10000038	14.23333359	296	249.56717	3.50423074	0.25	0.34999999	0.02278772	19.45105171		22	129
34	4832827.383	2020331.476	0.32030001	23.10000038	14.23333359	319	249.77515	3.91032399	0.25	0.34999999	0.02278772	21.62047958		22	126
35	4832827.383	2020430.125	0.32030001	23.10000038	14.23333359	317	249.77515	3.91032399	0.25	0.34999999	0.02278772	21.62047958		22	126

Figure 27. Excerpts from the data table compiled with R.

As an example figure 28 shows the graphical summary (histogram and box & whisker plot) of the descriptive statistics of soil organic carbon stock (0-200 cm) for the area of the Alta Murgia National Park; the data have been retrieved by sampling the raster (100 m resolution) provided by ARIES-SEEA from SoilGrids (2017).

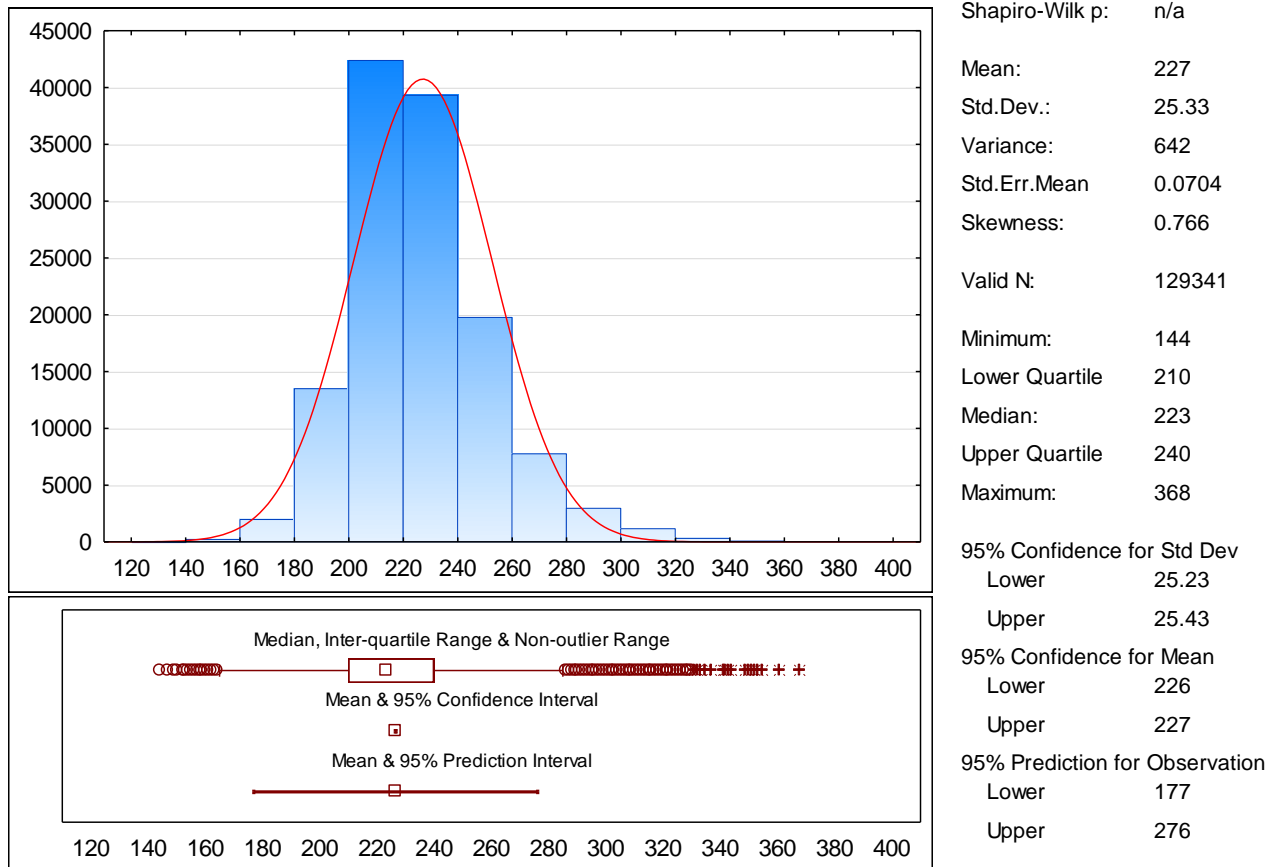


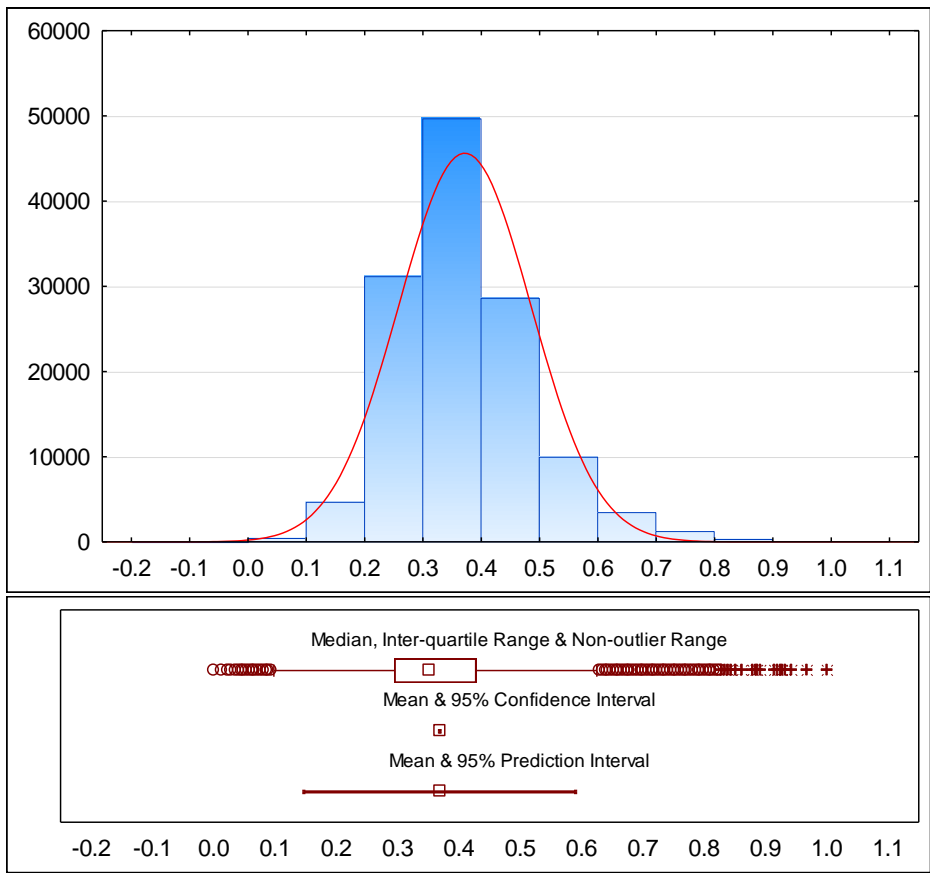
Figure 28. Graphical summary of the descriptive statistics of soil organic carbon stock (0-200 cm) for the area of the Alta Murgia National Park.

In order to derive a relative indicator of ecosystem service provision, C stock data are standardized as numbers in the range 0 to 1 (Wu et al., 2013) resorting to an interval normalization as follows:

$$X_{i\ 0-1} = (X_i - X_{\min}) / (X_{\max} - X_{\min})$$

where $X_{i\ 0-1}$ is the standardised [0-1] value, X_i is the actual value, X_{\min} and X_{\max} are the minimum and the maximum respectively of each considered variable in the dataset. The formula gives values close to 1 to higher values of the considered input variable or indicator; the lowest value, 0, does not indicate that the input variable value is equal to 0 or that the function is not provided, but that it is the lowest in the considered area. It is of pivotal importance then to tailor the assessment to the scale of investigation and to the goal of the analyses, as results will be deeply affected by the degree of variability observed in soil measured and estimated soil properties, whose ranges are strongly scale dependent and different for each variable.

Figure 29 shows the graphical summary (histogram and box & whisker plot) of the descriptive statistics of the indicator of soil organic carbon sequestration (0-200 cm) for the area of the Alta Murgia National Park.



Shapiro-Wilk p:	n/a
Mean:	0.369
Std.Dev.:	0.113
Variance:	0.0128
Std.Err.Mean	0.00031
Skewness:	0.766
Valid N:	129341
Minimum:	0
Lower Quartile	0.295
Median:	0.353
Upper Quartile	0.429
Maximum:	1.000
95% Confidence for Std Dev	
Lower	0.113
Upper	0.114
95% Confidence for Mean	
Lower	0.368
Upper	0.369
95% Prediction for Observation	
Lower	0.147
Upper	0.590

Figure 29. Graphical summary of the descriptive statistics of the indicator of soil organic carbon sequestration (0-200 cm) for the area of the Alta Murgia National Park.

The spatial distribution of soil organic carbon stock (0-200 cm) and of the relative indicator of soil carbon sequestration are shown in figures 30 and 31, respectively. The figures show also the limits of the soil mapping units (SMUs) from the 1:50,000 scale soil map. The soil map (Fig. 32) allows to calculate mean values of the indicator for each SMU and to assess statistically the significance of differences in mean values (Table 12). Testing means values with the Tukey-Kramer HSD test for unequal N ($p < 0.05$), results in 56% of all possible mean values comparisons being statistically significant, as can be visually grasped from the box & whisker plot shown in Fig. 33.

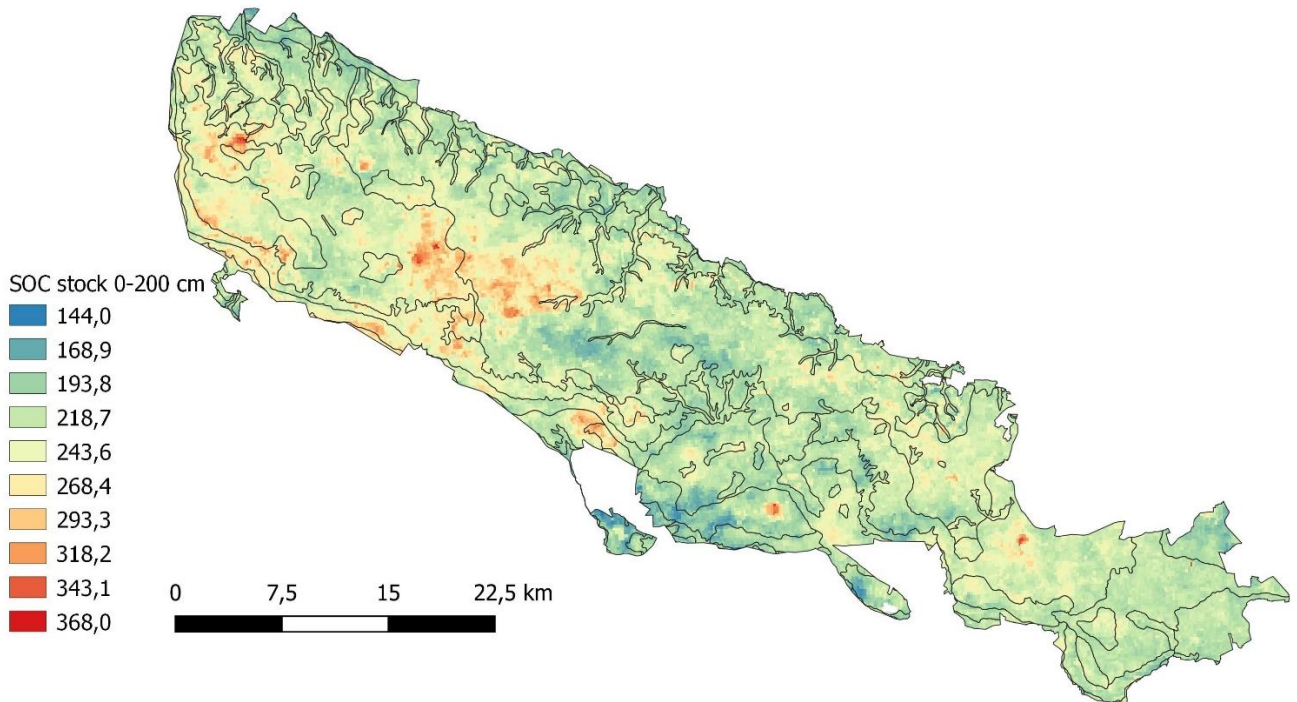


Figure 30. Alta Murgia National Park: spatial distribution of soil organic carbon stock (0-20 cm).

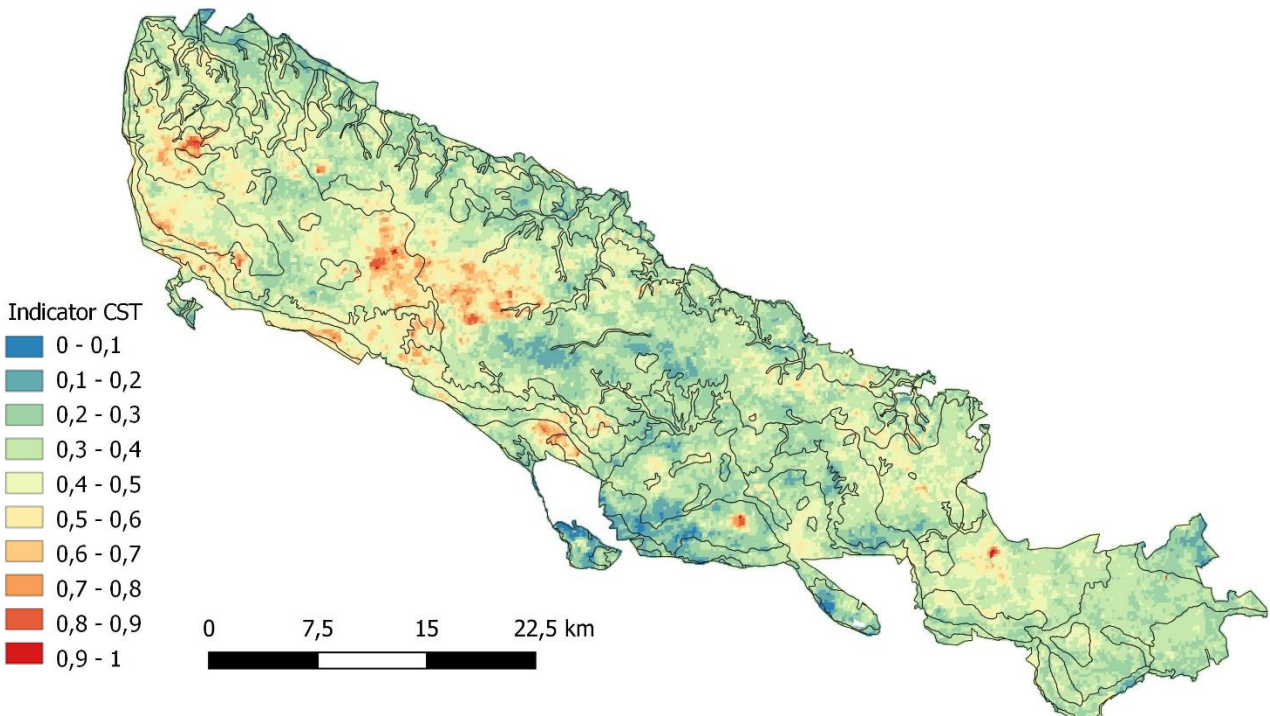


Figure 31. Alta Murgia National Park: spatial distribution of indicator of soil organic carbon sequestration.

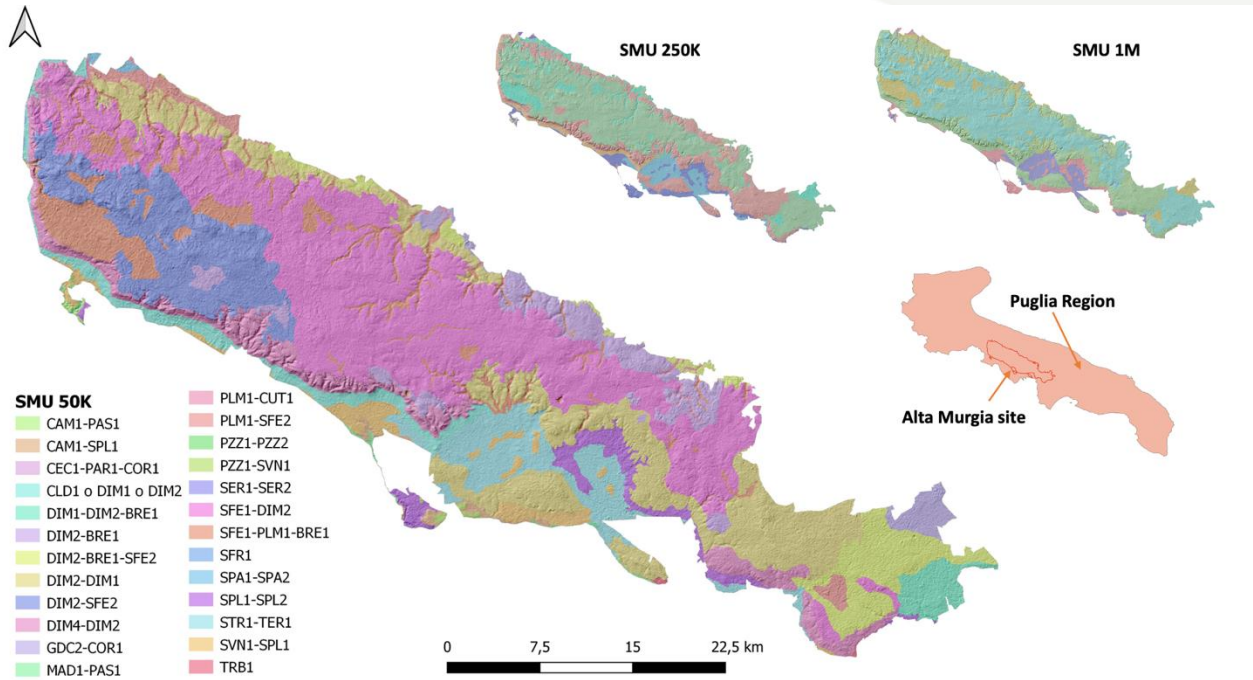


Figure 32. Alta Murgia National Park: soil map 1:50,000. The soil maps at 1:250000 and 1:1,000,000 scales are shown as well.

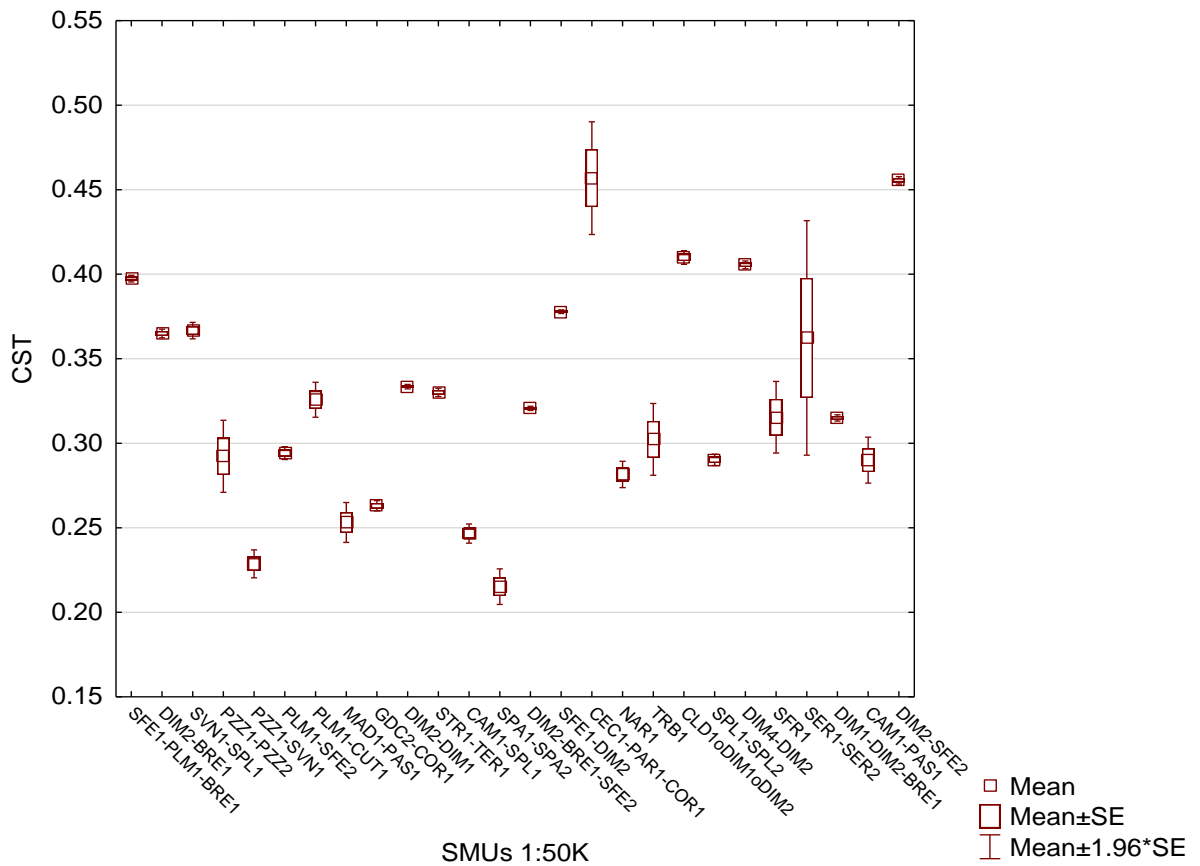


Figure 33. Box & Whisker plot for the indicator of soil organic carbon sequestration in the 1:50,000 SMUs of Alta Murgia National Park.

SMU 50K	Soil C stock (0-200 cm)						Indicator Soil C sequestration				
	N	Means	Std.Dev.	Min	Median	Max	Means	Std.Dev.	Min	Median	Max
CAM1-PAS1	108	208.96	16.11	186.00	205.00	249.00	0.29	0.07	0.19	0.27	0.47
CAM1-SPL1	594	199.25	15.84	155.00	199.00	255.00	0.25	0.07	0.05	0.25	0.50
CEC1-PAR1-COR1	9	246.33	11.43	225.00	244.00	262.00	0.46	0.05	0.36	0.45	0.53
CLD1oDIM1oDIM2	3734	235.82	28.42	170.00	234.00	326.00	0.41	0.13	0.12	0.40	0.81
DIM1-DIM2-BRE1	2102	214.56	9.89	187.00	214.00	251.00	0.32	0.04	0.19	0.31	0.48
DIM2-BRE1	5945	225.75	22.92	172.00	222.00	332.00	0.36	0.10	0.13	0.35	0.84
DIM2-BRE1-SFE2	6778	215.83	11.67	170.00	215.00	352.00	0.32	0.05	0.12	0.32	0.93
DIM2-DIM1	20474	218.71	21.58	150.00	218.00	355.00	0.33	0.10	0.03	0.33	0.94
DIM2-SFE2	12621	246.05	28.46	178.00	241.00	368.00	0.46	0.13	0.15	0.43	1.00
DIM4-DIM2	8219	234.84	23.60	171.00	234.00	325.00	0.41	0.11	0.12	0.40	0.81
GDC2-COR1	1851	202.92	14.98	164.00	203.00	273.00	0.26	0.07	0.09	0.26	0.58
MAD1-PAS1	187	200.71	18.47	158.00	202.00	244.00	0.25	0.08	0.06	0.26	0.45
NAR1	30	207.07	4.86	197.00	205.00	217.00	0.28	0.02	0.24	0.27	0.33
PLM1-CUT1	444	216.97	24.86	170.00	211.00	300.00	0.33	0.11	0.12	0.30	0.70
PLM1-SFE2	1636	209.90	17.53	165.00	208.00	274.00	0.29	0.08	0.09	0.29	0.58
PZZ1-PZZ2	32	209.47	13.79	185.00	210.00	238.00	0.29	0.06	0.18	0.29	0.42
PZZ1-SVN1	172	195.22	12.39	167.00	198.00	219.00	0.23	0.06	0.10	0.24	0.33
SER1-SER2	6	225.17	19.42	201.00	224.50	245.00	0.36	0.09	0.25	0.36	0.45
SFE1-DIM2	40765	228.63	24.23	169.00	226.00	342.00	0.38	0.11	0.11	0.37	0.88
SFE1-PLM1-BRE1	10128	233.02	22.50	174.00	232.00	343.00	0.40	0.10	0.13	0.39	0.89
SFR1	20	214.65	10.82	195.00	220.00	228.00	0.32	0.05	0.23	0.34	0.38
SPA1-SPA2	169	192.20	15.64	163.00	191.00	222.00	0.22	0.07	0.08	0.21	0.35
SPL1-SPL2	3190	209.00	21.81	144.00	211.00	271.00	0.29	0.10	0.00	0.30	0.57
STR1-TER1	7127	217.95	23.52	156.00	216.00	327.00	0.33	0.11	0.05	0.32	0.82
SVN1-SPL1	2914	226.13	30.04	155.00	219.00	329.00	0.37	0.13	0.05	0.33	0.83
TRB1	86	211.72	22.49	165.00	206.00	258.00	0.30	0.10	0.09	0.28	0.51
All Grps	129341	226.59	25.33	144.00	223.00	368.00	0.37	0.11	0.00	0.35	1.00

Table 12. Descriptive statistics for soil C stock (0-20 cm) and soil C sequestration indicator for the 1:50,000 SMUs of the Alta Murgia National Park.

The same analysis can be performed in terms of land cover type (Figure 32), returning the results synthetized in figure 35 and in table 13. Among agricultural land uses, the highest values of C stock (0-200 cm) are observed for pastures ($231.3 \pm 0.9 \text{ Mg ha}^{-1}$) and non-irrigated arable land ($225.1 \pm 0.2 \text{ Mg ha}^{-1}$), while the lowest values are observed for vineyards ($203.4 \pm 1.7 \text{ Mg ha}^{-1}$) and complex cultivation patterns ($208.9 \pm 0.4 \text{ Mg ha}^{-1}$). Among forest and semi natural areas, the highest values of C stock (0-200 cm) are observed for mixed forests ($240.5 \pm 6.7 \text{ Mg ha}^{-1}$) and natural grasslands ($235.6 \pm 0.3 \text{ Mg ha}^{-1}$), while the lowest values are observed for broad-leaved forests ($211.5 \pm 1.7 \text{ Mg ha}^{-1}$) and sclerophyllous vegetation ($207.9 \pm 1.7 \text{ Mg ha}^{-1}$).

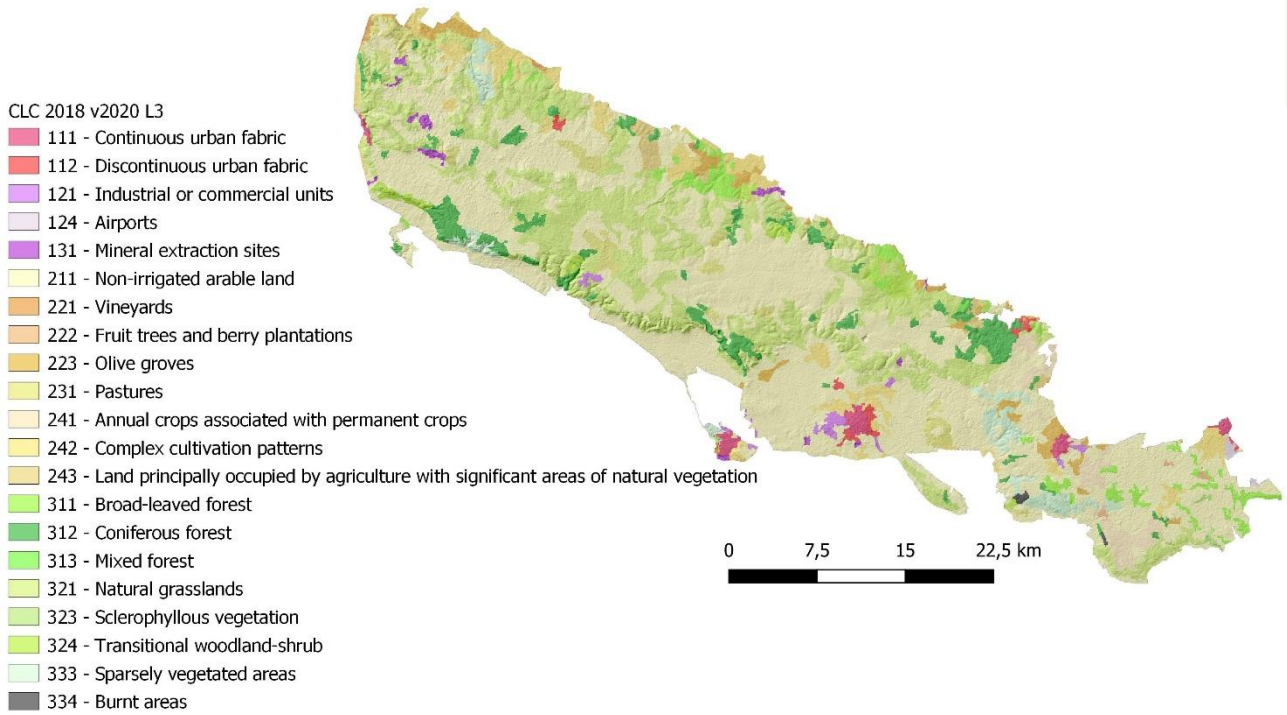


Figure 34. Alta Murgia National Park: CORINE land use/land cover map, 2018 v2020, L3.

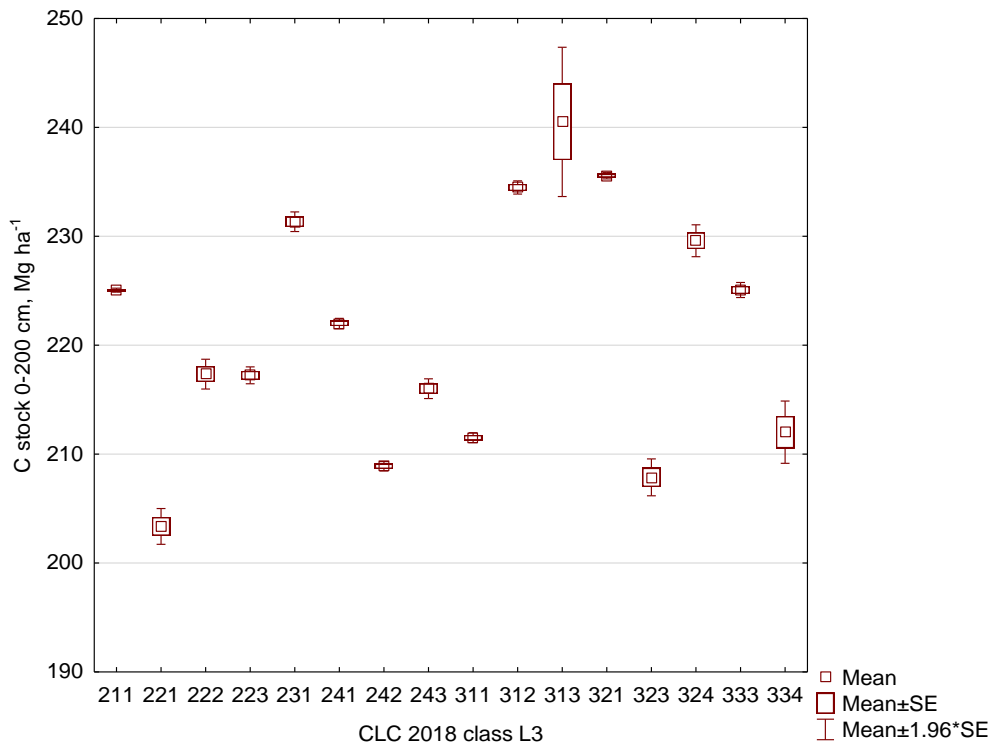


Figure 35. Alta Murgia National Park: C stock 0-200 cm, mean values for CORINE LULC units. See figure 34 for units' legend. Artificial surfaced were excluded from the analyses.

CORINE L3	Soil C stock (0-200 cm)						Indicator Soil C sequestration				
	N	Means	Std.Dev.	Min	Median	Max	Means	Std.Dev.	Min	Median	Max
211	63175	225.1	23.8	150.00	223.00	352.00	0.362	0.106	0.027	0.353	0.929
221	195	203.4	11.7	178.00	203.00	233.00	0.265	0.052	0.152	0.263	0.397
222	120	217.4	7.6	201.00	216.00	243.00	0.327	0.034	0.254	0.321	0.442
223	2576	217.2	20.0	165.00	214.00	286.00	0.327	0.089	0.094	0.313	0.634
231	3497	231.3	27.2	177.00	228.00	309.00	0.390	0.121	0.147	0.375	0.737
241	2731	222.0	12.4	195.00	221.00	270.00	0.348	0.055	0.228	0.344	0.563
242	6398	208.9	17.5	157.00	207.00	282.00	0.290	0.078	0.058	0.281	0.616
243	1073	216.0	15.1	179.00	215.00	260.00	0.321	0.067	0.156	0.317	0.518
311	3469	211.5	13.6	174.00	210.00	275.00	0.301	0.061	0.134	0.295	0.585
312	6373	234.5	24.6	172.00	232.00	332.00	0.404	0.110	0.125	0.393	0.839
313	55	240.5	25.9	199.00	239.00	285.00	0.431	0.116	0.246	0.424	0.629
321	30518	235.6	26.8	152.00	232.00	368.00	0.409	0.120	0.036	0.393	1.000
323	220	207.9	12.8	165.00	208.00	248.00	0.285	0.057	0.094	0.286	0.464
324	1679	229.6	30.6	178.00	224.00	343.00	0.382	0.136	0.152	0.357	0.888
333	3419	225.1	20.5	144.00	226.00	314.00	0.362	0.092	0.000	0.366	0.759
334	120	212.0	16.0	185.00	211.00	255.00	0.304	0.071	0.183	0.299	0.496
All Grps	125618	226.7	25.0	144.00	223.00	368.00	0.369	0.111	0.000	0.353	1.000

Table 13. Descriptive statistics for soil C stock (0-20 cm) and soil C sequestration indicator for the CORINE land use/land cover units of the Alta Murgia National Park.

The use of standardized indicators can also allow for direct comparisons of different ecosystem services, as shown for example in figure 37, where the values (0,1) of the indicator for soil carbon sequestration in the different SMUs or CLC units are plotted together with the standardized values of net primary production (NPP, source: MODIS/Aqua) and NDVI (source: Copernicus Global Land Service), which can be assumed as proxies for the provisioning service of biomass production.

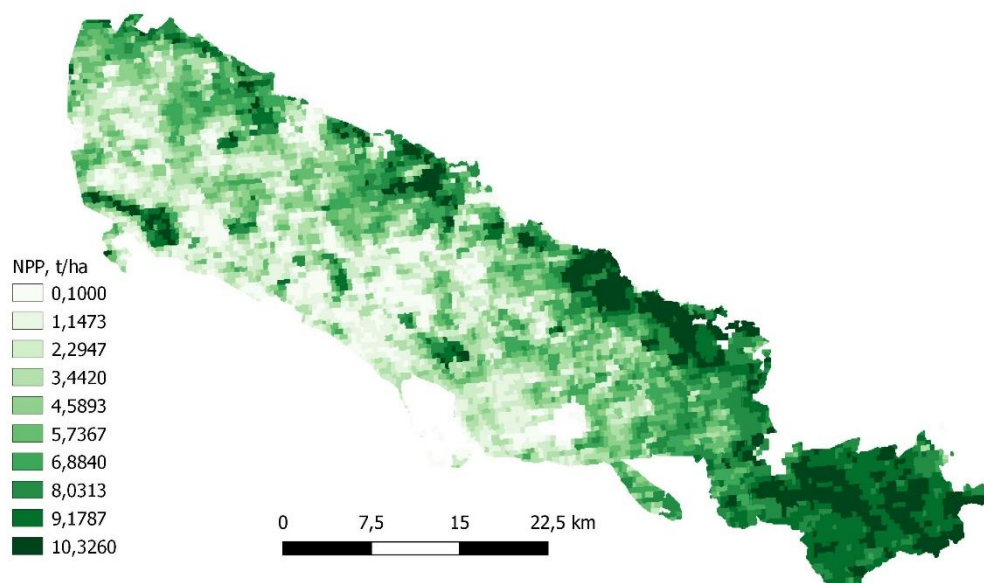


Figure 36. Alta Murgia national Park: spatial distribution of net Primary Production ($t\ ha^{-1}$).

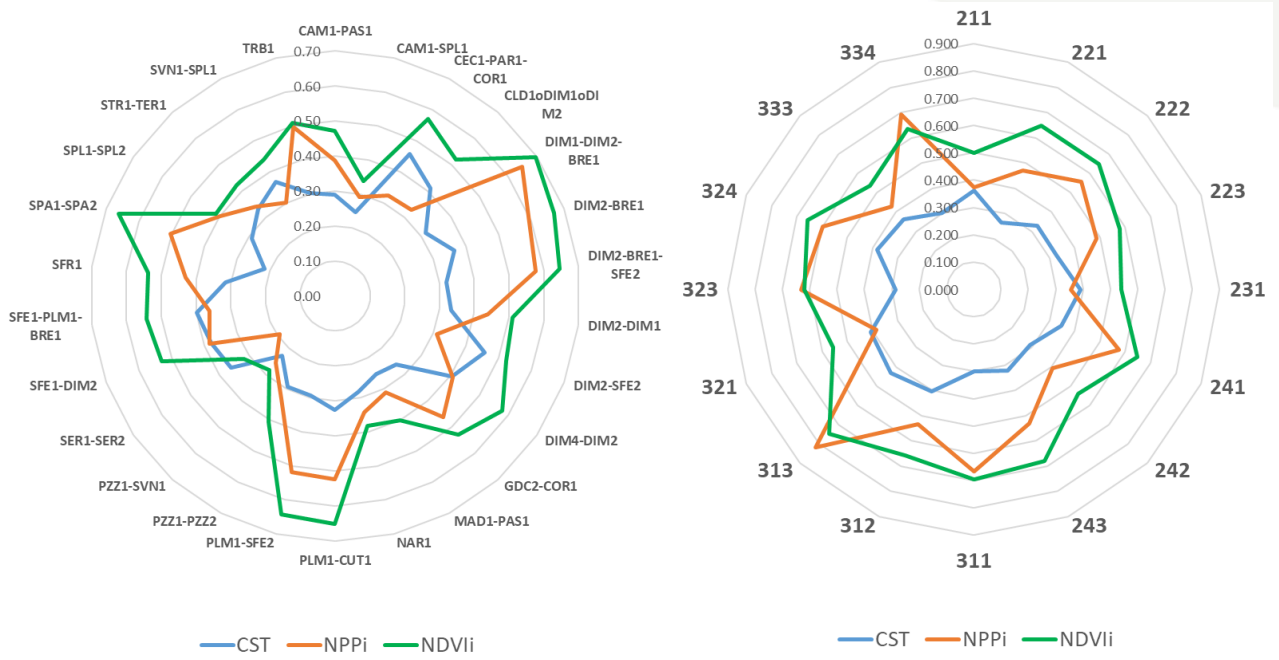


Figure 37. Synergies and trade-offs between ecosystem services indicators in the SMUs (left) and in the CLC class units (right) in the area of the Alta Murgia National Park.



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