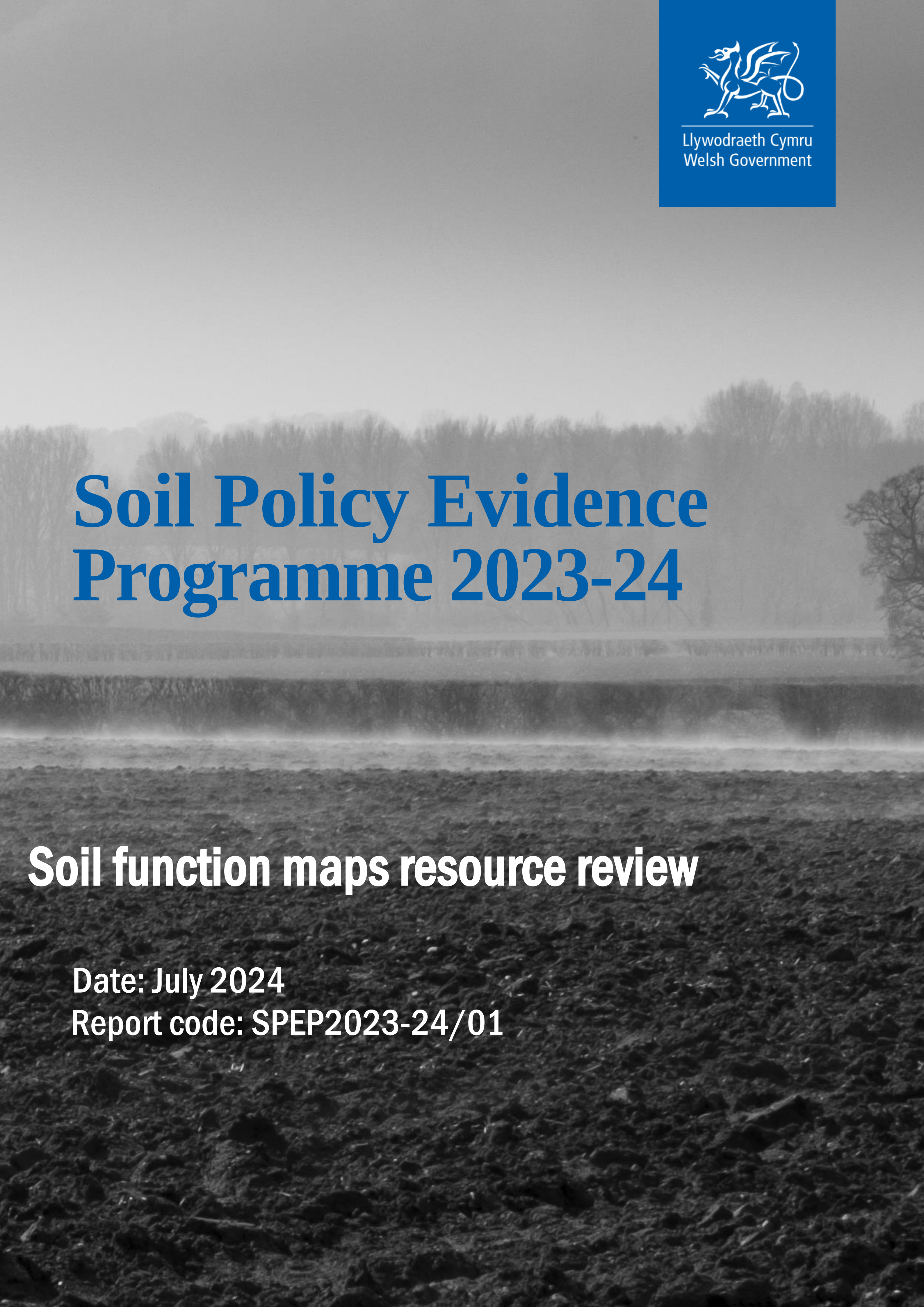

Llywodraeth Cymru
Welsh Government

Soil Policy Evidence Programme 2023-24

Soil function maps resource review

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Soil function maps resource review

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Alison Rollett and John Williams

ADAS

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Contents

Introduction

Soil is the foundation of all terrestrial ecosystems and provides multiple ecosystem services including the provision of food and fibre, climate regulation and carbon storage, the regulation of water flow and quality, the support of both above and below ground biodiversity and an "archive of geological geomorphological and archaeological heritage" (European Commission, 2021). The basis of these functions is the soil natural capital, the stocks of soil material (Robinson *et al*., 2017). The range and interaction of different soil properties (e.g., soil texture, depth, structure, stone content, and hydrological regime) influences the types of ecosystem services that different landscapes provide. Land management, climatic and site factors (e.g., altitude, topography) interact with soil properties to further influence the provision of ecosystem services.

Different soils deliver some ecosystem services more effectively than others. For example, lowland mineral soils under arable and grassland management are important for food production, while deep peats in upland areas support semi-natural habitats, provide carbon storage and climate regulation.

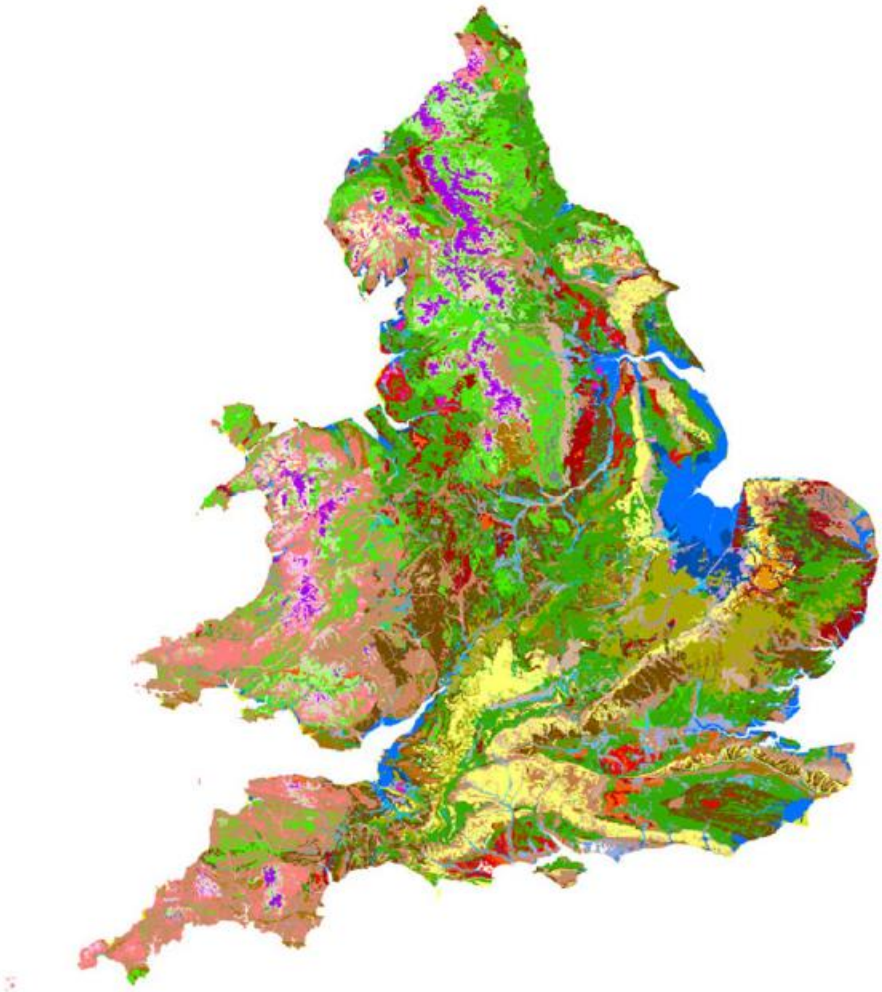
In England and Wales soil characteristics are defined at four levels (major group, group, sub-group and series) in a hierarchical system, general characteristics being used at the highest level to give broad separations and more specific ones at lower levels to give increasingly precise subdivisions (Hallett *et al*., 2017). There are 10 major soil groups (based on pedogenic characteristics) within the soil classification for England and Wales, >60 groups, 80 sub-groups and 100s of series. To provide a general overview of the soil characteristics (e.g., texture, drainage, topsoil carbon, etc.) 27 'soilscapes' have been described by Cranfield University to provide 'extensive, understandable and useful soil data for a non-soil specialist', **Figure 1**. There is no direct relationship between the major soil groups and the soilscapes, the first classification forms part of an in-depth site-specific assessment whereas the latter is intended to give a broader overview. The wide variation in soil characteristics fundamentally affects the nature and extent of their relationships to the delivery of ecosystem services (Haygarth and Ritz 2009).

Objectives

The Welsh Government Soils and Land Use Policy Team are considering the development of a soil functions and services map of Wales. The aim of the map will be to provide best available information to support and balance land use decisions where trade-offs between soil functions and land use demands compete. Demonstrating the supply of functions and services provided by different landscapes, their spatial distribution and variation across Wales, will help decision makers make informed and balanced considerations of the impact of land use change on ecosystem service provision. The map will allow specialists and non-specialists to understand and quantify the impact of land use and policy decisions on a range of soil functions and services.

In support of these objectives this scoping study has:

- Carried out a high-level review of existing soil service and functions maps developed in Wales, the UK, EU and internationally.
- Collated and reviewed soil property, functions, and services datasets from Wales, the UK, Europe and internationally.
- Identified gaps in datasets and limitations for development of soil services and functions maps for Wales.
- Produced an accompanying spreadsheet that describes and critiques available soil services and function datasets.



ID	Description
	Blanket bog peat soils
	Fen peat soils
	Freely draining acid loamy soils over rock
	Freely draining floodplain soils
	Freely draining lime-rich loamy soils
	Freely draining sandy Breckland soils
	Freely draining slightly acid but base-rich soils
	Freely draining slightly acid loamy soils
	Freely draining slightly acid sandy soils
	Freely draining very acid sandy and loamy soils
	Lime-rich loamy and clayey soils with impeded drainage
	Loamy and clayey floodplain soils with naturally high groundwater
	Loamy and clayey soils of coastal flats with naturally high groundwater
	Loamy and sandy soils with naturally high groundwater and a peaty surface
	Loamy soils with naturally high groundwater
	Naturally wet very acid sandy and loamy soils
	Raised bog peat soils
	Restored soils mostly from quarry and opencast spoil
	Saltmarsh soils
	Sand dune soils
	Shallow lime-rich soils over chalk or limestone
	Shallow very acid peaty soils over rock
	Slightly acid loamy and clayey soils with impeded drainage
	Slowly permeable seasonally wet acid loamy and clayey soils
	Slowly permeable seasonally wet slightly acid but base-rich loamy and clayey soils
	Slowly permeable wet very acid upland soils with a peaty surface
	Very acid loamy upland soils with a wet peaty surface

Figure 1. Simplified spatial distribution of principal soil types (27 soilscapes) in England and Wales. (Source: Cranfield University LandIS)

Soil functions

Biophysical soil functions include nutrient cycling, water dynamics, filtering and buffering, physical stability and support of plant systems and human structures, and promotion of biodiversity and habitat. Soil functions are directly linked to soil ecosystem services which account for the immediate benefits that human societies derive from soils (**Figure 2**).

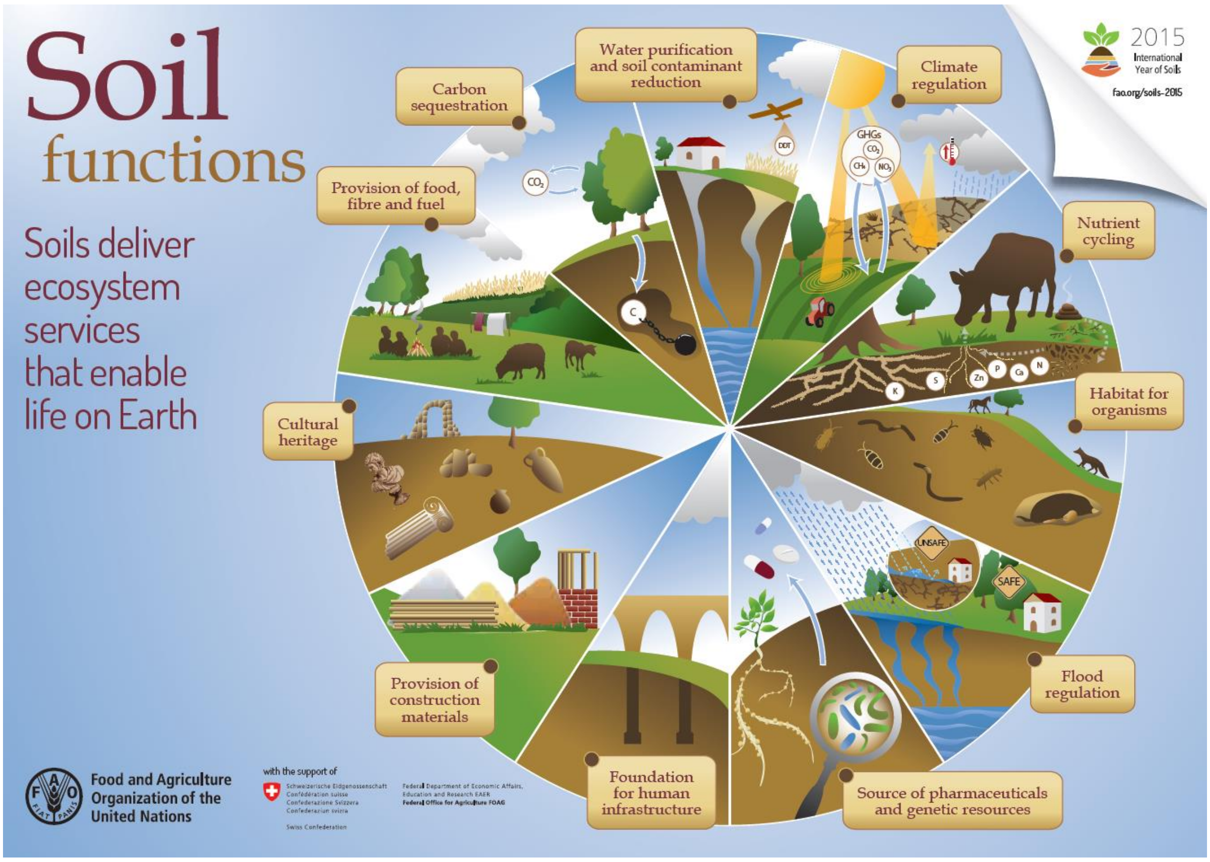


Figure 2. Soil functions (Source: FAO, 2015).

The concept of soil functions first gained prominence through the proposed European Soil Thematic Strategy (European Commission, 2006). The Strategy included seven soil functions, namely the production of biomass, the storing, filtering and transforming of nutrients, substances and water, the provision of a physical and cultural basis for humans and their activities, the provision of habitats and gene pools, the function as a source of raw materials, and the function as geological and archaeological archives.

There is no one single definition of soil functions. Vogel *et al*. (2019) illustrated (**Figure 3**) the juxtaposition of different soil functions and their interdependence. They suggested that the fulfilment of a function by a soil would, in general, affect the extent to which it could fulfil others. For example, on a given piece of land, a farmer's decision to change the land use or its management, e.g., by planting a forest instead of having a field or a pasture, on which livestock feeds (Renison *et al*., 2010), or by switching from industrial agricultural practices to a form of conservation agriculture or organic farming, will likely have a marked effect on the percolation of water down the soil profile, which in turn will affect the recharge of groundwater and/or the filtration of chemicals (Baveye *et al*., 2016).

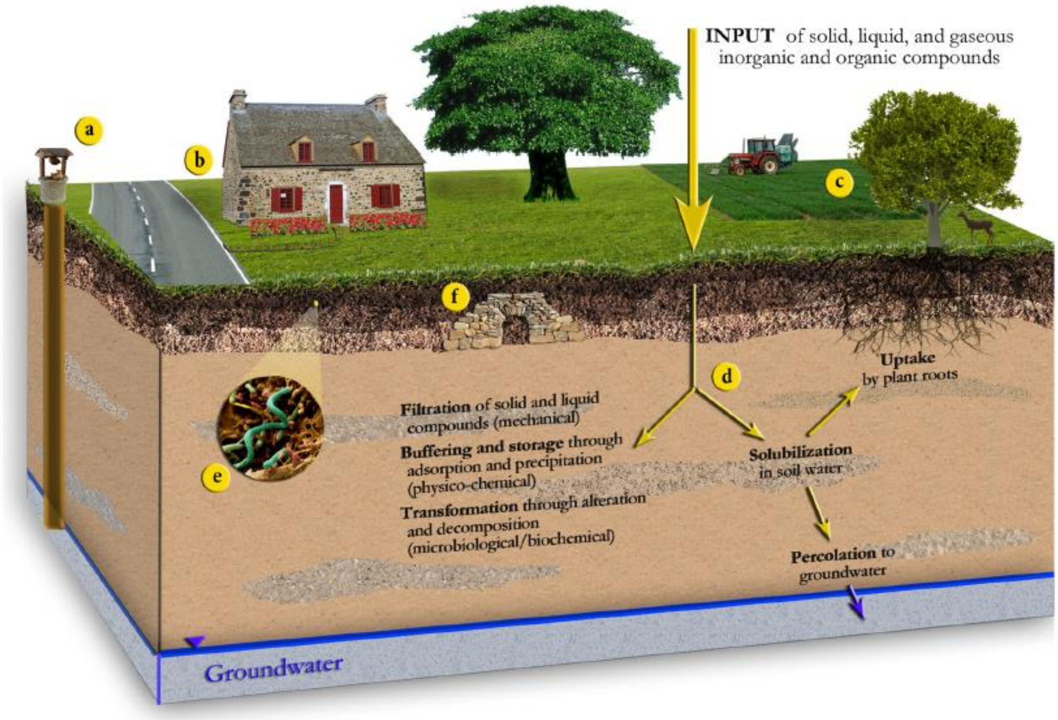


Figure 3. Schematic illustration of the different functions of soils according to Blum's (1988) classification. The six categories of soil functions correspond, respectively, to (a) the extraction of raw materials and water, (b) physically supporting buildings and other man-made structures, (c) the production of biomass, (d) filtration, buffering, storage, and chemical/biochemical transformations, and(e) the preservation of biodiversity or potentially useful genetic material, as well as of geogenic and cultural heritage. (Original drawing by P. Baveye. Source: Vogel *et al*., 2019).

Ecosystem services

Ecosystem services are the benefits that people receive from ecosystems (**Figure 4**). They depend on ecosystem structures (e.g., biotic and abiotic ecosystem elements) and on their energetic and material relationships, i.e., their functions, and on the biological, chemical and physical processes (processes) underlying them.

The 2005 Millennium Ecosystem Assessment grouped ecosystem services into four categories: (i) provisioning services (direct or indirect food for humans, freshwater, wood, fibre, and fuel); (ii) regulating services (regulation of gas and water, climate, floods, erosion, biological processes such as pollination and diseases); (iii) cultural services (aesthetic, spiritual, educational and recreational); and (iv) supporting services (nutrient cycling, production, habitat, biodiversity) (Millennium Ecosystem Assessment, 2005).

Soil ecosystem services can be understood as flows of soil natural capital stocks that benefit humans and can be classified into regulation, provision and cultural (Dominati *et al*., 2010) services. Also, services, functions and processes are driven by the properties of soil. In general, properties are directly measurable and express chemical (for example, pH), physical (density and aggregation) and biological (floral and faunal communities) characteristics (Rodrigues *et al*., 2021). Soil processes are understood as the transformation of inputs into products, for example, the decomposition of organic matter to form humus or the compaction of the soil that reduces infiltration and promotes water run-off (Dominati *et al*., 2010).

Figure 4. Europe's natural treasures: a map of the distribution of ecosystem services in Europe ([Metzger *et al.* 2018])

Soil ecosystem services

Common International Classification of Ecosystem Services-CICES

Defining ecosystem services supplied by soils can be problematic because ecosystem services are usually the result of interactions between multiple ecosystem compartments (Adhikari and Hartemink, 2016). CICES has been designed to help measure, account for and assess ecosystem services in a standardized way and is one of several internationally utilized typologies of ecosystem services. It is the most detailed classification with a linguistic taxonomy that follows a strict nested hierarchical structure and is very influential in the European Union (Czúcz *et al*., 2018). CICES defines 83 specific classes representing 56 biotic and 27 abiotic services. Accordingly, ecosystem services are soil related if their supply is directly and quantifiably controlled by soils and their properties, processes and functions. Of the 83 classes defined in the CICES, Paul *et al*. (2021) identified 29 classes that were consider soil related, comprising 14 provisioning services and 15 regulation and maintenance services (Table 1). Paul *et al*. (2021) did not include any of the cultural services listed in CICES, because “cultural services are not directly and quantifiably determined by soil properties, processes or functions”.

Table 1. Soil-related ecosystem services. Paul *et al*. (2021) CICES class names to aid understanding.

CICES code	Biotic provisioning services	CICES code	Biotic regulation & maintenance services
1.1.1.1	Cultivated terrestrial plants for nutrition	2.1.1.1	Biotic remediation of waste
1.1.1.2	Cultivated terrestrial plants for materials	2.1.1.2	Biotic filtration, sequestration and storage of waste
1.1.1.3	Cultivated terrestrial plants for energy	2.2.1.1	Erosion control
1.1.5.1	Wild plants (terrestrial and aquatic) for nutrition	2.2.1.3	Hydrological cycle and flood control
1.1.5.2	Wild plants (terrestrial and aquatic) for materials	2.2.2.3	Nursery populations and habitats
1.1.5.3	Wild plants (terrestrial and aquatic) for energy	2.2.3.1	Pest control (including invasive species)
1.2.1.1	Genetic material from plants to maintain populations	2.2.3.2	Disease control
1.2.1.2	Genetic material from plants for breeding	2.2.4.1	Soil quality by weathering processes
	Abiotic provisioning services	2.2.4.2	Soil quality by decomposition and fixing processes
4.2.1.1	Surface water for drinking	2.2.5.1	Chemical condition of freshwaters
4.2.1.2	Surface water for non-drinking purposes	2.2.5.2	Chemical condition of salt waters
4.2.2.1	Groundwater for drinking	2.2.6.1	Chemical composition of atmosphere and oceans
4.2.2.2	Groundwater for non-drinking purposes	2.2.6.2	Local regulation of air temperature and humidity
4.3.1.1	Mineral substances for nutrition		**Abiotic regulation & maintenance services**
4.3.1.2	Mineral substances for materials	5.1.1.3	Abiotic filtration, sequestration and storage of waste
		5.2.1.2	Control of liquid flows

Paul *et al*. (2021) suggested that the CICES classification has several problems when applied to soils, including the distinction between services provided by living elements of the ecosystem and services provided by abiotic ecosystem components. They suggested that because soils exist at the intersection between the pedosphere, atmosphere, hydrosphere and biosphere, this distinction is problematic. The authors highlighted the value of close cooperation between the soil research and ecosystem services to ensure better consideration of soils in future CICES updates.

Categories of soil ecosystem services

Several authors have categorised the key goods and services provided by soil systems. Haygarth and Ritz (2009) suggested 18 categories of ecosystem services and functions that were relevant to soils and land use in the UK, which are summarised conceptually in **Figure 5**.

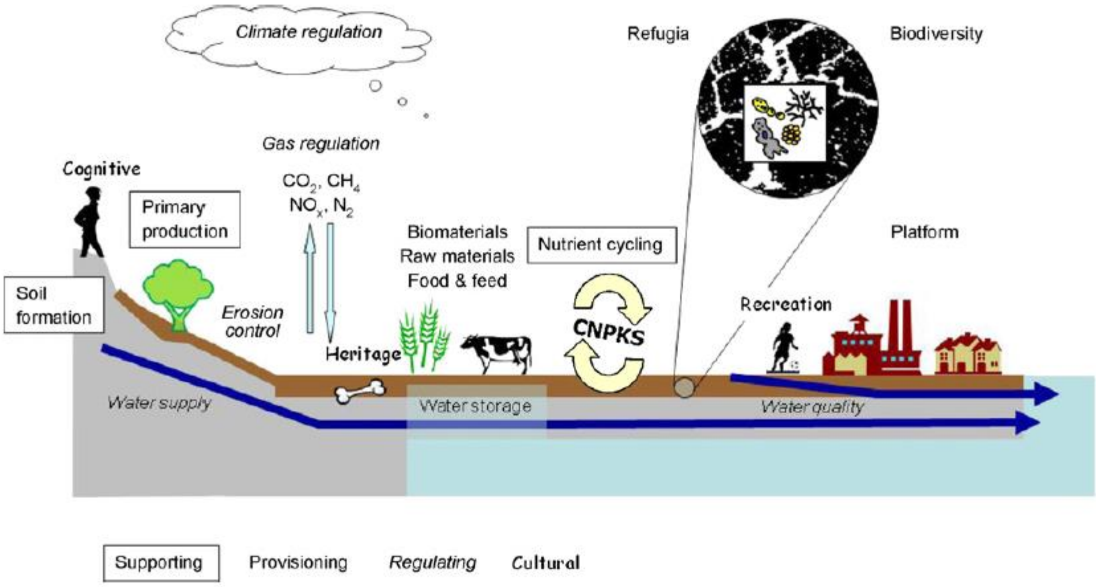


Figure 5. Categorisation and nature of the key ecosystem goods and services provided by soil systems (Source: Haygarth and Ritz, 2009).

Dominati *et al*. (2010) proposed a conceptual framework for classifying, quantifying and modelling soil natural capital and ecosystem services which linked soil ecosystem services to soil natural capital (**Figure 6**). It showed how external drivers impacted on processes that underpin soil natural capital and ecosystem services and how soil ecosystem services contribute to human well-being. The framework consisted of five main interconnected components: (1) soils as natural capital; (2) natural capital formation, maintenance and degradation; (3) the drivers of soil processes; (4) provisioning, regulating and cultural soil ecosystem services; and (5) human needs fulfilled by soil ecosystem services. A similar, framework was reported by Rodrigues *et al*. (2021) drawing on ideas proposed by Dominati *et al*. (2010), Robinson *et al*. (2013); Baveye *et al*. (2016) and Baveye *et al*. (2020), **Figure 7**.

Adhikari and Hartemink (2016) examined the relationship between soils and ecosystem services through a review of the literature. Linkages between soil and ecosystem services were investigated through a diagram (**Figure 8**) that conceptualizes the connection of key soil attributes to ecosystem services through soil functions. A table linking given ecosystem services to the specific soil attributes was generated (**Table 2**).

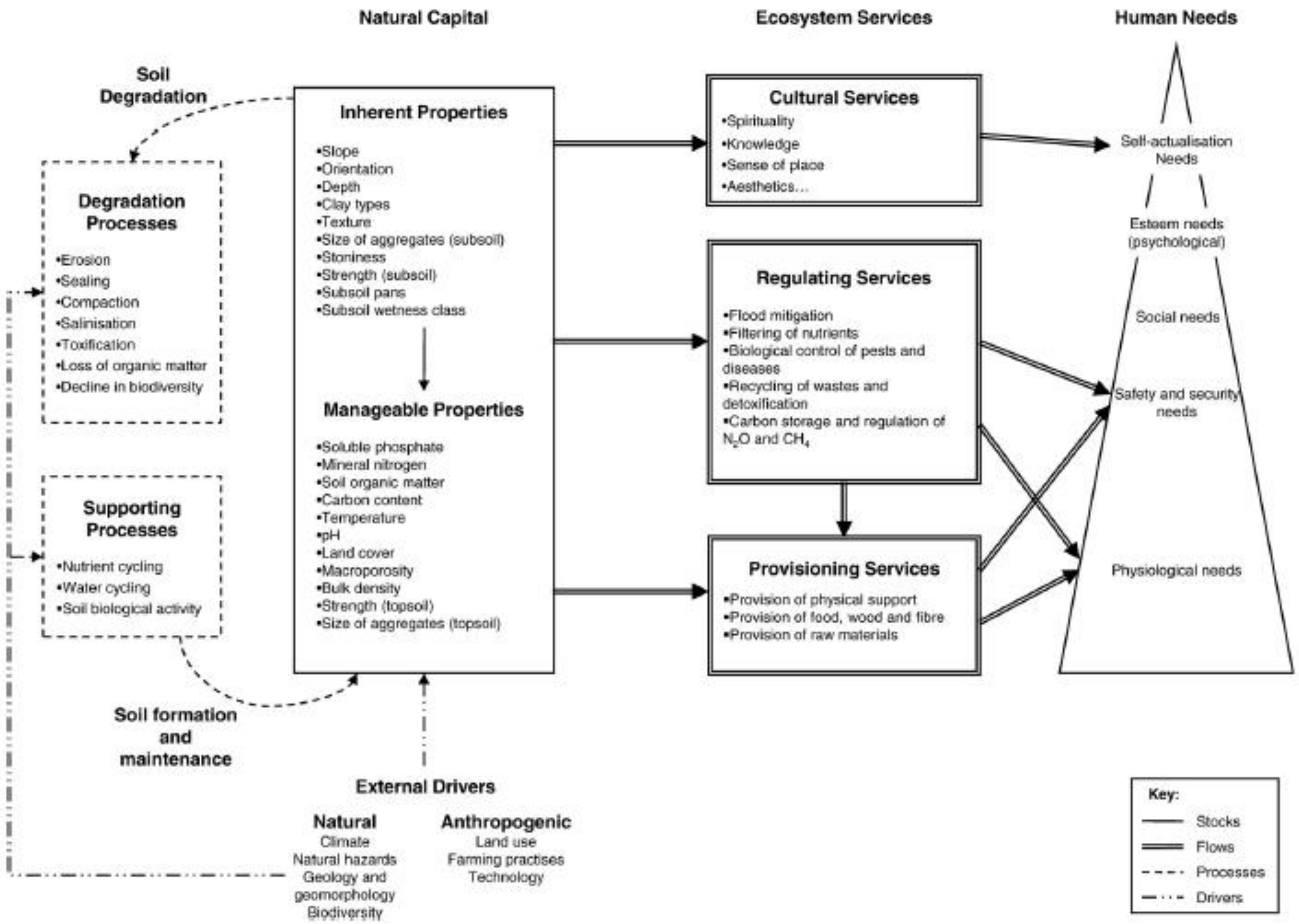


Figure 6. Framework for the provision of ecosystem services from soil natural capital (Source: Dominati *et al.*, 2010).

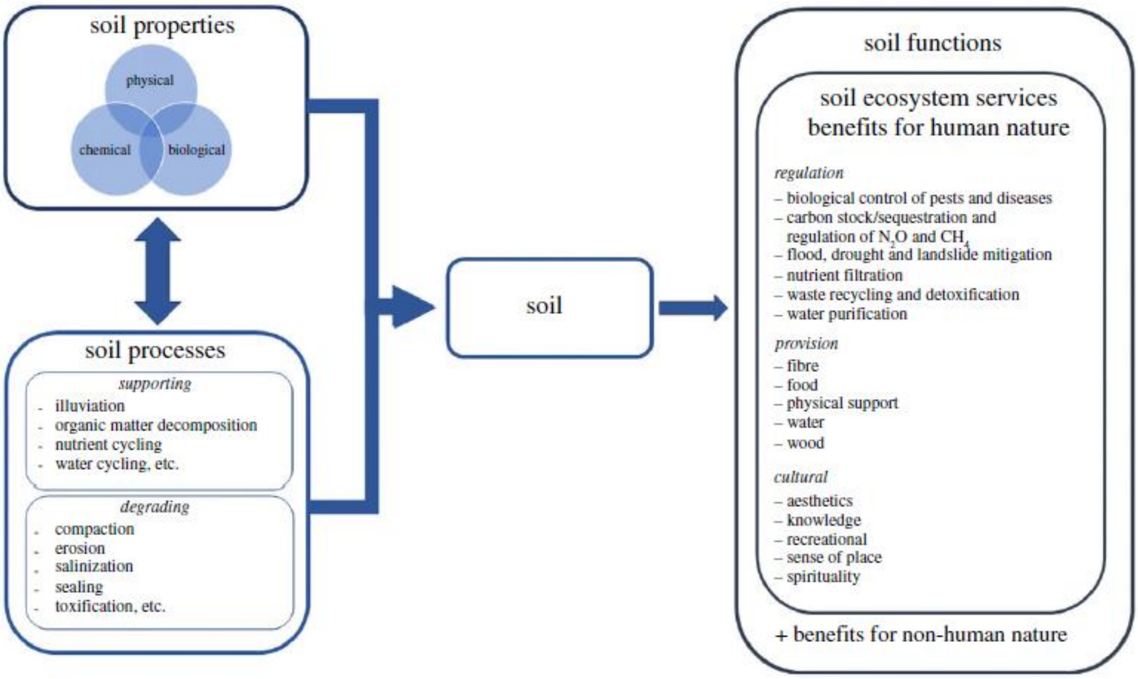


Figure 7. Illustrative framework of soil ecosystem services and their associated concepts—soil properties, soil process and soil functions (Source: Rodrigues *et al*., 2021).

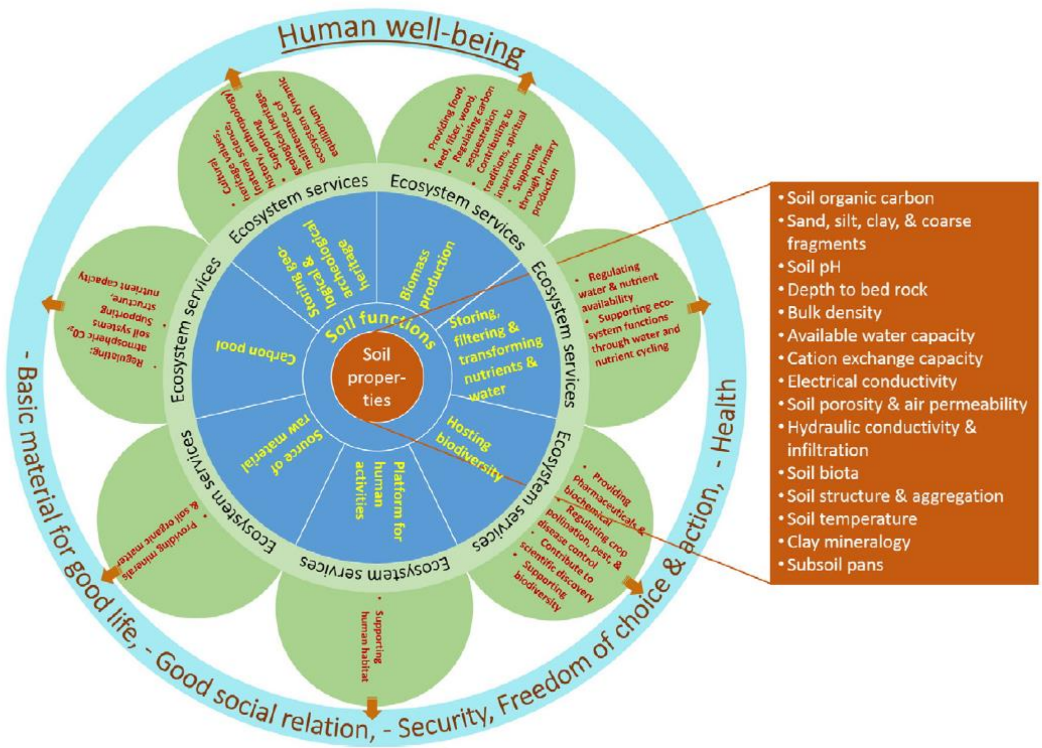


Figure 8. A conceptual diagram linking key soil properties to ecosystem services through soil functions for the well-being of humans (Source: Adhikari and Hartemink, 2016).

Table 2. List of soil properties related to provisioning and regulation ecosystem services (Source: Adhikari and Hartemink, 2016).

Soil property	Provisioning services				Regulating services						
	Food, fuel & fibre	Raw materials	Gene pool	Fresh water, water retention	Climate & gas regulation	Water regulation	Erosion & flood control	Pollination, seed dispersal	Pest & disease regulation	Carbon sequestration	Water purification
Soil organic carbon											
Sand, silt, clay & coarse fragments											
pH											
Depth to bed rock											
Bulk density											
Available water capacity											
Cation exchange capacity											
Electrical conductivity											
Soil porosity & air permeability											
Hydraulic conductivity & infiltration											
Soil biota											
Soil structure & aggregation											

Soil temperature											
Clay mineralogy											
Subsoil pans											

Table 3. List of soil properties related to cultural and supporting ecosystem services (Source: Adhikari and Hartemink, 2016).

Soil property	Cultural services				Supporting services		
	Recreation, ecotourism	Aesthetic, sense of place	Knowledge, education, inspiration	Cultural heritage	Weathering, soil formation	Nutrient cycling	Provisioning of habitat
Soil organic carbon							
Sand, silt, clay & coarse fragments							
pH							
Depth to bed rock							
Bulk density							
Available water capacity							
Cation exchange capacity							
Electrical conductivity							
Soil porosity & air permeability							
Hydraulic conductivity & infiltration							
Soil biota							
Soil structure & aggregation							
Soil temperature							
Clay mineralogy							
Subsoil pans							

Mapping ecosystem services

Spake *et al*. (2019) noted that a major sustainability challenge is determining where to target management to enhance natural capital and the ecosystem services it provides. Achieving this understanding is difficult, given that the effects of most actions vary according to wider environmental conditions; and this context dependency is typically poorly understood.

Maps facilitate decision making by providing an efficient way of conveying complex information through visual representation and are valuable in systematic conservation planning to ensure the long-term capacity of ecosystems to provide ecosystem services (Schröter *et al*., 2014; Gonzalez-Redin *et al*., 2016). A major challenge lies in the complexity of the relationships between ecosystem condition and ecosystem services and in the fact that these relationships greatly vary depending on the scale of analysis which may not coincide with the scale of landscape planning (Cimon-Morin *et al*., 2013; Maes *et al*., 2012; Turkelboom *et al*., 2018). Linking soil features and characteristics to ecosystem services has been done in several ways, including the use of stakeholder opinion in weighting the relevance and importance of individual feature (Rutgers *et al*., 2012).

Maps are useful for spatially explicit prioritisation and problem identification, especially in relation to synergies and trade-offs among different ecosystem services, and between ecosystem services and biodiversity (Maes *et al*., 2013). Further, maps can be used as a communication tool to initiate discussions with stakeholders, visualizing the locations where valuable ecosystem services are produced or used and explaining the relevance of ecosystem services to the public. Gret-Regamey *et al*., 2013 demonstrated that the integration of local expertise and knowledge into the modelling process is important for the reduction of uncertainty and the correct valuation of ecosystem services. Maps can contribute to the planning and management of biodiversity protection areas and implicitly of their ecosystem services at sub-national level. Primary data are often used to map provisioning service, e.g., food or fibre supply whereas many regulating, supporting and cultural services often rely on proxies for their quantification (Maes *et al*., 2012).

Mapping of ecosystems services gained prominence in Europe under the EU Biodiversity Strategy to 2020 (European Commission, 2011). Target 2 (maintain and restore ecosystems and their services) Action 5 (Improve knowledge of ecosystems and their services in the EU) of the Strategy asked member states "with the assistance of the Commission to map and assess ecosystems and their services on their national territory". Action 5 was implemented by the working group MAES on Mapping and Assessment of Ecosystems and their Services; the work formally started on 22 September 2011 with a stakeholder workshop in Brussels (Maes *et al*., 2015). After several rounds of iteration within the working group and following a consultation with several biodiversity research networks a final framework was adopted to ensure coherent mapping across Europe, **Figure 9**. The framework links socio-economic systems with ecosystems via ecosystem services, and drivers of change that exert pressures on ecosystems including their biodiversity either as consequence of using the services or as indirect impacts due to human activities in general (Maes *et al*., 2013).

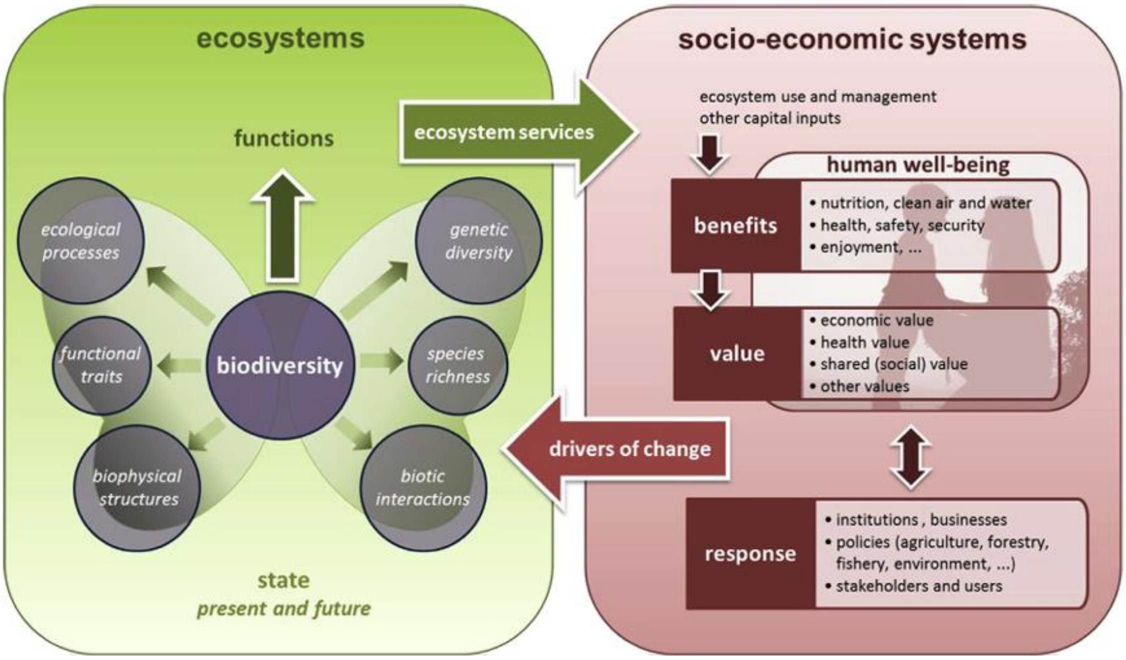


Figure 9. Conceptual framework for EU and national ecosystem assessments under Action 5 of the EU Biodiversity Strategy to 2020 (Source: Maes *et al*., 2013).

The maps were produced either using the ESTIMAP model or by downscaling indicators available at national scale to a 10 km grid. Example maps for ‘capacity to avoid soil erosion’ and ‘water retention index’ are shown in **Figure 10**.

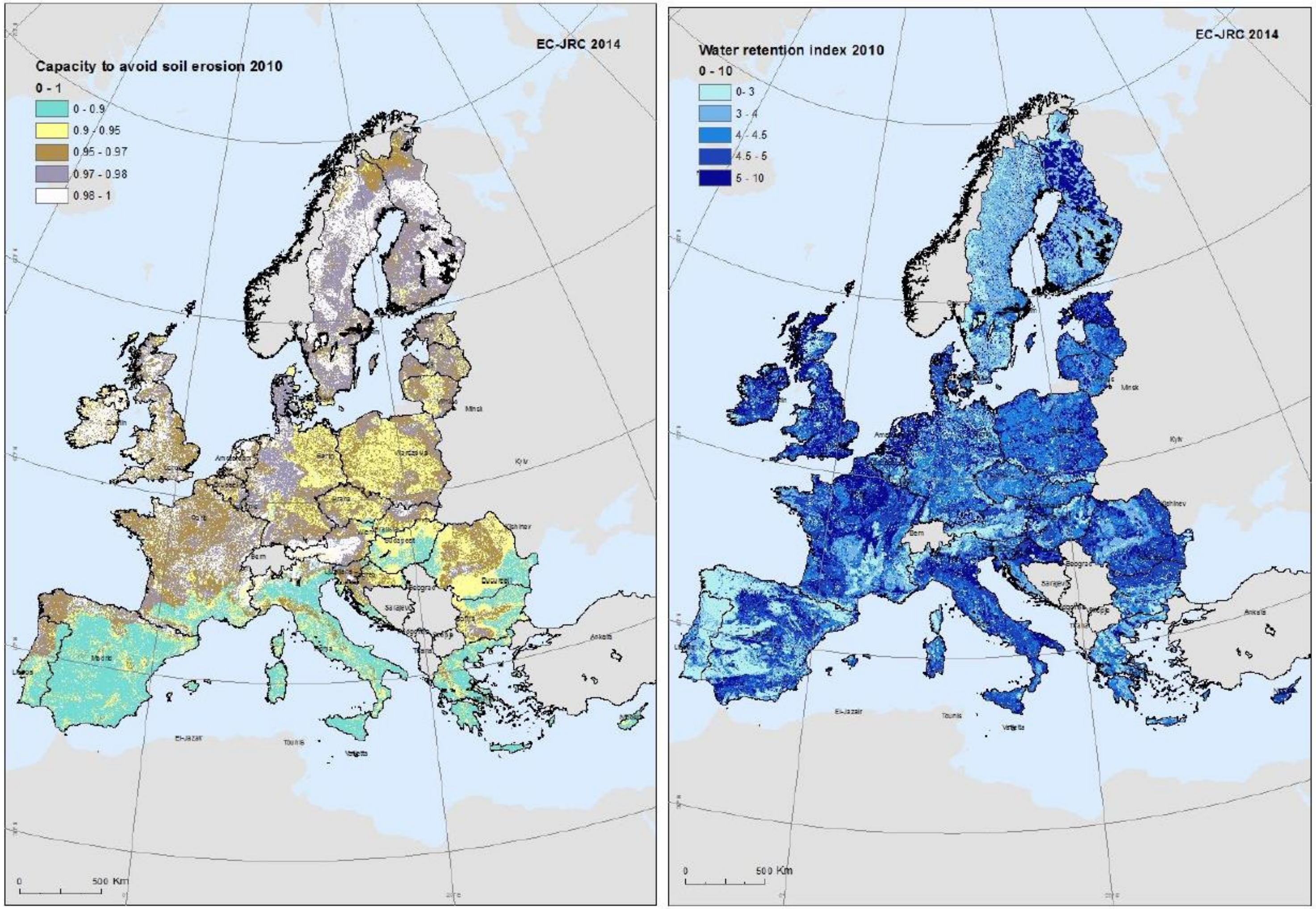


Figure 10. Example ecosystem services maps, a. capacity to avoid soil erosion and b. water retention index (Source: Maes *et al.*, 2015)

Maps for ecosystem services are made for a broad set of purposes. Jacobs *et al*. (2017) suggest that these include advocacy (awareness raising, justification, decision support), ecosystem assessment, priority setting, instrument design, ecosystem accounting, economic liability and scientific spatial analysis. **Figure 11** illustrates the theoretical relationship between mapping purposes and quality requirements.

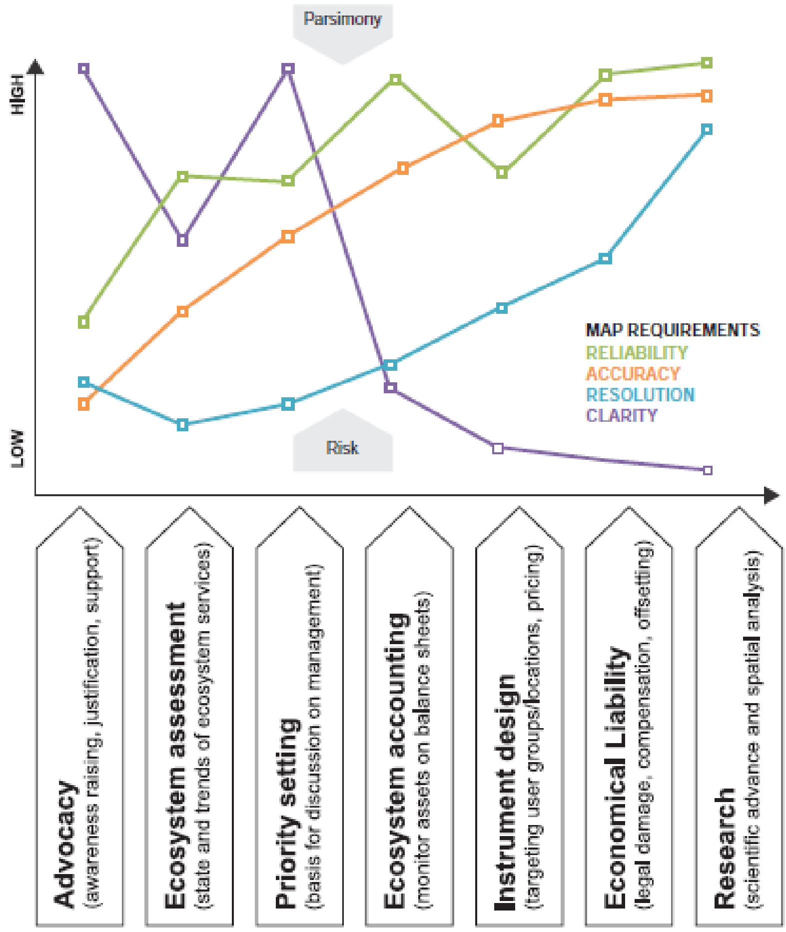


Figure 11. Ecosystem services mapping requirements according to purpose (Source: Jacobs *et al*., 2017).

Mapping methods

The EU working group on MAES provided practical guidance through a common assessment framework along with a selection of indicators to map and assess ecosystem condition and ecosystem services. Burkhard *et al*. (2018) reorganised the MAES framework into several practical steps to be followed to guide the ecosystem assessment work as required by Action 5: (i) Mapping of ecosystems; (ii) Defining the condition of the ecosystem; (iii) Quantification of the services provided by the ecosystem; and (iv) Compilation of these into an integrated ecosystem assessment.

The operational framework for integrated MAES that was proposed is composed of nine consecutive steps (**Figure 12**):

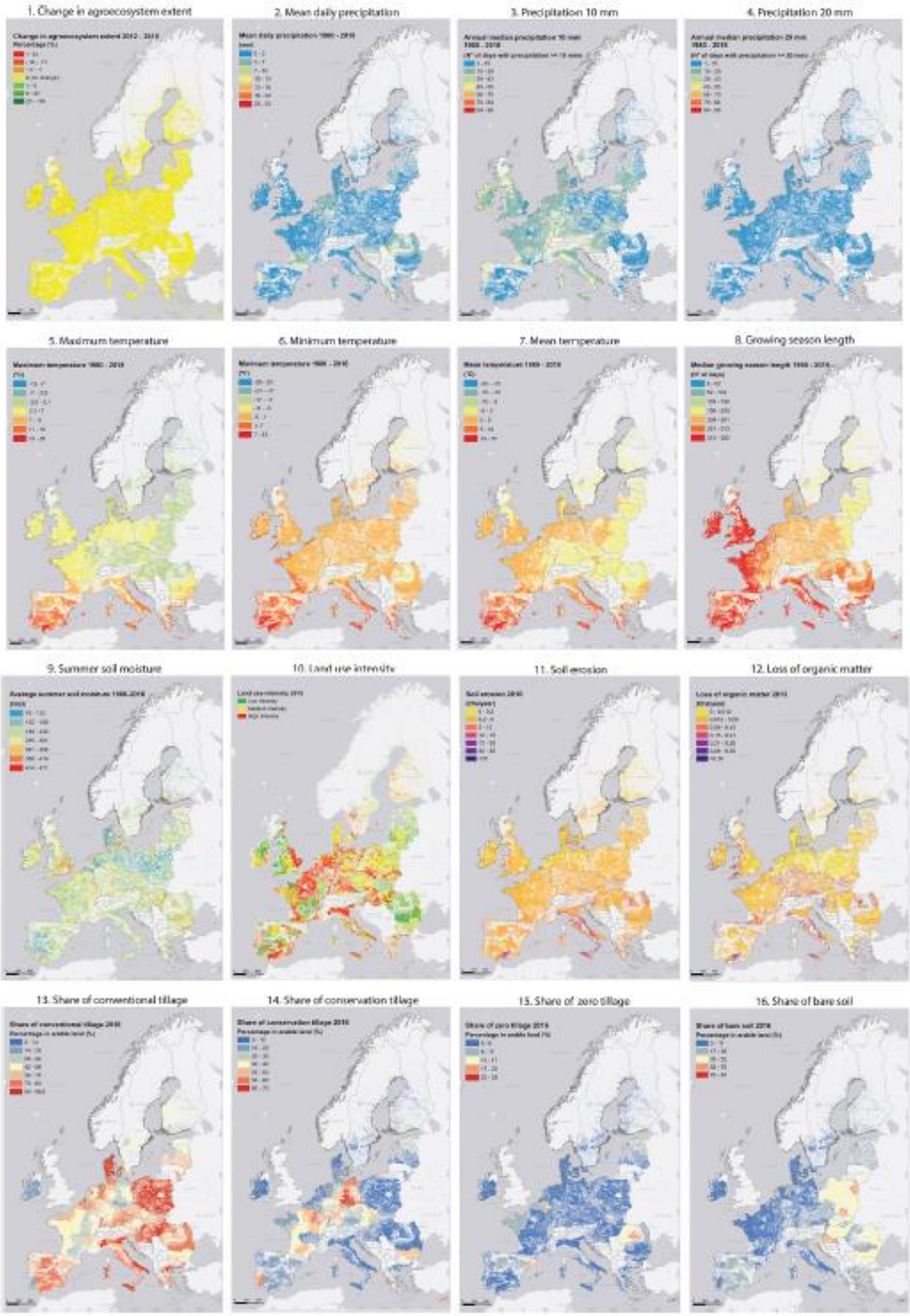
- Step 1: Question and theme identification.

- Step 2: Identification of ecosystem types.
- Step 3: Mapping of ecosystem types.
- Step 4: Defining ecosystem condition and identification of ecosystem services delivered by ecosystems.
- Step 5: Selecting indicators for ecosystem condition and ecosystem services.
- Step 6: Ecosystem condition and ecosystem services indicator quantification.
- Step 7: Mapping ecosystem condition and ecosystem services.
- Step 8: Results integration; and
- Step 9: Dissemination and communication of results.

Figure 12. Framework for integrated mapping and assessment of ecosystems and their services. Based on Burkhard *et al*. (2018) (Source: Rendon *et al*., 2022).

Rendon *et al*. (2022) based their assessment on the framework for integrated mapping and assessment of ecosystems and their services proposed by Burkhard *et al*. (2018) and the indicators proposed by Maes *et al*. (2018). They calculated and mapped the indicators for pressures, ecosystem condition and control of erosion rates using a wide range of datasets; the maps covering the distribution of the indicators in the entire study area are shown in **Figure 13**.

Rendon *et al*. (2022) quantified and mapped indicators for ecosystem condition, environmental and anthropogenic pressures and soil erosion control. The authors explored the relationships between the respective indicators and the capacity of agroecosystems to control soil erosion across environmental zones (EZ). The results emphasise that patterns in the complex interactions between this ecosystem service and ecosystem condition indicators should be analysed at a sub-European scale to address variations in landscapes, climate and therefore also erosion processes and rates. On the level of *EZ*s, found that the control of erosion rates is correlated positively with multiple condition indicators and negatively with pressure indicators. The results also helped identify *EZ*s where actions should be taken to mitigate the environmental and anthropogenic pressures on agroecosystems and improve their condition.


1. Change in agroecosystem extent
2. Mean daily precipitation
3. Precipitation 10 mm
4. Precipitation 20 mm
5. Maximum temperature
6. Minimum temperature
7. Mean temperature
8. Growing season length
9. Summer soil moisture
10. Land use intensity
11. Soil erosion
12. Loss of organic matter
13. Share of conventional tillage
14. Share of conservation tillage
15. Share of zero tillage
16. Share of bare soil

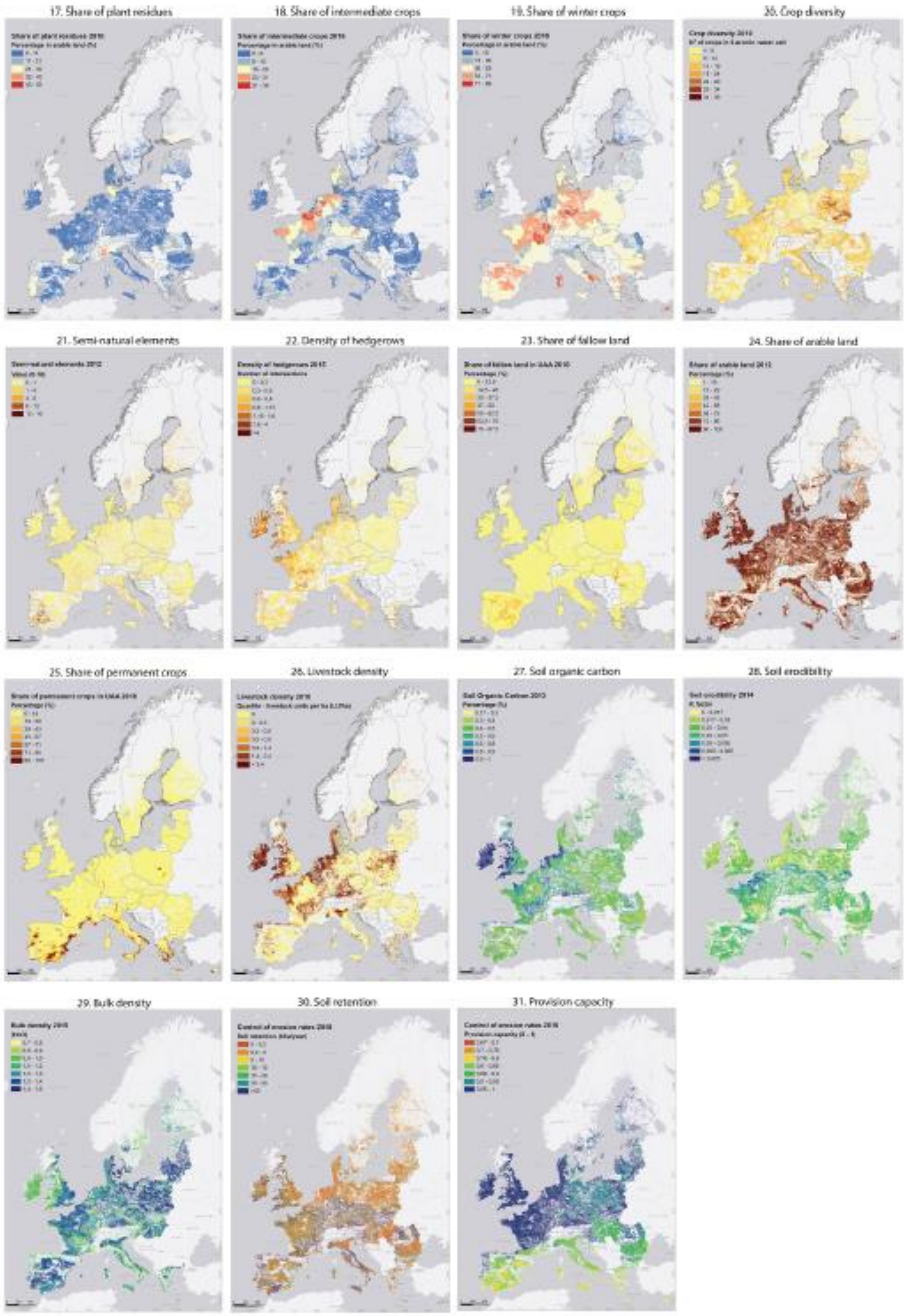


Figure 13. Maps of indicators of environmental pressures, ecosystem condition and control of erosion rates in the EU (for larger maps see Rendon *et al*., 2022 supplementary information).

Mapping approaches

Grêt-Regamey *et al*. (2017) suggested that ecosystem services mapping approaches could be broadly classified into five categories:

1. A simple and widely used approach that directly links ecosystem services to geographic information, mostly land cover data and is often referred to as the “lookup table” approach. The land cover data are used as proxies for the supply of (or demand for) different ecosystem services. The ecosystem service in the lookup table can be derived from statistics such as crop yield for agricultural production.
2. Approaches, that mainly relying on expert knowledge include expert estimates of ecosystem values in lookup tables but also other methods such as Delphi surveys.
3. The “causal relationship” approach that estimates ecosystem services based on well-known relationships between services and spatial information from literature or statistics. For example, timber production can be estimated using harvesting statistics for different areas, elevations and forest types provided in a national forest inventory.
4. Approaches that estimate ecosystem services extrapolated from primary data such as field surveys linked to spatial information.
5. Quantitative regression and socio-ecological system models that combine field data of ecosystem services as well as information from literature linked to spatial data.

The authors proposed a tiered approach to ecosystem service mapping based on the decision tree in **Figure 14**. For example, tier 1 may be appropriate if the purpose of the map is mainly to provide an overview of ecosystem services (e.g., abundance or presence/absence), tier 2 may be suitable when ecosystem services information is required at a certain level of detail but not linked to an explicit management and tier 3 may be best for explicit evaluation of management measures (Grêt-Regamey *et al*., 2017). **Figure 14**, associates the five categories of mapping (above) with different tier levels.

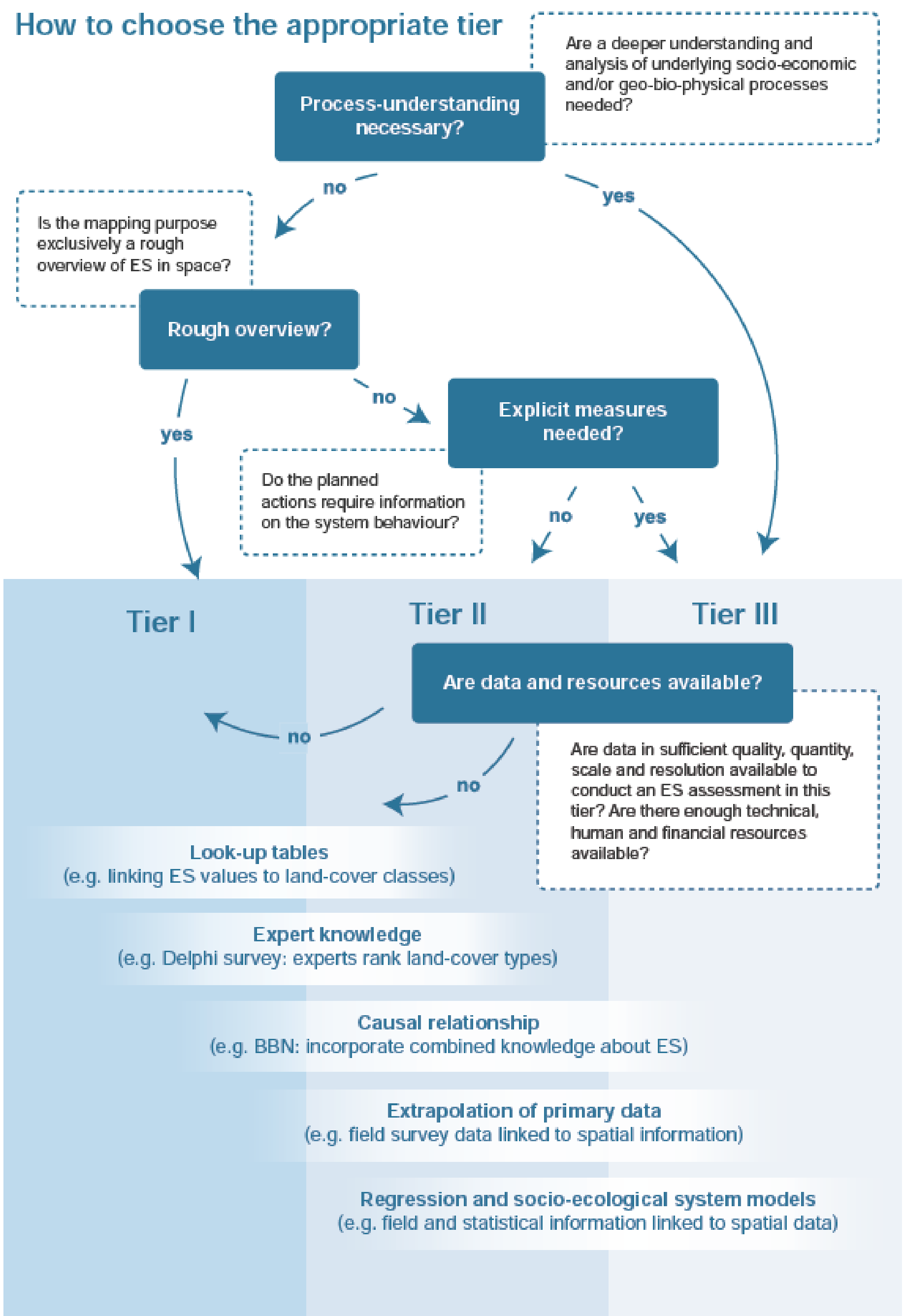


Figure 14. Decision tree guiding the selection of tiers for ecosystem mapping (Source: Grêt-Regamey *et al*., 2017).

Ecosystem services matrix

One commonly used mapping method is the ecosystem 'matrix' approach, which links ecosystem services to appropriate geo-biophysical spatial units (Burkhard, 2017). Service supply, flow and demand are ranked using a relative scale ranging from 0 to 5 (not relevant to very high, see **Figure 15**). Based on this normalisation of rankings, various ecosystem services are made comparable and different points in time (including scenarios) can be assessed. The authors suggest that the equal intervals classification methods should be used to group the data into the 0-5 classes.

As shown in **Figure 15**, the basic steps of application include:

1. Selection of ecosystem services study area.
2. Selection of relevant geo-biophysical spatial units (assessment matrix lines/y-axis).
3. Collection of suitable spatial data (e.g., land cover/land use data, soil map).
4. Selection of relevant ecosystem services (assessment matrix columns/x-axis).
5. Definition of suitable indicators for ecosystem services quantification.
6. Quantification of ecosystem services indicators (using various methods).
7. Normalisation of ecosystem services indicator values to the relative 0-5 scale.
8. Interlinking geospatial units and scaled ecosystem service values in the matrix.
9. Linkage of ecosystem services 0-5 rankings to geospatial units to create maps and
10. Interpretation, communication and application of resulting ecosystem maps.

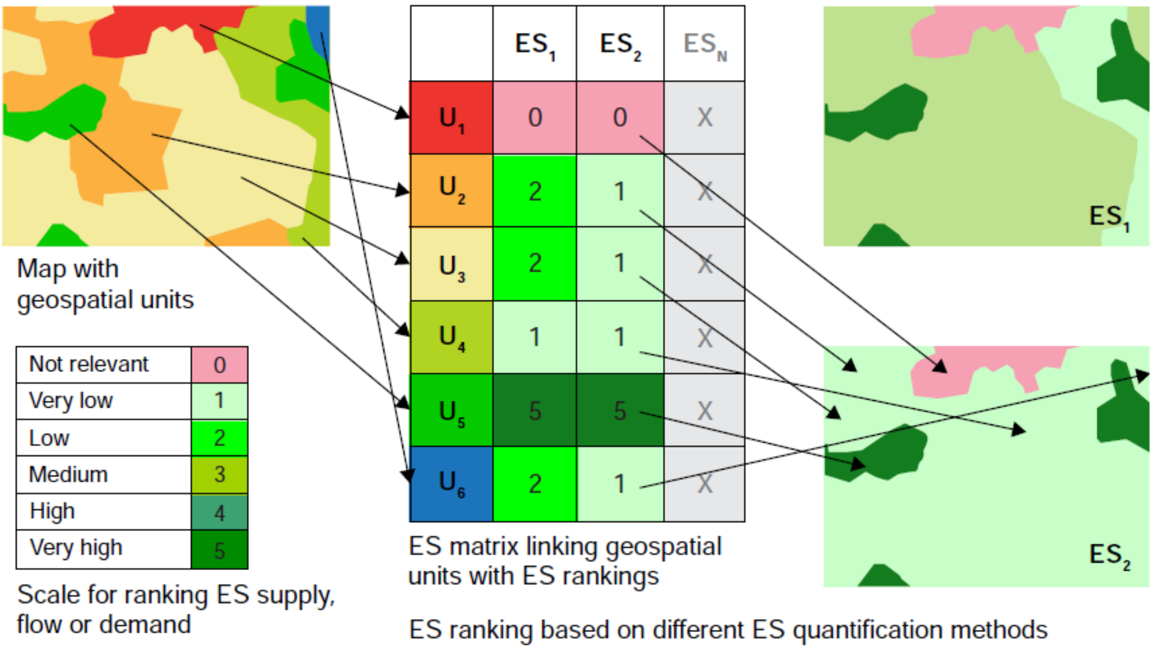


Figure 15. Overview of the ecosystem services matrix approach, based on geospatial map data, the actual matrix and resulting ecosystem services maps (Source: Burkhard, 2017).

Uncertainties associated with the matrix approach.

The matrix delivers results relating to ecosystem services supply and demand patterns in look-up tables and resulting maps by integrating data from various sources. However, Burkhard (2017) noted the following uncertainties relating to the 10 steps of application:

- *Selection of ecosystem service study area*. The case study area should be representative for the addressed question and region. It should reflect the specific local, natural and cultural settings, land management and changing socio-ecological system conditions.
- *Selection of relevant geo-biophysical spatial units*. Generalisation and categorisation of complex landscapes into a limited number of classes include simplification and uncertainties. Spatial units are also dependent on spatial data resolution and study area size.
- *Collection of suitable spatial data*. Information availability (e.g., appropriate biophysical data on soils) and data access often limit comprehensive ecosystem service studies. Further

uncertainties can be based on inaccuracies in spatial and thematic data and unsuitability of spatial and temporal scales.

- *Selection of relevant ecosystem services*. Which ecosystem services are relevant in the case study area and which user groups are benefitting? Are ecosystem services imported and exported to or from the region? Especially for data-driven studies, many ecosystem services are neglected due to data availability.
- *Definition of suitable indicators for ecosystem quantification*. Ecosystem services indicators should be robust, scalable and sensitive to changes. Furthermore, appropriate indicator-indicandum (i.e., the subject to be indicated) relations need to be identified and defined. Various indicators are needed for ecosystem services trade-off and synergy assessments.
- *Quantification of ecosystem services indicators*. Uncertainties can be due to the lack of appropriate data for ecosystem service quantifications and the use of surrogate indicators, model, measurement and statistical data uncertainties, mismatches between geo-biophysical data and statistical data spatial units or limited knowledge about complex ecosystem functions.
- *Normalisation of ecosystem services indicator values*. Comparability of data from different sources, varying quality and quantity and across various ecosystem services categories is not always given. Moreover, subjectivity in the scoring procedures and data classification include uncertainties.
- *Interlinking geospatial units and ecosystem services in the ecosystem services matrix*. The averaging of ecosystem service data over space and time is difficult. Usually, ecosystem service supply takes place spatially and heterogeneously and aggregation of data, models and indicators without losing relevant information is not easy.
- *Linkage of ecosystem 0-5 rankings to geospatial units*. Mismatches of selected spatial units and ecosystem services, including definition of appropriate service providing areas and ecosystem flows can lead to uncertainties of ecosystem services maps. Limited knowledge about complex socio-ecological system linkages, data extrapolation to different or larger regions, the proper representation of multiple ecosystem services and GIS software/data issues also add further uncertainties.
- *Interpretation, communication and application of resulting ecosystem services maps*. Badly designed maps and insufficient end-user interfaces might cause interpretation problems. Data and map misinterpretation can also be due to lacking knowledge of the study area or general lack of expert knowledge, for example, concerning interactions between landscape management and ecosystem services supply. Ecosystem services information is often too complex and too aggregated for easy and fast understanding. Model and map validation and respective uncertainty or reliability measures are, in most cases, not provided with the ecosystem services map.

Example maps/mapping approaches

Ecosystem services in upland Wales

Hardaker *et al*. (2020) reviewed and identified ecosystem services and ecosystem dis-services supplied by upland land use in Wales and compared the relative level of supply by the two dominant land uses in the Welsh uplands (defined as the Severely Disadvantaged Area (SDA) under the Less Favoured Area (LFA) designation (EC Directive 75/268)). In this study ecosystem services were defined as the flows of services and goods from ecosystems that provide benefits to humans (de Groot *et al*., 2010; Haines-Young and Potschin, 2010) and ecosystem dis-services were defined as the flows of dis-services that provide costs to humans.

The authors used a literature review to determine which ecosystem services and dis-services the two dominant land uses (forestry and agriculture) and their associated constituent land cover types in the Welsh uplands had the capacity to deliver. They used the Terrestrial Phase 1 Habitat Survey (Natural Resources Wales, 2018) spatial data to delineate land cover types as proxies for ecosystem structures and functions that support service/dis-service delivery and thus capacity to supply ecosystem services.

Hardaker *at al*. (2020) used an adapted version of the matrix approach (Burkhard *et al*., 2010, 2012) to quantify the level of potential service and dis-services and net ecosystem service supply (NES) and to link this to varying land cover types. The matrix contained 12 services and dis-services on the x-axis and the land use and land cover types on the y-axis (**Table 4**). At the intersections, the authors assessed (based on evidence from the literature review) the level of supply of individual ecosystems services for different land types on a scale consisting of 0 = no supply, 1 = very low supply, 2 = low supply, 3 = moderate supply, 4 = high supply and 5 = very high supply. For dis-services, the same scale was used but with negative values. Where the ecosystem service had an ecosystem dis-service analogue, and the land cover type had the capacity to supply either the ecosystem service or dis-service a range score from negative to positive was given. The spatial representation of ecosystem services, dis-services and net ecosystem supply are shown in **Figure 16**, **Figure 17** and **Figure 18**, respectively.

Table 4. Qualitative assessment matrix: potential ecosystem service and dis-service supply from upland agricultural and forestry land use in Wales. Potential ecosystem services supply is indicated using a five-point scale ranging from very low (1), low (2), moderate (3), high (4) to very high (5). For ecosystem dis-services a negative five-point scale is used ranging from very low (−1), low (−2), moderate (−3), high (−4) to very high (−5), finally 0 indicates no evidence of provision. Uncertainty level: red = uncertain, evidence lacking, yellow = uncertain, contradictory evidence, green = established but evidence incomplete, light blue = well established, evidence in agreement and dark blue = certain, high consensus (Source: Hardaker *et al*., 2020).

		Type of ecosystem services and dis-services (CICES Classification)														
		Provisioning					Regulation and maintenance				Cultural					
Upland land use	Associated land cover	Livestock production	Arable crops	Timber production	Water supply	Potable water quality	Carbon sequestration	Greenhouse gas emissions	Livestock shelter and shade	Local flood risk deviation	Employment	Landscape amenity/ diversity	Recreation	Total potential ES supply score[2]	Total potential EDS supply score[2]	Total net potential ES supply score[2]
Forestry	Conifer	0	0	5	2	-2 to 1	5	-4	3	3	3	1	3	23	-6 to -4	19 to 23
	Recently felled conifer	0	0	0	3	-3 to 0	1	0	0	-2	3	0	1	8	-5 to -2	3 to 8
	Broadleaf	0	0	3	2	4	4	-3	3	2	2	4	4	28	-3	25
	Recently felled broadleaf	0	0	0	3	-3 to 0	1	0	0	-2	2	0	1	7	-5 to -2	3 to 5
	Mixed (conifer/ broadleaf)	0	0	4	2	-2 to 2	4	-3	3	3	3	3	3	27	-5 to -3	22 to 24
	Recently felled mixed	0	0	0	3	-3to 0	1	0	0	-2	3	0	1	7	-5 to -2	2 to 5
Agriculture	Unimproved grassland	2	0	0	3	-2	4	-3	0	-3	3	4	3	19	-8	11
	Semi-improved grassland	3	0	0	3	-3	3	-4	0	-4	3	3	3	18	-11	7
	Improved grassland	4	0	0	3	-4	3	-4	0	-5	4	2	3	19	-13	6
	Marshy grassland	2	0	0	3	-2	4	-3	0	-3	2	4	3	18	-8	10
	Ffridd	2	0	0	3	-2	4	-3	0	-3	2	4	3	18	-8	10
	Heathland	2	0	0	3	-2	2	-3	0	-3	2	4	3	16	-8	12
	Tall Herb and Fern	1	0	0	3	-2	2	-3	0	-3	2	3	2	13	-8	15
	Mire	2	0	0	4	-2	3	-3	0	- 3 to 3	2	4	2	20	-8 to -5	12 to 15
	Arable	0	3	0	3	-4	1	-3	0	-5	3	2	2	14	-12	2

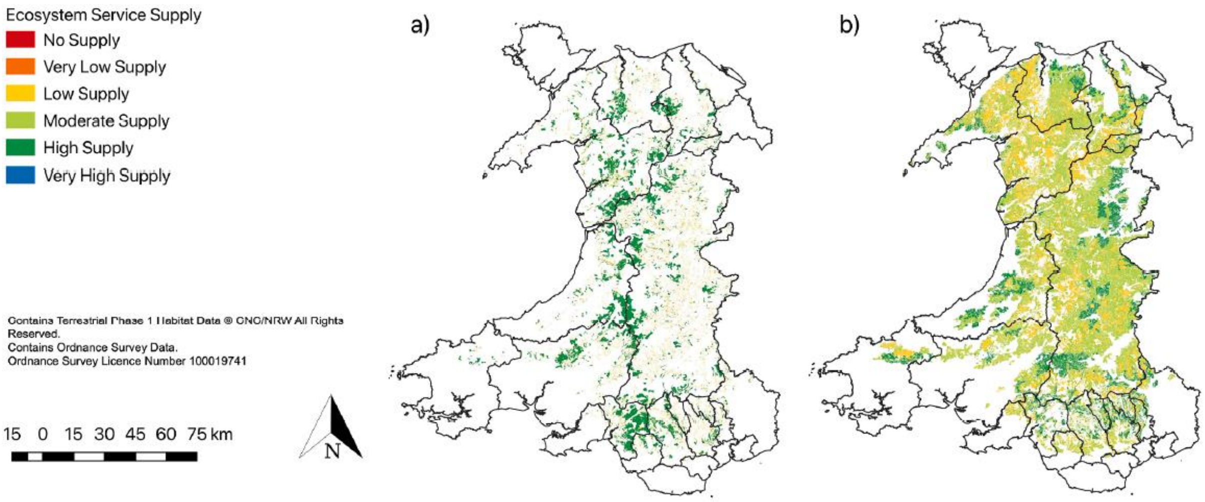


Figure 16. Ecosystem service supply from a) upland forestry and b) agricultural land use in Wales. The ecosystem services comprise livestock production, arable crops, timber production, carbon sequestration, local flood risk mitigation, maintenance of potable water quality, employment and recreation. The maps were created using the following scale: 0 = no supply, 1 to 6 = very low supply, 7 to 12 = low supply, 13 to 18 = moderate supply, 19 to 24 = high supply and = > 25 = very high supply (Source: Hardaker *et al.*, 2020).

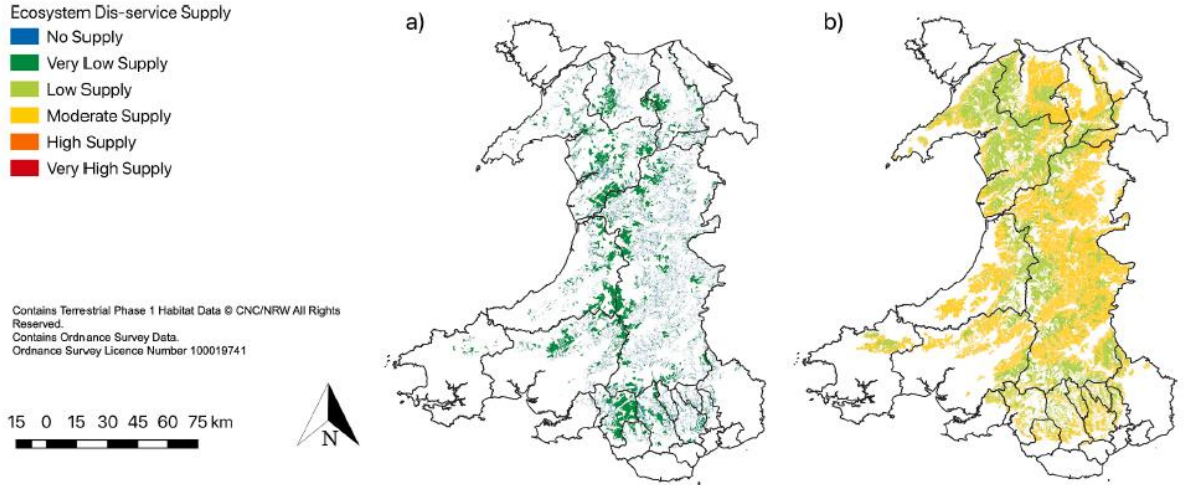


Figure 17. Ecosystems dis-service supply from a) upland forestry and b) agricultural land use in Wales. The ecosystem dis-services comprise increased local flood risk, GHG emissions and reduction of potable water quality. The maps were created using the following scale: 0 = no supply, −1 to −6 = very low supply, −7 to −12 = low supply, −13 to −18 = moderate supply, −19 to −24 = high supply and = < −25 = very high supply (Source: Hardaker *et al.*, 2020).

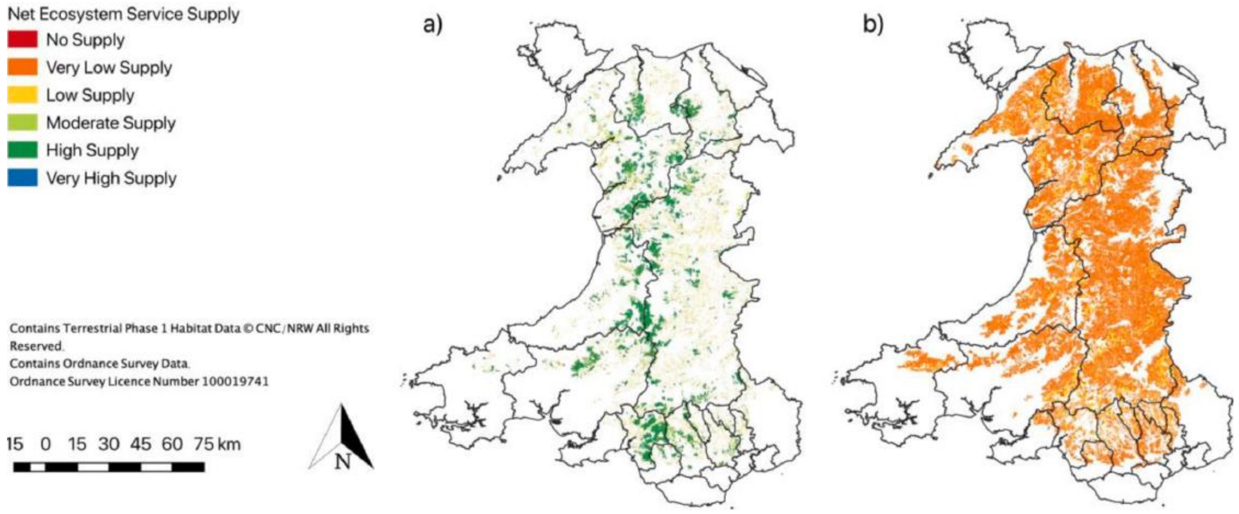


Figure 18. Net ecosystem service supply from a) upland forestry and b) agricultural land use in Wales. The net ecosystem service supply level comprises the supply of ecosystem services less the supply of ecosystem dis-services. The ecosystem services comprise livestock production, arable crops, timber production, carbon sequestration, local flood risk mitigation, maintenance of potable water quality, employment and recreation. The ecosystem dis-services comprise increased local flood risk, GHG emissions and reduction of potable water quality. The maps were created using the following scale: 0 = no supply, 1 to 6 = very low supply, 7 to 12 = low supply, 13 to 18 = moderate supply, 19 to 24 = high supply and = > 25 = very high supply (Source: Hardaker *et al*., 2020).

Soil ecosystem services in England

Habitat type approach

Natural England mapped soil function potential based on habitat types, which were scored according to their potential to provide soil services (Dales *et al*., 2014), **Figure 19**. The map focused on the factors that led to good quality soils rather than the final services which good quality soils help to regulate. However, the authors noted that to fully understand and map this service required a complete move away from a habitat-based approach and stated that 'the approach we have taken only shows where good quality soils may exist, but such a broad based, non-qualitative approach, is barely helpful'. Dales *et al*., 2014 concluded that to enable a more accurate map to be developed, and to further understand which other services soil quality contributes required the use of soil data in addition to habitat data.

1.1.1 Four-step mapping approach

Butlin *et al*. (2015) used a four-step mapping methodology to map ecosystem services in Liverpool. The first, referred to as typology mapping, described the green infrastructure within the study area using a mixed land cover/land use classification. The second, referred to as functionality mapping, described the supply of ecosystem services by the green infrastructure identified in the first step. The third, referred to as needs mapping, described the demand for ecosystem services within the study area. The fourth and final step combined the outputs of the second and third steps to determine where demands were met and where they are not met (**Figure 20**). The authors suggested that this final step was particularly useful for informing policy.

Table 7 Soil function - Habitat scoring table

Sub habitat type	Score
Littoral rock	1
Littoral sediment	1
Supra-littoral rock	1
Supra-littoral sediment	1
Arable and horticulture	1
Improved grassland	1
Neutral grassland	1
Freshwater	2
Fen, Marsh & Swamp	3
Bog	3
Dwarf shrub heath	3
Inland rock	3
Montane habitats	3
Acid grassland	3
Calcareous grassland	3
Rough low-productivity grassland	3
Built up areas and gardens	2
Broad leaved, mixed, & yew woodland	3
Coniferous woodland	3

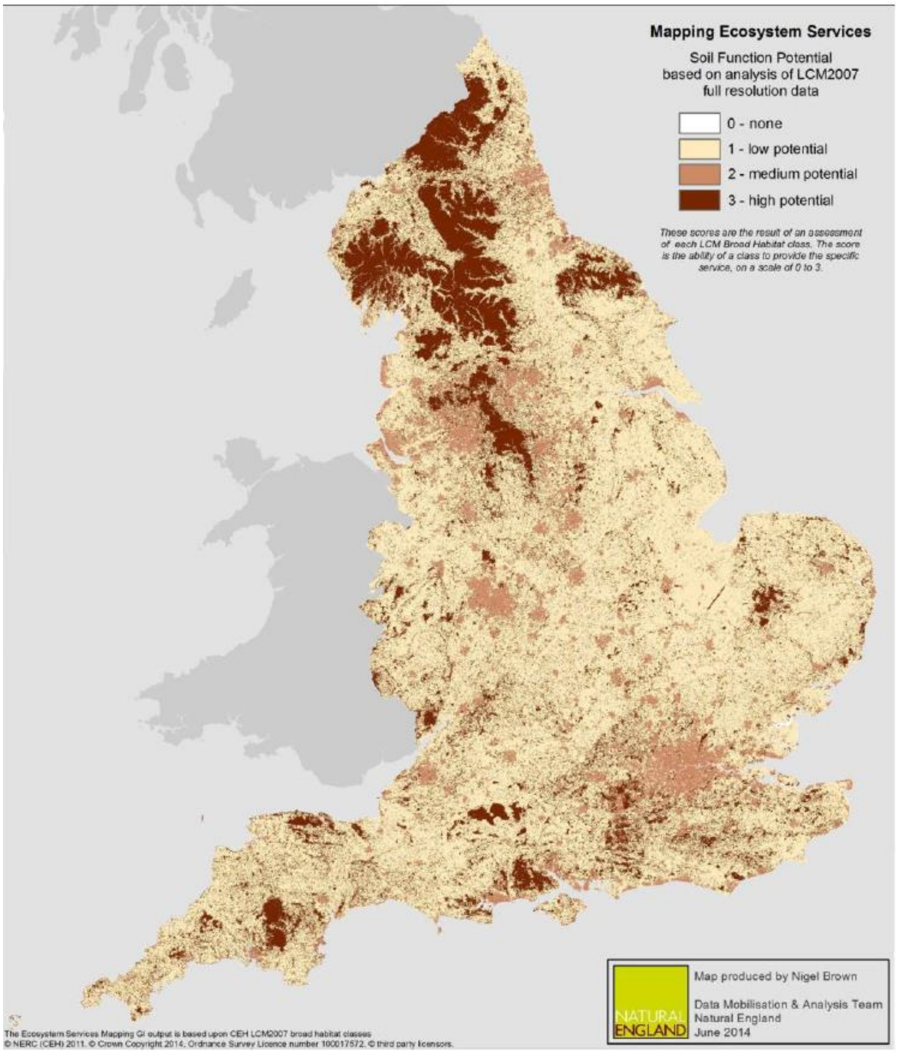
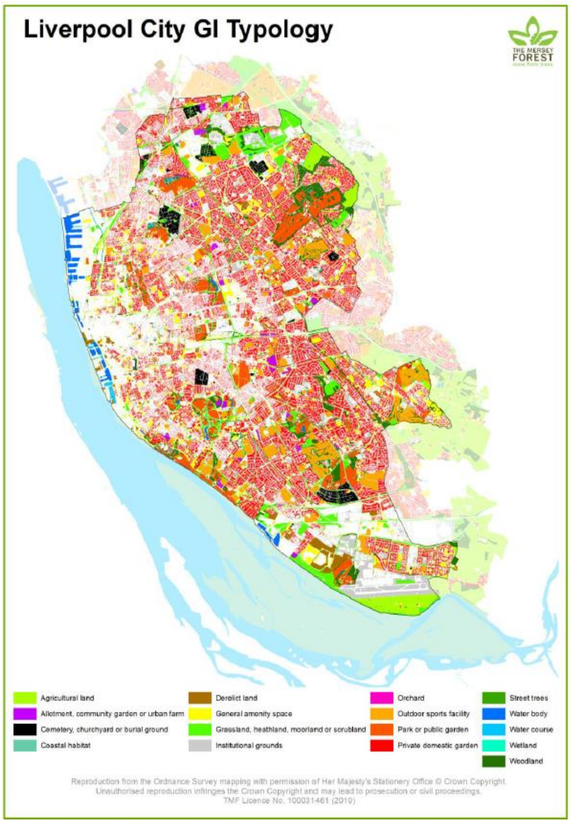


Figure 19. Soil function map (Source: Dales *et al*., 2014).

a.



Liverpool City GI Typology
THE MERSEY FOREST
Agricultural land
Allotment, community garden or urban farm
Cemetery, churchyard or burial ground
Coastal habitat
Derelict land
General amenity space
Grassland, heathland, moorland or scrubland
Institutional grounds
Orchard
Outdoor sports facility
Park or public garden
Private domestic garden
Street trees
Water body
Water course
Wetland
Woodland
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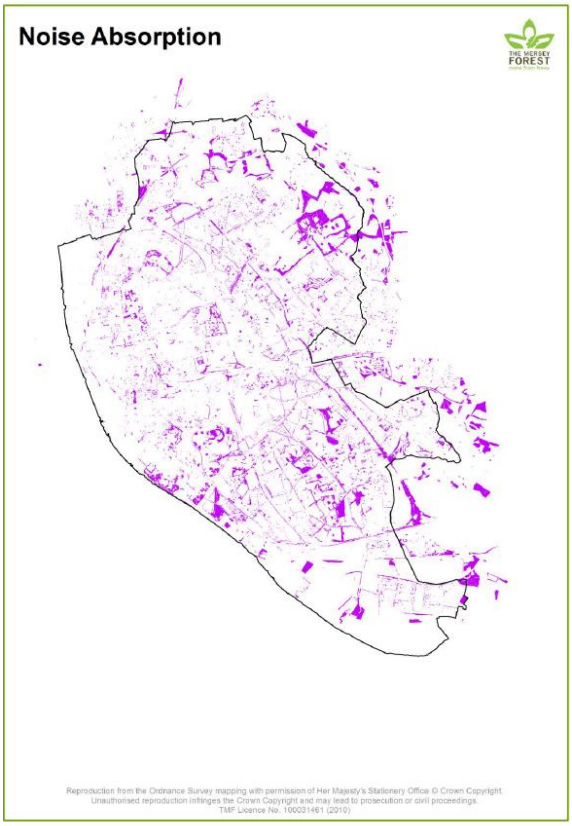
b.



Noise Absorption
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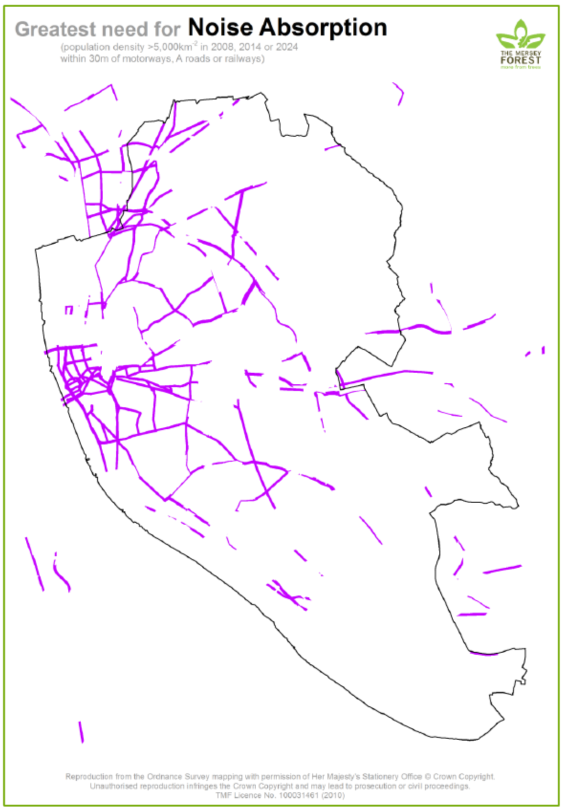

Greatest need for Noise Absorption
(population density >5,000km-2 in 2008, 2014 or 2024
within 30m of motorways, A roads or railways)
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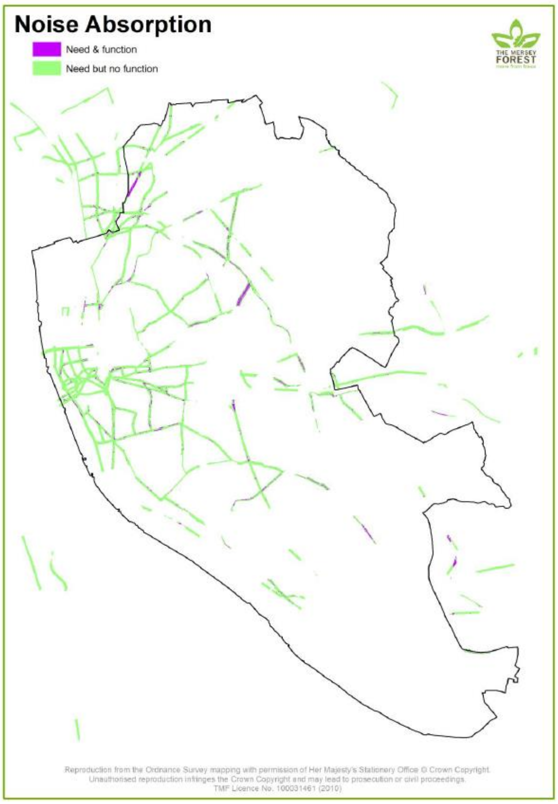

Noise Absorption
Need & function
Need but no function
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Figure 20. a. typology, b. service supply, c. service demand and d. demand met/not met (Source: Butlin *et al*., 2015).

Land cover scoring approach.

Smith and Dunford (2018) applied a land cover scoring approach to a case study of Warwickshire, Coventry and Solihull (WC&S) as part of the EU-funded OpenNESS project (Operationalisation of natural capital and ecosystem services). The approach was well suited to WC&S because a detailed Phase 1 Habitat and Biodiversity Assessment survey (HBA) was available.

Experts scored 16 key land cover classes from the HBA based on the capacity of the land cover to deliver each ecosystem service, using a six-class system (i.e., from 0 to 5) where zero was no delivery capacity and 5 was very high delivery capacity. Median stakeholder scores were used to create a summary matrix for these key land cover classes. As well as scoring individual services, Smith and Dunford (2018) created average scores for all regulating services, all provisioning services, all food provisioning services and all cultural services. These scores were then applied to the HBA layer within GIS to generate maps of each individual service or of groups of services, **Figure 21**. Although the method is very simple and is based largely on expert judgement, Smith and Dunford (2018) reported that stakeholders found the maps very useful for demonstrating and visualising the provision of ecosystem services in WC&S. Recommended improvements to the methods included score validation, modification to reflect ecosystem condition and comparison with maps generated using different approaches.

Figure 21. Flood protection ecosystem service (Source: Smith and Dunford, 2018).

Soil ecosystem services in Scotland

Aitkenhead and Coull (2018) described a framework for estimating the distribution of soil ecosystem service supply based on the concept of matrix multiplication (**Figure 22**). This approach enabled relationships between fundamental soil variables and associated environmental characteristics to be linked to soil processes, and hence to ecosystem functions and ecosystem services.

The parameterization of these relationships was achieved using a combination of data from the Scottish Soils Database and expert knowledge. Baseline data to allow mapping of processes, functions and services across Scotland was from digital maps of soil classes. The matrix multiplication approach constrained the relationship linkages to linear relationships and ignored potential synergies between factors at each stage, but did provide a mechanism for relating fundamental soil characteristics to ecosystem services.

	Process A	Process B
Parameter A	i1	i2
Parameter B	i3	i4
Parameter C	i5	i6

X

	Function A	Function B	Function C	Function D
Process A	j1	j2	j3	j4
Process B	j5	j6	j7	j8

=

	Function A	Function B	Function C	Function D
Parameter A	i1j1 + i2j5	i1j2 + i2j6	i1j3 + i2j7	i1j4 + i2j8
Parameter B	i3j1 + i4j5	i3j2 + i4j6	i3j3 + i4j7	i3j4 + i4j8
Parameter C	i5j1 + i6j5	i5j2 + i6j6	i5j3 + i6j7	i5j4 + i6j8

Figure 22. The concept of matrix multiplication as applied to soil parameters, processes and functions (Source: Aitkenhead and Coull, 2018).

The values given in **Table 5** reflect the available information on relationships between soil functions and ecosystem services; for each of the three ecosystem services given in Table 4, mapping was carried out using the same process. Aitkenhead and Coull (2018) note that the intention of this work was not to provide an approach to accurate quantification of soil functions or ecosystem services, but to provide a framework within which existing knowledge could be represented, gaps could be identified and addressed and the multifunctionality of soils could be characterized.

Maps of the ecosystem services agricultural capability and carbon sequestration are shown in **Figure 23**. A higher weighting indicates that the ecosystem service provision is greater in those areas than in areas with a lower weighting. For example, the agricultural capability map shows low values on steeper and high-altitude areas, and medium/high values in lowland and east coast areas where farming predominates.

Table 5. Matrix of relationships strengths linking soil functions to soil ecosystem services (Source: Aitkenhead and Coull, 2018).

	Agricultural capability	Carbon sequestration	Drinking water provision
Water supply	1.0	1.0	1.0
Biocontrol/regulation of pests/diseases	0.5	0.0	1.0
Nutrient buffering	0.5	0.0	1.0
Nutrient availability	1.0	0.0	0.0
Capacity to maintain sufficient pollinators	1.0	0.0	0.0
Temperature buffering	0.0	0.5	0.0
Interception and infiltration	0.5	0.0	1.0
Support biodiversity	0.5	0.0	0.0
Nitrogen fixation	0.5	0.0	0.0
Nutrient cycling	0.0	−1.0	0.0
Peat accumulation	0.0	1.0	0.0
Primary production	0.5	1.0	0.0
Regulation of soil GHG emissions	0.0	1.0	0.0

a. b.

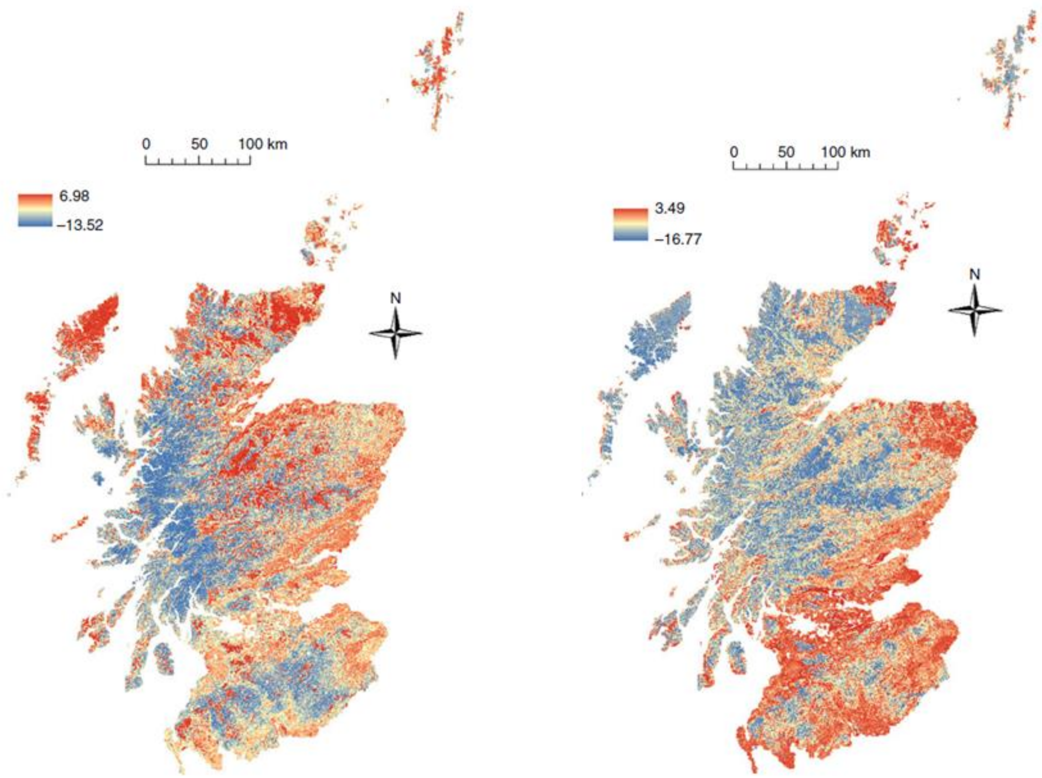


Figure 23. Weighting given to the ecosystem service a. "Agricultural Capability" and b. carbon sequestration (Source: Aitkenhead and Coull, 2018).

Mapping ecosystem services in Ireland

To fulfil their obligations under Action 5 of the Biodiversity Strategy, in Ireland Parker *et al*. (2016) worked with stakeholders to identify what needed to be mapped and what could be mapped, taking into consideration existing national spatial data sources and developing indicators for national ecosystem service mapping. The project sought to identify indicators that were appropriate for quantifying ecosystem service supply and demand, and document how they related to different habitats and their associated characteristics.

The mapping tool used was SENCE (Spatial Evidence for Natural Capital Evaluation), which was selected primarily for its ability to be manipulated to accept a wide range of data sources at different scales and its ability to deliver outputs for a variety of ecosystem services. It is a GIS system, which allows for stakeholder weighting to be applied and, therefore, local knowledge to be included. The tool was used to model selected ecosystem services to create maps of services including:

- Land temporarily storing water.
- Areas of land promoting good water quality
- Vegetation carbon
- Soil carbon
- Terrestrial food
- Terrestrial biodiversity: Habitats, management, ecological networks, and species

Parker *et al*. (2016) reported that the mapping and assessment work relied on the use of 'indicators' or 'surrogate' measures that could be used to quantify provision in a more indirect way. Information was brought together using a geoinformatics approach that considered the available data both spatially and quantitatively using a scientific 'rule-base' system based on scientific literature and local knowledge. This enabled bespoke maps to be developed which illustrated the spatial variation in service provision.

The map for the ecosystem service regulation of water quality is shown in **Figure 24**. The map was created using information on soil type from the Teagasc national soils and subsoils datasets, landform in terms of slope angle, and habitats from the derived habitat map. It used scientific knowledge to model which areas of land were likely to be filtrating water and which areas of land were potentially having an adverse effect by inputting impurities.

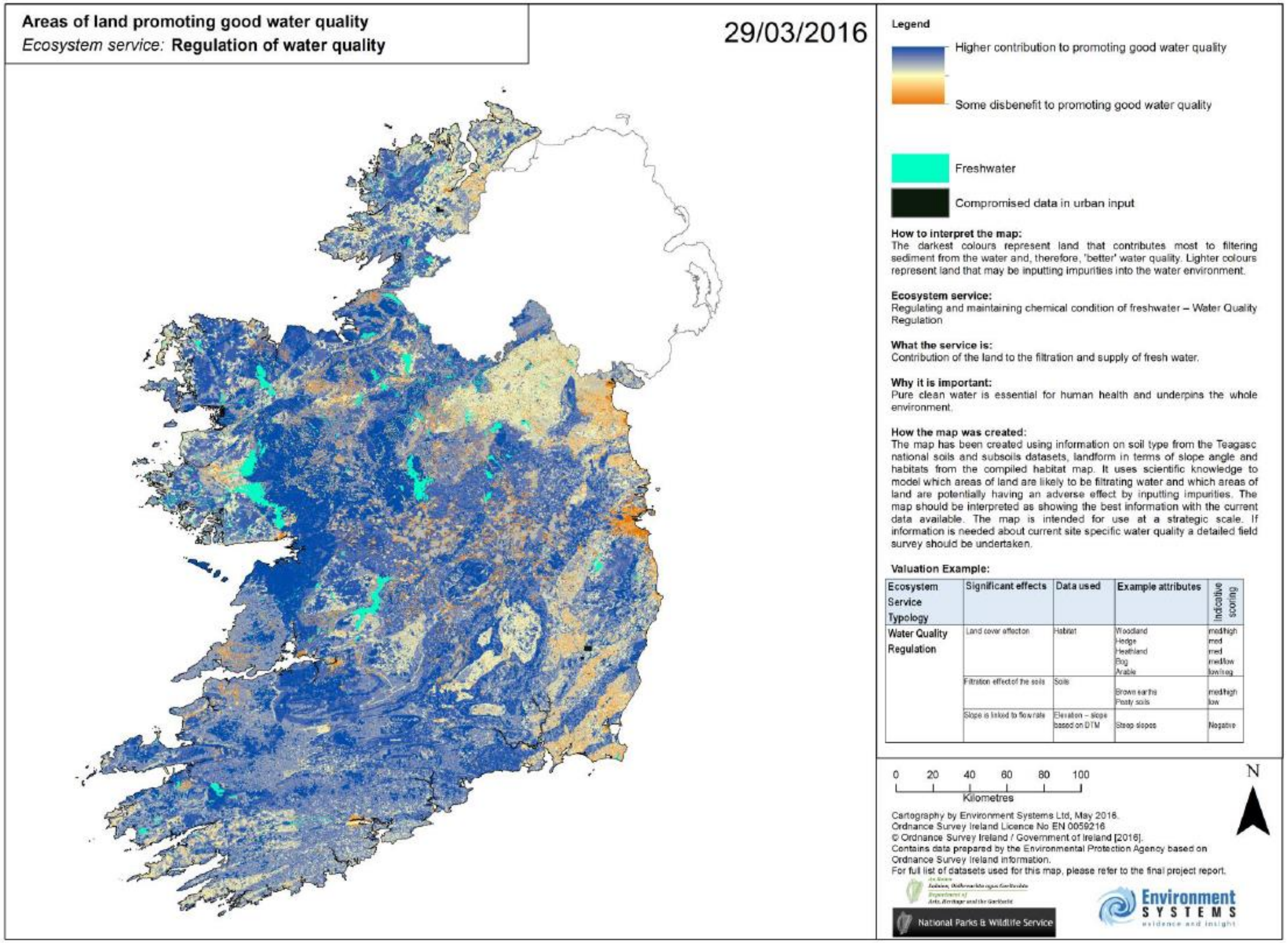


Figure 24. Example ecosystem services map for Ireland (Source: Parker *et al.*, 2016).

Mapping ecosystem services in Portugal

Laporta *et al*. (2021) detailed the methodological and analytical framework developed in the ptMAES (Portugal Mapping and Assessment of Ecosystems and their Services) project to map and assess ecosystem condition and ecosystem service supply. Also, to explore spatial relationships between ecosystem condition and service supply, and discuss the main challenges and opportunities encountered to inform the implementation of future MAES initiatives in Portugal and other member states.

The methodological framework chosen to map and assess ecosystems' condition and services consisted of a multi-tiered approach (ranging from spatialization of statistical data to analytical modelling), combining methods of varying complexity given data availability. **Figure 25** outlines the approach. All assessments were made on the most detailed land use class data available; four broad classes (agriculture, agroforestry, forest, shrubland) with 59 sub-classes.

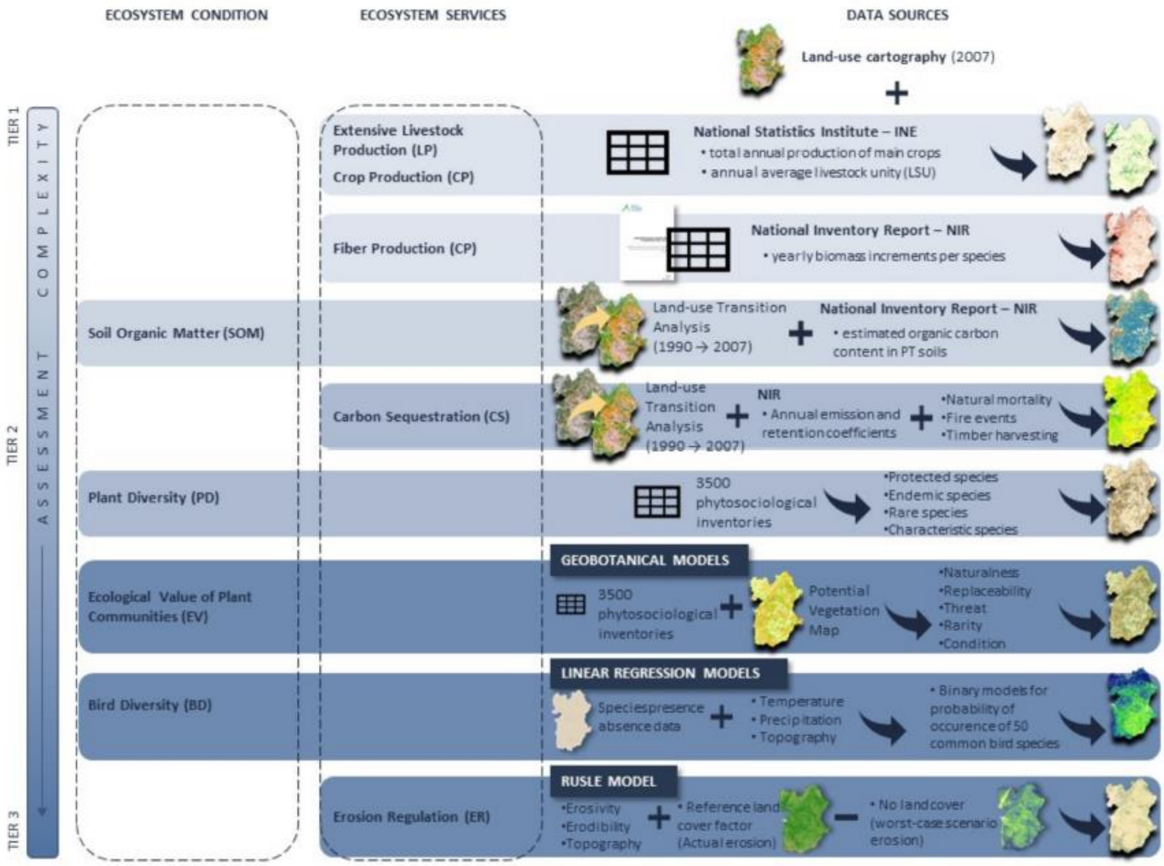


Figure 25. Methodological overview of process used to map ecosystem conditions and service supply capacity (Source: Laporta *et al*., 2021).

Mapped ecosystem condition indicators (**Figure 26**) were:

1. Soil organic matter (tonne Carbon/hectare/year),
2. Ecological value of plant communities (semi-quantitative score 1-5),
3. Plant diversity (semi-quantitative score 1-5) and
4. Bird diversity (semi-quantitative score 1-50).

Five ecosystem services (**Figure 27**) were quantified and mapped:

1. Crop production (t/ha/year),
2. Livestock production (livestock unit/ha/year),
3. Fibre production (m3/ha/year),
4. Carbon sequestration (t CO_2/ha/year) and
5. Control of erosion rates (t/ha/year).

The authors concluded that ecosystem mapping could provide useful insights to landscape planning at the regional scale, for instance, red-flagging areas where service supply might be unsustainable over time. However, they also identified several caveats:

1. Data availability (in terms of aggregation, scale, and coverage) limited the inclusion of process-based modelling.
2. Refinement of results could be achieved with the use of information collected by the public administration if data protection issues were overcome.
3. A wider range of ecosystem condition indicators and ecosystem services should be considered (particularly cultural services); and
4. The selection of ecosystem condition indicators should better reflect their relationship to ecosystem services.

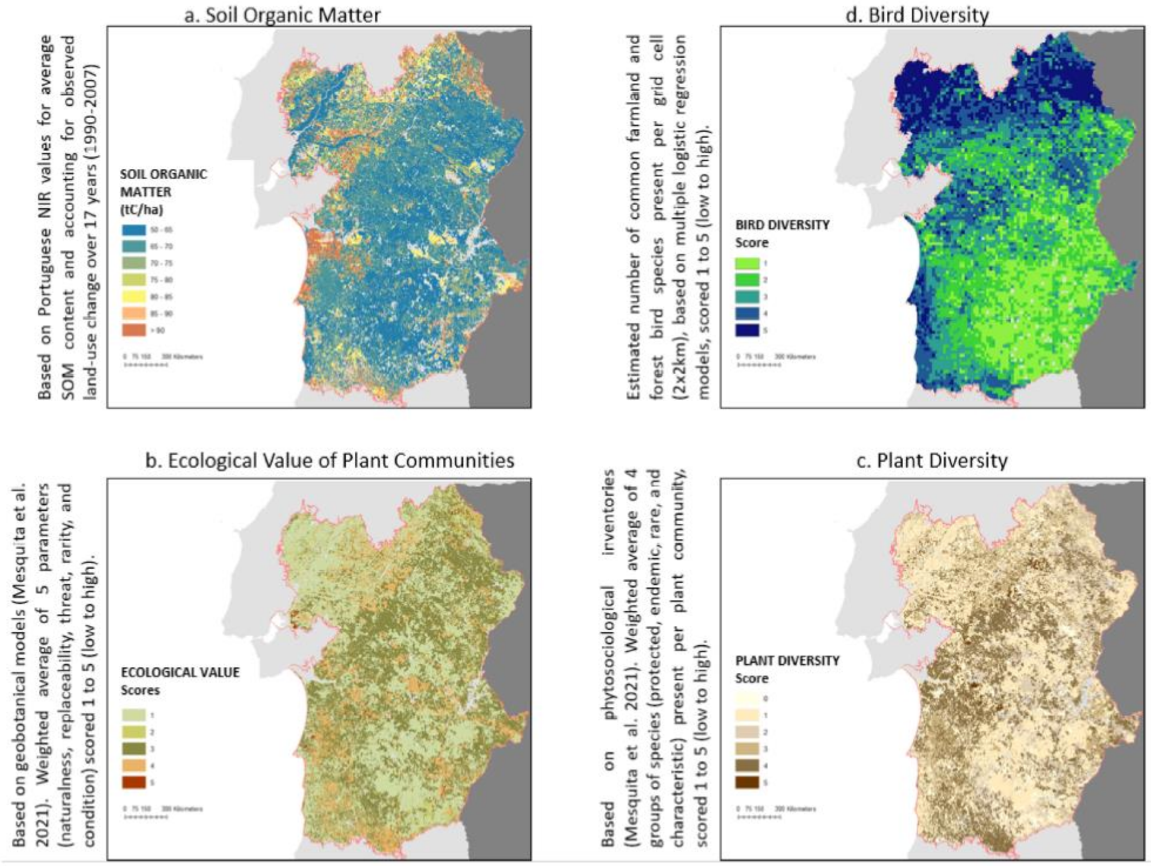


Figure 26. Ecosystem condition: (a) soil organic matter (b) ecological value of plant communities, (c) plant diversity and (d) bird diversity (Source: Laporta *et al.*, 2021).

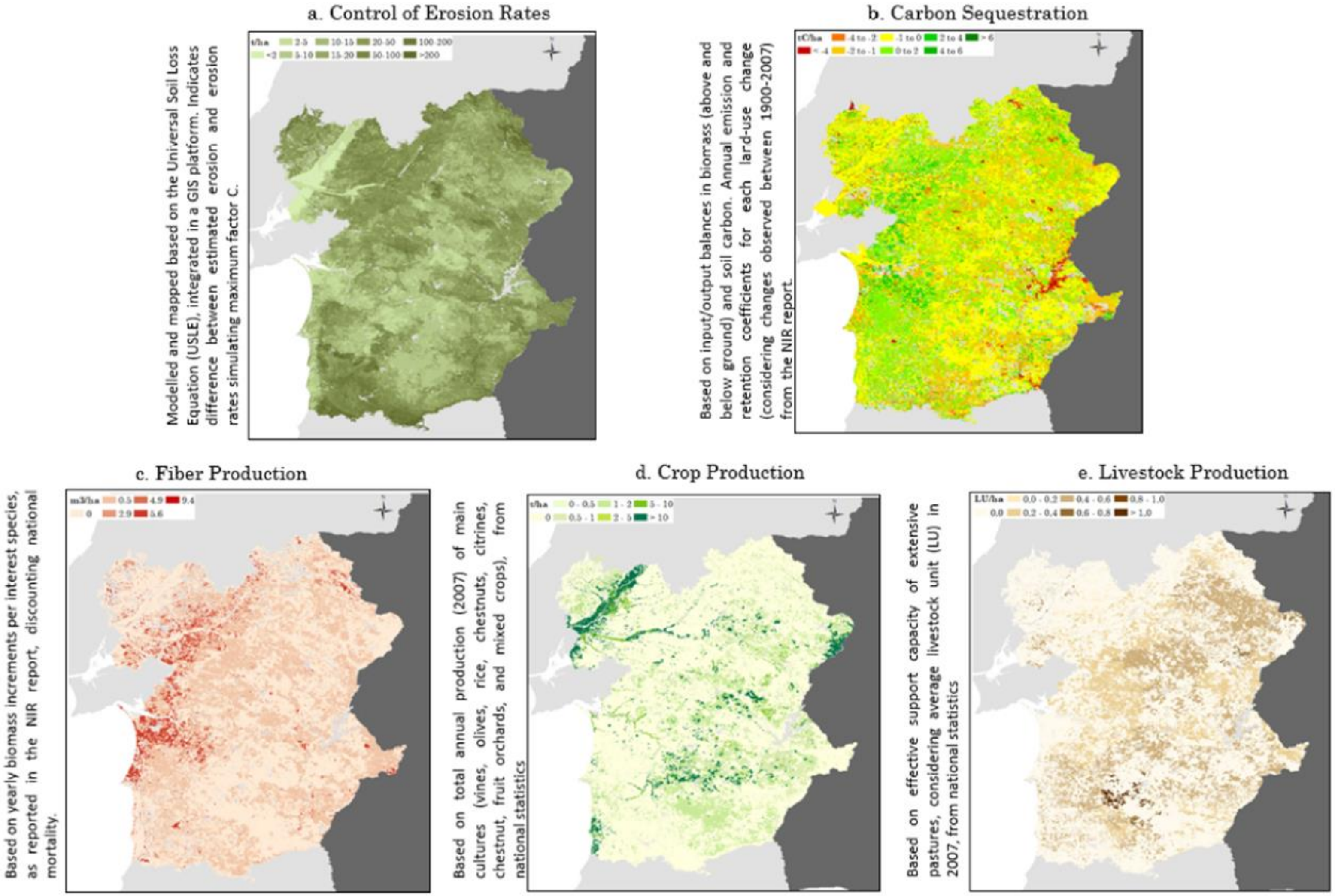


Figure 27. Ecosystem service supply for (a) control of erosion rates (b) carbon sequestration, (c) fibre, (d) crop and (e) livestock production (Source: Laporta *et al*., 2021).

Modelling ecosystem services in Italy

Rovai *et al*. (2023) proposed a method for mapping and bundling the supply of five ecosystem services produced in agricultural and forest areas, based on the processing of open-source data through the analytic hierarchy process (AHP). The method integrated the land use and land cover map with other data to obtain a comprehensive ecosystem service assessment, and then used cluster analysis to identify bundles of ecosystem services, **Figure 28**. The authors concluded that based on a first trial, the method showed potential as a Decision Support System to promote innovative governance models for ecosystem services management.

With multi-criteria analysis techniques, a set of relevant criteria is identified for comparing, evaluating, and ordering different alternatives. The chosen criteria are weighted according to the preferences of the decision-makers. Likewise, the alternatives are also weighted for each criterion. Once an ordering of the criteria and an ordering of the alternatives for each criterion have been obtained, they are re-aggregated into a single general ordering of preference of alternatives.

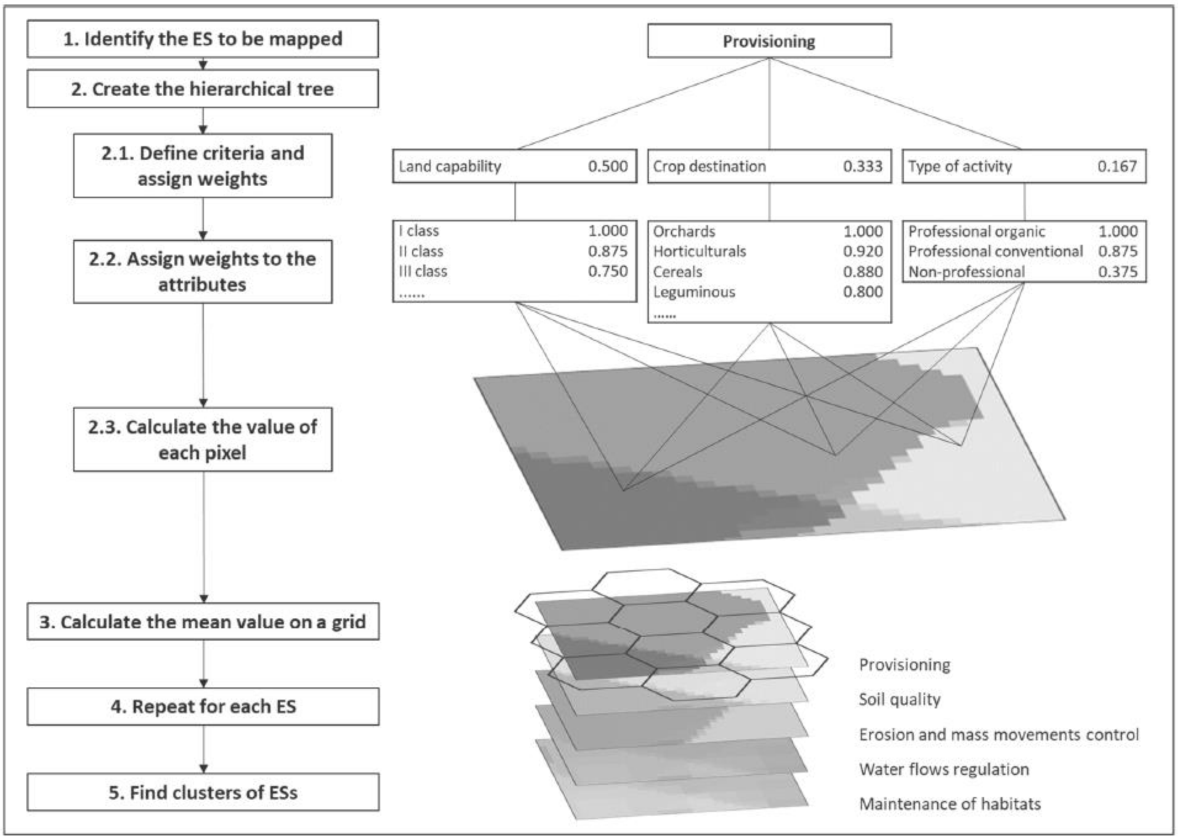


Figure 28. Flowchart of the process of ecosystem services mapping and example for the provisioning service (Source: Rovai *et al.*, 2023).

Rovai *et al*. (2023) mapped the following ecosystem services (**Figure 29**), based on the process described in **Figure 28**:

- Provisioning of food, fibres and other materials, plants for energy, and reared animals.
- Soil quality

- Erosion control and attenuation of mass movements.
- Water flows regulations
- Maintenance of habitats.

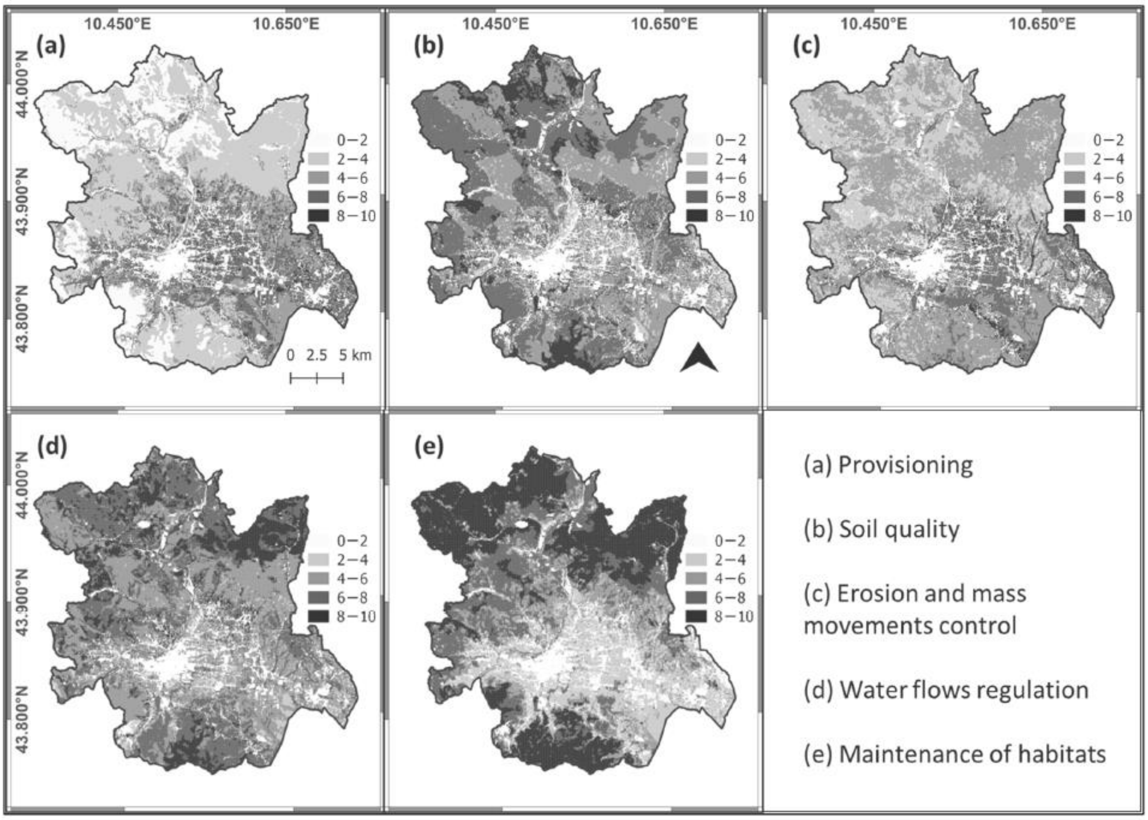


Figure 29. Ecosystem services maps (Source: Rovai *et al.*, 2023).

Using the ecosystem maps and cluster analysis Rovai *et al*. (2023) characterized the areas according to six ecosystem bundles that synthesized the capacity of different areas to supply different combinations of the five mapped ecosystem services, **Figure 30**. For example, bundle B1 accounted for 19.4% of the area and was characterized by a high capacity for provisioning service (6.9), due to a high level of agricultural activity, and by a good capacity for the erosion and mass movements control service (5.9), due to its topography. However, it was characterized by a lower supply capacity for the other regulating services considered: soil quality (4.6), water flows regulation (5.1), and maintenance of habitats (3.0). In comparison, bundle B2 accounted for 10.3% of the area total surface; these areas were characterized by a lower capacity for provisioning service (5.8), but by a higher capacity for the maintenance of habitats service (5.0) and by a good capacity for the other regulating services: soil quality (6.6), erosion and mass movements control (6.9), and water flows regulation (6.8). These areas were, therefore, those with the most balanced supply of the five ecosystem services mapped.

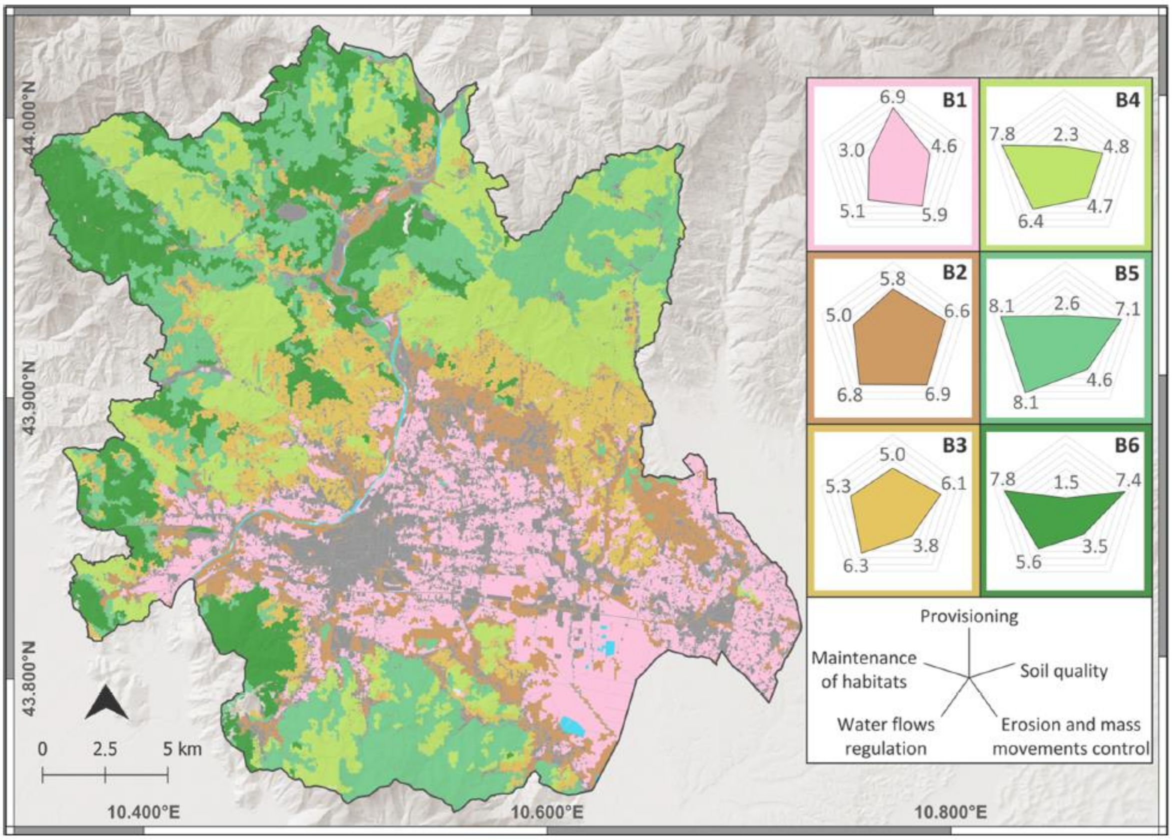


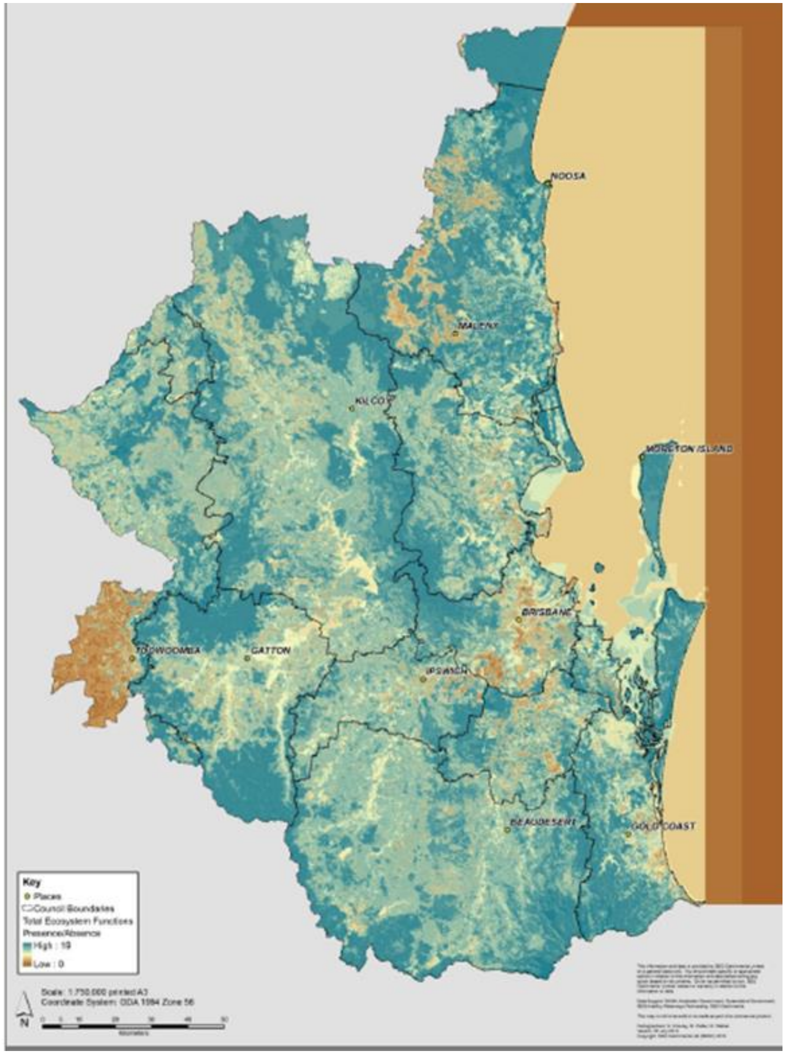
Figure 30. Ecosystem services bundles (Source: Rovai *et al.*, 2023).

Ecosystem services in Australia

Petter *et al*. (2012) developed and trailed a method of mapping ecosystem functions in South East Queensland using biophysical data layers in preference to land use surrogates. Biophysical data and surrogates were identified for 19 ecosystem functions and maps were produced for each. To develop the individual function maps, each of the data sets was standardized to produce a common currency to facilitate the overlaying process within the GIS environment. The aim of this standardization process was to reduce each data set to a “absence” or “presence” (0 or 1) and to ensure all data sets were at a consistent scale (25 m x 25 m grid). Two methods of standardization were applied, A. Expert advice and B. Quartile splits of numeric data, producing data with scores from 1 to 4 which were subsequently reclassified to 0 absent (scores of 1 and 2 from the quartile splits) or ‘1’ present (scores of 3 and 4 from the quartile splits). The 19 ecosystem function maps were produced by overlaying the selected suite of standardized data sets to produce extent maps for each ecosystem function. Total ecosystem function maps were produced by overlaying all 19 function maps resulting in maps with a data range of 0 to 19 and 0 to 76 for methods A and B respectively (**Figure 31**). Areas of high and low function overlap were similar in both maps but more defined in the quartile map given the larger data range.

The authors reported that the method produced maps that planners and decision makers considered credible and resulted in an ecosystem services framework (the SEQ Ecosystem Services Framework) being embedded in a statutory planning document and being used to influence planning decisions at a local government level. They noted that the ecosystem function maps were integral to the identification and measuring of ecosystem services to support this policy.

a


NOOSA
MALENY
KILCOY
MORETON ISLAND
BRISBANE
TOOWOOMBA
GATTON
IPSWICH
BEAUDESERT
GOLD COAST
Key
Places
Council Boundaries
Total Ecosystem Functions
Presence/Absence
High : 19
Low : 0
Scale: 1:750,000 printed A3
Coordinate System: GDA 1994 Zone 56
N
0 5 10 20 30 40 50
Kilometers

b

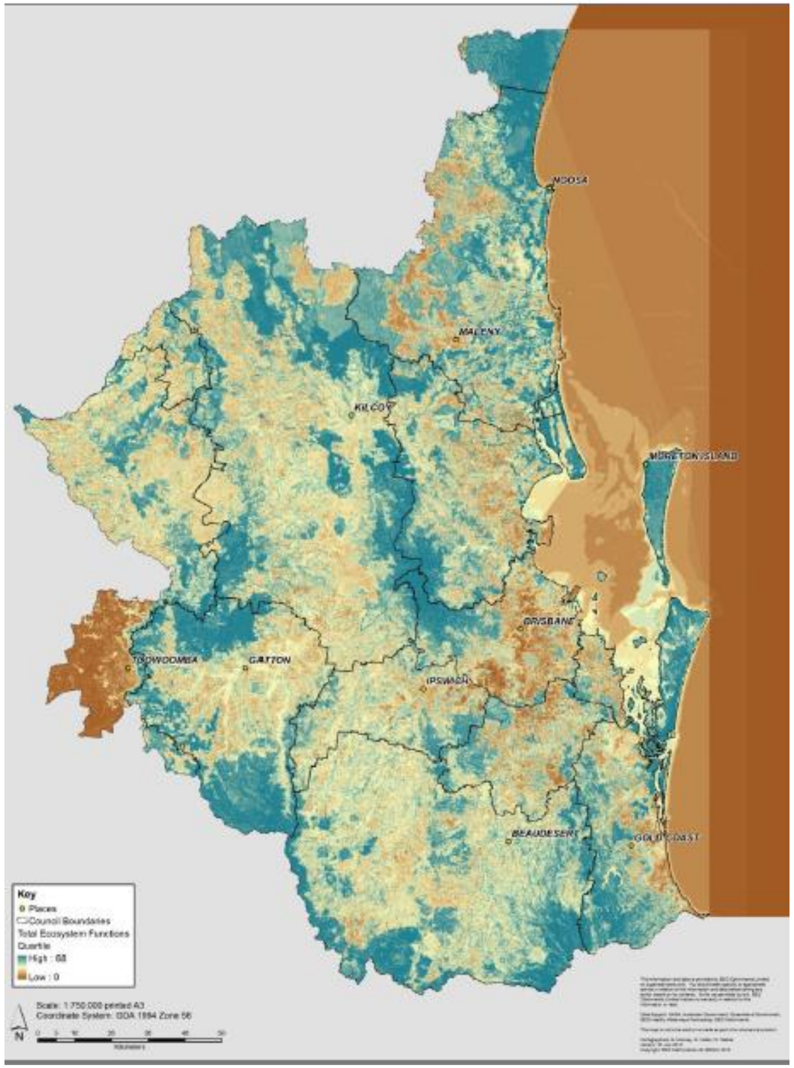

NOOSA
MALENY
KILCOY
MORETON ISLAND
BRISBANE
TOOWOOMBA
GATTON
IPSWICH
BEAUDESERT
GOLD COAST
Key
Places
Council Boundaries
Total Ecosystem Functions
Quartile
High : 68
Low : 0
Scale: 1:750,000 printed A3
Coordinate System: GDA 1994 Zone 56
N
0 5 10 20 30 40 50
Kilometers

Figure 31. Output Map of Total Ecosystem Function, a. simple overlap and b. quantile overlap. (Source: Petter *et al*., 2012)

Effect maps

Maps of ecosystem services typically indicate the state of the natural capital that underpins their provision, rather than how it responds to management (Maseyk *et al*., 2017). However, managing natural capital and ecosystems services sustainably requires an understanding of how changes in key predictors ('drivers') acting at local and landscape scales affect natural capital. An understanding of where natural capital and ecosystem services respond to particular drivers should allow appropriate targeting of management practices (Rieb *et al*., 2017).

Spake *et al*. (2019) outlined a generally applicable analytical framework that achieved this through the creation of 'effect maps' that quantified how the effects of key drivers of ecosystem responses varied across broad geographic extents, **Figure 32**.

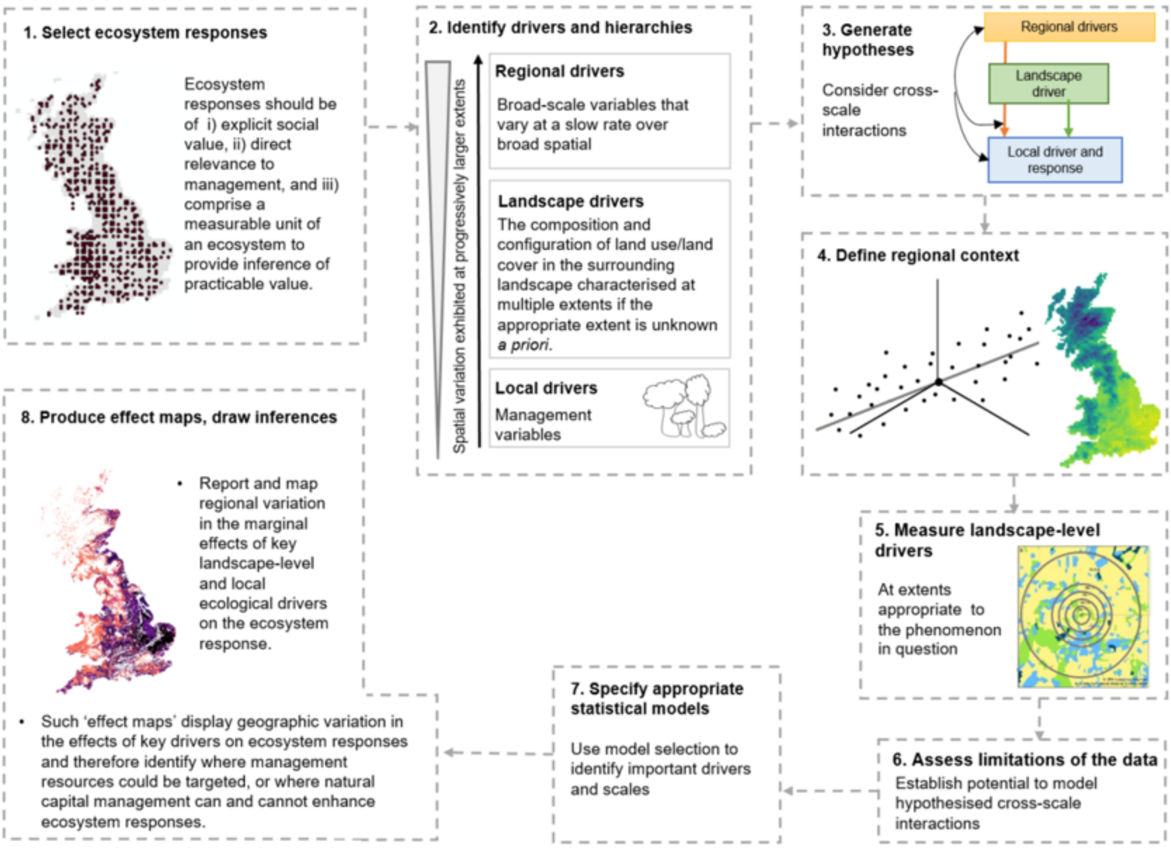


Figure 32. Outline of an analytical framework, which enables the production of effect maps that show how and where to manage natural capital sustainably (Source: Spake *et al*., 2019).

Spatial scale of ecosystem mapping

Previous analysis of practical applications has revealed the significance of the spatial scale at which input data are obtained. This issue is particularly problematic with soil data that is often unavailable or available only at coarse scales or resolutions in various part of the world. Scammacca *et al*. (2022) compared four soil-based ecosystem services, namely biomass provision, water provision, global climate regulation, and water quality regulation using three soil maps at the 1:1,000,000, 1:250,000 and 1:50,000 scales.

The resulting individual and joint ecosystem service maps were compared to examine the effects of changing the spatial scale of soil data on the ecosystem levels and spatial patterns. Scammacca *et al*. (2022) reported that the three soil maps were equally useful when ecosystem service levels were averaged over the whole 100 km^2 territory (**Figure 33**) with average scale effects of *c*.10%. However, the maps at the 1:1,000,000 and 1:250,000 introduced biases in the assessment of ecosystem service levels over spatial units smaller than 100 and 10 km^2, respectively. The simplification of the diversity and spatial distribution of soils at the two coarsest scales resulted in local differences in ecosystem levels ranging from several 10 to several 100%. Scale effects according to relief (plateau, slope or valley), land use (agricultural and natural areas) and municipality are shown in **Figure 34**. The authors noted that it was not straightforward to select the optimal scale to obtain a reliable spatial representation of ecosystem services; the most appropriate scale is likely to be context specific and may vary between ecosystem services.

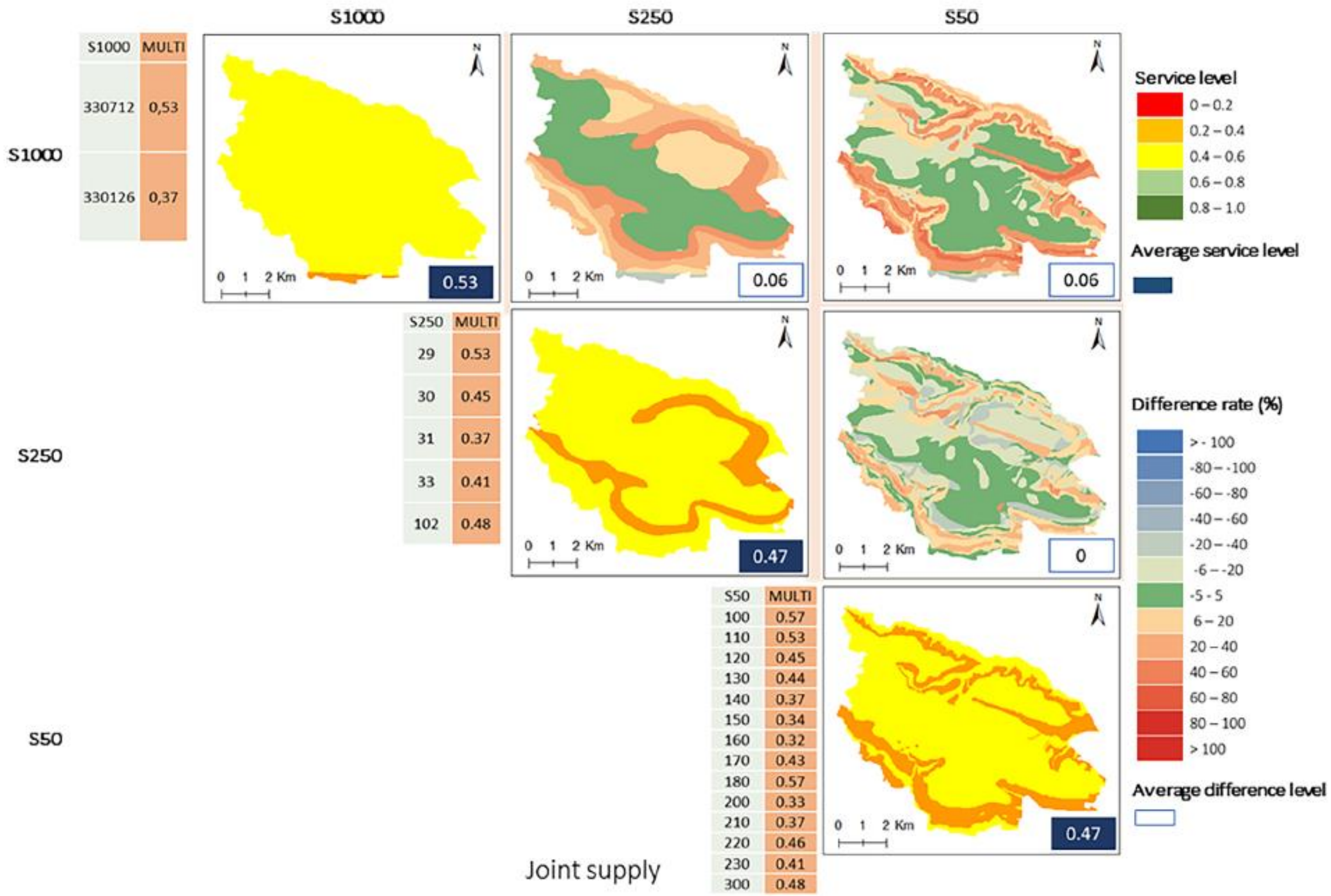


Figure 33. Maps of the spatial co-occurrence of the four selected ESs or joint supply of the four selected ESs according to the different soil maps used as input data (i.e., S1000, S250, S50). Maps at the intersection between similar scales in line and in column are the ES joint-supply maps derived from the soil map at this scale. Maps at the intersection between different scales in lines and in columns represent the relative difference between ES joint-supply maps derived from the soil map at the scale in line minus that at the scale in column. The numbers at the bottom right of these maps are the averaged ES joint-supply or the averaged difference between ES joint-supplies over the whole study area respectively in ES joint-supply map and in ES joint-supply deviation maps. The tables detail the ES joint-supply for each Soil Mapping Unit (SMU) at each spatial scale (Source: Scammacca *et al.*, 2022).

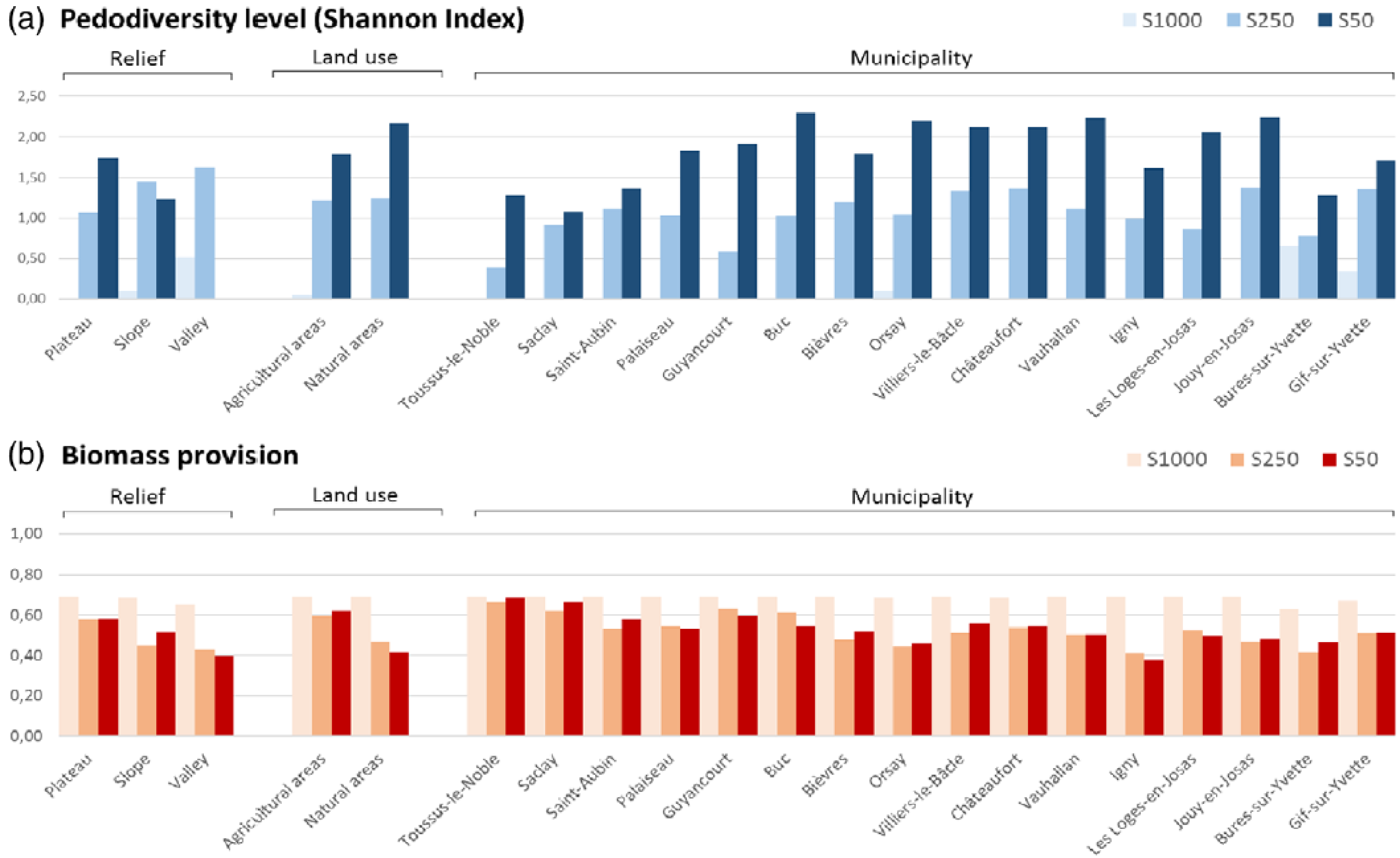


Figure 34. Soil diversity (a) and ecosystem service biomass supply level (b) according to the three soil maps used as input data for the assessment (i.e., S1000, S250 and S50) and the different spatial levels of aggregation (i.e., relief, land use, and municipality) (Source: Scammacca *et al.*, 2022).

Ecosystem services in South Africa

Perschke *et al*. (2023) aimed to develop and apply a broadly applicable, flexible and spatially accurate method for comprehensive ecosystem services mapping using Ecological Infrastructure (EI), called PROSPER. The authors evaluated the demand, flow, and capacity of three ecosystem services (sports events, recreation, and coastal protection) along the South African coast using causal relationships, including ecological condition of the EI, and approximated EI performance as a measure of its importance to society. This resulted in a high-resolution map of EI performance per service and a cumulative map of multiple-service performance created by integrating the three single-service maps.

PROSPER comprised two main steps: 1, identification of the specific EI sites for each service (i.e., where does the service take place); and 2, quantification of the EI performance using models based on causal relationships (i.e., how much flow, capacity and demand is there per service per site). The method used simple, additive indicator models of demand, flow, and capacity for each service based on causal relationships (**Figure 35**). These models are flexible because they can comprise different variables (and components) depending on different contexts, data availability, and service complexity and can be easily adjusted and adapted as needed (Lavorel *et al*., 2017).

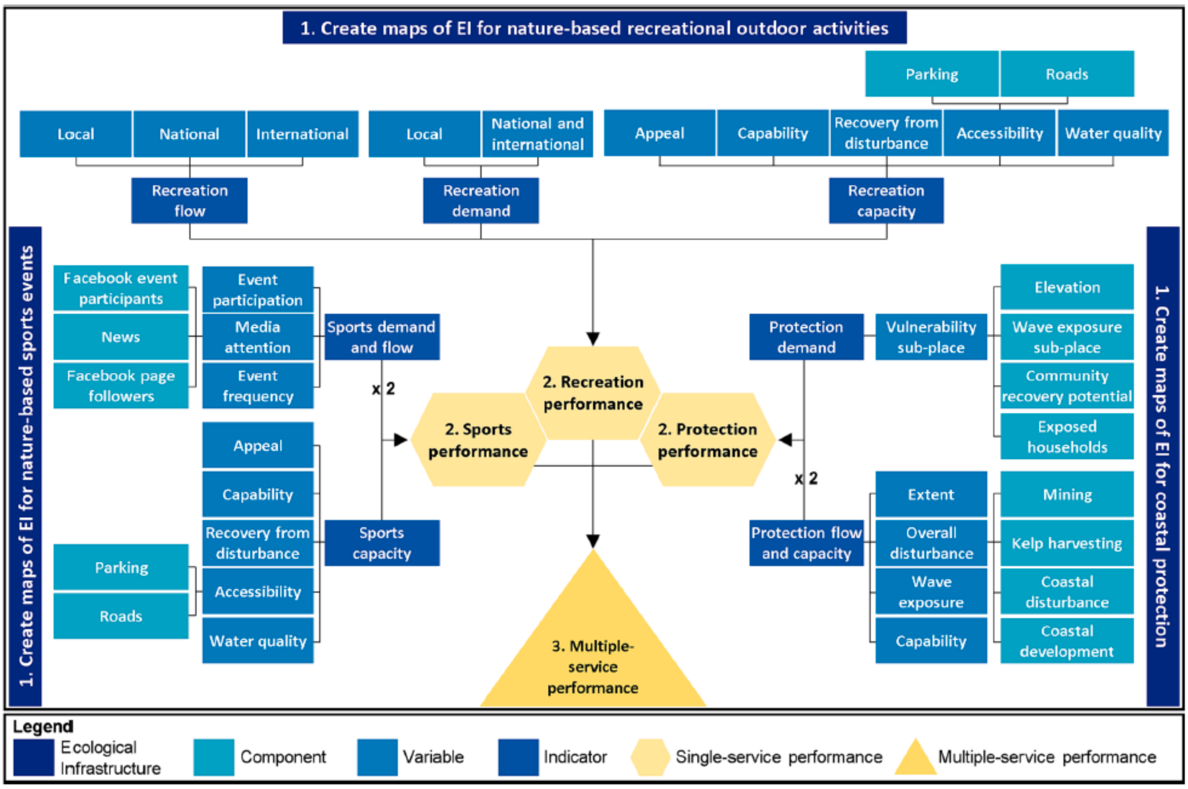


Figure 35. Overview of PROSPER. In step 1, maps of Ecological Infrastructure (EI) are created for each ecosystem service, e.g., nature-based recreational outdoor activities (recreation); nature-based sports events (sports); and coastal protection from flooding and erosion (protection). In step 2, models based on causal relationships are built from components, variables and indicators to evaluate the performance of the mapped EI per service. In an optional step 3, single-performance values are combined to measure multiple-service performance per EI site. Note that the 'x2' indicates that the indicator is doubled when calculating EI performance because it represents two of the three possible aspects (demand, flow, and capacity) (Source: Perschke *et al*., 2023).

Some ecosystem service mapping/modelling tools

Similar tools to PROSPER exist that also use composite and deterministic modelling approaches. For example: 1) InVEST, which was designed to inform natural resource management at multiple scales (Natural Capital Project[1]); 2) the "Artificial Intelligence for Ecosystem Services" (ARIES) tool, which aimed to create dynamic models of ecosystem service sources, sinks and uses using artificial intelligence to inform management (Bagstad *et al*., 2011); and 3) the "Ecosystem Service Mapping Tool", mainly applied for European ecosystem service mapping and decision making (Zulian *et al*., 2013). The availability of data, study context and aim, and modeller's assumptions and understanding of the modelled concepts resulted in differences between the tools (Seppelt *et al*., 2011; Schulp *et al*., 2014; Boerema *et al*., 2017).

The InVEST model.

InVEST™ is a suite of free, open-source software models used to map and value ecosystem goods and services (Stanford University Natural Capital Project). The toolset includes distinct ecosystem service models designed for terrestrial, freshwater, marine, and coastal ecosystems, as well as several "helper tools" to assist with locating and processing input data and with understanding and visualizing outputs. InVEST models are spatially explicit, using maps 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). The InVEST model has been used in many published papers which are listed on a searchable database.

The ARIES model.

ARIES is an artificially intelligent modeller rather than a single model or collection of models. It adopts a uniform conceptualization of ecosystem services that gives equal emphasis to their production, flow and use by society, while keeping model complexity low enough to enable rapid and inexpensive assessment in many contexts and for multiple services. To improve fit to diverse application contexts, the methodology is assisted by model integration technologies that allow assembly of customized models from a growing model base. By using computer learning and reasoning, model structure may be specialized for each application context without requiring costly expertise.

ARIES chooses ecological process 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. The model can be used to either

[1] Natural Capital Project, 2023. InVEST 3.14.0. Stanford University, University of Minnesota, Chinese Academy of Sciences, The Nature Conservancy, World Wildlife Fund, Stockholm Resilience Centre and the Royal Swedish Academy of Sciences https://storage.googleapis.com/releases.naturalcapitalproject.org/invest-userguide/latest/en/index.html

evaluate and explore (general users with a web browser) or produce data and model (specialised/skilled users); it can be accessed online.

ESTIMAP

The Ecosystem Services Mapping tool (ESTIMAP) is a collection of spatially explicit models to support the mapping and modelling of ecosystem services at European scale (Zulian *et al*., 2013). The main objective of ESTIMAP is to support EU policies with spatial information on where ecosystem services are provided and consumed. It runs a set of spatial operations in a GIS environment to calculate the following indicators:

1. Removal of NO_2 by urban vegetation (ton/ha/year)
2. Capacity of ecosystems to avoid soil erosion (dimensionless indicator between 0 and 1)
3. Coastal protection capacity and demand (dimensionless indicators between 0 and 1)
4. Water retention index (dimensionless indicator between 0 and 10)
5. Pollination potential (dimensionless indicator between 0 and 1)
6. Soil retention (ton/ha/year)
7. Habitat quality based on common birds (dimensionless ratio)
8. Nature-based recreation opportunity spectrum (share of land pixels with varying recreation potential and proximity)
9. Forest carbon potential (percent change relative to 2000)

INCA

A Knowledge Innovation Project (KIP) on an Integrated system for Natural Capital and ecosystem services Accounting (INCA) was set up by the European Commission in 2015 to design and implement an integrated accounting system for ecosystems and their services in the EU, compliant with SEEA (the official standard of ecosystem accounting, the System of Environmental-Economic Accounting). INCA includes the

- *Ecosystem service potential*: quantifies what ecosystems can provide, independently of whether there is a use or not.
- *Ecosystem service demand*: the socio-economic side of ecosystem services
- *Ecosystem service actual flow*. When the ecosystem service potential matches with the ecosystem service demand, a use is generated.

When the ecosystem service potential does not match with the ecosystem service demand, three distinct types of mismatches are identified:

- *Unmet demand*: the absence of ecosystem able to provide the services.
- *Overuse:* the use of the service which exceeds its regeneration or absorption rates
- *Missed flow:* the gap existing between what could be currently provided and what is effectively provided.

The results of the INCA project are available online, although this tool was designed for accounting purposes it also includes an assessment of the biophysical aspects of in tabulated format and via a map viewer (**Figure 36**, **Figure 37**).

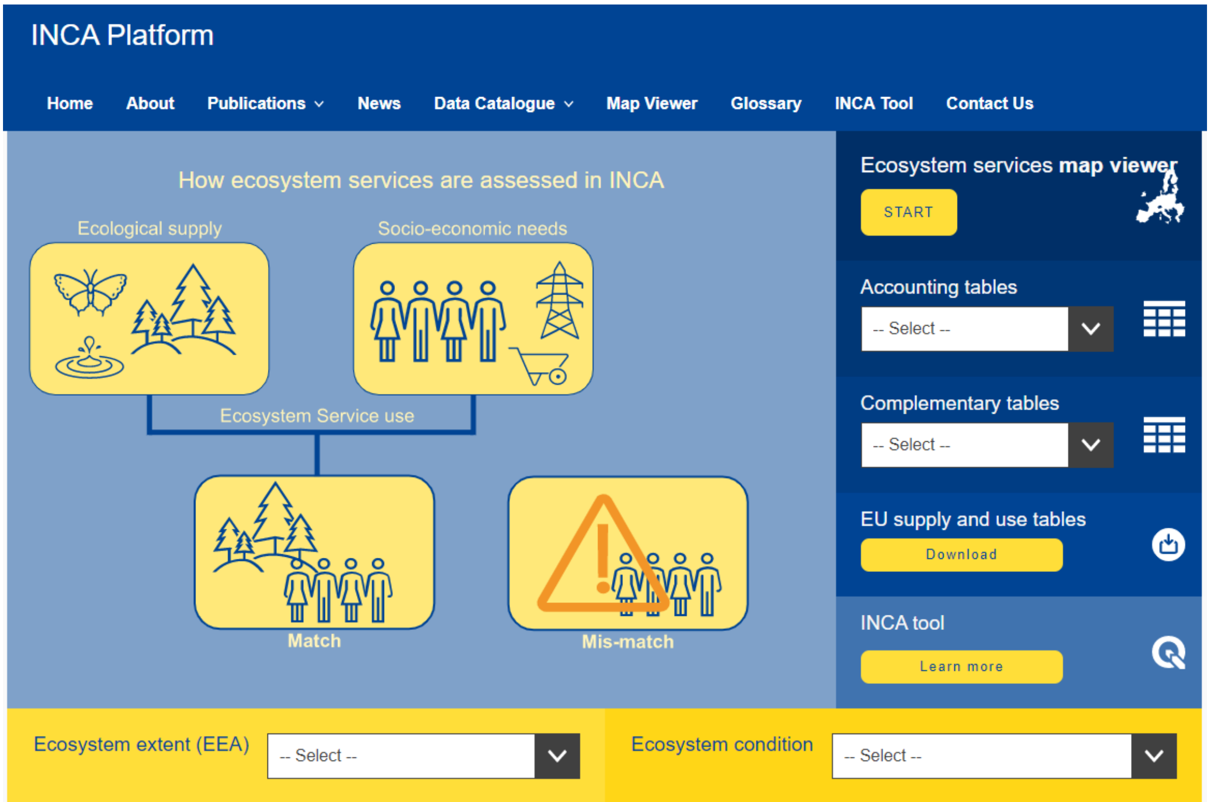


Figure 36. INCA platform home page

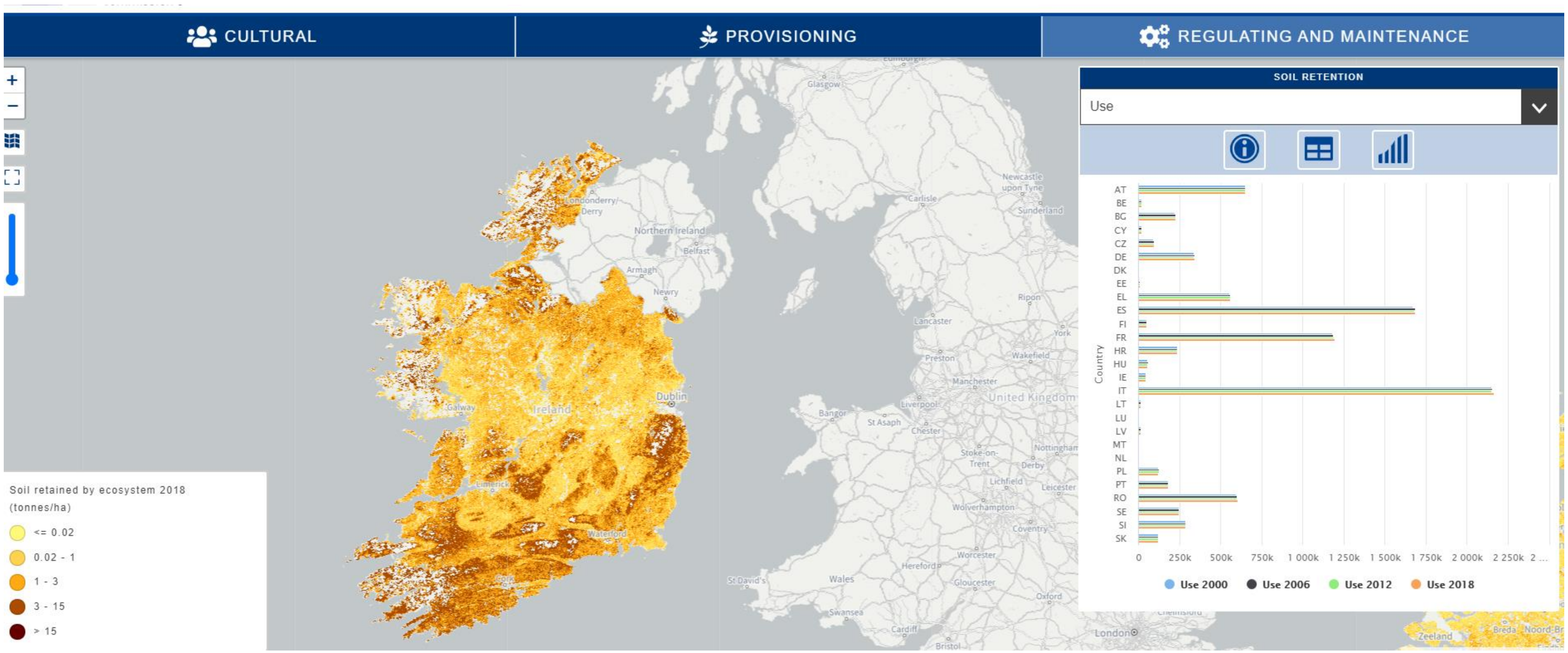


Figure 37. Example map for soil retention tonnes/hectare (category: use) (Source: INCA platform map viewer)

Some constraints to ecosystem service mapping

Bitoun *et al*. (2021) carried out a systematic review of the scientific literature (135 papers published between 2008 and 2020) which revealed diverse technical and conceptual challenges that could prevent the effective use of ecosystem service concepts and methods outside the academic realm. The authors identified two major constraints to the operationalization of ecosystem mapping: (1) the lack of a common language in the field and the diversity of mapping methods; and (2) the insufficient participation of stakeholders in ecosystem study design. They suggested that to increase map usability, paths for improvement are threefold: (1) improving the ease with which new users can map ecosystem services and use existing maps to achieve high performance in decision-making; (2) developing generic indicators customizable to local conditions; and (3) increasing the reproducibility of mapping methods.

As advocated in the FAIR Data Principles, scientific data should be Findable, Accessible, Interoperable, and Reusable (Wilkinson *et al*. 2016). Bitoun *et al*. (2021) suggest that ecosystem mapping methods and tools should follow similar principles to improve their implementation. This could promote the operational, consistent, and replicable use of tools and methods. The authors propose that developing a collaborative open-data Web platform to collect ecosystem maps could be one of the ways to move forward. Such a platform would not only increase the visibility of ecosystem service mapping outputs to decision and policymakers but also allow researchers to identify blank areas where ecosystem service assessments are needed and reveal inconsistencies with other maps to encourage scientific collaboration.

Conclusions and recommendations

Soil ecosystem services

- Soils are fundamental to the delivery of all four categories of ecosystem services, 1) provisioning services (source of raw materials and biomass production) 2) regulating services (e.g. climate, flood regulation or prevention of erosion), 3) cultural (e.g., archaeological archive, aesthetic or recreation) and 4) supporting (e.g. habitat or biodiversity). The range and interaction of different soil properties (e.g., soil texture, depth, structure, stone content, and hydrological regime) influences the types of ecosystem services that different landscapes provide. Land management, climatic and site factors (e.g., altitude, topography) interact with soil properties to further influence the provision of ecosystem services.
- There are several international typologies of ecosystem services, including the Common Internation Classification of Ecosystem Services (CICES), which is often used in the EU. In the CICES ecosystem services are soil related if their supply is directly and quantifiably controlled by soils and their properties, processes and functions. Of the 83 classes of ecosystem services defined in the CICES, Paul *et al.* (2020) identified 29 classes (35%) that were consider soil related. Although, the CICES definition does not include any soil related cultural services.
- Several authors have outlined frameworks to link soil functions and soil ecosystems. These relate inherent (e.g. soil texture, depth, stoniness) and manageable (e.g., nutrient supply, pH, land cover) soil properties, with soil processes (e.g. nutrient or water cycling), external drivers (e.g., land use, climate, farming practices) and ecosystem services.

Mapping soil ecosystem services

- Maps facilitate decision making by providing an efficient way of conveying complex information through visual representation and are useful for spatially explicit prioritisation and problem identification. They are an important communication tool for discussion with stakeholders enabling visualisation of where ecosystem services are produced and/or used.

Mapping of ecosystems services gained prominence in Europe under the EU Biodiversity Strategy to 2020 (EU, 2011), which established a framework for mapping based on linkages between ecosystems and socio-economic systems. To effectively support decision making maps should be robust, transparent and stakeholder relevant (Wileman *et al*., 2015).

- Mapping ecosystem services facilitates an understanding of not only how much of a service is provided but the spatial distribution of that service. Maps can be used to identify where ecosystem services are provided/used, in decision-making (e.g. planning) relating to the exploitation of services, in ecosystem valuation, to communicate with stakeholders and to determine synergies and trade-offs between ecosystem services.
- Mapping approaches have been grouped into five categories, 1) the 'lookup' table (e.g. linking ecosystem services values to land cover classes), 2) expert knowledge, 3) established knowledge of causal relationships between services and spatial information, 4) extrapolation from primary data such as field surveys and 5) quantitative regression and socio-ecological system models. The first two methods are most appropriate if the purpose of the map is to provide an overview of ecosystem services (e.g. presence or absence). In contrast the latter methods may be able to produce maps with a greater degree of precision (depending on data availability).

Datasets

- As part of this project meta data relating to UK, European and global databases of relevance to soil functions and ecosystem services were compiled in accompanying Excel spreadsheets. The spreadsheets described each dataset including its location, authors, content (i.e. types of soil data), spatial extent and resolution, relevance to Wales, data source, availability and useability, methodology, limitations, format and any associated publications.
- Details for >70 potential UK data sources were collated including from the UK Soil Observatory, the Land Information System (LandIS), UKCEH land cover maps and DataMapWales. In addition, meta data relating to another *c*.60 European (from the European Soil Database) and global sources (e.g. harmonized world soil database or the world soil information service) have been collated. The datasets include a range of soil parameters which could potentially be used in the development of ecosystem service maps but do not provide data on the services themselves.

Recommendations

The following factors should be considered when mapping ecosystem services or soil functions:

1. **The primary purpose of the map**. Maps are an efficient way to convey complex information that varies spatially. Detailed or more complex maps are not necessarily more effective. A map that is intended to give a general overview of the distribution of ecosystem services (e.g. presence or abundance) will need much less detail than one intended to evaluate the impact of a specific management measure on ecosystem service delivery.
2. **Mapping methodology**. Five broad categories of mapping approach have been described in the literature (for more details see Section 0 and **Figure 14**):
    i. The lookup table. A simple and widely used approach that directly links ecosystem services to geographic information. The most common are land cover data which can be used as proxies for the supply of (or demand for) different ecosystem services. An example of a lookup table approach would be to derive an ecosystem service from statistics such as crop yield for agricultural production (for more details see Section 0 and **Figure 15**).

ii. Expert knowledge. Approaches, that mainly relying on expert knowledge include estimates of ecosystem values in lookup tables but also other methods such as Delphi surveys (an iterative multistage process designed to transform opinion into group consensus).
iii. Causal relationships. An approach that estimates ecosystem services based on well-known relationships between services and spatial information from literature or statistics. For example, timber production can be estimated using harvesting statistics for different areas, elevations and forest types provided in a national forest inventory.
iv. Extrapolation from primary data. Approaches that estimate ecosystem services extrapolated from primary data such as field surveys linked to spatial information.
v. Quantitative regression and socio-ecological system models. Approaches that combine field data of ecosystem services as well as information from literature linked to spatial data.

3. **Data availability, quality and reliability**. One of the key constraints to successful mapping can be the lack of reliable up-to-date data. Primary data are often used to map provisioning services, e.g., food or fibre supply whereas many regulating, supporting and cultural services often rely on proxies for their quantification. Where it is necessary to use indicators or proxies these should be based on well-established scientific evidence and known links between the proxy and the service or function being mapped. Pedotransfer functions (i.e. (functions that predict secondary soil properties from measured properties) can be used but their applicability in specific settings should be assessed (many will have been determined under specific soil or environmental conditions). Alternatively, 'expert opinion' can be used to define links between functions and services, but the limitations of subjective data should be acknowledged. The minimum reliability, accuracy, resolution and clarity of the map should be determined.
4. **The end users of the map**. The complexity of the map should be appropriate for the stakeholders that will be using the information it contains. Well-designed maps and user interfaces ensure that maps are easy to interpret and a useful tool for visualising the location of soil functions or ecosystem services. For example, stakeholders found a simple map produced by Smith and Dunford (2018), largely based on expert judgement, very useful to demonstrate the provision of ecosystem services at a local level (see Section 0 and **Figure 21** for more details).
5. **The scale and geographic area of the map**. The selection of an appropriate area to map is important because soil functions and ecosystems services can operate at different scales. The goal of the map (i.e., the question it is intended to help answer) or the soil function or ecosystem service being mapped, will determine the geographic extent. This can range from the field or farm, through to administrative areas, counties, regions, national, international or global coverage. In addition, to the spatial extent of the map it is also necessary to choose an appropriate scale. A coarse scale dataset may be suitable for national or regional scale, but a finer resolution may be appropriate at the local scale. The scale of the map should match the scale at which relevant decisions are made; fine scale maps can assess the effect of changes in land management at a local scale whereas coarser scale maps are appropriate for use in national land use policy decision making. There may be some trade-offs between scales, accuracy and feasibility. For example, Scammacca *et al*. (2022) compared four soil-based ecosystem services using three soil maps at the 1:1,000,000, 1:250,000 and 1:50,000 scales to examine the effects of changing the spatial scale of soil data. They found that the three soil maps were equally useful when ecosystem service levels were averaged over a

large area (100 km^2) with average scale effects of *c*.10%. However, the maps at scales of 1:1,000,000 and 1:250,000 introduced biases in the assessment of ecosystem service levels over spatial units smaller than 100 and 10 km^2, respectively. The simplification of the diversity and spatial distribution of soils at the two coarsest scales resulted in local differences in ecosystem service levels ranging from several 10 to several 100% (for more details see 0, **Figure 33** and **Figure 34**).

6. **Ecosystem supply and demand. When mapping soil ecosystem services, the capacity for service provision and the level of services provided are important as well as the demand for those services.** For example, Butlin *et al*. (2015) used a four-step mapping approach to assess noise absorption of green infrastructure. The four maps were used to 1) identify the type of green infrastructure, 2) quantify the amount of noise abatement supplied by that green infrastructure, 3) identify demand for noise abatement and 4) identify areas where demand was met or not met (for more details see Section 1.1.1 and **Figure 20**).
7. **Requirement for a baseline.** A baseline represents the initial conditions or ecosystem service provision. It provides a starting point against which changes over time and space can be monitored over the short or long term or against which targets can be set. Where data exists, the baseline could be based on past data to identify changes up to the current date.
8. **Interactions between ecosystems or soil functions**. Most ecosystems can deliver more than one ecosystem service. However, in some situations not all services can be delivered simultaneously resulting in trade-offs which can change the type, extent and mix of services delivered by an ecosystem. For example, Rovai *et al*. (2023) mapped five ecosystem services (provisioning, soil quality, erosion and mass movement controls, water flows regulation and maintenance of habitats) using cluster analysis. For each service, a score of between 0 (low supply) and 10 (high supply) was allocated. The cluster analysis identified and mapped six 'ecosystem service bundles' that were homogeneous in terms of capacity to provide specific combinations of the five mapped ecosystem services. The resulting map (and accompanying radar graphs) allowed the identification of areas with balanced or unbalanced supply of the five ecosystem services (for more details see Section 0 and **Figure 30**).
9. **Estimates of uncertainty and accuracy.** Almost all maps present outputs from models, which (like the maps themselves) are simplifications of reality. Best mapping practices are explicit in describing model assumptions, underlying data and model approaches, and state the purpose of map creation (Willemen *et al.,* 2015). Model validation processes can include, experts, cross validation with other models, comparison with other models and/or validation with primary or field data.

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