Biophysical Mapping and Assessment Methods for Ecosystem Services

Deliverable D3.3

Biophysical Mapping and Assessment Methods for Ecosystem Services

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ESMERALDA

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Preface

Mapping and assessment of ecosystems and their services (ES) are core component to the EU Biodiversity (BD) Strategy. They are essential if we are to make informed decisions. Action 5 sets the requirement for an EU-wide knowledge base designed to be: a primary data source for developing Europe's green infrastructure; resource to identify areas for ecosystem restoration; and, a baseline against which the goal of 'no net loss of BD and ES' can be evaluated.

In response to these requirements, ESMERALDA (Enhancing ecoSysteM sERvices mApping for poLicy and Decision mAking) aims to deliver a flexible methodology to provide the building blocks for pan-European and regional assessments. The work will ensure the timely delivery to EU member states in relation to Action 5 of the BD Strategy, supporting the needs of assessments in relation to the requirements for planning, agriculture, climate, water and nature policy. This methodology will build on existing ES projects and databases (i.e. MAES, OpenNESS, OPERAs, national studies), the Millennium Assessment (MA) and TEEB. ESMERALDA will identify relevant stakeholders and take stock of their requirements at EU, national and regional levels.

The objective of ESMERALDA is to share experience through an active process of dialogue and knowledge co-creation that will enable participants to achieve the Action 5 aims. The flexible methodology proposed will integrate biophysical, social and economic mapping and assessment methods. ESMERALDA is organized based on six work packages, which are organised through four strands, namely policy, research, application and networking, which reflect the main objectives of the project (Figure 1).

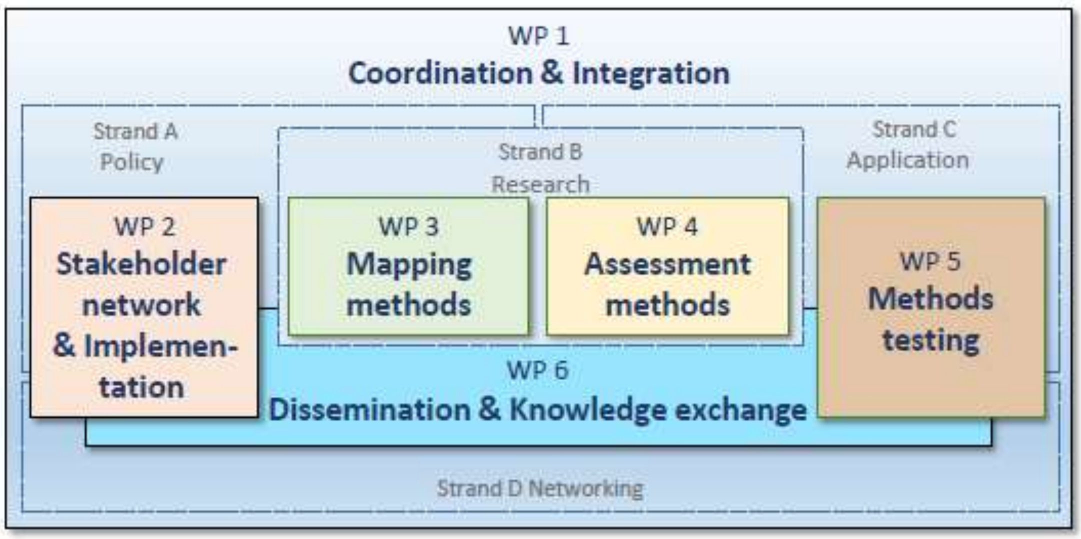


Figure 1: ESMERALDA components and their interrelations and integration within the four project strands.

This report sits within work packages WP 3 “Mapping methods” and WP4 “Assessment Methods”. When making the proposal, the original idea was to investigate similarities and differences when using methods for the mapping and/or assessment of ecosystem services. At the end it was very difficult to make a clear distinction between biophysical methods for mapping and/or assessment methods; there was also potential duplication of material between the two elements. A discussion within the project community, led to the decision to produce only one deliverable on biophysical methods for mapping (WP3) and assessment (WP4) of ecosystem services.

The aims of this report are:

1) to gather the latest knowledge of biophysical mapping and assessment of the ecosystem services, including methods, data, tools, and software commonly used; building on the literature surveys conducted in ESMERALDA and previous projects such as OpenNESS, OPERAs, and the work done under WG MAES pilots for the European Commission;

2) based on the above findings, to suggest a harmonised methodology describing how different biophysical quantification and mapping methods could be used, possibly under a tiered approach; and

3) to give recommendations for how mapping methods could be used for integrated ecosystem assessment (the work done under the WP4 of ESMERALDA) and how these can be implemented in policy-support of different levels of governance.

Summary

This report (D3.3) provides an overview of biophysical mapping and assessment methods for ecosystem services (ES) and their use in ecosystem assessments. It is part of ESMERALDA work package 3, and together with reports of socio-cultural methods (D3.1) and economic methods (D3.2), it describes the key elements of a flexible ecosystem assessment methodology. In addition to these reports, a report on interlinkages between methods (D3.4) will focus on the integration of these different perspectives on ecosystem assessments. The process of mapping ecosystem service values falls within the broader process of ecosystem service assessment. The term “assessment” is defined in the ESMERALDA project as “the analysis and review of information derived from research for the purpose of helping someone in a position of responsibility to evaluate possible actions or think about a problem”.

Mapping and assessment of ecosystems and their services are essential if we are to make informed decisions. The EU Biodiversity Strategy, Action 5 in particular, sets the requirement for an EU-wide knowledge base designed to be: a primary data source for developing Europe’s green infrastructure; resource to identify areas for ecosystem restoration; and, a baseline against which the goal of ‘no net loss of biodiversity and ecosystem services’ can be evaluated. ESMERALDA (Enhancing ecoSysteM sERvices mApping for poLicy and Decision-mAking) aims to deliver a flexible methodology to provide the building blocks for pan-European and regional assessments, and to support MAES (Mapping and assessment of ecosystems and their services) process. The mapping approach will integrate biophysical, social and economic assessment techniques. Flexibility will be achieved by the creation of a tiered methodology that will encompass both simple (Tier 1) and more complex (Tier 3) approaches.

Biophysical quantification and representation of the ES data on maps is fundamental for social and economic mapping and assessment. Both economic and social mapping and assessment can be conducted without precise biophysical quantification for case studies, however reliable biophysical data is required for sustainable use and management of ecosystems, ecosystem services and natural capital accounting at country and EU level. Biophysical data can be gathered either by direct observations and measurements, by indirect methods such as proxies or spatial extrapolation, or by modelling. In practice, multiple different methods are often used together, e.g. via integrated modelling platforms such as InVEST or ARIES, or through purpose-fitted selection of appropriate data and methods.

1. Introduction to biophysical mapping and assessment methods

Ecosystem services (ES) are human derived benefits flowing from the environment; their provision and flow are dependent on the ecological structures and functions, which make up the biophysical environment. When we consider the biophysical quantification of ES, we are in principle operating on the left side of the cascade model (Haines-Young & Potschin 2010, cf. Fig. 2), i.e. measuring ecosystem structure and functioning powered by biodiversity; derived ES benefits can also be described in biophysical terms, for example cover and condition of blueberry populations in the boreal forests and their yearly berry yield (structure and functions of ES) versus harvest (benefit & value of ES).

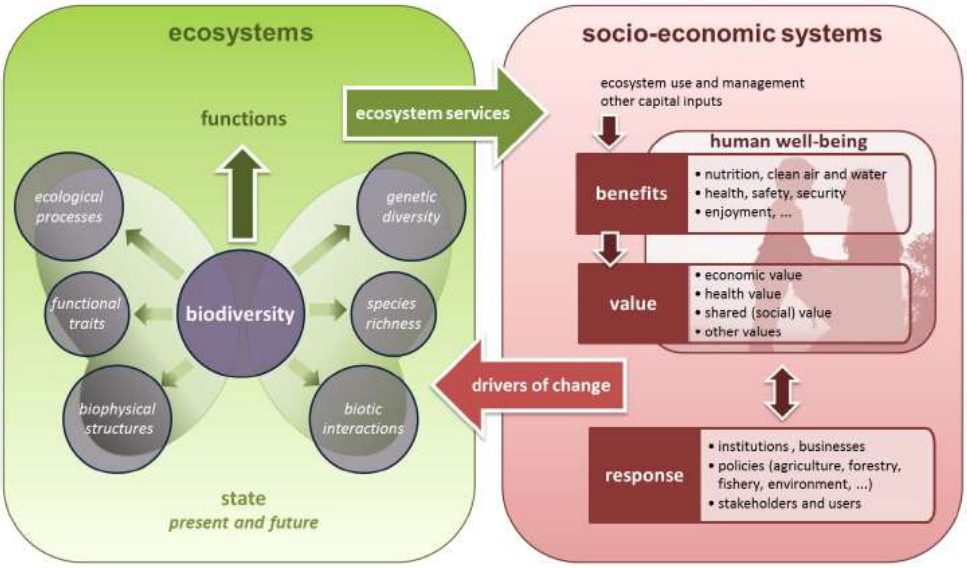


Figure 2. Conceptual framework for EU wide ecosystem assessments.

Biophysical methods for mapping ecosystem services are used to quantify ecosystems' capacity to deliver ecosystem services (also referred to as "supply") and the amount of harvested yield of such capacity for human benefit (also referred to as "use" or "demand"). Biophysical measures are closely related to the methods, and are often used as input data to social and economic mapping methods, and form the basis for natural capital accounting. There are also slight differences when discussing biophysical *quantification*, *mapping* or *assessment* (cf. Glossary D1.4 – Potschin-Young et al., 2018). Methods for these are numerous due to varying features of different ES. However, before they can be applied, indicators (or proxies) for quantification are needed (Fig 2). Different methods can also be linked to the tiered approach developed in the ESMERALDA project (cf. section 5). The basic idea of the tiered approach is to have either a light and fast method, or a more detailed and comprehensive approach to map ecosystem services, depending on the outputs needed for the different decision-making purposes. Variation in the methods used can also help to assess and decrease the levels of uncertainty they have.

There has been considerable development in conceptual and methodological approaches over the last couple of years. For example, projects such as OPERAs[1] and OpenNESS[2] have improved our understanding of various quantification methods and operationalisation of ecosystem services, while ESMERALDA focuses more on mapping methods and integrated ecosystem assessment. In the OpenNESS project for example, 25 potential models or methods were identified, of which six were selected for use in the case studies of the project (Harrison & Dunford 2015; Dunford et al. 2017, Harrison et al. 2017). These six models were spreadsheet-type methods, ESTIMAP, Bayesian Belief Networks, State and Transition Models, QUICKScan, and InVEST. In the OPERAs project, models were classified based on their ecologically relevant similarities, e.g. ability to describe structure or function (Lavorel et al. 2014). In the ESMERALDA project, more than 90 different models or methods were identified in the scientific literature, which describe ES quantification. The identification of these models helped to build up a wider picture of the different methods used, and to compare how these were classified.

Biophysical quantification is built on spatial and temporal measures of ecosystem processes; while their extent and timing may vary a lot depending on the ES studied. Sometimes it is easier to use proxies for ES supply, such as ecological structure parameters. These proxies can be static, and easily measured and updated based on the observed change of the proxy parameter. For example, land cover or land use can be used to assess and quantify the ES (see Box 1). In addition to assessment of ES by biophysical quantification, the condition of ecosystem structure or function may also affect ES delivery and therefore also needs assessment. Land cover changes can alter the entire flow of ecosystem services, including from changes in the state and amount of habitats, and the realisation of benefits derived from them. Simply put, biophysical quantification approaches describe the delivery of certain ES by using direct measurements and practical units which can vary depending on the ES studied. For instance, standing stock and yearly increment in timber stocks can be measured in cubic metres at the selected study site (area). Information received from direct measurements can be extrapolated or modelled over the gap areas. Quite often it is impossible to use direct measurements for biophysical quantification for wide areas, due to limited resources or lack of data. In those cases, it is necessary to consider various mapping and modelling methods to quantify ES over the desired spatial scale.

Quantification of ecosystem services is a prerequisite of understanding their cascading values for society. Biophysical methods for assessing ecosystem services should help to assess their level of sustainable use, and the provision of this information to support decision-making. The assessment of ES needs to consider both the condition of the ecosystem (structure and function) and empirical (and also historical) levels of sustainable use.

[1] http://www.operas-project.eu/
[2] http://www.openness-project.eu/

2. Frameworks for biophysical mapping and assessment and the key concepts

The main aim of ESMERALDA is to develop "a flexible methodology for mapping and assessment of ecosystems and their services". The different steps of the methodology can be characterised with the guiding questions: ***What to measure? How to measure? How to map? How to assess on the basis of biophysical information?*** Here we suggest a workflow that will address these questions. The three stages in this process (focused on biophysical aspects) are: 1) ***quantification*** of ecosystem services, 2) ***mapping*** of ecosystem services, and 3) ***assessment*** of ecosystem services where biophysical assessment is one part of a wider integrated assessment in addition to social and economic parts (that will be comprehensively discussed in the ESMERALDA project's work package 4, see D4.7 – Potschin-Young 2018). Both mapping and assessment of ES are closely linked to each other and thus they both are considered together in this report. During the project it has become clear that defining mapping and assessment methods is often difficult, and separating out the two definitions is not necessary in many cases. However, some methods apply biophysical approaches which belong more closely to decision-support methods (see also section 7, Fig 5). In the following sections we will mainly focus on possible mapping and assessment methods and their linkages to the different tiers.

Quantification has already been covered widely in the OpenNESS and OPERAs projects. In addition to the various methods, it is important to clarify the other resources that are needed to carry out ecosystem assessments, such as technical and human resources, and the time needed for certain analyses. The methods vary greatly depending on the required expertise, availability of the data and its coverage, available software, time, and financial costs. The most suitable approach will depend on the research questions which need to be addressed, whether the study will be an assessment, or if maps are also required.

For mapping methods, the level of scale should be considered: what level of detail is necessary? The limitations are often set by the availability of the data; it might not be accessible, or it might be costly, or it might not be consistent for the use to cover the area well. For small research areas more detailed data sources, or even opportunities to conduct field measurements, may be available. However, for larger studies Earth Observation products may offer a solution for areas of poor data coverage. In addition to scale, it is also important to pay attention to the purpose of which the assessment is aimed at. Which biophysical units can and should be used to gain information on ecosystem services? Do we want to know if sufficient ecosystem service potential is available, or do we wish to quantify the rate at which the ecosystem service is delivered? Also, do we wish to deliver spatially explicit information for the chosen locations? The most suitable methods should be identified and selected according to the answers to these questions. See section 5 for further details on the tiered approach.

2.1. Building from previous experiences

Ecosystem service mapping methods have been discussed in earlier projects on which this report also builds (Tables 1 & 2). In this section, we present the recent accomplishments of these projects. In the OpenNESS project, 27 case studies (see http://www.openness-project.eu/), predominantly from Europe, applied the ecosystem service concept to address their individual needs. To do this, the research teams worked to assist case study practitioners assess and select ES methods to target the specific management challenges of their case. The methods available included a range of biophysical, monetary, and socio-cultural approaches and techniques capable of addressing case study questions regarding both the supply and demand of ecosystem services and their value to the people benefiting from them. Dunford et al. (2017) attempt to synthesise these experiences to provide suitable and practical "take home messages" that illustrate where, and in what contexts, different methodological combinations were used. This also sought to provide suggestions for those working in ecosystem service assessments, drawn from the experiences of the 27 case studies. The findings of the OpenNESS case studies highlight that methodological plurality, flexibility, and creativity are key if case studies are to best address practical local-to-regional problems. Yet, comprehensive stakeholder engagement is at the heart of the success of the methods to be applied. In that sense, we need more methodological co-design, including the analysis of policy and societal needs to reach integration of state-of-the-art models, data, and data analytics within them. Another EU project, OPERAs, used five classes to group biophysical models which we considered to be very useful core classes in our work (Lavorel et al. 2014). Many of the identified special models or methods were dropped into these classes that are listed in Table 2.

One of the opportunities for participatory engagement could be facilitated through Oppla (www.oppla.eu), an established, rapidly growing, and fully engaged online community of practitioners, policy makers, and researchers who are addressing the challenges of sustainable land management. These synergies with Oppla could facilitate the true co-design of outcomes with a diverse range of stakeholders, ensuring thorough consultation and testing of different approaches and their transferability to other contexts/locations.

Table 1. Methods that were presented in detail in OpenNESS report (Harrison & Dunford 2015; Dunford et al. 2017).

Methods explained in OpenNESS report
- Spreadsheet-type methods
- ESTIMAP
- Bayesian Belief Networks
- State and Transition Models
- QUICKScan
- InVEST

- Species distribution models
- ECOPLAN-QUICKScan
- MapNat smartphone application
- RUSLE (Revised Universal Soil Loss Equation) Erosion model
- Blue-green factor scoring
- Photoseries analysis
- Eco Chain Participatory Biodiversity Management

Table 2. Model classes developed in OPERAs project (Lavorel et al. 2014).

Methods explained in OPERAs report
1) Spatial proxy models
2) Phenomenological models
3) Macro-ecological models
4) Trait-based models
5) Process-based models

2.2 ESMERALDA review

The methods used in biophysical ecosystem service mapping were identified during an extensive review process (Santos-Martin et al. 2018). In a first phase (October 2015 - November 2016), a set of over 300 scientific articles describing dozens of biophysical methods was reviewed by a team of ESMERALDA partners and students from partner organisations, and in addition, a workshop was arranged where these results were elaborated and updated by a number of experts (Potschin et al. 2016). During the process, basic information about each biophysical mapping method was coded with information on all of the ES focused upon, and the biophysical, social and economic methods used (cf. D3.1 and D3.2). The database was later updated with a questionnaire that was sent to ESMERALDA members to gather further information on different methods. The data was collected in 2017. A total of 317 scientific articles, 48 reports and 50 case study examples were coded in the database with information on the methods used (Santos Martin et al. 2018).

The high number of methods supported the decision to use classes to clarify the wide variety. The methodological similarity was the primary reason for grouping methods. Different classifications could have also been provided, for instance reflecting the systems' ecological functions as the first grouping principle; for instance, classes such as atmospheric models, hydrological models, soil erosion models, ecological models etc. However, the technical orientation was preferred, and resulted in 15 classes for biophysical methods; those are presented in sections 3 and 4.

3. Classification of biophysical methods

The biophysical methods are based on quantification of different parameters of biotic and abiotic structures which determine the provision of ecosystem services. Biophysical quantification is built on spatial and temporal measures of ecosystem processes. To quantify ecosystem services in biophysical terms we need to define: what and how it is measured (Vihervaara et al. 2017a). In this report we divided biophysical methods into the three main categories in relation to the character of the measurements and how the necessary information is extracted (Figure 3).

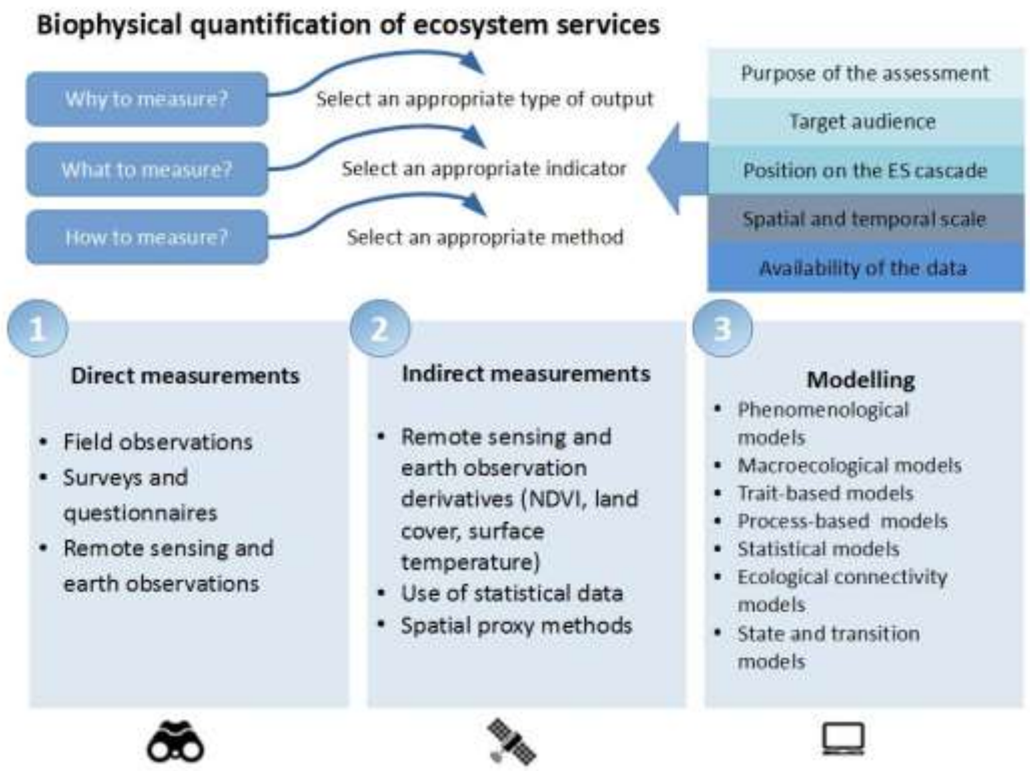


Figure 3. Classification of biophysical methods (modified from: Vihervaara et al. 2017a).

Direct measurement methods (1) of ecosystem services are the measurements of a state, a quantity, or a process from ecosystem observations, monitoring, surveys, questionnaires, or data from remote sensing and earth observations, which cover the entire study area in a representative manner. Direct measurements deliver a biophysical value of ES in physical units which correspond to the units of the indicator, and quantify or measure a stock or a flow value. Direct measurements are also used as primary data to other methods, as they are one of the most accurate ways to quantify ES. However, they are often impractical and expensive beyond the site level, and therefore are usually used as an input for a different biophysical mapping method or to validate certain mapping and assessment elements. In some cases direct measurements are simply not available for all ES. **Indirect measurement methods** (2) rely on the use of different data sources which rely on biophysical value in physical units, but this value needs further interpretation, certain assumptions, or data processing before it can be used. They can be based on remote sensing and Earth observation derivatives such as land cover, Normalised Difference Vegetation Index (NDVI), surface temperature, or soil moisture which are extracted from the original sources by specific procedures. For example, land cover can be derived from remote sensing images through visual interpretation or automated classification, whereas NDVI is derived by measuring the difference of particular spectral bands. **Modelling methods** (3) includes several groups of modelling approaches from ecology (phenomenological, macro-ecological, trait-based), statistics, or other earth sciences fields such as hydrology, climatology, soil science etc. Conceptual models and integrated modelling frameworks are also considered under this class. Integrated modelling frameworks are common also for socio-cultural and economic methods.

4. A comprehensive review of biophysical methods

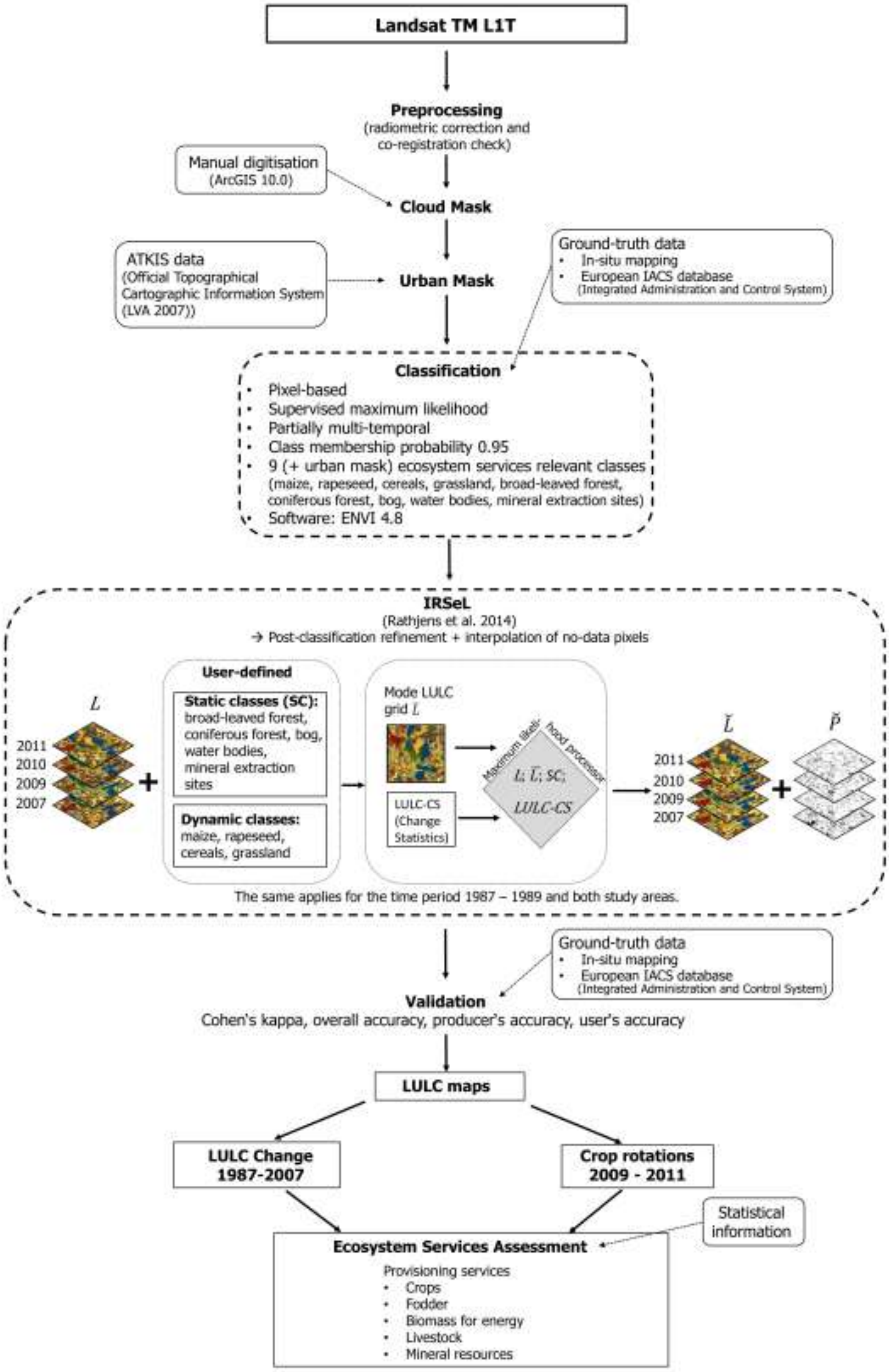
4.1. Direct measurement methods

Field Observations

The primary approach to data collection in the natural sciences has generally focused on making observations in the field, and taking direct measurements (based on physical units). This should not be forgotten when considering the mapping and assessment of ES. In a sophisticated form, field observations can be part of national or regional sampling systems, such as national forest inventories, biodiversity surveys, or LUCAS land cover measurements in the EU. Moreover, all kinds of *in situ* and citizen science observations (which are becoming increasingly important), also belong in this group. The advantage of using field observations is that they are spatially explicit and when stored in GIS databases can be used to validate and calibrate results of the other methods. (Box 1)

Box 1. A direct measuring method in practice

Within this study in the Northern German case study area Bornhöved Lakes District, several provisioning ecosystem services were assessed with the direct measuring method based on a remote sensing approach. The aim of the study was to detect temporal changes in the supply area of the provisioning ecosystem services crops, fodder and biomass for energy. By means of a pixel-based maximum likelihood classification approach of 11 Landsat TM 5 scenes (for the years 1987, 1989, 2007, 2009-2011), a decline in grassland area of about 50% was detected as the most obvious change in these two decades. Due to good data availability and a post-classification refinement with the IRSel tool, it was possible to distinguish individual crop plants. The decline in grassland led to a further alteration in provisioning services (e.g. livestock) due to the shift to energy-plants (maize for biogas plants). The causes for change in crop rotation as well as the consequences on the landscape were discussed within the ecosystem services framework. Combining remote sensing and research on ecosystem services supports the assessment and monitoring of ecosystem services on different temporal, spatial, and semantic scales.



Source: Kandziora, M., K. Dörnhöfer, N. Oppelt & F. Müller (2014): Detecting Land Use And Land Cover Changes In Northern German Agricultural Landscapes To Assess Ecosystem Service Dynamics. - *Landscape Online* 35: 1-24

Surveys and Questionnaires

This method is often used to get a quick overview of the study, and assist in selecting which other models can be used in mapping and assessment. Surveys and questionnaires can provide expert information on ecosystem services, but they can also be used to evaluate uncertainties of other methodologies. Their role in ecosystem assessment and decision-support is important.

Remote Sensing and Earth Observation

The role of novel Earth observation techniques and data sets is becoming increasingly important in environmental monitoring, both for biodiversity (Vihervaara et al. 2017b), and for ecosystem services (Cord et al. 2017). Satellite Earth observation, as well as airborne and drone observations, have huge potential to improve quantification, mapping, and assessment of ecosystems and their services. Optical, radar, and Light Detection And Ranging (LiDAR) data can be used for direct measurements, or to gather information that feeds into the models.

Table 3. Direct measurement methods - data and software needs, and examples of detailed methods by the classes.

Class	Data and software needs	Examples of methods
Field observations	Data: In-situ measurements Software: GPS, basic maps, online maps (e.g. google earth)	Field experiment Tye et al. 2013 http://dx.doi.org/10.1016/j.geoderma.2013.05.004 Field sampling Questa 2017 link to publication
Surveys and questionnaires	Data: Online questionnaires, expert interviews Software: Online tools e.g. Harava, Maptionnaire	Assessment of coastal protection Liquete et al. 2013 http://dx.doi.org/10.1016/j.ecolind.2013.02.013
Remote sensing and earth observations	Data: Satellite images, airborne images, LIDAR points Software: Remote sensing softwares e.g. Erdas Imagine, ENVI, GIS softwares and tools e.g. QGIS, ArcGIS, TerraScan, LasTools, FUSION	Green oriented urban development Martinico et al. 2014 http://dx.doi.org/10.3832/ifor1171-007 SIAM (Satellite Image Automatic Mapper) García-Feced et al. 2014 http://dx.doi.org/10.1007/s13593-014-0238-1

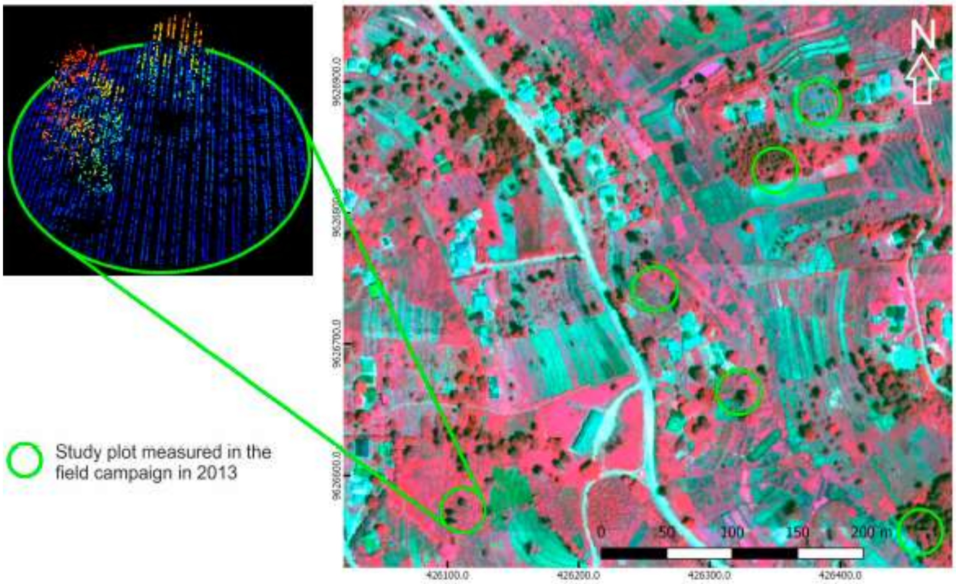
4.2. Indirect measurement methods

Remote Sensing and Earth Observation Derivatives

Remote sensing and Earth observation can also be used indirectly to get derivatives for ecosystem services. Examples of such measurements are NDVI, land cover, and surface temperature. These act as proxies for the state of ecosystem services, and they also feed into models. (Box 2)

Box 2. Classification of Tree Species in a Diverse African Agroforestry Landscape Using Imaging Spectroscopy and Laser Scanning

This study applied remote sensing derivatives for the tree species classification in a diverse tropical landscape in Taita Hills, Kenya. Due to the high number of different tree species (31) with limited sample size (499) the combination of imaging spectroscopy and airborne laser scanning data was used to identify important tree features using feature selection, and to evaluate the impact of combining the two data sources. Surface reflectance at wavelengths between 400–450 nm and 750–800 nm, and height to crown width ratio, were identified as important features. Nonetheless, a selection of minimum noise fraction (MNF) transformed reflectance bands showed superior performance. Support vector machine classifier performed slightly better than the random forest classifier, but the improvement was not statistically significant for the best performing feature set. Results provided important insights into the spectral and structural features that differentiate the tree species in diverse agroforestry landscapes. This is important knowledge for biodiversity mapping and act as a proxy for the state of ecosystem services.



An example of AisaEAGLE data (color-infrared) and point cloud derived from laser scanning data from the study area.

Source: Piiroinen et al., 2017. http://doi.org/10.3390/rs9090875

Use of statistical data

Data from national and regional institutions which are responsible for environmental monitoring and statistics (such as air and water quality) can also be used as proxy data for ecosystem services. This data is not often spatially-explicit, but can be collected from wider regions, such as governance units (e.g. NUTS (Nomenclature des Unités Territoriales Statistiques used in EU), municipalities, counties), or from national statistics. Interaction with national statistics can also be bi-directional – published statistics can assist in mapping and assessing ecosystem services; however, there is also an urgent need for improved statistical information of ecosystem services (see KIP-INCA[3] – Integrated Natural Capital Accounting – project, and SEEA-EEA[4] – System for Environmental-Economic Accounts – Experimental Ecosystem Accounting).

Spatial proxy methods

Spatial proxy methods are derived from indirect measurements which deliver a biophysical value in physical units, but these values need further interpretation or data processing, rely upon certain assumptions, or need to be combined in a model with other sources of environmental information before they can be used to measure ecosystem services. In many cases, variables collected through remote sensing also qualify as indirect measurements. Examples for terrestrial ecosystems include land surface temperature, NDVI, land cover, water layers, leaf area index, and primary production.

Table 4. Indirect measurement methods - data and software needs, and examples of detailed methods by the classes.

Class	Data and software needs	Mapping examples
Remote sensing and earth observation derivatives	Data: Land cover data (GIS layers): terrain, vegetation, soil, bathymetry, habitat distribution etc. Software: Remote Sensing software e.g. ENVI, Erdas Imagine, GIS software e.g. ArcGIS	Emergy assessment Mellino et al. 2014 http://doi.org/10.1016/j.ecolmodel.2012.12.023
Use of statistical and socio-economic data	Data: Population data, statistics Software: Statistical software e.g. R, SPSS, GeoDa	Using literature review and statistical data to map ES Mizgajski, A. and Stępniewska, M. link to publication
Spatial proxy methods	Data: Empirically measured data/ expert scoring/statistics for indicators Land cover data (GIS layers): terrain, vegetation, soil, bathymetry, habitat distribution etc. Software: Statistical software, spreadsheet, GIS software, Independent modelling tools	Green Frame Kopperoinen, L. et al. 2014 http://doi.org/doi.org/10.1007/s10980-014-0014-2 QuickScan Greˆt-Regamey et al. 2008 http://doi.org/10.1016/j.jenvman.2007.05.019

[3] http://ec.europa.eu/environment/nature/capital_accounting/index_en.htm
[4] https://unstats.un.org/unsd/envaccounting/eea_project/default.asp

	Green and blue space availability models Larondelle, N. & Haase, D. 2013 http://dx.doi.org/10.1016/j.ecolind.2012.12.022

4.3. Modelling methods

Biophysical models deliver information on the relationship of biophysical characteristics and ES. Preliminary work on classifying how biophysical models consider biodiversity and data needs has been carried out in the OPERAs project (Lavorel et al. 2014). This identified a need for additional classes as there are methods that did not fit properly into any of the five OPERAs method classes. The special targets of using different methods for mapping are now emphasised more by creating the additional classes described below. In addition to purely biophysical methods, conceptual methods have been included in this group. Some integrated modelling environments are designed to consider different complexity levels in ES modelling (cf. integrated modelling frameworks). Whereas other model integrations can be aimed at supporting decision-making, e.g. via virtual laboratories (Holmberg et al. 2015). Involvement of policy makers and stakeholders should also be considered as well as interpretation of the results for the public (Braat et al. 2014). The classes are formulated based on their functioning principles and ultimate targets (Table 4).

Phenomenological models

The phenomenological models describe empirical relationships between biodiversity or ecosystem components and ecosystem services. They are based on the understanding that biological mechanisms underpin ES supply, for instance, vegetation effect to hinder snow slides in mountainous areas.

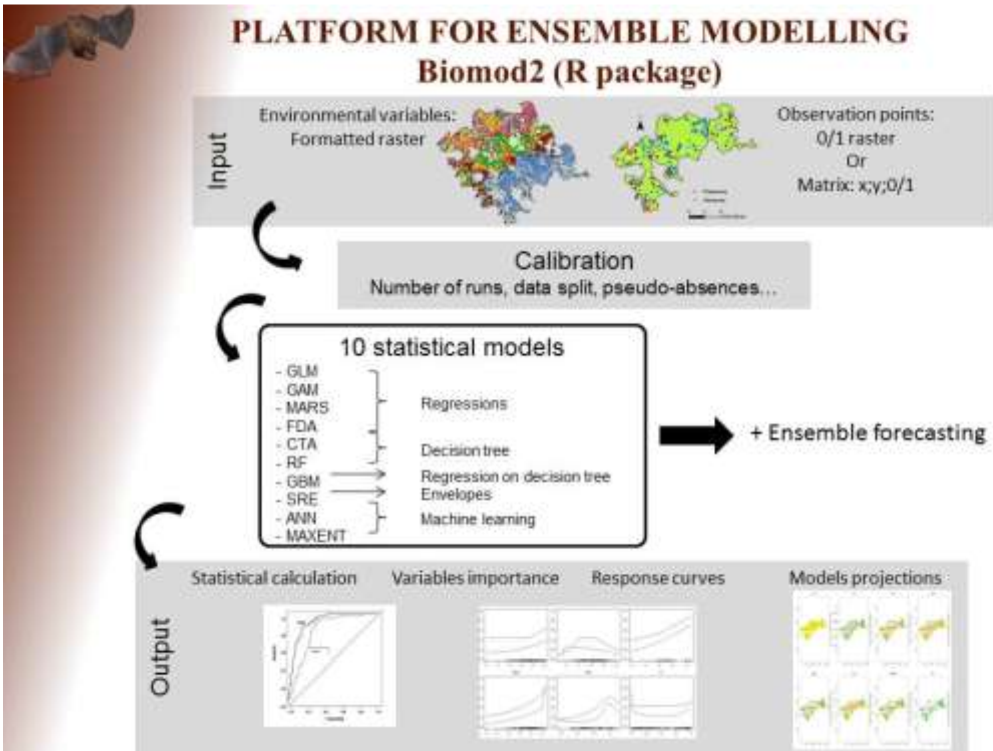
Macro-ecological models

Models that assess ES supply, based on the presence (or abundance) of specific components of biodiversity, are referred to as Ecosystem Service Providers (ESP) or Service Providing Units (SPU), depending on their geographic distribution. The contribution of different species, species groups, guilds, alliances or communities (for vegetation) or functional groups, for example, to the ES of interest is assessed based on specific traits (e.g. trophic guilds) or expert knowledge. This class includes also habitat models. In particular, Species Distribution Models (SDM) have shown great potential in helping to achieve planning goals oriented towards conservation by refining our knowledge of species distributions. There is wide variety of SDM methods (e.g. Thuiller et al. 2009; http://cran.r-project.org/web/packages/biomod2/index.html, each with their own characteristics). (Box 3)

Box 3. Example of methodological steps for ensemble modeling, based on an example from forest dwelling bats species in the Vercors area, France

The best way forward to model species and habitat distributions is combining top-down modelling with bottom-up knowledge. However, exploitation of bottom-up knowledge demands a lot of efforts in terms of data collection and harmonization. Then decision to use the right modelling approach for a specific project can be difficult. It is important not only to have clear aims of the study but also identification of stakeholders' needs and possible responses remains key on the selection of scales and type of spatial habitat models. Reliability of models should be a main issue in the ecosystem domain applications, giving priority to the development of dynamic response models that can be linked to ecosystem services flows and bundles. The use of remote sensing combined with geoinformation and field data is essential in order to reduce uncertainty in the modelling domain. SDMs extrapolate species distribution data in space and time, usually based on statistical model. These models identify areas that are ecologically suitable for the presence of species. The spatially-explicit models obtained (Le Roux et al, 2017) were proven crucial for prioritizing foraging habitats, roost sites and key corridors for conservation. Hence, results are being used by key stakeholders to help integrate conservation measures into forest management and conservation planning at the regional level. The approach used can be integrated into conservation initiatives elsewhere

In all, integrating large databases at different biological levels (species, plant communities, and landscape) while coupled with spatial modelling techniques opens fascinating and new perspectives for indicator species and key habitats towards implementation of European nature policy; but a great effort from different communities still lies ahead to reach a common understanding.



Source: Le Roux et al. 2017.

Trait-based models

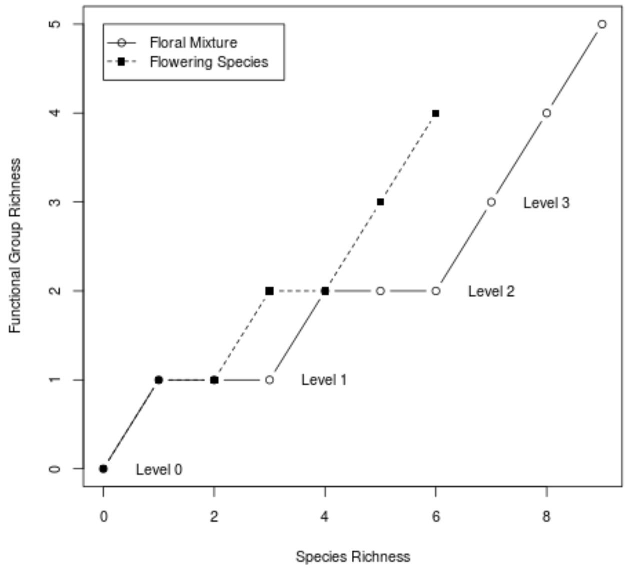
Functional traits are associated with ecosystem functioning, and thus with the delivery of ES. There is increasing evidence for relationships between traits of organisms and ES supply (e.g. Lavorel 2013). Trait-based models can organize ecosystem functioning by species response to environment, for instance, species capacity to nutrient uptake, i.e. traits. They can also address scientific and management questions about the provision of multiple services, while progress is needed in understanding how functional trade-offs and synergies within organisms scale up to interactions between ecosystem services (Lavorel & Grigulis 2012). Trait-based models can quantify ES supply based on relationships between functional traits of ESPs and ecosystem properties, for example carbon sequestration in relation to varying vegetation composition. (Box 4)

Box 4. Utilisation of plant functional diversity in wildflower strips for the delivery of multiple agroecosystem services

This study investigates the effect of increased plant diversity in cropping systems on the delivery of arthropod-mediated ecosystem services and on crop production. During a field experiment, repeated over 2 years, the following factors were measured: (i) the effect of increasing plant functional diversity on community structure of arthropod visitors (ii) the abundance of multiple pests and induced crop damage (iii) fruit production in two varieties of tomato. Plant resources (floral and extra-floral nectar and pollen) were included within experimental plots in four levels, with each level increasing the plant functional group richness, based on floral morphology and availability of resources, in a replacement series. The presence of sown flower mixtures in experimental plots was associated with increased abundance and diversity of natural enemy functional groups and an enhanced abundance of bees. However, relatively small variability in arthropod visitors among types of mixtures was detected, and increased abundance of natural enemies did not translate into stronger pest suppression or reduced crop damage. Lepidoptera pest damage was significantly higher in plots adjacent to wildflower strips, an ecosystem disservice, but a significantly higher crop productivity was recorded from these plots. Results provide evidence that inclusion of non-crop plant resources in agroecosystems can improve the conservation of beneficial arthropods and may lead to increased crop productivity.

(a)

(b)



(a) Flower strips were established in an experimental field trial with tomato crop. (b) Three flower strip mixtures were provided to create an increasing gradient of plant species and functional diversity.

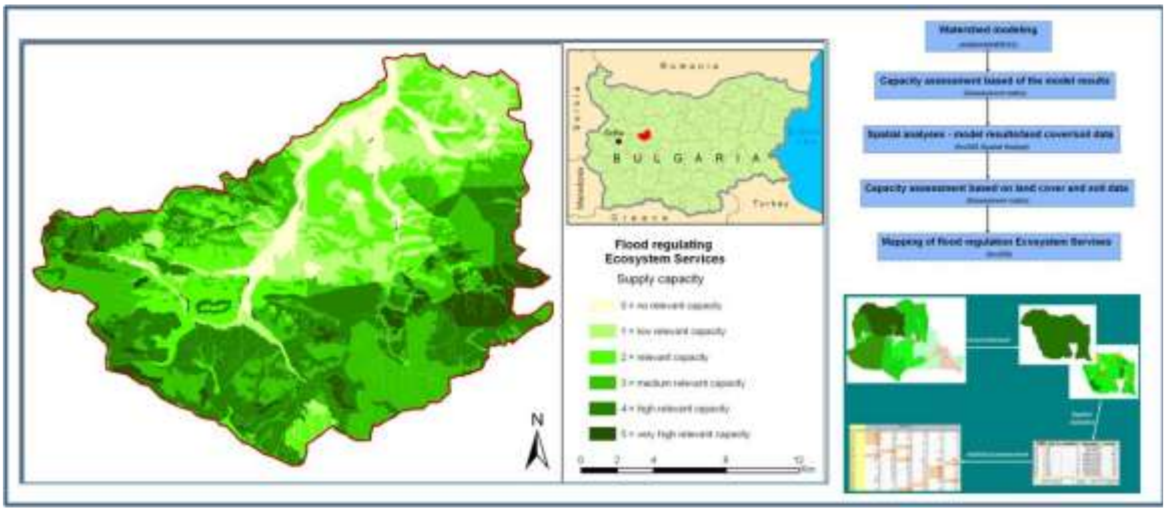
Source: Balzan et al., 2016. https://doi.org/10.1111/eea.12403

Process-based models

Process-based models rely on the explicit representation of ecological and physical processes, such as carbon sequestration or nutrient cycling, that determine the functioning of ecosystems. These models provide functional means of ecosystem processes that are universal rather than specific to one biome or region. One purpose of these models is to explore the impact of perturbations caused by climatic changes and anthropogenic impact on ecosystems and their biogeochemical processes. Many process-based models allow the net effects of these processes to be estimated for the recent past and for future scenarios. In terms of ecosystem services, these types of models are most widely applied to quantify climate regulation, water supply from catchments, and food provision, but also in the wider frame of habitat characterisation, also including landscape function models. (Box 5)

Box 5. Mapping of flood regulation using hydrologic modelling in mountain watersheds in Bulgaria

In this study, the capacities of different ecosystems to regulate floods were assessed through investigations of water retention functions of the vegetation and soil cover. The use of the watershed based hydrologic model KINEROS and the GIS AGWA tool provided data about functions for the formation of rivers' peak flows and the capability of different land cover types to "capture" parts of the water which reveals their regulation capacity. AGWA incorporates KINEROS (and SWAT) model, which is suitable for application in relatively small (up to 100 km^2) watersheds with predominantly surface runoff. The model simulates water balance parameters within the watershed which are used to quantify the regulation function for the different ecosystems. The required input includes: land use, DEM, soil, precipitation and river discharge. The outputs of the model used as indicators for flood regulation are infiltration, surface runoff and peak flow. The method allows quantifying the flood prevention function of the ecosystems in the watershed. The model results in combination with spreadsheet method and GIS based algorithm allows transferring the flood regulation assessment to other areas with similar geographical features which allows extending the mapping and solving the problem with the limited area of the model application. Resulting map (the figure bellow) shows the ecosystems' flood regulating service capacities in the case study area of the Malki Iskar river basin above the town of Etropole in the northern part of Bulgaria. The use of hydrologic models gives the opportunity to quantify flood regulating ecosystem services and to define the capacities of different land cover types to supply flood regulation. A combination of model results with further data from hydrological measurements or monitoring is possible.



Source: Nedkov and Burkhard, 2012 https://doi.org/10.1016/j.ecolind.2011.06.022

Statistical models

Statistical models are mathematical models that measure the attributes of certain populations or a representative sample of the population. The use of statistical models to map ecosystem services are usually based to the estimation of the relationship between the response variable (i.e. ecosystem service) and explanatory variables (e.g. biophysical functions), such as soils, climate, etc. There is a wide range of different techniques to analyze and model this relation that may help to understand the state of ecosystem service and its dependency of the surrounding biophysical processes. (Box 6, 7)

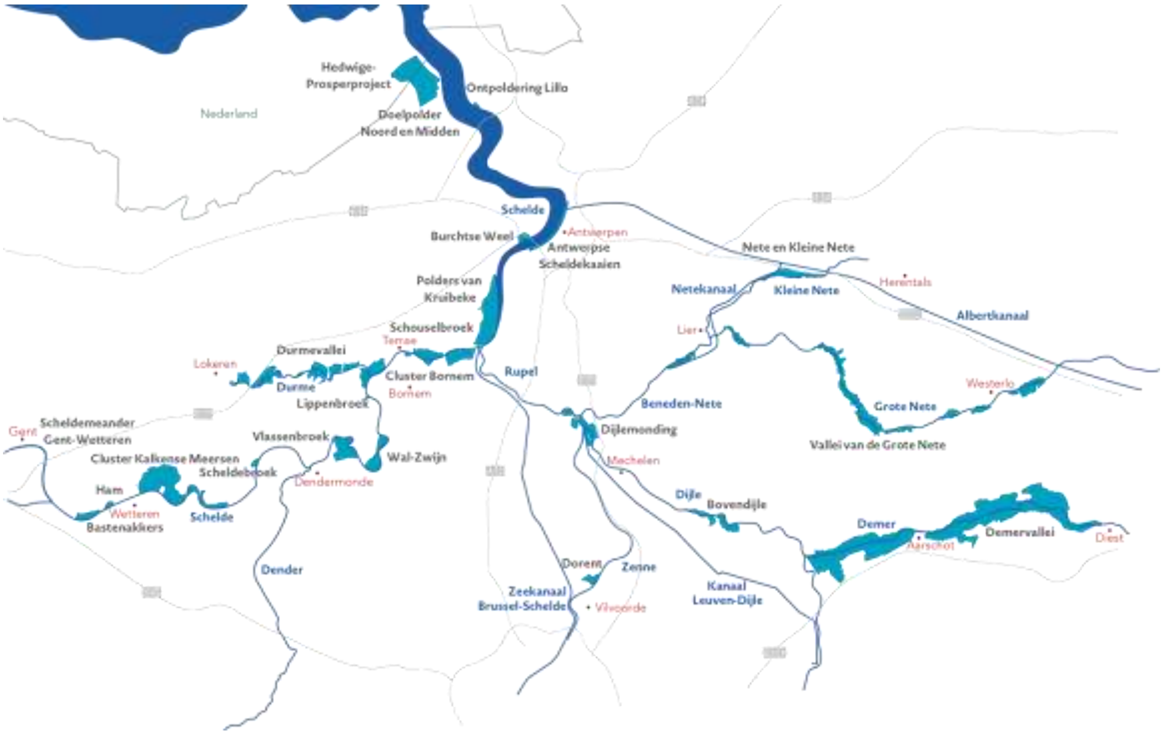
Box 6. Use of statistical methods to quantify ecosystem services supply in flood areas

The Scheldt estuary, flowing from Belgium into the Netherlands, is vulnerable for storm floods coming from the North Sea. A plan to protect the land from flooding was created (Sigmaplan). Different measures were considered. A cost-benefit analysis was carried out, taking into account for the first time ecosystem services provided by the new flood plains created. It shows that an intelligent combination of dikes and floodplains can offer more benefits at lower costs than more drastic measure such as a storm surge barrier near Antwerp.

The ecosystem services of the floodplains, except flood protection, were largely calculated using statistical methods. Based on literature and measurements in a test floodplain, regression functions were derived using the statistically most relevant explanatory variables of which also wider data exist for the whole area e.g. soil characteristics, flooding regimes (based on hydrodynamic modelling), For the recreational value a contingent valuation study was used to derive this function.

Then, the regression functions were filled out with the location specific parameters for every flood area to calculate the specific supply of the ecosystem service for that particular area. We used this method to calculate sequestration of carbon and nutrients, nutrient removal, enhance oxygen in water, erosion control and recreational value.

Based on the results of the study the Flemish government approved an integrated management plan consisting of the restoration of approximately 2500 ha of intertidal and 3000 ha of non-tidal areas and the reinforcements of dikes.



Source: www.sigmaplan.be

Box 7. A web application to support the quantification and valuation of ecosystem services

The online Nature Value Explorer tool (www.natuurwaardeverkenner.be) is a tool that enables users to quantify the change in ecosystem services supply in a planning process.

A trade-off is made between different ecosystem services. The quantification of a number of these ecosystem services is based on statistical methods. We use as an example the storage of soil organic carbon, underpinning the regulation of global climate. Based on measurements in general-purpose soil survey projects and in monitoring schemes of agricultural and forest soils, a multi-level generalisation approach and digital soil mapping techniques were applied to derive statistical functions(Ottoy et al. 2017). These functions estimates the maximum potential stock of soil organic carbon in a particular soil under a particular land use. These functions are used in the tool to estimate change in yearly storage of carbon in land use change scenarios.

A similar approach is followed for other regulating services such as caption of dust, erosion control and nutrient retention.

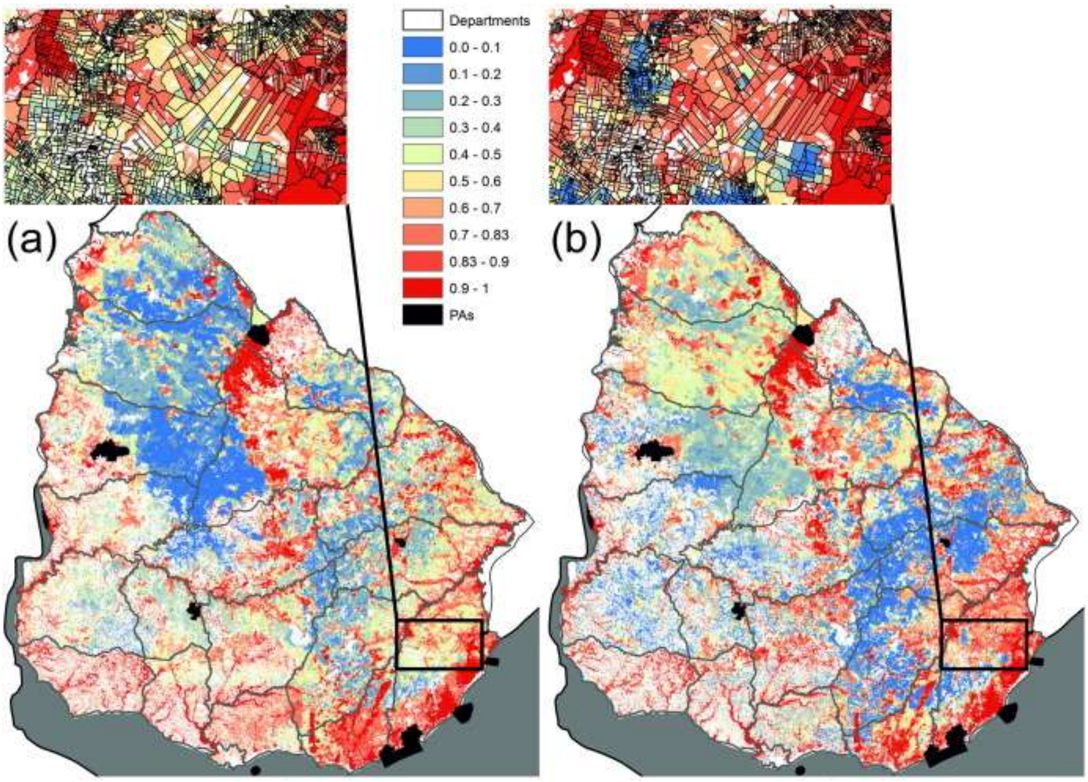
Source: Ottoy, S., De Vos, B., Sindayihebura, A., Hermy, M. and Van Orshoven, J.,2017 Assessing soil organic carbon stocks under current and potential forest cover using digital soil mapping and spatial generalization.*Ecological Indicators*, **77**, (139)

Ecological connectivity models

Ecological connectivity models are used to evaluate the structural and/or functional degree to which the landscape facilitates or impedes movement of different ecological processes. Connectivity of the landscape (e.g. green urban areas) promotes the provision of many ecosystem services, as connectivity is fundamentally linked to the ecological processes providing these services. Structural connectivity models usually use Land Use Land Cover (LULC) data derived, for example, from remote sensing as a basis to generate the geometry of the landscape elements and perform connectivity or fragmentation analyses. The latter are used to define the spatial pattern of the SPUs and their capacity to provide services. Functional connectivity models use data from species dispersal in addition to physical attributes of the landscape. (Box 8)

Box 8. Ecological connectivity models: Zonation

Zonation is an ecological connectivity model that prioritizes areas based on their BD values in terms of connectivity, complementarity and balance. Primarily the software is designed to produce prioritization maps for ecological connection and the results reflect which areas are most important in sustaining as much BD as possible. Applications with ecosystem services have also been made. Di Minin et al. (2017) computed a Zonation analysis to explore the most important locations for conservation actions in Uruguay. The target was to maximize BD and ES and analyse the trade-offs with most important forms of land use; agriculture and commercial forestry. Data quality is important for Zonation. Here, an extensive selection of data from species distribution models, landscape units, ecosystem services, threatened ecosystems and ecoregions were used to represent biodiversity and ecosystem service features. Planning units, protected areas, land cost, suitability for agriculture and afforestation were used as other layers. The analysis identified priority areas for conservation actions (Fig. X in red). Land use scenarios were applied from a business as usual scenario (incl. BD and ES only) to a potentially unsustainable scenario (priority with higher land use rate). The need for meeting the conservation targets were evaluated being significantly lower with current land use compared with the unsustainable scenario where conservation targets should be increased by 41% to maintain the crucial levels of endangered ecosystems and ES.



Priority rank maps for the conservation of biodiversity and ecosystem services in Uruguay obtained by (a) including only biodiversity and ecosystem services; (b) biodiversity, ecosystem services and alternative land uses.

Source: Di Minin et al. (2017). https://doi.org/10.1016/j.biocon.2016.11.037

State and transition models

State and transition models (STM) assume there are a number of states in which a system can exist, but there are specific conditions that can drive the system between states. The main focus of these models is the threshold point that separates one state from another and marks the transition between them. STMs are developed using information from a combination of sources including expert knowledge, historical observations, monitoring, and controlled experiments. They can be a good tool for examining natural systems by providing managers with better ways of understanding and communicating changes in the ecosystem as well as to provide broad predictive capabilities to assess and estimate potential future changes, given certain management and environmental conditions. The combination of STM with ecosystem services approaches is useful for identifying multiple functions and benefits directed to improve decision-making. (Box 9)

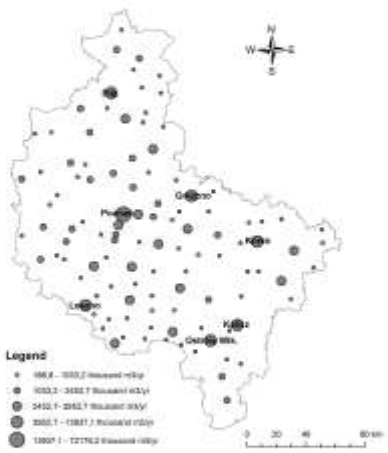
Box 9. Water footprint as an indicator of water supply ecosystem service - a case of Wielkopolska Region, Poland

The purposes of the study is to assess ecosystem services related to water supply using a water footprint (WF) indicator. The total WF of regional consumption is considered in division into its direct and indirect components (water withdrawal and consumption of agricultural and industrial goods, respectively). Additionally, the blue, green and grey elements of WF are determined, taking into account water source (ground or surface) and water pollution. To assess the degree of strain on water resources, the relation between the water demand and water availability is examined.

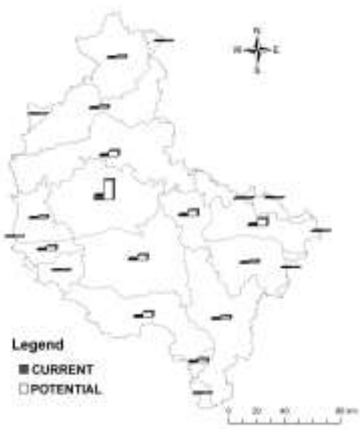
The total WF of regional consumption in the period 2008-2009 was 2750 million m^3/yr. The average consumer had a WF of 1437 m^3/yr. Agricultural goods were responsible for the largest part of the total WF (1284 m^3/person/year), industrial goods were responsible for 145 m^3/person/year and domestic water usage for approximately 8 m^3/person/year.

In order to gather insight into the impact of water consumption, the water use was compared to the actually available water resources. Two scenarios were analyzed: Scenario 1 (CURRENT) - water scarcity level expressed as the ratio of the withdrawal to the total renewable water resources; Scenario 2 (POTENTIAL) - water scarcity level expressed as the ratio of the total blue WF to the total renewable water resources.

The average share of water withdrawal in the total renewable groundwater resources in the region was 3,6% in 2009 (Scenario 1). Scenario 2 reflects a hypothetical situation in which the total water needs of residents (both direct and indirect water use) would be satisfied from the groundwater resources available in the region. In this scenario, the average value of water scarcity was 16.8%, therefore it was almost 5-fold higher than in current state. This shows the scale of water saving as a result of the trade of commodities. Use of regional water resources is significantly reduced through the import of water contained in agricultural and industrial products.



The grey water footprint
of the industrial products consumption



The degree of strain on groundwater resources
caused by addressing water needs

Source: Stępniewska, 2012

Integrated modelling frameworks

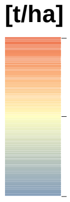
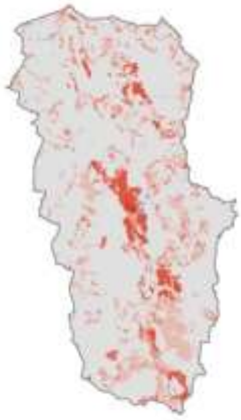
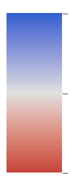
This group includes tools designed specifically for ecosystem services modelling and mapping that can assess tradeoffs and scenarios for multiple services. They integrate various biophysical, but also social and economic methods, to assess and map different services. The methods are usually organized in modules, where each of them is designed for assessment of particular service. Integrated modelling frameworks utilise GIS software as a means to operate with spatial data and produce maps. They can work as extensions of commercial or open-source software packages, stand-alone tools or web-based applications. They are designed to help researchers in ES assessment and enable decision makers to assess quantified tradeoffs associated with alternative management choices, and to identify areas where investment in natural capital can enhance human development and conservation. (Box 10)

Box 10. Integrated Valuation of Environmental Services and Tradeoffs (InVEST)

Integrated Valuation of Environmental Services and Tradeoffs (InVEST) are models that assist to quantify and map values of ecosystem services (Kareiva et al. 2011, Sharp et al. 2016). InVEST is spatially explicit modelling tool that predict changes in ecosystem services, biodiversity conservation and commodity production levels. This approach to quantification and spatial determination of the production of ecosystem services can assist decision-making in conservation and make decisions in natural resources more effective, efficient and defensible (Nelson et al., 2009).

InVEST represent a suite of models developed by the Natural Capital Project initiative at Stanford University (https://www.naturalcapitalproject.org/invest/), to enable the assessment and evaluation of ecosystem services on various landscape scales. Originally developed as a freeware ArcGIS toolkit extension, InVEST currently presents a suite of free, open-source software models covering 18 various terrestrial, freshwater, coastal and marine ecosystem services. InVEST have been applied in ecosystem service mapping and valuation in various research projects worldwide, especially in order to analyse ecosystem service trade-offs and compare different scenario-based alternatives of potential future landscape development (Kareiva et al. 2011, Nelson et al. 2009, Tallis et al. 2009).

In Třeboňsko Protected Landscape Area and Biosphere Reserve (the Czech Republic), InVEST was applied to analyse trade-offs across landscape scenarios for regulating ecosystem services (Harmáčková and Vačkář 2015). We assessed the provision of regulating ecosystem services of climate regulation in terms of carbon storage and sequestration, and water quality improvement in terms of nitrogen discharge and retention. The most favourable with regard to regulating ecosystem service capacity was the Conservation scenario, where the current state of landscape is maintained and where degraded ecosystems (e.g. by gravel mining) are restored.

ES	Scenario 2006 – 2050			Legend
	Exploitation	BaU	Conservation	
Water quality: Nitrogen				
Water quality: Sediments				
Climate regulation				

The spatial pattern of change in the provision of regulating ecosystem services (water quality regulation and climate regulation) in Třeboň Basin BR for three scenarios to 2050 (in comparison with the baseline).

Sources: Harmáčková & Vačkář 2015; Kareiva et al. 2011; Nelson et al. 2009; Sharp et al. 2016; Tallis & Polasky 2009.

Table 5. Modelling methods - data and software needs, and examples of detailed methods by the classes.

Class	Data and software needs	Examples of methods
Phenomenological models	Data: Information from other studies/ meta-analysis Land use or land cover (GIS data), soil conditions, climatic conditions, accessibility Software: Statistical software, GIS software, Independent modelling tool	Snow slide susceptibility model Schröter et al. 2014 http://dx.doi.org/10.1016/j.ecolind.2013.09.018 Preliminary assessment method (PAM) Zepp, H. et al. 2016 Link to publication
Macro-ecological models	Data: Species distribution data (e.g. Atlases, in-situ data) inventories Habitat / land cover data (GIS data), additional parameters: soil, climate, land use etc. Remote sensing to derive environmental variables and processes to be coupled with models. Software: Statistical software, GIS software, Independent modelling tool	Maximum entropy modelling (MAXENT) Vallecillo et al. 2016 https://doi.org/10.1016/j.ecolind.2016.05.008 Extensive Niche Modelling Rolf et al. 2012 http://dx.doi.org/10.1080/21513732.2012.686121
Trait-based models	Data: Observational or empirical data on functional traits, plant traits, traits of soil microorganisms Explanatory variables: land use/ land cover, soil variables, climate variables Software: Statistical software, GIS software, Independent modelling tool	Utilisation of plant functional diversity Balzan et al. 2015 http://dx.doi.org/10.1111/eea.12403
Process-based models	Data: High-quality data on climate, atmospheric CO2 concentrations, land use conservation, sequestration Software: Note: Process-based models require very good expertize to use the models properly	KINEROS Nedkov & Burkhard 2012 http://dx.doi.org/10.1016/j.ecolind.2011.06.022 MedREM model Guerra, A. C. et al. 2014 http://dx.doi.org/10.1007/s10021-014-9766-4 MOSES Aitkenhead et al. 2011 http://dx.doi.org/10.1016/j.ecolmodel.2011.09.014
Statistical models	Data: Environmental variables Software: Statistical software (e.g. R, SPSS, MatLab) Visualisation could be done separately in GIS software.	K-mean cluster analysis Queiroz et al. 2015 https://doi.org/10.1007/s13280-014-0601-0 Principal Component Analysis (PCA) García-Nieto et al. 2015 https://doi.org/10.1016/j.ecoser.2014.11.00 Moran's Index Palomo, I. et al. 2014 https://doi.org/10.1007/s10113-013-0488-5

Ecological connectivity models	Structural connectivity Data: Land cover or land use data, habitat data, features restricting movements, e.g. road and rail networks Functional connectivity Data: Species/ habitats distribution data, species suitability data, land cover or land use data, habitat data, features restricting movements, e.g. road and rail networks Software: Conefor (also plugin for Qgis or ArcGis available), Guidos, Fragstats, MatrixGreen, FunCon, GraphHab. Many calculations could be done separately in GIS softwares	Conefor Vogt et al. 2007 https://doi.org/10.1016/j.ecolind.2006.11.001 Morphological spatial pattern analysis Esterguil et al. 2012 MSPA: European forest connectivity Conefor Vogt et al. 2009 https://doi.org/10.1016/j.ecolind.2008.01.011 Zonation Moilanen et al. 2005 https://doi.org/10.1098/rspb.2005.3164
State and transition models	Data: Temporal land use data, remote sensing data, Software: GIS-softwares, RS softwares	Land use scenario modelling Larondelle, N. & Haase, D. 2012 https://doi.org/10.1016/j.ecolind.2012.01.008 Carbon emission models Vleeshouwers & Verhagen 2002 https://doi.org/10.1046/j.1365-2486.2002.00485.x
Conceptual models	Data: Information from other studies Software: Visualisation tools	Cascade model Haines-Young, R. and Potschin, M. 2010 Link to publication DPSIR Santos-Martin et al. 2013 https://doi.org/10.1371/journal.pone.0073249
Integrated modelling frameworks	Data: Land cover data (GIS layers): terrain, vegetation, soil, bathymetry, habitat distribution etc.. environmental statistics Software: GIS-softwares, stand-alone tools e.g. InVEST	InVEST Lupa, P. 2016 Link to publication MCDA Comino, E. et al. 2014 http://dx.doi.org/10.1016/j.landusepol.2013.09.006

5. Towards a tiered approach of biophysical mapping methods

As outlined in the previous section, the research question, data availability, data quality, available resources, expertise, and software requirements all affect to the decision on which methods could be employed for the analysis. Different methods are suitable at different spatial scales, and all methods are not applicable at all scales. Selection criteria for the most appropriate method and real word examples are described further in the this section and in the section 6.

The vast variety of biophysical mapping methods complicate the selection of an appropriate approach that provides useful information to decision makers in a specific context, i.e. a certain stage of the decision-making process at a specific scale, for a particular set of services, and given particular data availability options. Tiered approaches are a well-known instrument to structure the variety of methods by assigning them to different tier levels. A tiered approach provides guidance in the selection of methods and enhances the comparability of different approaches used, which facilitates communication and supports monitoring over time. Usually, a tier 1 approach uses readily available information while the level of detail of the method increases with higher tier levels. The approach has been implemented in the Intergovernmental Panel on Climate Change (IPCC) to structure the reporting on climate change: a decision tree guides the user to a relevant tier level, and for each tier level, detailed information about methods is available. Other examples include The Economics of Ecosystems and Biodiversity (TEEB) tiered approach, or the ecosystem services model suite InVEST.

A tiered approach for ecosystem services mapping has been suggested by Grêt-Regamey et al. (2017). The different tier levels are distinguished according to the purpose and the level of detail of the ecosystem service analysis that is required. This allows the resulting maps to provide relevant information to decision makers, and avoid the application of over-complex or over-simplified methods. Thus, the suggested tiered approach enhances the efficiency of ecosystem services mapping and is likely to increase their suitability for decision-making.

Before the identification of the relevant tier and associated methods, the goal of the assessment and the different components of the analyzed human-environment system should be described together with their interactions and dependencies. These components include the ecosystems, the services they provide, beneficiaries of these services, as well as governmental and non-governmental institutions. For crop production for example, the relevant ecosystem is agricultural land, the services provided are the crops, the users are the consumers of the crops, and the institutions are governmental agencies that regulate the use of pesticides for example, but also farmers associations. In this step, the system boundaries relevant for the mapping, as well as the scale, should be made explicit. Once these components have been defined, the tier level and associated method can be selected, guided by a decision tree (Fig. 4).

A tier 1 approach is suitable for a rough overview, for example of hot and cold spots of ecosystem services provision and demand. If the ecosystem services map is used to evaluate management measures or the suitability of different locations for an intended use, then a tier 2 approach is suitable. A tier 3 approach should be applied if explicit measures are implemented that affect not only the service itself but also other components of the system, which was defined in the first step. In case data and other resources are severely limited, it is possible to choose a lower tier, but efforts should be made to achieve the originally identified tier to best support decision-making.

The methods associated with the different tiers are based on the classification suggested by Martinez-Harms and Balvanera (2012), and is similar to the different methods mentioned in section 4.4. Spatial proxy models refer to look-up tables, phenomenological models to causal relationships, trait-based models to the extrapolation of primary data, and process-based models to regression and socio-ecological system models. Macro-ecological models could be assigned to tier 2. As indicated by the shading in Figure 3, the methods are not strictly assigned to a single tier, but usually have a focus at a certain tier level. Most of the methods can be implemented at different levels of detail, for example the relationships described in Bayesian Belief Networks (BBN) can be very simplistic with very few nodes, or extremely complex. Thus the method itself is not suitable to distinguish the tier level. However, as a BBN is rarely used to provide a rough overview, the focus of this method was assigned to tier 2. Another example would be the well-known lookup-tables, which can be filled based on land-cover classes or using other information, such as statistics. This approach is suitable and has mostly been applied so far to provide a rough overview, thus it was assigned to tier 1. Approaches assigned to higher tier levels require a higher level of detail of input and output data as they should inform specific management questions. This high level information can either be estimated through rather complex models or through the extrapolation of primary data or a combination of both. One very precise field survey might thus substitute several other datasets that would have been used to estimate the survey values. Thus, the number of datasets is also not a criterion to distinguish the different tiers but rather the level of tier.

While it is not always required and meaningful to apply highly complex, and resource-intensive methods, information about the possibilities and limitations of the selected mapping approaches, such as accuracy, precision or uncertainty, are also crucial for decision makers. However, these characteristics cannot directly be linked to a certain method: As described in the example above, the same method (e.g. Bayesian Belief Networks BBN) can be applied very roughly with high uncertainty and low precision, or very detailed with lower uncertainty and higher precision.

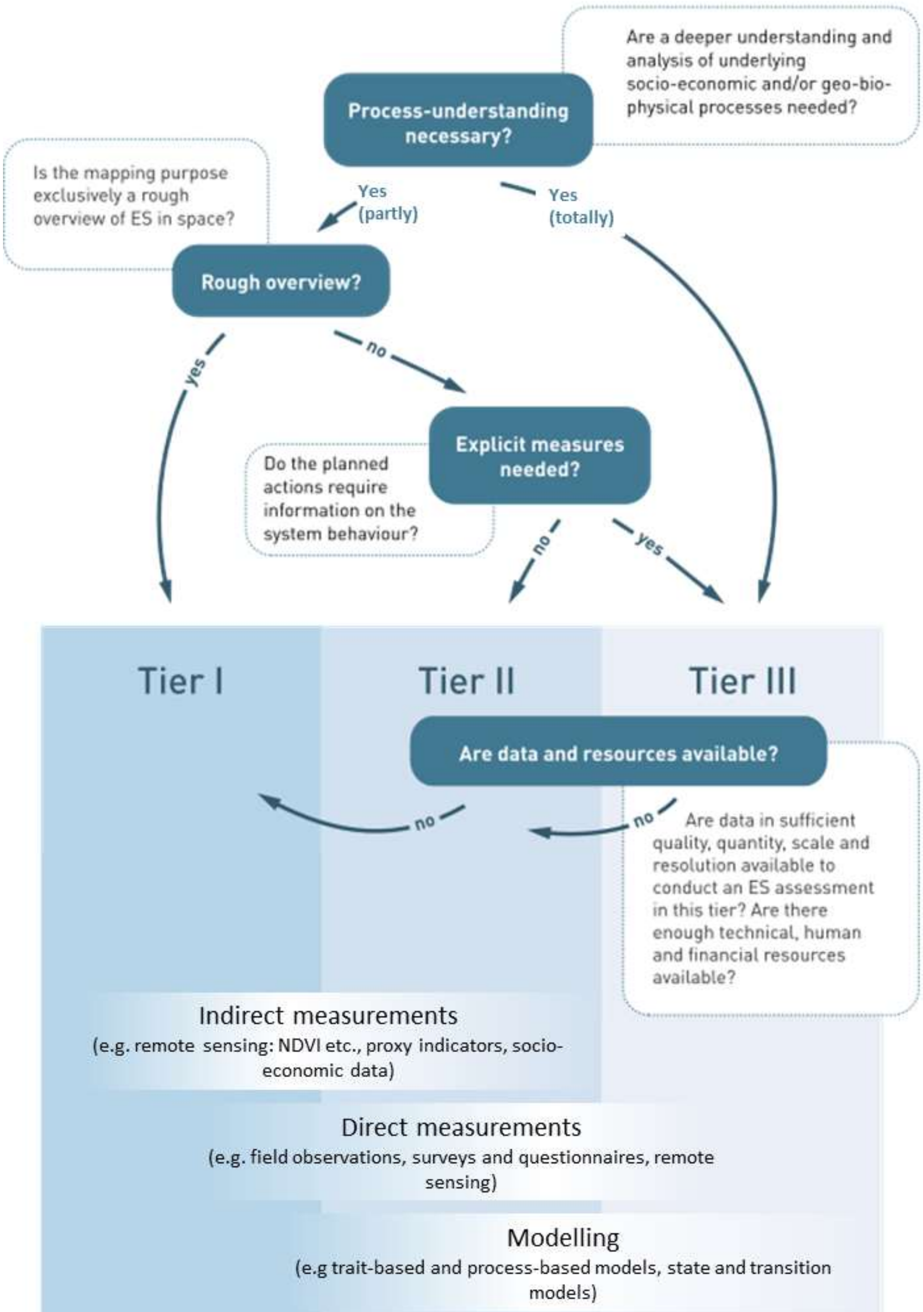


Figure 4: Decision tree guiding the selection of tiers for ES mapping (methods are not strictly assigned to a single tier but usually have a focus at a certain tier level).

The different tier levels are not related to a certain scale: a tier 1 approach can be applied at the local scale to get a first understanding of the presence, absence and abundance of ecosystem services; a tier 2 or tier 3 approach is required to better target national or even pan-European land management measures.

6. Operationalising biophysical methods in decision-support

6.1. Spatial data

In this section we will discuss some of the challenges and requirements related to spatial data in the biophysical mapping and assessment of ES. We focus on scale and resolution, and data availability of potential data sources by using examples from the literature and case studies presented in ESMERALDA workshops. We also outline some of the data requirements for different tiers.

Scale defines data accuracy

Biophysical mapping and assessment methods are strongly dependent on reliable biophysical data. In the series of ESMERALDA workshops aimed at testing the flexible methods under development in real-world case studies, the issues related to spatial data were discussed. Data quality with adequate resolution and availability was identified as one of the most crucial factors affecting the accuracy of results (e.g. Mononen et al. 2017). In the literature, the relationship between quantification of ES and the degree of generalisation/resolution of the input data and the spatial scale at which a given service is considered is also heavily discussed (e.g. Hein et al. 2006; Lupa & Mizgajski 2014; Tolvanen et al. 2016; Burkhard & Maes (Eds.) 2017).

The scale of a study determines the accuracy of the data needed for the mapping; for example higher resolution data is required to capture more detailed features of the environment. Local scale comprises, for example, point sources, communities, individual farms, or habitats. Moving from local scale to regional or national scale, less detailed or lower resolution data may be required as the aim is to describe the general aspects of features within large geographic areas, rather than fine scale analysis or descriptions. Regional scale studies can consist of administrative districts (counties, districts or municipalities), watersheds or landscapes whereas national scale includes administrative boundaries. However, the size of countries can vary substantially enabling high variation; for example, in a national scale context where a smaller country corresponds to a sub-region of a larger country. As trade-offs are common between the accuracy of the output and the effort required to obtain and process detailed high resolution datasets, it is advisable to consider sensitivity testing with different input data. As online geospatial data repositories and cloud computing platforms, such as Google Earth Engine are growing, the processing challenges of large high resolution datasets are now starting to decline, but the spatial limits of the underlying data should still be considered carefully.

Data sources and availability

Reviewing, acquiring, and compiling the required spatial data can be a challenging and laborious task, as the data are usually dispersed across various sources and/or may need to be pre-processed to be suitable for analyses, which can also be very time consuming. Biophysical data can be gathered either by using direct observations and field measurements, or through indirect methods such as proxies or by modelling. For example, in the mapping of cultural ecosystem services in marine areas in Latvia, the data used was based on benthic habitat maps (proxies) that were complemented with field survey results and expert knowledge (Ruskule & Veidemane 2016). Similar data combinations for biophysical mapping were discovered in almost every case study presented in the ESMERALDA workshops (see the ESMERALDA case study booklets). These real life examples of various combinations of diverse datasets requires particular attention to avoid errors, while interpreting the absolute values and comparing the results obtained on the basis of data from various sources (Lupa & Mizgajski 2014).

There are many factors affecting the availability of data in different countries, such as level of economic development, funding, or technological capabilities. As a result, harmonised datasets covering a large area can be sometimes difficult to find. Still, the development of technology applicable at the global scale has allowed for more opportunities to work with more detailed and accurate data. While increased computing power of devices allows for work on increasingly large datasets.

Many existing datasets are available for free or through co-operative arrangements; for example, by involving the data producer as a project partner and allocating project funding to the partner in question. Sometimes the data must be purchased from the data producer. A preliminary study on spatial data and analytical methods for assessing the ecosystem services and connectivity of the protected areas network of the Green Belt of Fennoscandia, i.e. a chain of protected areas on the borders of Russia, Finland and Norway, resulted in a list of 108 potential datasets across the study area varying from regional to global scales. Of the datasets reviewed, only eight were commercial while others were available freely or through co-operation (Itkonen et al. 2014, see Appendix 1).

In some cases, the existing datasets may not be available at all due to confidentially or other restrictions; for example, in marine environments, where several member states have laws in place to restrict gathering and publication of marine data such as bathymetry and seafloor substrate composition. Sea chart level bathymetric data and coarse data on substrate (e.g. EMODNET marine data portal) are available in most EU-member states through national maritime authorities, geological research facilities, and local research projects. These data sets can be used for broad-scale analyses but are often not accurate enough for regional level and smaller scale work. In local scale studies the importance of the local actors increases, as they are capable of providing more detailed data and expert knowledge of the field of research, such as mapping pollination and seed dispersal in Malta (Balzan 2016).

Data requirements for different tiers (1-3)

Referring to the definition of tiers presented by Grêt-Regamey et al. (2017), Tier 3 data can be described as more detailed than Tier 1 data, i.e. with more classes of LU data and/or presented at a higher resolution. However, the amount of data used does not correlate with the tiers because one can have a single high resolution dataset at Tier 3 (e.g. based on a survey) and several coarse datasets at lower tiers. While the accuracy and level of detail of ES assessments increases from Tier 1 to Tier 3, the required technical expertise and data requirements are not necessarily increasing from lower to higher tiers: if very precise datasets such as cadastral information or surveys are available, they are suitable for a Tier 3 approach without collection of new data. Furthermore, a Tier 3 approach might only use high resolution survey data which does not require a high level of technical expertise. On the other hand, a Tier 1 approach combining different readily available datasets might also be technically challenging. For more general methods (i.e. Tier 1), existing datasets such as data from EEA (e.g. CORINE land cover data) can be used and are operationally available for most areas of Europe. More complex and detailed mapping methods (i.e. Tier 2-3) usually require more spatially explicit data from multiple data sources and needs to be reviewed in a region or local level. For more information of the tiered approach of biophysical mapping methods see section 4.

6.2 Setting the targets – What to measure and map?

From direct measurements to models

Quantification is an integral part of ES mapping and assessments (Vihervaara et al. 2017a), and there is a diversity of methods that can be employed to support this. Therefore, the methods have been divided into classes that should aid the decision to choose a particular method. The decision on what to measures to employ to describe ecosystem services comprehensively needs careful consideration, and the use of indicators is a common approach used to do so (Mononen et al. 2016). The indicators used can focus on measuring ES supply, demand or budgets, and the input measurements for these can use direct field measurements (e.g. Fontana et al. 2014) or proxies due to low data availability or difficulties in measuring the ES directly (Maes et al. 2012). Where ecosystem condition is the focus of the assessment, analysis could use species distribution or population data, habitat condition information, or other factors of quality (EC 2016). Pressures on ecosystem condition and the capability to deliver ES can also be used as indicators (van Oudenhoven et al. 2012, Syrbe and Waltz 2012). For sophisticated methods, for example process-based models, multiple indicators and datasets are needed in order to produce information on the ecosystem process. The selection of ecosystem services and suitable indicators requires a careful process to understand the definitions and the stage of ecosystem flow that is being assessed (Maes et al. 2014; Heink et al. 2016). Often they express only one stage in the cascade model, for instance an indicator illustrating supply, but not demand (Boerema et al. 2017).

One of ESMERALDA's aims is to increase harmony for indicators that are used for measuring ES. Consistency is improving by the increased usage of classification systems for ES (EC 2014), such as the Common International Classification of Ecosystem Services (CICES) (Haines-Young & Potschin 2013), the Millennium Ecosystem Assessment (MA) (2003) or TEEB (2010) classifications which have been developed to ensure consistency in assessments (EC 2014). Harmonisation would help these classifications become more practical for monitoring purposes (Feld et al. 2009). The Working Group on MAES supports the implementation of indicators that are widely used and have sufficient input data that is easily accessible (EC 2014). For example, they can refer to either land cover classes that measure ES for each class, or smaller scale characteristics of vegetation (Vihervaara et al. 2012), for example.

Statistical methods can also be used for quantification, and for mapping and assessment (e.g. Breeze et al. 2011, and previous section). Assessment of ES can also be conducted through indices; for example, the Ecosystem-service performance index (Rutgers et al. 2012), or the Biodiversity combined index (Castro et al. 2014, 2015). They may also involve spatial data, as in the Multiple Ecosystem Services Landscape Index (MESLI) (Rodríquez-Loinaz et al. 2015), for example.

In summary, the requirements to consider at the beginning of any mapping activity include exploring the purpose of mapping; data format, availability, quality, and coverage; and what indicators could be relevant for use (e.g. supply, demand, budget). Additionally, spatial scale, expertise, software and resources should also be considered.

The potential of remote sensing in biophysical assessments

Remote sensing has become increasingly important in applications related to ecosystem services research (see Araujo Barbosa et al 2015). The application of aerial photography has developed and evolved greatly from its earliest iterations; the last decade has seen the rapid development of research efforts on the topic of ecosystem services, which has led to a significant increase in the number of scientific publications (Wolff et al 2015). Time series data would also allow monitoring of changes in ecosystem condition and ES.

New developments in remote sensing, such as using time series to demonstrate temporal changes, Very High Resolution (VHR) satellite imagery, or LiDAR techniques that support the measuring of vegetation structure among others parameters, can really help to speed up the process of mapping and monitoring at very fine scales. Nowadays, detailed data derived from remote sensing at different spatio-temporal scales could be used to compute layers representing various environmental characteristics that affect the provision of ecosystem services. Among the newest developments, the use of UAVs (Unmanned Aerial Vehicles) to support vegetation surveyors has opened new capabilities and applications to conduct detailed observations and monitoring down to the scale of several centimeters. Besides this, an increasing amount of satellite imagery is becoming available as open data, such as the imagery from the European SENTINELS – this is combined with the American satellite sensors such as MODIS and Landsat, which have had a longer tradition of open data policies(e.g. Thierion et al 2014). Using a mixture of remote sensing and field methods appears to deliver the best results (e.g Mikolajczak et al 2015). Yet, this requires ecologists and remote sensing experts to collaborate closely with the newest methods and capabilities. Some examples of these new technologies, such as the assessment produced by Dusseux et al (2014), provide important insights on the ability of optical images, SAR (Synthetic Aperture Radar) images, and the combination of both types of data to discriminate between grasslands and crops in agricultural areas. These methods can be applied also in the regions where cloud cover is very high most of the time, which restricts the use of visible and near-infrared satellite data. Furthermore, novel techniques are underway to measure β-diversity (referring to the change in community composition) from airborne or satellite remote sensing imagery and potentially relating these measures to species diversity in the field (see Rocchini et al 2018). The remote sensing of β-diversity is suggested to be based on methods such as multivariate statistical analysis, spectral species concept referring to species identification based on imaging spectroscopy, self-organising feature maps, multi-dimensional distance matrices, among other biodiversity indicators (Rocchini et al 2018).

As aforementioned, recent advances in Earth Observation (EO) allow advances to the design of a biodiversity observation system (cf. Vihervaara et al. 2015; 2017b). Such a system is needed to improve ecosystem services mapping that is consistent and cost effective, but its development and implementation remains a significant challenge (Mücher et al, 2015). As explained earlier, LiDAR and VHR multi-spectral sensors are becoming increasingly available. These approaches provide opportunities for land cover and habitat mapping with a very high spatial resolution of 1 or 2 metres (mapping scale ~ 1:4000), and a high thematic differentiation in such a way that the derived maps meet the demand of end-users, such as terrain and nature conservation managers. The launch of the multi-spectral Worldview-2 (WV-2) sensor with eight spectral bands (including the coastal, yellow and red edge, as well as a second (overlapping) NIR channel) and a spatial resolution of 2 metres provides new opportunities for discrimination of land cover/habitats (Lucas et al. 2015).

6.3 Application of biophysical mapping and assessment for various ecosystems and their services

Biophysical mapping and assessment of ES provide spatial data essential for decision-making on sustainable use and management of the ecosystems and the services they provide, as well as for natural capital accounting at MS and EU level. Depending on the decision-making level and context (e.g. strategic or spatial planning at municipality, regional or national level, strategic planning for a particular policy sector), biophysical mapping can be applied at various scales as well as being targeted to particular, or multiple, ecosystem types and the services they provide. The scale of mapping, data availability and data accuracy requirements all have influence on the selected mapping method (see section 4.3 spatial data and section 3 on tiered approach of biophysical mapping methods). However, the choice of appropriate method not only depends on the technical aspects, but also the decision-making context and policy questions. For example, in spatial planning, the planners require a method that is transparent, simple to use and understand, and the results of which can be implemented into land use planning.

Experience in application of ecosystem service mapping at various scales and ecosystems

The analysis presented below, on how the biophysical ES mapping methods are applied across various scales and ecosystem types is based on a review of the cases included in the ESMERALDA Ecosystem Services Mapping and Methods database (by December 2017). Almost half of the reported cases in the database were targeted at the regional scale, followed by local, then multi-national studies; while national level studies were comparatively less, with very few studies at the global scale.

The local scale studies range from single sites/experimental fields to cities as well as smaller administrative units (e.g. municipalities). Such studies usually require high resolution data in order to fit to the local features and the study context. The local scale also allows more labour-intensive methods of data collection and analysis. The ESMERALDA database reveals that a variety of methods of different levels of complexity have been applied at the local scale, starting from simple spreadsheet/spatial proxy methods, to more complex modelling and methods based on direct measurements. The most commonly applied methods were the process based models (e.g. ENVI-met model, BalanceMED, Damage Scanner Model etc.), followed by spatial proxy methods (including spreadsheet method), and integrated modelling frameworks (e.g. InVest, ESTIMAP, QuickScan, Multi-criteria ESA and Bayesian Belief Network). Local ES studies have also used statistical models and macro-ecological models. (Box 11).

Box 11. ***Assessing the values of green infrastructure in the city of Järvenpää in Finland***

The City of Järvenpää, Finland, is a compact city (40 km^2) with tight boundaries, but it is still expected that the population will grow by more than 10% per year. As a result, there is an exceptionally strong need for infill development to provide housing for new inhabitants. The city planners are keen to avoid causing deleterious impacts as the result of development on the natural values and ecosystem services provided by green and blue areas. As such, the assessment of green infrastructure (GI) was carried out in close collaboration between the city of Järvenpää and the Finnish Environment Institute (SYKE). The assessment included three parts: 1) potential provision of multiple different ecosystems services, 2) demand for ecosystem services and 3) ecological connectivity of GI. Here we focus on the potential provision of ecosystem services and ecological connectivity. To capture the detailed features in the city, the spatial delineation of GI was carried out using the best available data. Corine land cover and land use data with 25 metre pixel size was too coarse for this purpose, thus the final delineation consisted of multiple different local datasets which were complemented with manual digitisation. Potential provision of 12 different ecosystem services (including provision, regulating and maintenance, and cultural services) were analysed using the Green Frame method, belonging to the Spatial Proxy methods (Itkonen et al. 2014; Kopperoinen et al. 2014). The structural connectivity of GI was assessed using two different approaches. Firstly, we applied Morphological Spatial Pattern Analysis (MSPA) that classified the green patches based on geometry, area and edge size (Vogt et al. 2007). Secondly, we used graph theory based on the Matrix Green and Conefor software (Saura & Pascual-Hortal 2007) to quantify the importance of habitat areas in terms of the maintenance of connectivity, as well as evaluating the impacts on connectivity of habitat and landscape changes. Results supported the integration of GI and infill development by providing potential new housing sites for the spatial planners.

Regional scale studies can be applied to regional administrative units as well as to regions with similar biophysical or geographical characteristics (e.g. river catchment basin, mountain regions etc.). They can range from areas covering part of a country to part of the globe (e.g. Scandinavia). Since the requirements for data resolution are lower, regional studies can be based on commonly available aggregated land cover or land use data sets. This could be one of the reasons why the regional scale was found to be the most widespread in the biophysical ES mapping and assessment studies reviewed. A variety of ES mapping methods were also found to have been applied at this scale. Again, the most common of these were the spatial proxy methods and process based models, followed by phenomenological models (e.g. HIRVAC-2D, USLE, RUSLE) and integrated modelling frameworks (mainly InVest).

Comprehensive ES mapping at the **national level** has only been implemented by a few EU member states despite Target 2 of the EU Biodiversity Strategy requiring Member States to "map and assess the state of ecosystems and their services in their national territory" by 2014. Based on a review of national ecosystem assessment in Europe (Schröter et al. 2016), it was found that national scale ES mapping is most frequently based on literature reviews and national statistics, followed by expert judgement. Few countries (e.g. UK, Spain, Portugal, The Netherlands) have also completed modelling of the state of ES. The ESMERALDA database includes several national scale cases, which either cover whole national territories and all ecosystems (e.g. UK, Spain, Lithuania) or are targeted to specific ecosystem types (e.g. croplands and grassland in Czech Republic; wetlands, rivers and lakes in Greece). The process based models are reported as the most commonly used methods at the national scale, followed by statistical models and spatial proxy methods. (Box 12)

Box 12.National scale ecosystem service mapping in Scotland, UK

Multiple landscape functions were mapped in order to split the landscape into zones from which to evaluate the existing farmland afforestation policy in Scotland. This national scale study focused on highlighting win-win areas for ecological and socio-economic outcomes that would benefit most from the creation of small multifunctional woodlands. This approach used previously described methods for mapping biodiversity (van der Horst and Gimona, 2005), visual amenity (van de Horst 2006) and woodland recreation (Brainard et al., 1999; Hill et al. 2003), creating raster maps with a benefit score for each cell in the landscape. A map of potential biodiversity was created from habitat suitability models for 16 priority species using a spatial multi-criteria analysis method based on combining scores for each of the species for criteria such as preference for afforestation based on literature reviews, and a weighting combining relative range size, habitat scarcity and the reliability of mapping suitable habitat for the species. Similarly, a map of potential visual amenity was created using four variables including spatial proxy modelling, using distribution of viewing population and amount of woodland already visible in the local landscape, and from public viewpoints. Potential on site recreation was based on an inverse function of distance to where people live; scores were attributed to each 500m cell using a regression model. The three resulting maps were combined using weightings from a spatial multi-criteria analysis method and four scenarios to simulate the range of possible stakeholders. 'Multifunctional hotspots' for planting woodlands were highlighted from the resulting maps based on whether scores were above the median for each of the input layers. The Farm Woodland Premium Scheme (FWPS) is an agri-environment policy providing incentive payments to farmers for the planting of woodland. To evaluate how existing woodlands were placed under this scheme, an overlay of planted woodlands with the multifunctional hotspot map was made. Statistical analysis, including the use of Monte Carle simulations, was conducted which demonstrated that FWPS plantings performed, at best, no better than randomly planted woodlands, and in some weighted combinations, preferentially in low benefit areas. This study provided insights into the potential efficiency of the impacts of land use policies at the landscape level, and allowed informed decisions between conservation-oriented approaches and others to be made.

Multi-national studies were found to mostly represent cases that cover Europe or EU member states, but also include other specific regions (e.g. East European countries, Baltic Sea region, Mediterranean region). European scale studies are usually based on modelling approaches – mostly using process based models (e.g. GREEN model, SWAT, MAPPE model, Damage Scanner Model, Nutrient transport model, IMAGE, BalanceMED, ENVI-met model), followed by macro-ecological models (e.g. habitat modelling, convergence-evidence mapping), statistical models (e.g. variogram models, geostatistical simulations), and spatial proxy methods.

Only a few **global studies** are included in the ESMERALDA database, therefore it cannot be used to judge the applicability of ES mapping methods at the global scale. Nevertheless, there are several global models developed and applied by researchers for ES mapping and assessment; for example, the Integrated Model to Assess the Global Environment (IMAGE), the Global Unified Metamodel of the Biosphere (GUMBO), and the Global Biosphere management Model (GLOBIOM).

There appear to be no major differences in the ES mapping and assessment methods used for particular **ecosystem types**. This is a result of most of the studies reported in the ESMERALDA database covering a variety of ecosystems, and thus only few are targeted to a particular ecosystem type. Croplands and woodlands are the most frequently assessed ecosystem types (i.e. covered by most of the cases reported in the database). They are followed by grasslands, urban areas, wetlands, and rivers and lakes. The coastal and marine ES studies are the least represented. The process-based models and spatial proxy methods are reported as the most commonly used for mapping of terrestrial and freshwater ecosystems, while process-based, statistical and phenomenological models are more often used in coastal and marine ES studies.

Studies that focus on one particular ecosystem type are presented in Annex I. Such ecosystem specific studies are mostly implemented at local or regional scale, with the exception of coastal and marine ES studies, which cover regional to global scales. The majority of the ecosystem specific cases address the urban ecosystems at the local scale using process-based models and spatial proxy methods, as well as integrated modelling frameworks and phenomenological models. (Box 13)

Box 13. ***Marine ecosystem services of Latvian marine waters***

Biophysical mapping of selected ecosystem services was performed as an input for the Maritime Spatial Plan (MSP) for Internal Waters, Territorial Waters and Economic Exclusive Zone of the Republic of Latvia, developed in 2015-2016 by the Baltic Environmental Forum under the supervision of the Ministry of the Environmental Protection and Regional Development. This was the first attempt in the Baltic Sea region to apply the MAES process in an official MSP process at the national level (Veidemane et al. 2017). Mapping was performed in a relatively short time period with limited resources and data availability. Therefore, the tiered approach was followed in selecting suitable methods for mapping different ecosystem services. Tier-1 was applied for mapping of regulating and maintenance services. Based on expert knowledge, the potential of benthic habitats to supply the five services (bio-remediation, filtration of nutrients, maintaining of nursery populations and global climate regulation) was identified. This involved a simple qualitative assessment (spreadsheet method) using a binary scale (i.e. 'yes/no'). The benthic habitat map, developed using the HELCOM-HUB classification system, was used as a proxy for mapping potential distribution of ecosystem services. The Tier-2 approach was possible for provisioning and cultural services using the data on actual service supply. The spatial proxy method was used to assess provisioning services in an area covered by red algae, using field survey data as well as expert knowledge on habitat suitability for growth of the species. Another provisioning service - fish for food - was assessed using data from fishery log books; this was processed with the R Statistical Software to estimate total landing of commercial species (sprat, herring, cod and flounder) in a grid cell per species, for the period 2004–2013. The cultural service 'marine tourism and leisure possibilities at the coast' was assessed using the spatial multi-criteria analysis method by combining several criteria; for example, number of visitors, suitability of the area (or best place) for particular tourism or leisure activity, and accessibility. ES mapping results were applied to characterise the marine ecosystem as well as to assess the possible impacts of the sea uses on ES supply as part of the Strategic Environmental Assessment (SEA).

6.4 Purpose in application of biophysical mapping and assessment of ecosystem services for policy support and decision-making

Ecosystem services are acknowledged by policy makers as an important concept in supporting decision-making, because of their holistic understanding of interactions between nature and human beings, and their ability to reveal synergies and conflicts between environmental and socio-economic goals. The ES concept provides a comprehensive framework for trade-off analysis, addressing compromises between competing land uses and assisting to facilitate planning and development decisions across sectors, scales and administrative boundaries (Fürst et al. 2017).

The role of ES concept was highlighted for protection of biodiversity in 2010 at the tenth meeting of the Conference of Parties to the Convention on Biological Diversity (CBD), where the global Strategic Plan for biodiversity for the period 2011–2020 was adopted. The Plan includes so called "Aichi targets"[5], which besides traditional conservation-based biodiversity targets, aim to enhance the benefits to people from biodiversity and ecosystem services. It was followed by the adoption of the EU Biodiversity Strategy 2020, which sets the goal of maintaining and restoring ecosystems and their services, and included mapping and assessment of ecosystem services among the actions to be implemented by the EU Member States. In order to coordinate this process and to support the member states, the European Commission established the MAES working group. It provides an analytical framework as well as guidance for implementation of Action 5 of the Strategy within the EU and in the Member States, suggesting a set of indicators as well as mapping and assessment approaches. The MAES process involves spatially explicit biophysical quantification and valuation of ES for each Member State at the national scale. Although the Strategy stipulates that this mapping should be finished by 2014, so far this task has only been accomplished by a few countries (e.g. the

[5] www.cbd.int/sp/targets

Netherlands, Belgium, UK, Finland, France, Spain, Germany and Luxemburg). Combinations of various biophysical mapping methods have been applied in the national scale using national statistics or spatial proxy methods (involving expert judgement) as well as in some cases, spatial modelling to estimate the state and trends of ES supply (Schröter et al. 2016).

Another task set by the EU Biodiversity Strategy within Action 5, is the assessment of economic value of ES, and the integration of these values into accounting and reporting systems at EU and national level, which is to be implemented by 2020. Therefore, the MAES process also involves the development of a methodological framework for Natural Capital Accounting (NCA). This includes a step-by-step approach, which begins with biophysical quantification and continues for subsequent valuation steps. Such a biophysical quantification and measurement process requires clearly classified, well-structured, and spatially explicit input data sets (Maes et al. 2014). The United Nations Statistical Division (UNSD) has set up the System of Environmental-Economic Accounting (SEEA) for collecting internationally comparable statistical data on the environment in relation to the economy, and thus creating a basis for an ES accounting system. As a part of this work, the CICES framework was developed, and several EU Member States have started the development of their natural capital accounts (e.g. Lai et al. 2018).

The Intergovernmental science-policy Platform on Biodiversity and Ecosystem Services (IPBES) was established in 2012, aiming at strengthening the science-policy interface for biodiversity and ecosystem services. One of the main directions in the work programme of the Platform is the assessment of biodiversity and ecosystem services at regional and global levels, guided by the IPBES conceptual framework. IPBES also provides guidance for experts performing assessments within the Platform, as well as to scientists, stakeholders and decision makers on use of scenarios and models in regional, global and thematic assessments for particular decision-support activities (IPBES 2016).

Though the implementation of the MAES process and application of the ES concept in general is not only limited to advancement of biodiversity objectives, it is strongly related with implementation of other related policies, including water, marine, climate, agriculture, and forestry, as well as regional development (Maes et al. 2014). Ecosystem service mapping and assessment results can support sustainable management of natural resources, environmental protection, spatial panning, landscape planning and can be applied to the development of nature-based solutions and environmental education.

The results from MAES can contribute to **environmental policy** with regard to the assessment of risks and impacts to ecosystems or human health resulting from different human activities, as well as planning various mitigation measures. For example, the mapping of nutrient retention and the maintenance of chemical conditions of freshwater systems provide direct inputs into river basin management plans. Several regulating ES (e.g. climate regulation, maintenance of hydrological cycles and water flows, and control of erosion rates) are essential for planning climate change mitigation and adaptation measures, including disaster risk reduction related to extreme weather conditions and flood prevention, as well as the cooling capacity provided by green infrastructure in urban areas. Measures for controlling the dispersal of pollutants can be based on mapping the potential of mediation by biota or ecosystems (e.g. bio-remediation, filtration, sequestration, storage and accumulation), as well as mediation of flows (including water flow maintenance and air ventilation).

ES can be included within the **impact assessment procedures** (e.g. Strategic Environmental Assessment of plans and programmes, and Environmental Impact Assessments of projects), thus extending the scope of impact assessment from purely environmental considerations to other dimensions of human well-being. The potential contribution of ES information to impact assessment has been described in Geneletti (2011; 2015; 2016). In short, ES mapping and assessment can improve the overall outcome of actions, reduce the likelihood of plan or project delays due to unforeseen impacts, and reduce reputational risk to public authorities and developers from unintended social impacts. ES can be applied in all stages of impact assessment, including scoping (to indicate services on which action depends as well as services it affects), consultations (helping to focus debate and engagement of stakeholders), assessing impacts and trade-offs of development alternatives as well as proposing mitigation measures (Geneletti & Mandle, 2017). The scoping phase can involve simple spatial proxy/spreadsheet methods, while assessing the impacts of alternatives might require application of scenario planning methods as well as integrated modelling tools (e.g. InVest), that can assess trade-offs and scenarios for multiple services, or state-and-transition models, which allows assessing ecosystem dynamics after disturbance. Spatial analysis should allow impacts to be traced to specific beneficiaries, by illuminating where and how environmental changes are affecting benefits to people (Geneletti & Mandle 2017). It also enables identification of more efficient mitigation options by bringing together environmental and social aspects.

Furthermore, use of the ES concept in **spatial planning** provides greater opportunities to integrate environmental considerations into decision-making on land use change or management in strategic and practical levels. In particular, biophysical ES mapping can contributes to spatial planning by: i) identification of 'hotspot' areas with high potential of ES supply and/or sensitivity to particular impacts related to planning decisions; ii) assessment of the impacts of planning solutions through the SEA procedure; iii) visualisation of the trade-offs of different land use alternatives; iv) identification of the mismatch between areas of ecosystem service supply and demand; v) enhancing engagement of stakeholders and decision makers by communicating the overall benefits and shortcomings of the planning proposals; and, vi) enhancing citizens' participation in planning and decision-making by gathering people's local knowledge and perceptions, and enhancing knowledge exchange in terms of ecosystems and their services. The degree of detail used in ES mapping, and the selection of methods and indicators applied depends upon the planning purpose and statutory requirements of the particular planning instrument. ES mapping and assessment has already been used to support planning and decision-making from national to local level in EU countries. For example, in Finland many regional strategic and local practical plans aim at enhancing, restoring or creating ecosystems and related services. ES mapping has also been introduced in the ongoing European maritime spatial planning initiatives in order to assess use potential, as well as the likely impacts on marine ecosystems.

Agriculture and forestry are among the sectors with high potential for applying the ES concept, for instance to increase synergies of recreation and carbon sequestration with timber production in forests, or pollination and biological control in agricultural environments. These sectors are inextricably linked with the supply of ES as well as depending on ES supply (e.g. pollination, pest and disease control, maintaining of soil fertility), and at the same time, having direct impacts on ecosystem condition and the supply of other services (e.g. maintaining habitats, chemical condition of freshwaters, global climate regulation etc.). The level of supply and impacts of these services directly depends on the applied management practice. Thus, ES mapping and assessment results can be used to address the trade-offs within and between sectors, to target policy objectives and required measures for improving ES supply and related payment schemes. For example, restoring and preserving ES has been already included as one of the priorities in the rural development pillar of the EU's Common Agriculture Policy.

The IPBES methodological assessment (2016) illustrates how different types of scenarios and modelling approaches can serve the major phases of the policy cycle, including agenda setting, policy design, policy implementation and policy review (IPBES 2016). For example, "exploratory scenarios" that examine a range of plausible futures, based on potential trajectories of drivers can contribute to problem identification and agenda setting, while "intervention scenarios", which evaluate alternative policy or management options, can contribute to policy design and implementation. The IPBES assessment states that exploratory scenarios are most widely used in assessments on the global, regional and national scales, while intervention scenarios are usually applied in the decision-making on national and local scales. While scenarios capture different policy options, various models can be applied to translate the scenarios into consequences for nature, nature's benefits to people and quality of life.

Application of ES in spatial planning and policy-making through scenario development, modelling of impacts, and trade-off analysis can provide added value by synthesising and organising knowledge from various datasets as well as facilitate cross-scale and cross-sector planning, thus contributing to integrative resource management. Nevertheless, there is still a need to develop guidance and criteria on how to apply ES within different planning contexts as well as through the decision-making process (Fürst, 2017). Furthermore, integration of various ES mapping and assessment methods and tools are required to address the complexity of socio-ecological systems, and support the decision-making process across different scales and sectors.

7. Integration of biophysical methods with economic and social methods, and further considerations

The key outcome of this report D3.3, together with the reports D3.1 and D3.2, are to review the biophysical, economic and sociall methods, and their classification, into meaningful groups. In the early phases of the project, it became clear that terminology was used and interpreted in very diverse ways in the literature, and by experts in workshops and meetings. We have tried to collate this information and categorise it in order to frame the path towards a flexible methodology for the mapping and assessment of ecosystems and their services. This is presented in the figure 5.

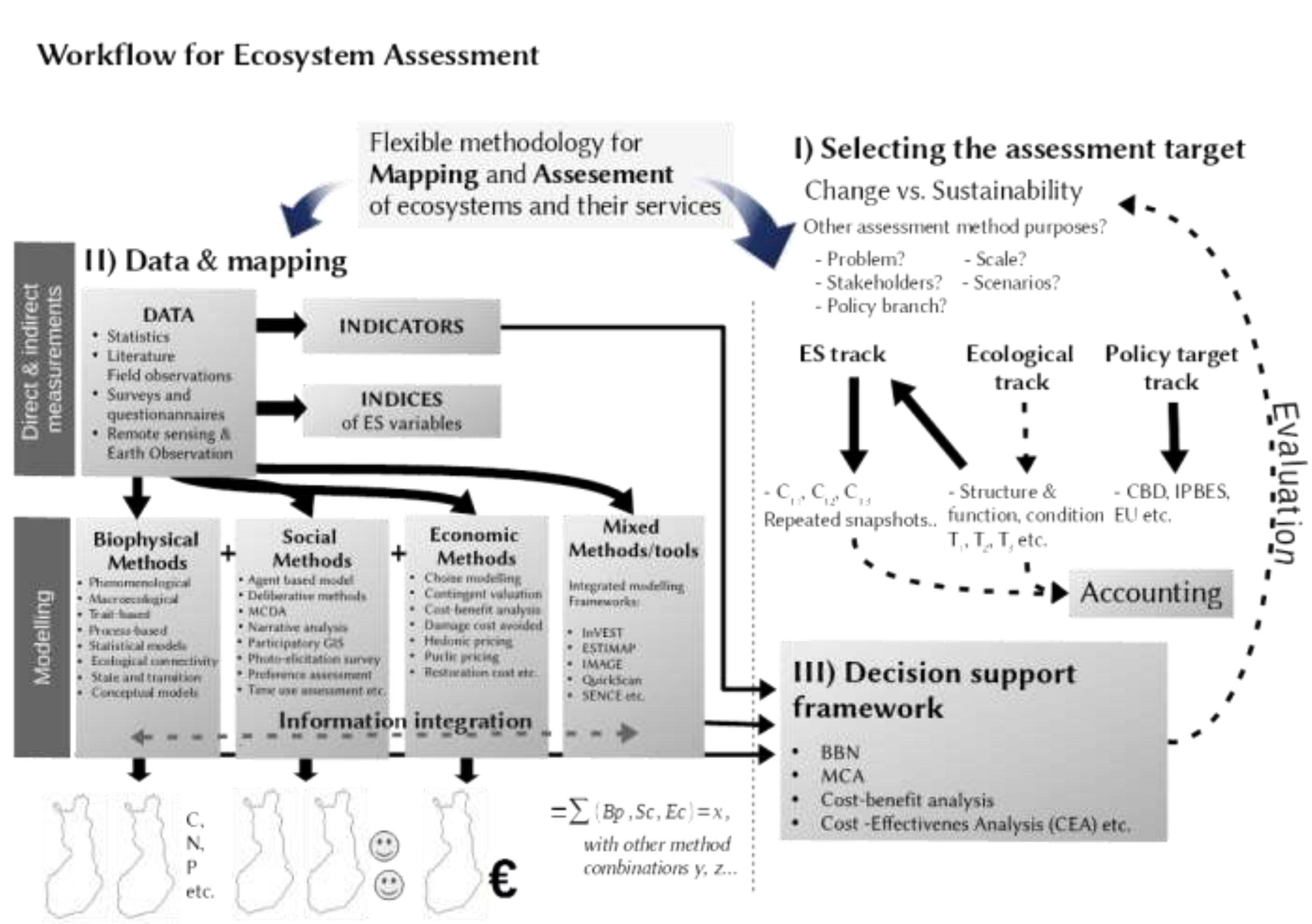


Figure 5: The structure of this figure is the core of the report, especially parts "Data & Mapping (II)" from the biophysical point of view, and "Decision support framework (III)".

A synthesis of the results presented in this report, and those previously compiled in workshops and other expert meetings throughout the ESMERALDA project, revealed possibilities and challenges that need to be considered further in the ESMERALDA project. Specifically, work package 5 on 'case studies' (WP5) and work package 4 on 'assessments' (WP4), will seek to address this.

The challenges related to the data quality and selection of the used methods for various cases was highlighted in this report. Availability and accuracy of data may vary between areas, for instance between terrestrial and marine areas, between MS in EU, and between provisioning and regulating or cultural ES. In many cases identified in the literature review, various data types were used for analysis: expert judgement, direct field or remotely sensed measurements, extrapolations based on models, the combination of the first ones, or proxies. This also has an obvious influence on the results and accuracy of the mapping exercises. Also the spatial and temporal extent of the data was thought to affect the outcomes of ES mapping, and there was also variation between the different tiers. The role of abiotic data is an integral part of many models, and can also be used as a proxy for vegetation occurrence, and thus a proxy for associated ecosystem services. It is important to note that biophysical data is often used as an input for various economic and socio-cultural methods.

Glossary and semantics should be clarified in the early stage of any ES mapping or assessment project, because people from different disciplines may have multiple interpretations to the terms used. Unifying definitions of what is meant, for instance, by index, model, method, tool, and software for example, was clarified in this report (Fig 4).

Evaluation of the quality and accuracy of the data, methods and models is challenging, as the different ecosystem services require very different techniques. In addition, the environmental variability may affect the results – and so this needs to be taken into account. Complexity in using more than one type of method to quantify and map certain ecosystem services might end up with significantly different outcomes. This variation and uncertainty from the different methods should be considered in the ecosystem assessments.

Classifying the used data, methods and models under the 3-tiered classification system, was difficult to do, and that requires further development. This becomes increasingly complex when different tiers of biophysical, economic and socio-cultural methods are used in the studies: In many cases, the components could be assigned to multiple tiers. Many of the methods are interlinked to each other, and in some cases the methods are combined together and have elements from different tiers. Thus attention should be given to define workflows and the data, computation and the resources needed.

Finally, visualisation and communication are important aspects of ecosystem service mapping, and especially assessment. Informative maps can provide valuable support for decision-making, but they also have to clearly show the uncertainties included in the methods used. Effectively mapping different ecosystem services on different scales can be a challenge, especially if maps need to be used to assess trade-offs and to solve conflicts. The challenge of integrating biophysical maps to economic and socio-cultural maps will be discussed in more detail in the ESMERALDA deliverable D3.4.

This report on biophysical mapping and assessment methods contributes to the development of the ESMERALDA main objective to develop a flexible methodology for mapping and assessment activities in the EU. Mapping and assessment studies require the linking of biophysical, economic and socio-cultural methods. This is where the outputs of one method are used as inputs into another method, and provide a knowledge production process to produce policy relevant information. In addition, there may be a need to integrate separate outputs from biophysical, economic and socio-cultural mapping and assessment applications. This is where the combination of complementary pieces of information are used to address different aspects of an ecosystem service (e.g. sustainability, value and distribution) to support decision-making. The ESMERALDA deliverable D3.4 also provides guidance on how to integrate information produced by biophysical, economic and socio-cultural methods.

8. Conclusions

- Biophysical quantification and mapping is a prerequisite of integrated ecosystem assessment, and sustainable use and management of ecosystem services (ES). Biophysical quantification reflects to structure and function blocks of the cascade model (i.e. ecosystem capacity to deliver ecosystem services, supply).
- ES quantification is well researched and documented in the published literature and large EU funded research projects such as OPERAs and OpenNESS. ESMERALDA focus more on mapping and assessment of ES, but builds on this past information and provides updated knowledge, especially on developing flexible methods for the mapping and assessment of ecosystems and their services.
- This report combines past and present understanding of mapping and assessment, and classifies the multiple methods and definitions found in the literature into a number of appropriate groups. Applicability and usability of independent methods and method combinations are evaluated and demonstrated through different case studies.
- Altogether, over 90 biophysical methods were found from the literature. These have been divided into **three direct measurement classes**: Field observations, Statistics and questionnaries, and Remote sensing and Earth observations; **three indirect measurement classes**: Remote sensing and Earth observation derivatives, Use of statistical and socio-economic data, and Spatial proxy models; and **nine modelling method classes**:

Phenomenological models, Macro-ecological models, Trait-based models, Process-based models, Statistical models, Ecological connectivity models, State and transition models, Conceptual models, and Integrated modelling frameworks.

- A workflow from mapping to assessment was developed. This helps to harness diverse terminology found from the literature. For example, categories of data include statistics, direct (field) measurements, and Earth Observation data, which can further be developed into indices and proxies that can subsequently feed into biophysical models. The methods vary in approach: some are more analytical (e.g. process-based models), while others assist more in decision-making processes (e.g. multi-criteria analysis or Bayesian belief-networks). It is important to note which part of the data-knowledge cycle each method can contribute to.
- A tiered approach for ecosystem services mapping has been suggested to help find the most appropriate method according to the purpose and the required level of detail of the ecosystem service analysis. This will help to ensure the resulting maps provide information relevant to decision makers, and avoid the application of over-complex or over-simplified methods.
- Before the identification of the relevant tier, the goal of the assessment and the different components of the analysed human-environment system should be described together with their interactions and dependencies.
- Data quality with adequate resolution and data availability are crucial factors affecting the accuracy of mapping results.
- Demonstration of the use of different methods has already been conducted in many cases over various ecosystem services, ecosystems, scales and regions. Local knowledge is always a valuable input to all different the methodologies.
- For integrated assessments and natural capital accounting, accurate biophysical data is needed from each step of the cascade model, and data should be spatially-explicit and scalable whenever possible.
- Numerous experts from different disciplines and regions in Europe were consulted and were convened at an ESMERALDA workshop during the process. This provided several possibilities to improve and critically evaluate classification of biophysical mapping methods, which has also helped to harmonise the terminology and approaches used.
- Despite the promising development towards a flexible harmonised methodology for mapping and assessing ecosystem services, further progress can still be made. For example, additional work is required to fully integrate biophysical methods with economic and socio-cultural methods, to map uncertainties, and to improve input data from various models on the basis of rapidly improving remote sensing technologies.

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Annex I. Real world examples of the application of biophysical mapping methods at different ecosystems and mapping levels.

Ecosystem types	Global	Multi-national	National level	Regional level	Local level
Terrestrial ecosystems					
Urban (A1)			Ecosystem services in Polish urban areas – assessing 4 regulating and 1 cultural services using a **spatial proxy and phenomenological models**. Mizgajski, A. & Stępniewska, M. (2014), Mizgajski et al. 2014	Burkhard & Maes (Eds). 2017 Uusimaa region, FI**,** **Spreadsheet method (GreenFrame)** Holt et al. 2015, Sheffield, UK **Spatial proxy model** **Macro-ecological model** **State and transition model** Haase et al. 2012, Leipzing-Halle, DE **Phenomenological model** **Process based model** **Spatial proxy model** Kroll et al. 2012, DE, Leipzig–Halle **Phenomenological model (HIRVAC-2D),**Van Wetten et al. 2012, NL, Haarlem, Den Haag, Almelo, Delft, Apeldoorn, Deventer, Zwolle, Eindhoven **Process-based model** (BalanceMED) Grêt-Regamey et al. 2017 Ventós area **Integrated modelling framework** (Multi-	Sibbesborg – OpenNESS, FI Provision of Cultural ES in a new planning area of Sipoo, **Integrated modelling framework (ESTIMAP)** Kopperoinen et al. 2017, FI, Järvenpää, **Spatial proxy method** Madureira & Andersen 2014, Planning of Green Infrastructure in Porto, Portugal **Spatial proxy model** Lehmann et al. 2014,Dresden, DE; Vihervaara et al. 2010, Lapland, FI **Process based model** Tratalos et al. 2007, UK Edinburg, Glasgow, Leicester, Oxford, Sheffield **Spatial proxy models** **Statistical analysis** (Variogram, geostatistical simulations) Giergiczny & Kronenberg 2012, PL, Lodz **Phenomenological model** (HIRVAC-2D), **Process-based model** (BalanceMED)

				criteria ESA model)	Hougner et al. 2006, SE, Stockholm National Urban Park **Phenomenological model** (HIRVAC-2D)**,** Depietriet al. 2013, DE, Cologne urban area **Process-based model** (Damage Scanner Model) Borysiak & Mizgajski 2016, PL Urban allotment gardens in the Poznań **Process-based model** (ENVI-met model) Radford & James 2013, UK Greater Manchester **Process-based model** (STREAM) Bastian et al. 2011, DE urban park in Leipzig **Integrated modelling framework** (QuickScan)
Cropland (A2)		Breeze et al. 2014, Europe Pollination **Process based model**	Breeze et al. 2011, UK Pollination **Statistical analysis**	Lorenz et al. 2013, DE, Dresden, Saxony, **Spatial proxy model** **Process based model** **Phenomenological model (USLE, RUSLE)** Gissi et al. 2014, IT, Province of Rovigo **Spatial proxy model,**	Sylla 2016, PL, The capacity of ecosystem to provide winter wheat crop service **Spatial proxy** Balzan et al. 2015, IT, Experimental fields **Trait based model** **Macro-ecological model** Aitkenhead et al. 2011, IE, Carlow, **Process based model (MOSES)**

				Integrated modelling (InVest)	Czajkowski et al. 2014, PL, Village Zywkowo **Process-based model** (ENVI-met model)
Grasslands (A3)					Borysiak 2012, PL **Trait based model** **Macro-ecological model** **Spatial proxy model** Gos, & Lavorel 2012, FR Lautaret, Central French Alps **Process-based model** (Damage Scanner Model) Lamarque et al.2011, FR mountain grasslands in the French Alps **Process-based model** (ENVI-met model) Lindemann-Matthies et al. 2010 Swiss Alps **Process-based model** (ENVI-met model)
Woodlands (A4)			Gimona & van der Horst 2007, UK, Scotland **Spreadsheet, QuickScan, Macro-ecological model, Statistical analysis** (Variogram, geostatistical simulations) Czajkowski et al. 2014, PL **Process-based model** (Damage Scanner Model)	Carvalho-Santos et al. 2014, Northern PT **Spatial proxy model** **Process based model** Gret-Regamey 2013, CH, Swiss Alps **Spatial proxy model** **Integrated modelling framework (QuickScan)** Vihervaara et al 2010, FI, Lapland **Spreadsheet,**	Carvalho-Santos 2014, Portugal, **Spatial proxy** Zandersenet al. 2007 ,DK Vestskovenn area **Process based model (LUISA; MAPPE model)** Hölzinger 2012, UK, Moseley Bog and Joy's Wood Local Nature Reserve **Process-based model** (BalanceMED)

				Spatial proxy model, **Trait-based model,** **Process based model** Zandersenet al. 2007, DK Tisvilde, Frederiksborg, Kronborg, Jægersborg, and Copenhagen **Process-based model** (ENVI-met model)	Gonzalez-Redin et al. 2016, FR Quatre Montagnes', French Alps **Integrated modelling framework** (BBN)
Wetlands (A7)		Jansson et al. 1998, Baltic sea drainage basin **Statistical analysis** **Connectivity models (IDRISI)** **State and Transition Model** **Phenomenological model** **Integrated modelling framework (BBN)**		Grossmann 2012, DE Restored floodplain wetlands in the Elbe River basin **Spatial proxy models** **Phenomenological model** **Process based model** (BalanceMED)Hein et al. 2006, NL De Wieden wetlands **Process based model, MAPPE model** **Trepel 2010, DE, North-Germany** **Integrated modelling framework (BBN)**	Nedkov & Burkhard 2014, BL, Seven Rila Lakes area **Spreadsheet** Hefting et al. 2013 BE, Catchments of Rhine and Scheldt, **Spatial proxy model** Hölzinger & Dench 2011, UK Gwen Finch wetland reserve **Process-based model** (BalanceMED)
Freshwater ecosystems (B)		La Notte et al. 2017, Europe, **Process based model (GREEN model)**	Vidal-Abarca et al. 2016, ES Spanish River Basins **Conceptual framework**	Gilvear et al. 2013, UK The Eddleston Water **Phenomenological model** Marques et al. 2013, ES	Carolli 2017, IT Noce River in northern Italy **Macro-ecological model: Habitat modelling** Magnussen et al. 2014, NO,

				Francolí River basin **Integrated modelling (InVest)** Gilvear et al. 2013, UK The Eddleston Water **Process-based model** (ENVI-met model)	water bodies in urban Oslo area **Process-based model** (BalanceMED) Van der Biest et al. 2013, BE Groete Nete **Process-based model** (BalanceMED) Oglethorpe 2000, GR, Lake Kerkini **Process-based model** (ENVI-met model**)** Vorstius & Spray 2015, UK Catchment on Scottish border **Integrated modelling framework** (EcoServ-GIS; SENCE)
Marine ecosystems (C)	Ghermandi & Nunes, 2013, Global map of coastal recreation values **Statistical analysis (Variogram, geostatistical simulations) Process-based model (MAPPE model)**	Liquete et al. 2013 European coastline, **Spatial proxy model** Ghermandi 2015, Coastal EU, **Statistical analysis (Variogram, geostatistical simulations) Integrated modelling (InVest**) Process-based model (MAPPE model) Galparsoro et al. 2014, European North Atlantic Ocean, benthic habitats **Statistical analysis (Variogram,**	Veidemane et al. 2017, LV National marine waters **Spreadsheet Spatial proxy model Integrated modelling framework** (Multi-criteria spatial analysis) Depellegrin & Blažauskas 2013, LT, Lithuanian coastal zone **Process based model (LUISA)** Šiaulys et al. 2012, LT Lithuanian exclusive	Brenner et al. 2010, ES Coastal zone of Catalonia **Process based model (LUISA) Process-based model (ENVI-met model)** Monioudi et al. 2014, GR East Crete **State and Transition Model Morphodynamic modelling** Guerry et al. 2012, CA West Coast of Vancouver Island, British Columbia **Integrated modelling (InVest**)	Stithou & Scarpa 2012, GR Zakynthos **Process-based model** (ENVI-met model)

		geostatistical simulations)	economic zone (EEZ) **Statistical analysis (Variogram, geostatistical simulations)**	Wiethüchter 2007, DK, Limfjord, **Process-based model** (BalanceMED) De Nocker et al. 2015, BE,FR Dune regions at North Sea coast **Process-based model** (ENVI-met model)	