Biophysical quantification

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MAPPING ECOSYSTEM SERVICES

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Benjamin Burkhard
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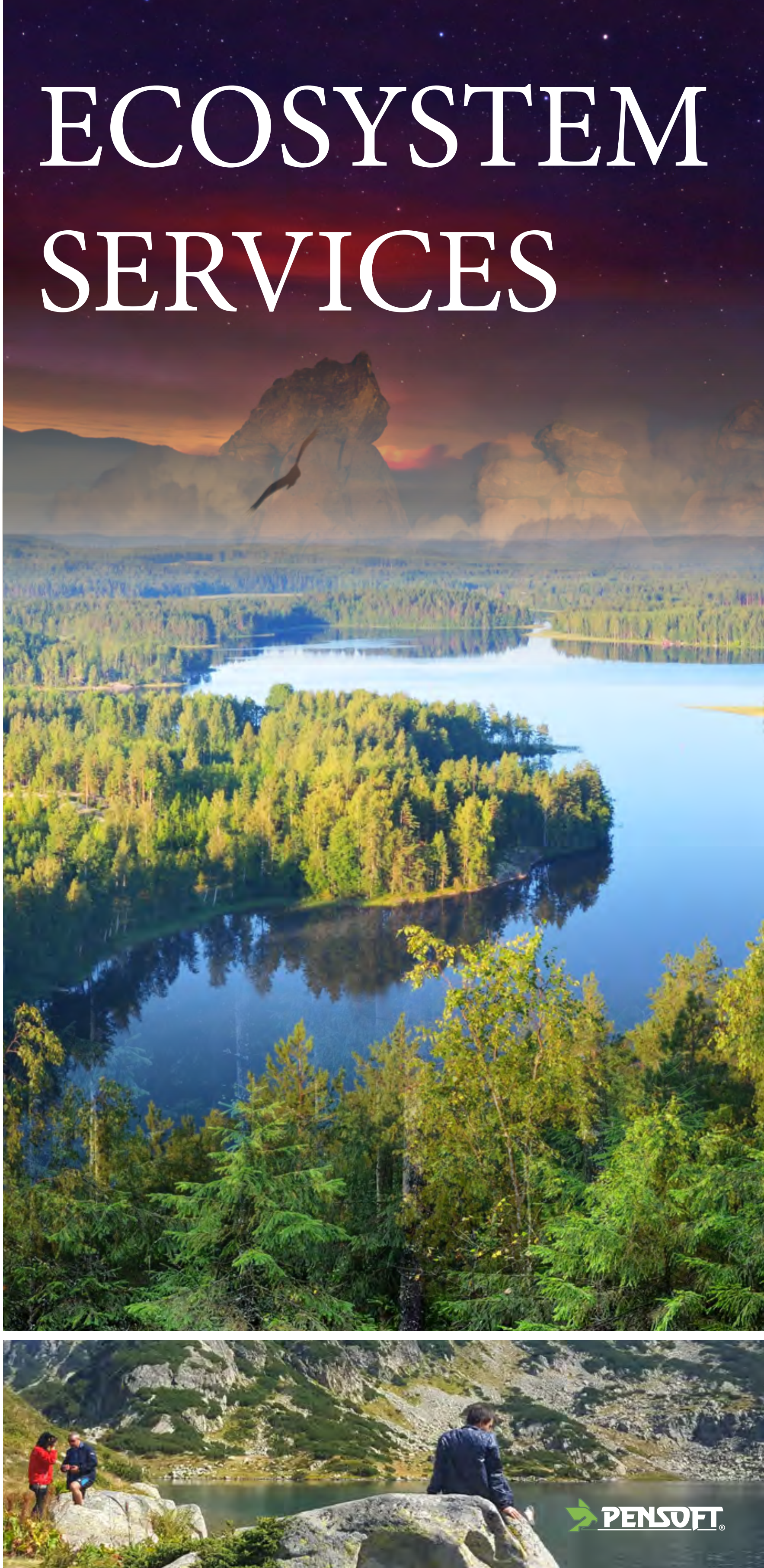

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4.1. Biophysical quantification

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Introduction

Ecosystem services (ES) arise when ecological structures and ecological processes directly or indirectly contribute to human well-being and meet a certain demand from people. This flow of ES from ecosystems to society is well represented by the ES cascade concept (see Chapter 2.3). Ecosystems provide the necessary structure and processes that underpin ecosystem functions which are defined as the capacity or potential to deliver services. ES are derived from ecosystem functions and represent the realised flow of services in relation to the benefits and values of people. This model is useful for quantifying ES. Consider the following example: wetlands (an ecosystem or a structure) provide habitat for bacteria which break down excess nitrogen (denitrification, a process). This results in the removal of nitrogen from the water (a service) resulting in better water quality (a benefit). People can value increased water quality in multiple ways (e.g., by expressing their willingness to pay for clean water). Each of these different steps can be quantified using biophysical, economic or social valuation methods.

This chapter focuses on biophysical quantification which is the measurement of ES in biophysical units. Biophysical units are used to express, for example, quantities of water abstracted from a lake, area of forest or stocks of carbon in the soil. Looking at the ES cascade, it seems evident that biophysical quantification focuses, in particular, on the measurement of ecosystem structures, processes, functions and service flows (also known as the left side or the supply side of the cascade). Benefits and values (also known as the right side or demand side of the cascade) are more often measured using social (see Chapter 4.2) or economic units (see Chapter 4.3). Nonetheless, benefits and values can sometimes be expressed in biophysical units as well. Consider again the above example of water purification in wetlands. The benefit from this ecosystem service is clean water and this can be expressed as the concentration of pollutant substances.

To quantify ES along the different components of the ES cascade, we need to address two questions: what do we measure and how do we measure (Figure 1)? For the purpose of this chapter, we assume that the question as to why we measure (e.g., policy questions, scope of an ecosystem assessment) has been answered.

The first question is addressed in the scientific literature by developing and proposing indicators. Ecosystem service indicators are used to monitor the state or trends of ecosystems and ecosystem service delivery within a determined time interval. In recent years a substantial indicator base has been developed world wide to assess or measure ES.

Once an indicator is proposed or selected for inclusion in an ecosystem assessment, the second question becomes important: how can we measure the service or the indi-

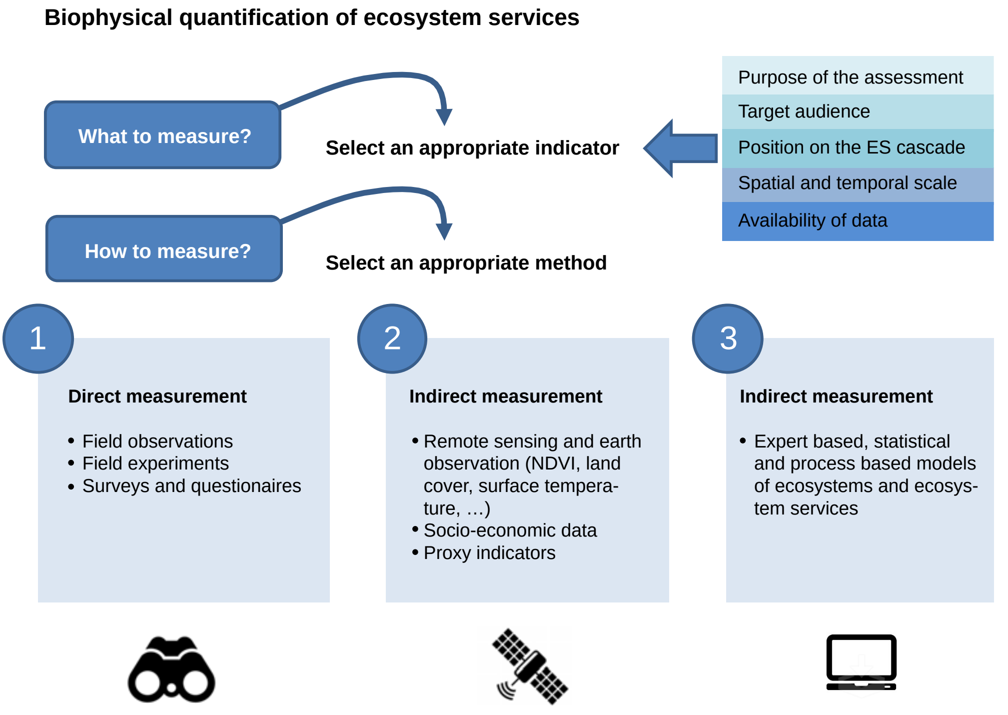

Figure 1. Biophysical quantification of ecosystem services (Icons by Freepik).

cator in biophysical terms or units? Which methods or procedures should be applied to come to an reasonable estimate of the quantity of service provided?

What to measure: Ecosystem service indicators

ES indicators are information that efficiently communicates the characteristics and trends of ES, making it possible for policy-makers to understand the condition, trends and rate of change in ES.

Different indicators can be used to measure or indicate a single ecosystem service. The choice for an indicator depends on many factors including the purpose, the audience, its position on the ES cascade, the spatial and temporal scale considered and the availability of data.

Purpose and target audience are important criteria for selecting or designing indicators for ES. It makes a difference if indicators are used to inform policy makers, journalists, conservation and land managers, scientists or students. Not everybody has an equal understanding of the flow of ES which is indeed a relatively complex concept. Therefore, indicators are sometimes expressed in relative terms by setting a reference value equal to, for instance, 100 and by calculating other values relative to this reference. This facilitates interpretation for some user groups. Of equal importance is the purpose of an indicator. Why is it used? Many ES indicators are proposed to report the state and trends of ES under different biodiversity policies from global to local scale. But such indicators are not necessarily useful for application by spatial planners or for scientific support to river basin management. Consider pollination, a regulating ecosystem service. A scientist could be interested in the diversity and density of different bee and bumblebee populations; a farmer may wish to know how far he can rely on wild pollination to help pollinate his fruit trees; a biodiversity policy officer may need to know if, at national scale, pollination services are declining or increasing. Clearly, these stakeholders have different information requests which require different indicators with different biophysical units although pollination is the common denominator.

The above example also illustrates the importance of spatial and temporal scales. The issue of scale is frequently presented in all textbooks on ecology as biodiversity and the ecological processes it supports (and thus also the delivery of ES) are heavily dependent on time and space. Processes are influenced by different time cycles (day-night, seasons) and take place at different rates (see also Chapter 5.3). The self-purifying capacity of water is, for instance, highly dependent on the velocity at which water flows. Water purification services, for example, which can be measured by the amount of pollutant removed, differ between fast running streams and stagnant lakes with the latter ecosystems having, in general, a higher capacity (more time) to remove nitrogen but a lower capacity to clean organic pollution. Also spatial scale matters. Bees and bumblebees deliver their pollination services within a distance of a few hundred metres whereas the storage of carbon in trees operates at almost global scale. Indicators and, in particular, their units of measurement have to consider the scale at which ES are relevant. Sometimes indicators are designed to be scale independent. This means they can be upscaled or downscaled, a very useful technique for mapping.

An important question often raised in literature on ES is: should indicators measure the stock and the flow? A service flow refers to the actual use of the actual benefits people receive from ecosystems. A stock refers to the capacity of ecosystems to deliver those benefits. Flows are always expressed per unit of time. Timber production serves as a good example to illustrate the difference between an indicator which measures the stock and an indicator which measures the flow. Timber production is often measured by quantifying the harvest (how much timber is cut, usually expressed in a volume of wood per unit area and per unit of time, for example, m^3/ha/year). Sometimes timber production can also be indicated by the available timber stock which can be harvested. This difference is subtle for the case of timber. If the stock is harvested, stock becomes flow. However, for other services, the difference between stock and flow is important because indicators for stock and flow cannot always be expressed in the same units. Wetlands have a certain capacity to clean water but it is not always straightforward to express this capacity in terms of pollutant removal (e.g., amount of nitrogen removed or immobilised in the sediment in kg/ha/year). Often the size of the wetland (in ha) is used as proxy to indicate this capacity. The rationale is that larger wetlands have more capacity to purify water than smaller wetlands. In this context, the concept of ecosystem condition is important as well (see Chapter 3.5). Not only the quantity (spatial extent) of an ecosystem is important to assess the physical values of ES capacity, ecosystem quality or ecosystem condition is also an important determinant of ecosystem delivery. Changes in ecosystems through degradation can thus alter the flows of ES and should thus be measured as well by indicators.

A final remark on indicators relates to composite indicators or indices which aggregate different sorts of information into a single number. Usually such indicators are made for specific purposes or to inform on particular challenges with a single value. In a similar context for ES, such indicators exist but usually they are composed of normalised versions of indicators for single services which are summed or aggregated. They cannot be quantified directly but depend on separate quantification of their individual components.

This chapter does not provide a list with indicators for ES for the simple reason that there are hundreds of indicators available. Many countries and regions have developed ES indicator sets; the setting of global or regional biodiversity targets has also spurred the development of indicators. Furthermore, the application of the ES concept for planning, natural resources management and conservation has created additional indicators. Therefore we list in Table 1 some important initiatives where readers can find a selection of indicators, organised from global to sectorial initiatives.

In summary, ES indicators express what to measure when quantifying ES in a biophysical manner. Good ES indicators come with information on their place on the ES cascade, on the available data, on the targeted audience and the objective and on whether they assess a stock or a flow.

Table 1. Examples of sources, websites and key publications for ecosystem service indicators.

Scale	Location	Publication
Global		Measuring Nature's Benefits: A Preliminary Roadmap for Improving Ecosystem Service Indicators (http://pdf.wri.org/measuring_natures_benefits.pdf) http://www.bipindicators.net/ (report ISBN 92-9225-376-X) Measuring ecosystem services: Guidance on developing ecosystem service indicators (ISBN: 978-92-807-4919-5) http://es-partnership.org/community/workings-groups/thematic-working-groups/twg-3-es-indicators/ A Global System for Monitoring Ecosystem Service Change (doi: 10.1525/bio.2012.62.11.7)
Sub-global	European Union	website: http://biodiversity.europa.eu/maes/mapping-ecosystems article: doi:10.1016/j.ecoser.2015.10.023
National	Finland	website: http://www.biodiversity.fi/ecosystemservices/home article: doi:10.1016/j.ecolind.2015.03.041
	Canada	Website: https://www.ec.gc.ca/indicateurs-indicators/
	Switzerland	Website: http://www.bafu.admin.ch/publikationen/publikation/01587/index.html?lang=en
	Germany	article: Towards a national set of ecosystem service indicators: Insights from Germany (doi:10.1016/j.ecolind.2015.08.050)
	Spain	Website: http://www.ecomilenio.es/informe-de-resultados-eme/1760 Article: doi:10.1371/journal.pone.0073249

How to measure?

Indicators must be measured but how is this done for ES? Some of the above given examples already provide the answer. The number of bees on a farmland, the timber harvest from a forest or the denitrification in a wetland can all be monitored or measured with different methods or devices. Yet measuring stocks or flows of ES is less evident than it seems. Here we present three approaches which can be considered to quantify biophysical stocks and flows of ES: direct measurements, indirect measurement and (numerical) modelling.

Direct measurements of ecosystem services

Direct measurements of an ecosystem service indicator is the actual measurement of a state, a quantity or a process from observations, monitoring, surveys or questionnaires which cover the entire study area in a representative manner. Direct measurements of ES deliver a biophysical value of ES in physical units which correspond to the units of the indicator. Direct measurements quantify or measure a stock or a flow value. Direct measurements are also referred to as primary data.

Examples of direct measurements of ES (see also Table 2) are counting the number of visitors visiting a national park (nature based recreation); measuring the total volume of timber in a forest stand (timber production); monitoring the release of nitrous oxides of a reed bed or deposition of sulphur dioxide on leaves (water and air filtration); recording the crop yield of a farm (crops); measuring the volumetric capacity of a flood plain (flood control); monitoring over time the improvement of water quality (water purification); measuring the abstraction of water from ground water layers (water provision) or asking citizens how many times they visit a forest to pick berries, mushrooms or chestnuts (wild food products). When the spatial extent or relative surface area of ecosystems is used to approximate ES, also botanical and forest inventories, permanent plots or any other direct observation on the terrain can be used as proxy. In certain cases remote sensing can be considered also as direct measurement.

These examples of direct measurement share a number of characteristics. They are time and resource consuming and thus costly, mostly suitable for carrying out at site level or local scale and they measure tangible flows of ES, in particular for provisioning ES. Direct measurements are also feasible in case of a clearly defined service providing species (or areas) such as pollination, bird watching or biological control.

As many of these indicators are effectively measured for other reasons, it is not always needed to set up expensive measurement schemes. Most provisioning ES including crops, fish, timber and water are recorded by national and regional governments. Furthermore, certain species groups and taxa are monitored to assess trends in biodiversity.

TESSA[1] is a toolkit for rapid assessment of ES at site level which provides many procedures and suggestions for on-site measurement of ES.

Direct measurements and the use of primary data are the most accurate way to quantify ES but they become impractical and expensive beyond the site level or they are simply not available for all ES.

Therefore the next step to consider for biophysical quantification is indirect measurements.

[1] http://tessa.tools/

Table 2. Examples of different methods to measure ecosystem service indicators

Ecosystem services	What to measure	How to measure (method)		
(CICES class)	Indicator	Direct	Indirect	Model
Cultivated crops	Crop yield (tonne/ha/year)	Crop statistics (obtained through official reporting)	Remote sensing of crop biomass using NDVI and aerial photo analysis for long temporal changes Coupling structural observations with remote sensing information	Crop production models
Reared animals and their outputs	Livestock (heads/ha)	Livestock statistics (head counts obtained by reporting)		
Wild plants, algae and their outputs	Wild berry yield (tonne/ha/year)	Field observations and surveys of people harvesting wild fruits		Species distribution models; ecological production model
Animals from in-situ aquaculture	Fish yield (tonne/ha/year)	Aquaculture statistics (obtained through official reporting)		Fish production models
Water (Nutrition)	Water abstracted (m^3/year)	Water statistics (obtained through official reporting)	Remote sensing of water bodies and soil moisture	Water balance models
Biomass (Materials)	Timber growing stock (m^3/ha) and timber harvest (m^3/ha/year)	Forest stand measurements and forest statistics	Remote sensing of forest biomass using NDVI	Timber production models
(Mediation of waste, toxics and other nuisances)	Area occupied by riparian forests (ha)	Site observations	Earth observation land cover data	
	Nitrogen and Sulphur removal in the atmosphere or in water bodies (kg/ha/year)	Measurement of deposition of NO_2 and SO_2; field measurement of denitrification in water bodies	Remote sensing of canopy structure (leaf area index)	Transport and fate models for N and S
Mass stabilisation and control of erosion rates	Soil erosion risk (tonne/ha/year)	Field measurements of soil erosion		Soil erosion models (RUSLE)
Flood protection	Area of floodplain and wetlands (ha)	Site observations	Elevation models and data; aerial photo analysis; remote sensing of land cover	Modelling water transport

Ecosystem services	What to measure	How to measure (method)		
Pollination and seed dispersal	Pollination potential; number and abundance of pollinator species (number/m^2)	Field sampling of pollinator species; counts of bee hives		Species distribution models; ecological modelling of habitat suitability
Decomposition and fixing processes	Area of nitrogen fixing crops (ha)	Field surveys; crop statistics (obtained through official reporting)		Crop production models
Global climate regulation by reduction of greenhouse gas concentrations	Carbon storage (in soil or aboveground biomass) (tonne/ha); carbon sequestration (tonne/ha/year)	On-site measurements of carbon stock and carbon fluxes	Remote sensing of vegetation	Carbon cycle models
Physical and experiential interactions	Visitor statistics (number/year)	Visitor data and questionnaires of visitors	Monitoring parking lots, mapping trails or camping sites	Modelling potential use of nature reserves by people

Indirect measurements of ES

Indirect measurements of ES deliver a biophysical value in physical units but this value needs further interpretation, certain assumptions or data processing, or it needs to be combined in a model with other sources of environmental information before it can be used to measure an ecosystem service. Indirect measurements of ES deliver a biophysical value of ES in physical units which are different from the units of the selected indicator.

In many cases, variables that are collected through remote sensing qualify as indirect measurement. Examples for terrestrial ecosystems are land surface temperature, NDVI (Normalised Difference Vegetation Index), land cover, water layers, leaf area index and primary production. Examples for marine ecosystems include sea surface temperature, chlorophyll A concentration and suspended solids. Many of these data products do not measure stocks or flows of ES but they are highly useful to quantify global climate regulation as well as all those ES which depend directly on the vegetation biomass of ecosystems to regulate or mediate the environment. Soil protection and water regulation, for example, are strongly driven by the presence of vegetation which can be inferred from earth observation datasets. Local climate regulation can be inferred from spatially and temporally explicit patterns of surface temperature. Air filtration by trees and forest is directly related to the canopy structure which, in turn, can be measured by the leaf area index. In addition, micro-climate regulation in cities (temperature reduction during heat waves through evapotranspiration and provision of shade) can be approximated by measuring the total surface area of urban forest.

A specific role is reserved for land cover and land use data which are used for both direct and indirect quantification of ES. Detailed and accurate information on the extent of ecosystems or of ecosystem service providing units, constitute an essential data basis for all ecosystem assessments. Importantly, land data can also be used to quantify demand for ES.

Not all indirect measurements are provided by earth observation. The density of trails and camping sites may provide an indirect estimate of recreation and tourism (Table 2).

Indirect measurements, in particular earth observation, offer substantial advantages. They provide consistent sources of information often with global coverage and they are regularly updated which makes them suitable for natural capital accounting and monitoring trends.

Modelling as alternative to quantify ES

ES modelling can be used to quantify ES if no direct or indirect measurements are available. This is virtually always the case in any ecosystem assessment. With ES modelling, we understand the simulation of supply, use and demand of ES based on ecological and socio-economic input data or knowledge. Models can vary from simple expert based scoring systems to complex ecological models which simulate the planetary cycles of carbon, nitrogen and water. More details are also available in Chapter 4.4

In the context of biophysical quantification, models can be used for spatial and temporal gap filling of direct and indirect measurements, extrapolation of direct and indirect measurements, modelling ES for which there are no measurements available or for scenario analysis.

For regulating services, modelling is sometimes the only option in order to quantify actual ecosystem service flows. This is particularly evident when ecosystems are regulating or mediating stocks and flows of soil, carbon, nitrogen, water or pollutants. Consider soil protection - also termed as erosion regulation or erosion control – which is the role ecosystems and vegetation plays in retaining soil or avoiding soil being eroded as a result of wind or run-off water. Soil erosion can be measured directly on sites which are prone to erosion, usually cropland on slopes. However, estimating the quantity of soil that is not eroded due to the protective cover of vegetation cannot be measured. It can however be modelled by comparing the amount of soil erosion with a model which simulates the presence of vegetation with a model where the protective vegetation cover is deliberately set to zero or to parameters which correspond to parameters for cropland or bare soil. The difference between these two models results in an estimate of avoided soil erosion and can represent the realised service flow. A similar rationale applies to water purification, air quality regulation or other services which exert control on the fate and transport of abiotic and organic material.

Implementing biophysical methods for decision-making

Ecosystem service assessments have increasingly been used to support environmental management policies, mainly based on biophysical and economic indicators. Therefore ES assessments have to integrate data and information on biophysical ecosystem components, including biodiversity, with socio-economic system components and the societal and policy contexts in which they are embedded.

Quantification of ES using biophysical methods have been used for a number of perspectives and for a variety of purposes, including landscape management, natural capital accounting, awareness raising, priority setting of projects or policies and policy instrument design. However, transferring the outcomes of the biophysical assessments to policy is not straightforward and some additional work is required to ensure a minimum degree of consistency and avoid over-simplistic conclusions.

Different methods are relevant at different policy levels (ranging from international, EU, national, regional and local scales). Existing literature frequently acknowledges that, in these cases, the interrelationship between different scales must be taken into consideration, which can pose significant challenges. Broad framings for these methods include the work done globally of the Inter-governmental Platform on Biodiversity and Ecosystem Services (IPBES) and the Mapping and Assessment of Ecosystems and their Services (MAES) in the context of the EU Biodiversity Strategy. The initial methodological work on biophysical methods will be the basis for the assessment of the economic value of ES and promote the integration of these values into accounting and reporting systems.

Conclusions

"You can't manage what you don't measure". This well-known expression is also valid for ES which is, in essence, a concept to guide and support the management of natural resources, ecosystems and socio-ecological systems. ES represent the flows of material, energy and information from ecosystems to society. Accurate measurement of these flows as well as the extent and the condition of ecosystems which support these flows is therefore key to base decisions, to monitor progress to biodiversity targets and to create a sound knowledge base for natural capital.

Further reading

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