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Ecosystem service fact sheet on carbon sequestration

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1. Introduction

In line with the fundamental role Nature and its services play in the healthy functioning of human society and economy, Target 2 of the EU Biodiversity Strategy to 2020 calls Member States (MS) to maintain and restore the ecosystems and their services. To meet these goals an EU wide ecosystem assessment (the EU MAES assessment: "Mapping and Assessment of Ecosystems and their Services" – Maes et al., 2013; 2014; 2018; Erhard et al., 2016) will evaluate the condition of Europe's ecosystems and the services they provide to the society based on an analysis of available data. The assessment will cover the whole EU territory, including EU regional seas, and it complements the Member States' activities on mapping and assessment of ecosystems and their services. The EU MAES assessment serves two main policy requests: (1) provide an evaluation of Target 2 of the EU Biodiversity Strategy to 2020 and (2) provide support to the definition of smarter targets under the post-2020 biodiversity policy.

Ecosystem condition has a key role in the EU MAES assessment: adequate service provision requires healthy ecosystems in good condition (Fig. 1.1; Maes et al., 2014). The EU MAES assessment will evaluate the condition of ecosystems based on a set of key indicators in the context of 'thematic ecosystem assessments', grouped according to broad ecosystem types (urban ecosystems, agroecosystems (croplands and grasslands), forests, heathlands, wetlands, freshwater, and marine ecosystems; Maes et al., 2018). The assessment aims to evaluate the trends in the condition of Europe's ecosystems relative to a baseline situation (2010) and provide evidence on where ecosystems are in a degraded state. This series of fact sheets produced by ETC/BD gives additional guidance on how ecosystem condition can be meaningfully defined and measured for various services and in various ecosystems, based on a review of scientific studies (Czúcz et al., 2017, 2018).

In the following pages key messages are summarized first from a policy perspective: what can these studies teach about designing a relevant set of ecosystem condition indicators for the EU MAES assessment? Then, in the subsequent chapters these lessons will be expanded, giving a detailed account of how carbon sequestration is defined, which characteristics of the various ecosystem types are relevant for carbon sequestration, and what kind of indicators are available for these characteristics. A discussion on the options for improving the integration of condition indicators into ecosystem service modelling is particularly relevant for ensuring coherence between the different components of the EU MAES assessment. The fact sheet is concluded by a set of annexes, which contain all relevant metadata behind the whole analysis.

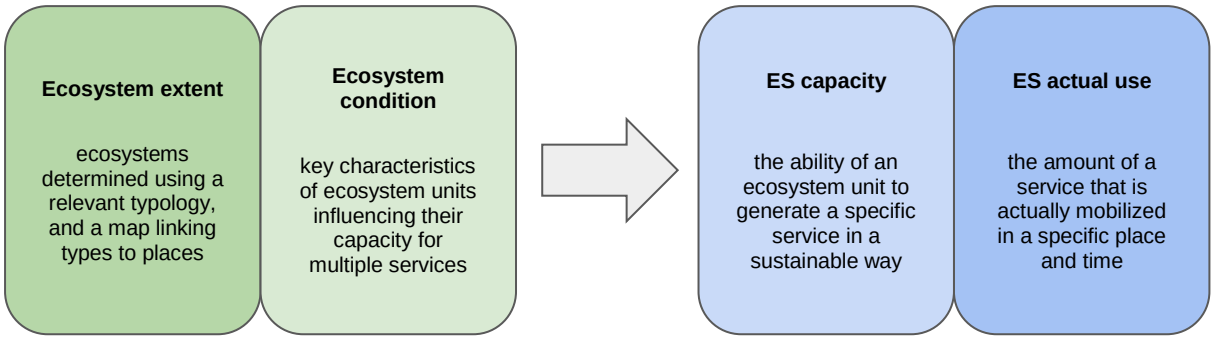

Figure 1.1: A simplified representation of the MAES conceptual framework (based on Maes et al., 2014; Burkhard et al., 2018; and MAES-INCA, 2018). The four boxes describe the main elements which need to be quantified (mapped and assessed) during the EU MAES assessment process.

2. Key messages

Carbon sequestration is the process of carbon dioxide uptake from the atmosphere by biological, chemical and physical processes. Carbon is stored in biomass of plants and soil of ecosystems (the focus of this factsheet is on terrestrial ecosystems). Most ecosystem types are markedly different in their 'typical' (average) levels of carbon sequestration and storage. Accordingly, the extent of each ecosystem type can already characterise the landscape from a carbon sequestration perspective. Nevertheless, this important and relatively easily accessible information (available e.g. from the European map of ecosystem types) should not be discussed in the context of condition (it belongs to 'ecosystem extent' see Fig. 1.1). There are, however, several further ecosystem characteristics that are relevant for carbon sequestration. In this fact sheet the following key aspects of ecosystem condition have been identified based on a systematic review of published literature, and the availability of potential indicators (Fig. 2.1):

- The amount of carbon stored in living biomass, deadwood and litter is a key condition aspect. This can be best characterised by indicators based on remote sensing and modelling including the normalized difference vegetation index (NDVI), leaf area index (LAI), net primary production (NPP) can be derived by proximity data set from remote sensing or the and some SEBI forestry indicators (growing stock: SEBI 017; deadwood: SEBI 018). A tree cover density indicator, that might be particularly useful for non-forest habitats, is provided by JRC.

- Soil organic matter is one of the major pools of carbon. Soil organic carbon (SOC) data, which are collected under the EU LUCAS monitoring scheme, can be seen as key condition indicators.

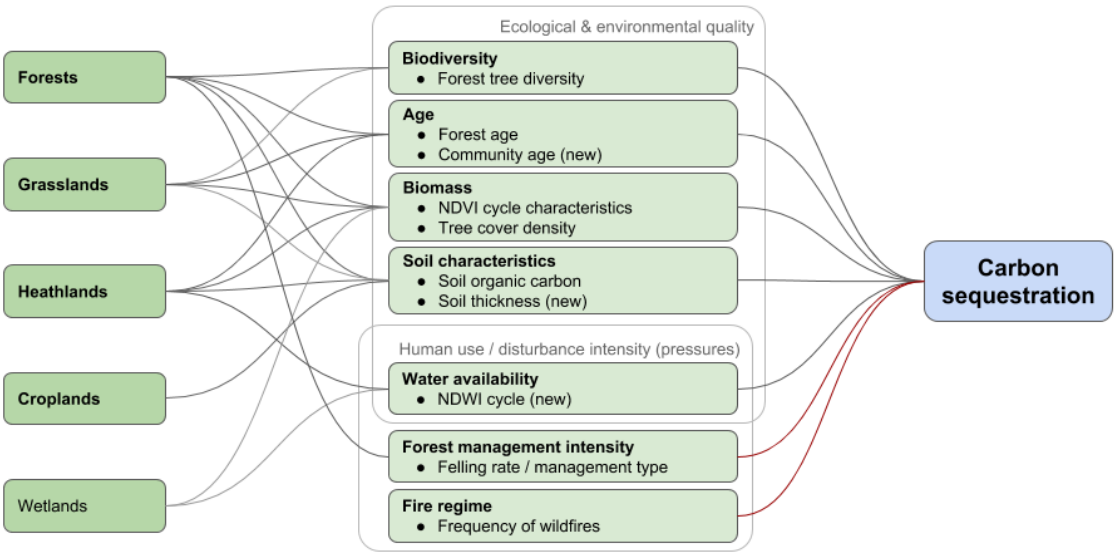

Figure 2.1: A graphical summary of this fact sheet. *Ecosystem types* (column 1) are connected to their *relevant characteristics* ('condition aspects'; column 2) and a possible set of *key indicators* (bullet points in column 2), which determine their *capacity for carbon sequestration* (column 3). Characteristics not connected to any ecosystem type are landscape-level characteristics. Condition–service connections are drawn based on a

systematic review (Czúcz et al., 2018). The negative relationships and the most important data gaps are highlighted in red.

- Evidence shows that some aspects of biodiversity can also influence carbon sequestration and storage. Forest tree species and their diversity can be seen as key indicators on forest ecosystem condition, which can be extracted from national forest inventories. Soil biodiversity positively influences carbon accumulation but corresponding indicators are not yet available. Invasive species can also be relevant, especially if they are threatening the health of ecosystems.
- The age of ecosystems and communities is also a relevant for carbon accumulation. A useful indicator on forest age could potentially be extracted from forest inventory datasets.

Several human induced pressures also have a significant direct influence on carbon sequestration. Most of these pressures can be integrated among ecosystem condition indicators in a straightforward way.

- Pressures related to land management intensity have a crucial impact on biomass and soil. EEA and EUROSTAT offer several useful indicators (intensification/extensification, soil erosion, ratio of fellings to increment).
- Disturbances and particularly fire regime can also critically influence long term carbon sequestration. The fire frequency indicator from JRC can also be seen as a key indicator.
- The normalized difference water index (NDWI) established by JRC provides basic information on water availability. Unfortunately, there is no direct indicator on wetland water table levels available yet.

3. Carbon sequestration as an ecosystem service

The process of carbon sequestration comprises the removal and storage of carbon dioxide (CO_2) from the atmosphere in carbon sinks through physical of biological processes, such as photosynthesis. Photosynthesis is the fundamental process affecting levels of carbon dioxide in the atmosphere.

Healthy, productive and resilient ecosystems are essential to remove carbon from the air, and thus combat climate change effectively. EU climate and biodiversity policies identify that ecosystems play a crucial role in mitigating climate change and adapting to its impacts. This makes the process of carbon sequestration an essential ecosystem service. The most important carbon sinks are oceans, terrestrial vegetation (also termed as "land cover" in the climate policy jargon, including the above and below ground biomass of e.g. forests, grasslands, or wetlands) and soils (including soil organic carbon and subsoil peat deposits). Consequently, land use and soil management influence carbon sequestration and require a comprehensive understanding on the effects of ecosystem services.

Table 3.1: The position of carbon sequestration in CICES (v5.1, Haines-Young & Potschin, 2018) and other major ES classification systems (IPBES: Pascual et al., 2017; TEEB, 2010; MA, 2005)

	CICES v5.1	Other classifications
Classification	**Section: 2** Regulation & Maintenance (Biotic) **Division: 2.2** Regulation of physical, chemical, biological conditions **Group: 2.2.6** Atmospheric composition and conditions **Class: 2.2.6.1** Regulation of chemical composition of atmosphere and oceans	**IPBES**: ● NCP **3** Regulation of air quality ● **NCP 4** Regulation of climate ● **NCP 5** Regulation of ocean acidification **TEEB**: Carbon sequestration and storage **MA**: Atmospheric regulation
Definition	**Scientific**: Regulation of the concentrations of gases in the atmosphere that impact on global climate or oceans **Simple**: Regulating our global climate	**IPBES**: NCP 3: Regulation (by impediment or facilitation) by ecosystems, of CO_2/O_2 balance (...) NCP 4: Positive or negative effects on emissions of greenhouse gases (e.g. biological carbon storage and sequestration; methane emissions from wetlands) (...) NCP 5: Regulation, by photosynthetic organisms (on land or in water), of atmospheric CO_2 concentrations and seawater pH, which affect associated calcification processes by many marine organisms important to humans (such as corals) **TEEB**: Ecosystems regulate the global climate by storing and sequestering greenhouse gases. As trees and plants grow, they remove carbon dioxide from the atmosphere and effectively lock it away in their tissues. In this way forest ecosystems are carbon stores. Biodiversity also plays an important role by improving the capacity of ecosystems to adapt to the effects of climate change
Example for service	Sequestration of carbon in tropical peatlands	
Example for benefits	(1) Climate regulation resulting in avoided damage costs (2) Mitigation of impacts of ocean acidification	

Carbon dioxide is not the only greenhouse gas that contributes to anthropogenic climate change. There are several further greenhouse gases (most notably methane: CH_4, and nitrous oxide: N_2O) whose global budget is influenced by ecosystems and their management. Nevertheless, as carbon dioxide is the most important driver for global warming, and as the role of ecosystems is also the most straightforward in the case of CO_2, climate change regulation as an ecosystem service is usually considered to be equal to the amount of carbon sequestered by ecosystems.

In addition to the flows of carbon that are sequestered, ecosystems can also help stabilizing the climate by keeping their historically sequestered carbon stocks in a stable and immobilized state. Thus carbon stored in ecosystems can also be an important indicator of climate regulation potential which is directly related to land use disturbances and land management practices.

There are many societal benefits from the elementary ecosystem functions related to photosynthesis, but the most direct is through the reduction/regulation of atmospheric (and oceanic) CO_2 content. Most of the other benefits are related to the cascading material & energy flow through food chains and ecosystem compartments for which photosynthesis is the starting point, and which eventually are necessary condition for the production of almost all ES. But according to the most recent definitions, these indirect contributions to later benefits should be considered as intermediate (or supporting) services, rather than real (=final) ecosystem services. This is the reason why carbon sequestration / climate regulation / atmospheric regulation are used interchangeably for the same underlying physical service.

According to IPBES NCP carbon sequestration is split into 3 NCPs, 2 of which contain other components unrelated to photosynthesis and carbon fluxes (Table 3.1). Carbon sequestration is closely related to other ES which strongly depend on the growth of vegetation most importantly timber / wood production (typically under 1.1.5.2 CICES 5.1).

4. Ecosystem characteristics influencing the supply of carbon sequestration

Increasing atmospheric CO_2 concentration and related climate change have stimulated much interest in the potential of biomass and soils to sequester carbon. As climate change progresses, the potential feedback from terrestrial ecosystems to the atmosphere through changes in carbon stocks, carbon sequestration, and general knowledge on biogeochemical cycles becomes increasingly important.

Table 4.1 provides an overview on the importance of the characteristics of the main ecosystem types involved in the delivery of carbon sequestration. According to the scientific literature sampled in the underlying systematic review, the most relevant characteristics are land cover and biomass. Biodiversity, in particular plants and tree biodiversity, is also an important factor regarding carbon sequestration. The review focuses primarily on terrestrial ecosystem types, so wetlands, freshwater and marine ecosystems, as well as their characteristics are largely missing from this overview. If this work will be continued, more emphasis should be laid on these ecosystem types, especially on wetlands, which can contain quite significant carbon pools.

Table 4.1: Results of the systematic review: ecosystem characteristics that have been documented to influence the supply of carbon sequestration, and the ecosystem types in which these relationships had been documented (Czúcz et al., 2018). Total / positive / negative / mixed: the number of papers which document any (or positive / negative / mixed) relationships between the studied characteristics and carbon sequestration. A more detailed and fully referenced version of this table can be found in Annex 1.

Characteristics type	Total	Positive	Negative	Mixed	Ecosystem types
Biomass at the site	**8**	8	0	0	forest, grass, heath
Biodiversity (in general)	**5**	5	0	0	forest, grass
plants (in general)	**2**	2	0	0	grass, forest
trees	**2**	2	0	0	forest
Age of site / community	**4**	4	0	0	forest, crop, grass, heath
since fire	**2**	2	0	0	forest
since abandonment	**1**	1	0	0	crop, grass, forest, heath
since cutting	**1**	1	0	0	forest
Occurrence / abundance of a specific species (functional) group	**3**	3	0	0	grass, forest, heath
tall herbs	**2**	2	0	0	grass
N fixers	**1**	1	0	0	forest
shrubs	**1**	1	0	0	grass, heath
Soil characteristics	**2**	0	1	1	forest, heath
Management / disturbance intensity	**1**	1	0	0	grass
grazing intensity	**1**	1	0	0	grass
Water availability	**1**	1	0	0	heath

* MAES ecosystem types: crop: cropland; grass: grassland; forest: woodland and forest; heath: heathland and shrub

Biomass of ecosystem/land use types plays an important role in both carbon storage and sequestration, the higher the amount of biomass the more carbon is stored and can be captured. Thus forests are particularly important as the C storage capacity of the forests exceeds that of other land uses. Shrubland constituting significant and important parts of European landscapes also has a high potential for above and belowground carbon storage (Beier et al. 2009). Meier and Leuschner 2010 state that temperate forests are continuous sinks for carbon even in their mature and senescent stages. However, modelling exercises indicate that a warmer and drier climate as predicted for parts of Central Europe may substantially alter the source/sink function of these economically important ecosystems. A study with European beech (Fagus sylvatica L.) concludes that the long-term consequence of a substantial precipitation decrease would be a reduction even in the mineral soil and organic layer SOC pools, mainly due to higher decomposition rates. This could turn temperate beech

forests into significant carbon sources instead of sinks under global warming. The influence of biomass of terrestrial ecosystems on soil carbon sequestration varies. There is growing evidence that temperate grasslands can also sequester relatively large amounts of carbon (Hönigová. et al., 2012). Carbon sequestered in temperate grasslands is related to net primary production (NPP) as a rate of C supply into soil. On the other hand, carbon is emitted from grassland by heterotrophic respiration, fires, and also changes in soil C pools induced by soil erosion or water drainage. The importance of land use (woodland and forest, cropland, grassland, wetland and other land) and land use change as a carbon sink or source of emissions is reflected in the annual greenhouse gas emission inventory reporting under the obligation of UNFCCC by National Inventory Reports (NIR).

Biodiversity affects carbon stocks and sequestration but often relatively little and in indirect ways compared to other factors (Wardle et al., 2011). Whereas Hulvey et al. (2013) found that f**orest tree species** diversity can directly influence carbon sequestration. Mixed-species stands, individual species, and in particular nitrogen-fixing trees, increased stand biomass and at times outperformed monoculture plantings. The higher the diversity (defined as species richness and/or stand composition) the higher the long term carbon sequestration, even in planted forests, which are increasingly used to offset carbon emissions. This result is similar to that found in grassland productivity studies. In managed grassland higher **plant species richness** increased the soil carbon storage after several years (Steinbeiss et al., 2008). Additionally the results show that higher plant biodiversity mitigated soil carbon losses in deeper horizons and carbon losses were significantly smaller with higher species richness. The diversity of soil organisms also effect carbon sequestration. Saprotrophic microorganisms within the decomposer chain have an important role in the decomposition processes of litter and dead roots and control soil carbon storage. Persiani et al. (2008) state that increasing **soil fungal biodiversity and** biochemical specialization in Mediterranean grasslan**ds** were related to higher soil carbon storage.

Literature also shows (see Table 4.1 and Annex 2) that the age of the stock (considering land abandonment and wildfire) also influences carbon sequestration. **Old-growth forests** may be more significant carbon sinks than recognized. Quantifying aboveground carbon stocks in primary forest systems (temperate spruce–fir forests) showed greater structural complexity compared to mature forests, including higher densities of large trees, more complex horizontal structure, and elevated aboveground biomass (Keeton et al., 2010). Old-growth Carpathian spruce–fir forests store 50% more carbon in aboveground tree parts alone than mature stands. Given the scarcity of primary spruce–fir forests remaining stands have high conservation value, both as habitat for late-successional species and as carbon storage reservoirs.

Disturbance regimes, especially that of wildfires are another important aspect of the ecosystems that influences carbon accumulation. For example, Jonson and Wardle (2010) found that in boreal forests **wildfire** was a major determinant of long term ecosystem C sequestration, and exerted direct effects on below-ground C storage (presumably through humus combustion) and indirect effects on both above-ground and below-ground C storage through altering plant-community composition. A study conducted in Northern Spain showed that **abandoned soils** preserved by perturbations like wildfire showed a higher potential for accumulating organic carbon (Emran et al., 2012).

The potential of **agricultural soils** to represent both carbon source and sink depends heavily on their management (the sink is greatest when there is low soil disturbance and low organic matter degradation). Other important factors influencing the carbon storage capacity are soil type, soil moisture and vegetation patterns. Soil moisture (water stress) impacts plant development in general and can cause crop failure or lower crop production in agricultural areas. It can also lead to reduction of the mineral soil and organic layer SOC pools, mainly due to higher decomposition rates (Meier and Leuschner, 2010). In particular in the case of wetlands the stability of water levels is of key importance for the stability of the underlying soil carbon stocks, which can be very large.

5. Ecosystem condition indicators relevant for carbon sequestration

The ecosystem characteristics listed in the previous chapter (Table 4.1) are not independent from each other. Biodiversity, for example, is roughly determined by habitat type, landscape context, and land use intensity. Thus not all of the identified / proposed aspects need to be covered by an ideal indicator system in order to be relatively comprehensive, and a focus on 'low hanging fruits' (aspects for which there are better / more readily available data) can be justified. Table 5.1 & Annex 2 provide overview of the potential condition indicators and their underlying data sources for each of the condition aspects listed in Table 4.1, with the exception of the pressure (management / disturbance intensity) indicators, which will be discussed in the next chapter.

Table 5.1: Indicators available for the ecosystem characteristics relevant for carbon sequestration. The 'usefulness' of each indicator is highlighted with a 'traffic lights' colour scheme.* Proposed **key indicators** are highlighted in bold.

U*	Indicator name	Comments
	Biodiversity (diversity/abundance of major species groups)	
	species in general	
2	Invasive alien species (richness)	the number of IAS can be negatively correlated w general biodiversity, and its relationship with carbon sequestration is also uncertain
3	Species diversity, richness (number and abundance of species, including vascular plants, vertebrates, etc)	proposed by forest pilot but can be relevant for more ETs, needs to be developed, data source unclear
	plants	
3	Plant functional types (diversity)	proposed by forest pilot but can be relevant for more ETs, needs to be developed, data source unclear
2	**Forest tree species (richness)**	perhaps the most relevant biodiversity indicator for carbon, the direction is (broadly and on the long run): more diversity –> more ES
3	Understory vegetation (richness)	still needs to be developed
	birds	
2	Bird indices (farmland, forest...)	multiple indicators (one for each ET), can probably be refined to a spatial resolution beyond NUTS2 based on existing data
	habitats	
2	Deadwood	only available at a very coarse spatial resolution
2	Naturalness (index or typology)	is conceptually close to "hemeroby", still needs to be implemented
	Age of site / community	
2	**Forest age (% of forest in age categories)**	this could be a conceptually important indicator, still needs to be developed
3	**Community age (time since last major intervention/ disturbance: felling, fire, abandonment, etc)**	this could be conceptually important, feasibility on a remote sensing basis should be tested
	Primary productivity (& ecosystem exchange processes)	
1	Plant productivity (NPP)	productivity is in this case more of an ES indicator than a condition aspect; if productivity is taken is taken into account here, then a single productivity indicator should do
2	Crop gross primary production	
2	Carbon sequestration (Dry matter productivity)	this is perhaps more of an ES indicator than a condition indicator
3	Carbon dioxide exchange and carbon balance (net ecosystem–atmosphere CO2 exchange)	this is perhaps more of an ES indicator than a condition indicator
3	Leaf respiration (net ecosystem–atmosphere CO2 exchange)	
2	Evapotranspiration	
	Biomass at the site	
1	**Normalized difference vegetation index (NDVI)**	instantaneous values are too variable, but (multi)annual characteristics can make useful condition indicators; a single biomass indicator can be enough
1	Leaf Area Index (LAI)	see above
2	Biomass volume (growing stock)	only available at a very coarse spatial resolution
2	Carbon stock	
3	Tree height	
3	**Tree cover density**	can also be relevant for non-forest habitats
3	Tree crown size (diameter)	
3	Canopy volume (from remote sensing)	

Table 5.1 continued.

U*	Indicator name	Comments
	Soil characteristics	
2	C/N ratio in soil	most important aspects of soil condition for carbon seem to be N content, pH, and obviously C content
1	**Soil organic carbon (SOC)**	sampling & database is primarily focussed at croplands
2	Soil pH	
3	Soil biodiversity (DNA-based richness)	under development, not available yet
2	Soil nutrients availability (nitrogen & phosphorus)	sampling & database is primarily focussed at croplands
1	**Soil thickness**	new proposal for a simple indicator, to follow the degradable stock behind erosion
	Water availability	
1	**Water and wetness probability index (WWPI)**	a key determinant of wetland carbon stock stability
1	**Normalized difference water index (NDWI)**	instantaneous values are too variable, but (multi)annual characteristics can make useful condition indicators
2	Soil moisture (summer water stress)	modelled variable, (multi)annual characteristics can be relevant
3	Water levels	needs to be developed, data source unclear
	The extent (abundance) of a specific subtype (of the target ecosystem type)	
1	**Extent of ETM subtypes**	EUNIS (level 2) subtypes themselves can be considered as being of different levels of condition (or naturalness, hemeroby, etc.)
3	**Extent of forest types**	still under development (?)
1	Density of embedded seminatural elements (hedgerows, lines of trees, etc.)	seminatural elements are the most important carbon traps in an agricultural landscape

** U: 'usefulness' score, which follows the 'traffic lights' scheme of the 2nd MAES report (Maes et al., 2014):*

1 *highly relevant for the specified aspect of forest condition, appropriate data are available at European scale, and easily understood by non-technical audiences (relevance, representativity, and data availability are all high – see details in in Annex 2)*

2 *relevant for the specified aspect of forest condition, some data are available, but still needs some work, or the indicator is difficult to be interpreted for non-technical audiences (relevance, representativity, or data availability is moderate)*

3 *relevant for the specified aspect of forest condition, but there are significant data or interpretation challenges (e.g. the indicator is just weakly linked to the characteristics that it is intended to indicate, thus representativity or data availability is low)*

Carbon storage essentially depends on land use and the corresponding **habitat type**. Forests and woodland cover around 40% of EU's land area and are critically important in terms of carbon storage (and carbon sequestration). Other ecosystem types (e.g. shrublands, wetlands, grasslands), might also contain considerable carbon pools, especially in soils, or they (e.g. croplands, grasslands) can have considerable annual carbon sequestration rates (largely depending on management / disturbance regimes). For most of the broad ecosystem types the EUNIS subtypes as mapped in ETM v3.1 (Weiss & Banko, 2018) make a considerable difference, as e.g. tundras (F1 in EUNIS), maquis (F5), and vineyards (FB) have very different average carbon sequestration capacities even though they all fall under 'heathlands and shrub' in the MAES ecosystem typology (Weiss & Banko, 2018).

Characteristics describing some of the carbon pools (e.g. living biomass, deadwood, litter, soil) or fluxes (primary production) can also be directly relevant for the supply of carbon sequestration (Maes et al. 2018). Such indicators (e.g. NDVI, LAI, NPP, forest growing stock, or tree cover densities) can most easily be computed from remote sensing imagery. In the case of rapidly fluctuating measures (**NDVI, LAI**) long term aggregates (yearly or multi-annual averages or maxima) are much more meaningful as condition indicators than instantaneous (daily, monthly) values. The **growing stock indicator** in forests highlights the balance between net annual increment and annual fellings and is one of the most basic statistics of any forest inventory. The standing volume of growing stock can be converted into estimates of above and below-ground woody biomass by applying biomass expansion factors (see SEBI 017). **Deadwood** (SEBI 018) could also be an ideal forest condition indicator, which is both directly (as a carbon stock) and indirectly (indicating healthier and more resilient forests) relevant for carbon sequestration. Nevertheless SEBI 018 comes with a very low spatial resolution (MS level) which seriously limits its usefulness in the MAES condition assessment.

Even though biodiversity affects carbon stocks in relatively indirect ways, there are several biodiversity indicators that might be relevant for this ES. The main **forest tree species** and their diversity can be seen as key indicators on forest ecosystem condition, and can also be extracted from national forest inventories. **Soil biodiversity** has an influence on carbon accumulation, the

corresponding indicators are under development**. Invasive species** can also be relevant, especially if they are threatening the health of forests or shrublands. General biodiversity indicators (e.g. forest bird species, or habitat naturalness) can also be indirectly relevant as condition parameters that ensure the resilience of the ecosystems including their carbon stocks.

Indicators describing the age of ecosystems and communities can also be used as efficient proxies for carbon stocks. **Forest age** (e.g. as a % of forest in age categories) can potentially also be extracted from forest inventory datasets, but this indicator is still under development (Maes et al., 2018). **Community age** (time since last major intervention/ disturbance: felling, fire, abandonment, etc) could also be the basis for a highly relevant condition indicator, which could theoretically be derived from satellite time series. Nevertheless, there is no such indicator available yet, and its development would still demand a lot of efforts.

Condition indicators describing soil carbon pools can be also highly relevant for carbon sequestration. **Soil organic carbon** (SOC) is an indicator which is relevant for almost all terrestrial ecosystem types. SOC is vital to diverse soil functions and ecosystem services and hence, a key indicator for ecosystem condition. Soil organic matter is the primary constituent of humus and one of the major pools of carbon. Data on organic carbon in soils are collected in more than 25,000 locations across the EU under the LUCAS monitoring scheme (Maes et al. 2018). The condition of soils can also be assessed by several indicators on soil biodiversity, soil moisture, compaction (bulk density) and erodibility, which can serve as proxies for estimating the stability / resilience of soil carbon stocks. Copernicus provides information on the probability of a water cover (**water and wetness probability index**, WWPI), and a **normalized difference water index (NDWI)**, both of which cover Europe at a high spatial resolution. These indicators can serve as the basis for a longer term water availability / water stress index. Both of these indicators can also serve as proxies for the stability of wetland water levels, but the reliability of this application should be tested in future indicator development work.

6. Integrating pressures among condition indicators

The intensity (frequency or magnitude) of recurrent human management activities and/or (semi)natural disturbance regimes can be seen as characteristics of the ecosystems that highly influence their capacity to supply various services. In the MAES conceptual framework (Maes et al., 2013; 2014; 2018) these characteristics are listed under the heading 'pressures', which are considered an "indirect approach" for measuring ecosystem condition (Erhard et al., 2016, p.31). However, most pressures (e.g. erosion, drainage/desiccation, fragmentation, pollution, etc.) can be associated to a state variable (e.g. soil thickness, water table level, connectivity, the concentration of specific pollutants, etc.) which is directly affected by the pressure. In most cases there are indicators available for both the 'pressure' (as a flux, flow or rate of change) and the underlying state variable. Wherever available, variables describing such 'degradable environmental stocks' **(**that are being degraded due to the specific pressures) are highly appropriate for use as condition indicators for the EU MAES assessment. This choice makes it possible to link pressures to changes in condition without compromising the conceptual integrity of the assessment.

Following the logic of the systematic review, pressure indicators have been clustered according to the ecosystem types and their typical management activities/disturbance regimes instead of the HIPOC categories. From the HIPOC classes, *overexploitation* and *pollution* can be relatively easily considered as ecosystem characteristics, and thus their indicators (like forest *felling cycle length*, or *acidification*) are well represented in Table 6.1. *Climate change* and *biological invasions* are, however, much more indirect pressures, and there are only a few indicators related to these pressures that can be conceptualized as ecosystem characteristics (e.g. the frequency of wildfires, or forest damage caused by invasive herbivores). *Habitat loss* has two important special cases: (1) when land is transformed to a different ecosystem type, and (2) processes 'internal' to a specific ecosystem type. Cases of (1) are best handled under the ecosystem extent 'box' of the MAES framework (Figure 1.1), and replicating them under the ecosystem condition 'box' creates inconsistencies in the whole MAES assessment framework. However, processes that are (2) 'internal' to an ecosystem type are included here, if they are relevant for carbon sequestration (e.g. soil sealing; Table 6.1).

The management of woodlands and forests definitely has a major influence on both carbon stocks and carbon sequestration. **The ratio of fellings to growth** is a key pressure indicator (see Table 6.1) of forest management sustainability, which could be a key management / pressure indicator for carbon sequestration too, but unfortunately this indicator is currently only available at a very coarse spatial resolution (MS level, SEBI 017).

A key pressure of the SOC stock is **soil erosion**, which is mainly related to inadequate management practices in agroecosystems, including deep ploughing, drainage, overuse of agrochemicals, and bad crop rotation practices (with reduced proportion of permanent soil cover). The amounts of the underlying 'degradable environmental stocks' (*soil thickness* or *soil carbon content* as discussed in the previous chapter) seem to be adequate indicators for the state of erosion as well. Using these state indicators is conceptually better than the using the related matter fluxes (erosion, organic matter loss) as proxies.

Agricultural intensification/extensification (available at the NUTS2 spatial resolution) can be seen as a key pressure indicator for agricultural management in this context, as well as **fertilizer consumption** which causes N_2O emissions. Similarly, high levels of grazing intensity in grasslands, can also indicate that the integrity of soil carbon stocks is at risk (see Table 6.1).

Table 6.1: Indicators available for pressures relevant for carbon sequestration. The 'usefulness' of each indicator is highlighted with a 'traffic lights' colour scheme.* Proposed **key indicators** are highlighted in bold.

U*	Indicator name	Comments
	All ecosystems and land uses	
2	Hemeroby	a newly proposed condition indicator with a long history, conceptually close to "naturalness", still needs to be implemented
2	Human Appropriation of Net Primary Production (HANPP)	
	Farming intensity	
2	Intensification / extensification	only available at NUTS2 level
2	Mineral fertilizer consumption	only available at NUTS2 level
2	Share of organic farming	only available at a very coarse spatial resolution
2	Share of fallow land	
	Grazing intensity	
2	Livestock density	is in a positive relationship w carbon sequestration (the opposite to what's expected from a pressure indicator)
	Forest use intensity	
2	**Long term ratio of annual fellings to net annual increment**	a key indicator for forest (use) sustainability
2	Length of the felling cycle	a key indicator for forest (use) sustainability
3	Damage by wildlife and herbivores	
3	Game density (or ratio to sustainable levels)	
	Nutrient / material balances	
2	Gross nitrogen balance	
2	Nitrogen deposition	
2	Critical load exceedance for nitrogen	multiple indicators (one for each ET)
2	Gross phosphorus balance	only available at a very coarse spatial resolution
2	Acidification	
2	Chemical status of surface/ground water	
2	Heavy metal concentrations in soil	
	Soil loss	
2	Soil erosion	the related 'stocks' (soil thickness, carbon content) are better state indicators, could also be seen as an ES indicator (for erosion control)
3	Loss of organic matter	the related 'stocks' (soil thickness, carbon content) are better state indicators, could also be seen as an ES indicator (for erosion control)
2	Imperviousness	
	Fire regime	
2	**Number of fires**	a key indicator for carbon pool stability
2	Burnt area	slightly redundant w fire frequency

** U: 'usefulness' score, which follows the 'traffic lights' scheme of the 2nd MAES report (Maes et al., 2014):*

1 *highly relevant for the specified aspect of forest condition, appropriate data are available at European scale, and easily understood by non-technical audiences (relevance, representativity, and data availability are all high – see details in in Annex 2)*

2 *relevant for the specified aspect of forest condition, some data are available, but still needs some work, or the indicator is difficult to be interpreted for non-technical audiences (relevance, representativity, or data availability is moderate)*

3 *relevant for the specified aspect of forest condition, but there are significant data or interpretation challenges (e.g. the indicator is just weakly linked to the characteristics that it is intended to indicate, thus representativity or data availability is low)*

Disturbances, and particularly fire regime can also critically influence long term carbon sequestration, so the fire frequency indicator from JRC can also be seen as a key condition indicator with respect to this ES. A lack of stability of wetland and heathland water tables, could also be seen as a disturbance or human pressure related to land use change or climate change, but this was already discussed in the previous chapter.

Indicators of general land use intensity (e.g. **hemeroby**) might also be relevant for carbon sequestration, primarily as proxies for human disturbance which might influence the stability of both soil and biomass carbon stocks.

Additionally habitat change can increase GHG emissions. For example, the land use change from forest to other land uses is a major source of CO_2 emissions as well as the ploughing up of grassland. (which is addressed accordingly by the Common Agricultural Policy e.g. maintenance of permanent grassland). Another relevant pressure is **soil sealing** (indicator is available at 100 m spatial resolution) which also reduces its function as a reservoir for carbon accumulation.

On the other hand, in order to be consistent with the Conceptual Framework (Fig. 1.1) the (total) land use/habitat areas is already taken into account as 'ecosystem extent', so it should not be considered as an ecosystem condition aspect too. Creating a condition indicator based on just the extent of habitat changes would introduce a serious inconsistency into the EU MAES assessment, no matter how important the amount of these areas is from an ES, conservation or policy perspective.

7. Integrating condition indicators into carbon sequestration capacity models

Lavorel et al. (2017) conducted a literature review where they classified ES models and associated geo-referenced metrics into simple model types according to the way in which land or marine use, ecological processes and especially biodiversity effects are represented. Five types of models were identified: proxy-based, phenomenological, niche-based, trait-based and full-process models (Fig. 7.1). Carbon sequestration is most commonly modelled with proxy-based models, where land cover/habitat types are associated with levels of ES supply, with the possible incorporation of additional environmental modifiers (e.g. altitude, soil type, climate). This simple and often used method consists in combining look-up tables allocating ES values per land cover with modifying categorical variables describing abiotic factors and ecological integrity see description below.

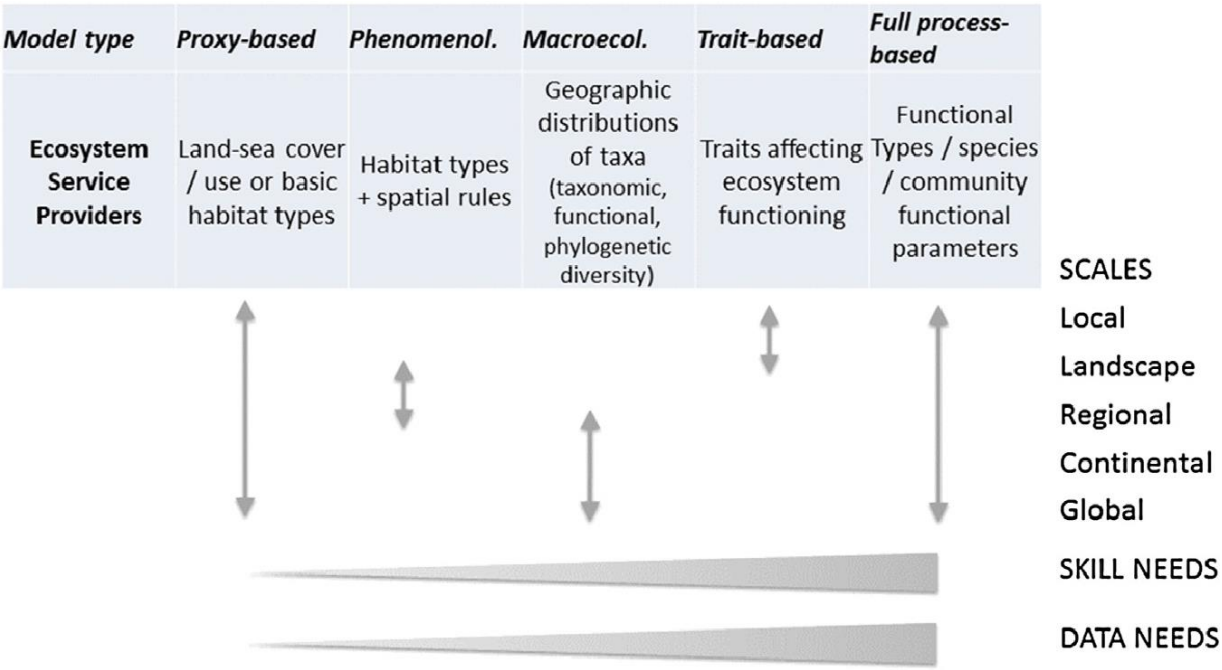

Figure 7.1: Biodiversity components incorporated into different categories of models of ecosystem service supply (from: Lavorel et al., 2017)

In the following two such proxy-based carbon sequestration models are presented in detail. The globally most well-known ES modelling toolkit, InVEST (Sharp et al., 2018) offers a simple but flexible carbon storage and sequestration model, which aggregates the amount of carbon stored in four pools (aboveground biomass, belowground biomass, soil, and dead organic matter) according to land use/land cover maps and classifications produced by the user.

The model simplifies the carbon cycle in a way that allows it to run with relatively little information, which subsequently leads to some limitations. For example, the model assumes that none of the LULC (land use / land cover) types in the landscape are gaining or losing carbon over time. Instead it is assumed that all LULC types are at some fixed storage level equal to the average of measured storage levels within that LULC type. Under this assumption, the only changes in carbon storage over time are due to changes from one LULC type to another. Therefore, any grid cell that does not change its LULC type will have a sequestration value of 0 over time. Furthermore the model relies on carbon storage estimates for each LULC type, thus the results are only as detailed and reliable as the LULC classification used. Carbon storage clearly differs among LULC types (e.g., tropical forest vs.

open woodland), but often there can also be significant variation within a LULC type. Another limitation of the model is that it does not capture carbon that moves from one pool to another. For example, if trees in a forest die due to disease, much of the carbon stored in aboveground biomass becomes carbon stored in other (dead) organic material. Also, when trees are harvested from a forest, branches, stems, bark, etc. are left as slash on the ground. The model assumes that the carbon in wood slash "instantly" enters the atmosphere.

A second major approach for modelling carbon sequestration over large areas is the "bookkeeping" approach used in several recent EU-level studies (e.g. Mouchet et al., 2017; Schulp et al., 2008; Fig. 7.2) to assess how future land use change (LUC) can influence future carbon stock change in soil and vegetation. This approach considers two major carbon pools (soil, biomass). Biomass carbon changes are considered only to be relevant in the case of forests (forest growth and deforestation, with values taken from forest inventories and growth models linked to them, e.g. Böttcher et al., 2012). Soil carbon changes, on the other hand, are taken into account for each major ecosystem type (grasslands, croplands, wetlands and forests), which are considered to have a constant yearly sequestration rate (values for each EU MS can be taken from the literature: e.g. Janssens et al., 2005; Karjalainen et al., 2003). Sequestration rates can also be negative (indicating carbon loss, which was typically the case of croplands and wetlands). Stock changes are calculated with discrete time steps. Carbon budgets are calculated at 1 km^2 based on changes in soil and biomass stocks and an emission factor. LU data are provided by Dyna-CLUE and forest-specific data by EFISCEN

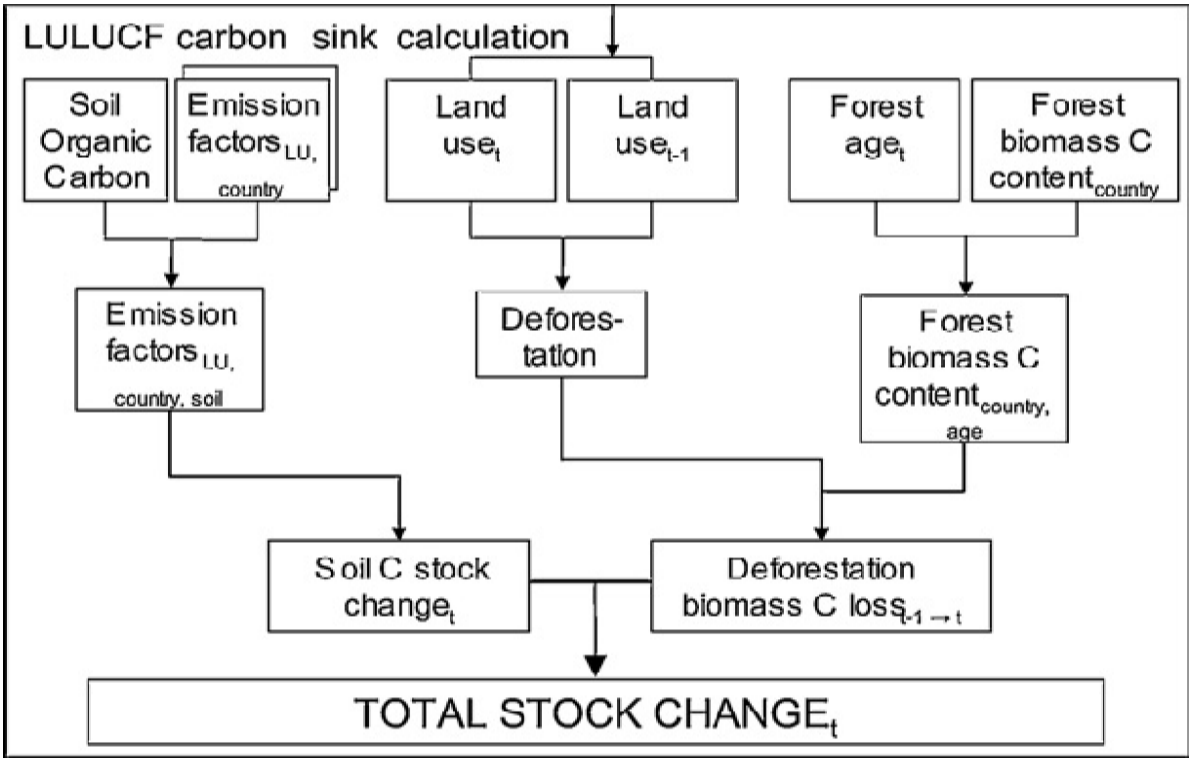

Figure 7.2: A schematic illustration of the "bookkeeping" approach used in carbon sequestration models (from Schulp et al., 2008)

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Annex 1: The papers studied in the systematic review

Table A1: This table identifies the scientific papers related to the ES carbon sequestration, that were reanalysed from the OpenNESS systematic review (Smith et al., 2017). The table follows the structure of Table 4.1, linking each 'functional relationship' documented to the underlying papers using unique IDs, which are resolved below this table. The codes in brackets (e.g. "[T mi]") link the main types of characteristics to the types listed in Czúcz et al. (2017), where all further details about the characteristics typology and the reanalysis work can be found. Columns TT and NN give an overview on the importance of each characteristic for carbon sequestration:

- **TT**: total influence (the number of papers which document an effect of the characteristics on any of the studied ES in any ecosystem type);
- **NN**: net influence (the number of papers documenting a positive ES effect minus the number of papers with a negative effect; mixed effects are not counted).

Higher values of TT are highlighted in darker shades in order to give a better visual overview of the importance of each line, and negative numbers in column NN are highlighted in red. All of the remaining columns refer to specific MAES ecosystem types (urb: urban; cro: cropland; gra: grassland; for: woodland and forest; hea: heathland and shrub; SVL: sparsely vegetated land; wet: wetlands; wat: rivers and lakes). The values in these columns are the unique IDs of the scientific papers, which document a 'functional relationship' and the specific ecosystem characteristic in the given ecosystem type. The IDs of the paper are resolved in a reference list at the end of this Annex.

Characteristics type	TT	NN	urb	cro	gra	for	hea	SVL	wet	wat
Management / disturbance intensity [T mi]	1	1			557					
grazing intensity	1	1			557					
Biodiversity (in general) [T di]	5	5			9, 507	420, 427, 447				
plants (in general)	2	2			9	420				
trees	2	2				427, 447				
Occurrence / abundance of a specific species (functional) group [T ab]	3	3			9, 368	447	368			
tall herbs	2	2			9, 557					
N fixers	1	1				447				
shrubs	1	1			368		368			
Age of site / community [T ta]	4	4			486	105, 420, 427, 486	486			
since fire	2	2				420, 427				
since abandonment	1	1			486	486	486			
since cutting	1	1				105				
Biomass at the site [T bi]	8	8			9, 507, 557	35, 105, 420, 447	368			
Soil characteristics [T so]	2	-1				35	368			
Water availability [T wa]	1	1					368			

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Annex 2: Annotated list of potential MAES ecosystem condition indicators

Table A2: This table lists all indicators available and feasible to describe ecosystem characteristics relevant for carbon sequestration in the context of the EU MAES ecosystem condition assessment. All indicators are scored according to three aspects of 'usefulness':

- **rel**: relevance for carbon sequestration (1: relevant, 2: slightly/indirectly relevant);
- **rep**: the degree to which the indicator represents the underlying condition aspect (1: good representation, e.g. indicator fully covers a major aspect → 3: poor representation);
- **ava**: availability of indicator (1: available with a good quality & spatial resolution (at least NUTS2) for most of the EU (might still need some feasible update), 2: there is something available (but needs more work), 3: still to be developed (or needs major enhancements));

Relevance (rel), representativeness (rep), and availability (ava) are highlighted with a colour scheme following that of the 2nd MAES report (Maes et al., 2014). The overall 'usefulness' of each indicator (the coloured numbers in Tables 5.1 & 6.1) is calculated as the maximum (=worst) of these three scores. The remaining columns contain the following information / metadata:

- **HI**: link to the HIPOC categories (just for pressures! – H: habitat loss, I: invasion, P: pollution, O: overexploitation, C: climate change);
- **indi.set**: link to high-level European indicator sets, if relevant (SEBI: Streamlining European Biodiversity Indicators, AEI: Agri-Environmental Indicators);
- **source**: the name of the data source / host institution, complemented with a weblink reference to a good description of the indicator where available;
- **unit**: the unit of the indicator;
- **pilot**: a list of previous studies (mainly MAES pilots: Maes et al., 2018) that had mentioned/proposed the indicator before (a: agroecosystems pilot; f: forest pilot; n: nature pilot);
- **date**: the reference period / years for which values of the indicator are available;
- **s.resol**: spatial resolution of the already available values of the indicator;
- **s.cover**: spatial coverage of the already available values of the indicator.

Unimplemented indicators (indicators under development) are highlighted in grey text, indicator families (which can/should be customized to the specific ecosystem types) are highlighted in *italics*, whereas the names of newly proposed indicators for filling gaps are highlighted in **bold**. The spatial resolution of indicators that don't reach the expected level of detail (at least NUTS2 region) is also highlighted in **bold**.

HI	rel	rep	ava	indicator name	indi.set	source	unit	pilot	date	s.resol	s. cover
				Biodiversity (diversity/abundance of major species groups)							
				species in general							
	2	1	2	Invasive alien species (richness)	SEBI 010	JRC-EASIN	1/area	f	?	10km	EU+
	2	1	3	Species diversity, richness (number and abundance of species, including vascular plants, vertebrates, etc)			index	f	?	?	?

HI	rel	rep	ava	indicator name	indi.set	source	unit	pilot	date	s.resol	s. cover
				plants							
	2	3	3	Plant functional types (diversity)			?	f	?	?	?
	2	2	2	Forest tree species (richness)		AFOLU, MS?	1/area	f	~1998	100m	EU28, BY, MD
	2	3	3	Understory vegetation (richness)			1/area	f	?	?	?
				birds							
	2	2	1	*Bird indices (farmland, forest...)*	SEBI 001	EBCC	index	afn	2002-	**MS**	EU
				habitats							
	2	2	2	Deadwood	SEBI 018	EEA	m3/ha	f	2000-2010	**MS**	25 from EEA39
	2	1	1	Naturalness (index or typology)			index	f	?	?	?
				Age of site / community							
	1	2	2	Forest age (% of forest in age categories)		JRC, MS?	% or y	f	?	?	?
	1	1	3	**Community age (time since last major intervention/ disturbance: felling, fire, abandonment, etc)**		?	y		?	?	?
				Primary productivity (& ecosystem exchange processes)							
	1	1	1	Plant productivity (NPP)		MODIS	t/ha/y	f	2000-	500m	Global
	1	2	1	Crop gross primary production		Agri4cast; CAPRI	t/ha/y	a	1995-2015	25km; HSU	EU28
	1	2	1	Carbon sequestration (Dry matter productivity)		Copernicus	t/ha/y	f	2014-	300m	Global
	1	2	3	Carbon dioxide exchange and carbon balance (net ecosystem–atmosphere CO2 exchange)			t/ha/y	f			
	1	3	3	Leaf respiration (net ecosystem–atmosphere CO2 exchange)			t/ha/y	f			
	2	2	1	Evapotranspiration		ECA&D	m3/ha/y	f	1950-	~25km	Europe
				Biomass at the site							
	1	1	1	Normalized difference vegetation index (NDVI)		Copernicus	index	f	1998-	1km	Global
	1	1	1	Leaf Area Index (LAI)		Copernicus	index	f	1998-	1km	Global
	1	2	2	Biomass volume (growing stock)	SEBI 017	EEA	m3/ha	f	1990-2010	**MS**	EEA39
	1	2	2	Carbon stock		FAO-FRA	t/ha	f	1990-2015	**MS**	Global
	1	1	2	Tree height		JRC, MS?	m	f	?	?	?
	1	1	2	Tree cover density		JRC, MS?, Copernicus?	%	f	?	?	?
	1	3	3	Tree crown size (diameter)		JRC, MS?, Copernicus?	m	f	?	?	?
	1	3	3	Canopy volume (from remote sensing)		JRC, Copernicus?	m3	f	?	?	?
				Soil characteristics							
	1	2	2	C/N ratio in soil		IMAP, LRTAP	%	f	2005	5km	EU
	1	1	1	Soil organic carbon (SOC)		LUCAS	% or g/kg	afn	2009, 2015	1km	EU25, EU28
	2	2	1	Soil pH		LUCAS	pH	af	2009, 2015	1km	EU25, EU28

HI	rel	rep	ava	indicator name	indi.set	source	unit	pilot	date	s.resol	s. cover
	2	1	3	Soil biodiversity (DNA-based richness)		LUCAS	1/area	afn	2018		EU28
	2	2	1	Soil nutrients availability (nitrogen & phosphorus)		LUCAS	mg/kg	afn	2009, 2015	1km?	EU25, EU28
	1	1	1	**Soil thickness**		LUCAS?	cm		?	?	?
				Water availability							
	1	1	1	**Water and wetness probability index (WWPI)**		Copernicus	%		2009-	100m	EEA39
	1	1	1	**Normalized difference water index (NDWI)**		JRC	index		?	1km	Europe
	2	1	2	Soil moisture (summer water stress)	IND-201, LSI 007	EEA, ECMWF	index	afn	1951-	25km?	EU28?
	1	1	3	**Water levels**		?	?		?	?	?
				The extent (abundance) of a specific subtype (of the target ecosystem type)							
	1	1	1	Extent of ETM subtypes	SEBI 004	CLC	%		1985-	100m	EU27
	1	1	3	Extent of forest types		forest inventories?	%	f			
	1	1	1	Density of embedded seminatural elements (hedgerows, lines of trees, etc.)		JRC	%	a	2006	1km	EU27
	1	1	1	HNV area		JRC	%	a	2000, 2006	100m	EU27
				Management / disturbance intensity (pressures)							
				All ecosystems and land uses							
O	2	1	1	**Hemeroby**		CLC, CAPRI, AFOLU			2006	100m	EU27
O	2	1	2	Human Appropriation of Net Primary Production (HANPP)		UNI Klagenfurt	kg/m2 /y of C	a	1990, 2000, 2006	1km	25 MS
				Farming intensity							
OP	2	1	1	Intensification / extensification	AEI12	Euro-stat	index (EUR)	an	1996, 2006	NUTS2	EU 27
OP	2	2	1	Mineral fertilizer consumption	~SEBI 019, AEI5	CAPRI	kg/ha/y	a	2000-2015	NUTS2	EU28
OP	2	1	1	Share of organic farming	SEBI 020, AEI4	FSS	%	a	2005, 2012-2016	**MS**	EU28
O(H)	2	1	1	Share of fallow land		FSS, CAPRI	%	a	2010; 2012	5km; HSU	EU28
				Grazing intensity							
O	2	1	1	Livestock density		FSS, CAPRI	LU/ha	a	2010, 2012	5km, HSU(?)	EU28
				Forest use intensity							
O	1	1	2	Long term ratio of annual fellings to net annual increment	SEBI 017	EEA	%	f	1990-2010	**MS**	EEA39
O	1	1	2	**Length of the felling cycle**		EEA, MS	y		?	?	?
O(I)	2	2	3	Damage by wildlife and herbivores			m3/y timber loss	f			
O	2	1	3	**Game density (or ratio to sustainable levels)**		MS for-estries	%		?	?	?
				Nutrient / material balances							
OP	2	1	1	Gross nitrogen balance	~SEBI 019, AEI15	CAPRI	kg/ha/y	a	1990-	1km (HSU)	EU28

HI	rel	rep	ava	indicator name	indi.set	source	unit	pilot	date	s.resol	s. cover
P	2	1	1	Nitrogen deposition		IMAP, LRTAP	kg/ha/y	af	2005	5km	EU
P	2	1	1	*Critical load exceedance for nitrogen*	SEBI 009	EEA	% of nat. area	n	2000, 2010	50km	EU27+
OP	2	1	1	Gross phosphorus balance	AEI16	CAPRI	kg/ha/y of P	a	1990-2016	**MS**	EU
P	2	1	2	Acidification	IND-30, CSI 005, AIR 004	JRC	kg/ha/y of S	f	?	?	?
P	2	1	1	*Chemical status of surface/ground water*	SEBI 016	WISE	index	a	1992-	RBMP	EU
P	2	1	2	Tropospheric ozone concentration	IND-30, CSI 005, AIR 004	EEA	ppb	f	1996-	**Points**	EU+
P	2	2	2	Heavy metal concentrations in soil		JRC D3	mg/kg/y	af	2009, 2020	1km	EU27-28
				Soil loss							
OH	2	2	1	Soil erosion	AEI21		t/ha/y	afn	2010	1km	EU28
OH	1	3	1	Loss of organic matter		LUCAS	%/y of SOC	an		1km	EU28
H	2	1	1	Imperviousness		Copernicus	%		2006-2015	20m	EEA39
				Fire regime							
C	1	1	2	Number of fires		JRC-EFFIS	1/ha/y	f	1980-	Point data	EU+
C	1	2	2	Burnt area		JRC-EFFIS	%/y	f	1980-	250m	EU+

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Annex 3: Key definitions

Actual use or **flow** (of an ecosystem service): The amount of an ecosystem service that is actually mobilized in a specific area and time (based on OpenNESS, 2014).

Benefits: Positive change in wellbeing from the fulfilment of individual or societal needs and wants (based on TEEB, 2010).

Biodiversity: The variability among living organisms from all sources, including inter alia terrestrial, marine, and other aquatic ecosystems and the ecological complexes of which they are part, this includes diversity within species, between species, and of ecosystems (based on CBD, 1992).

Capacity (for an ecosystem service): The ability of a given ecosystem to generate a specific ecosystem service in a sustainable way (based on SEEA-EEA, 2012).

Conceptual framework: A model describing the relevant elements of a physical or social system and the main connections between them for the purposes of understanding and communication.

Condition aspect: Meaningful groups / types of ecosystem characteristics, which should be taken into consideration for quantifying ecosystem condition in a particular assessment context. 'Condition aspects' are related to 'ecosystem condition' in the same way as 'ecosystem service types' are related to the concept of 'ecosystem services'. All condition aspects identified as relevant should be represented by quantitative condition indicators in the assessment process.

Conservation status (of a natural habitat): The sum of the influences acting on a natural habitat and its typical species that may affect its long-term natural distribution, structure and functions as well as the long-term survival of its typical species (EEC, 1992).

Conservation status (of a species): The sum of the influences acting on the species concerned that may affect the long-term distribution and abundance of its populations (EEC, 1992).

Ecosystem: 1 (in a general context): A dynamic complex of plant, animal, and microorganism communities and their non-living environment interacting as a functional unit. Humans may be an integral part of an ecosystem, although 'socio-ecological system' is sometimes used to denote situations in which people play a significant role, or where the character of the ecosystem is heavily influenced by human action (based on CBD, 1992 and MA, 2005). 2 (in a MAES context): An instance of an ecosystem type.

Ecosystem accounting: Ecosystem accounting is a coherent and integrated approach to the measurement of ecosystem assets and the flows of services from them into economic and other human activity (SEEA-EEA, 2012)

Ecosystem assessment: A social process through which the findings of science concerning the causes of ecosystem change, their consequences for human well-being, and management and policy options are brought to bear on the needs of decision-makers (UK NEA, 2011).

Ecosystem characteristic: Key attributes of an ecosystem unit describing its components, structure, processes, and functionality, frequently closely related to biodiversity. The term characteristics is intended to be able to encompass all of the various perspectives taken to describe an ecosystem. (based on SEEA-EEA).

Ecosystem condition: The overall quality of an ecosystem unit, in terms of its main characteristics underpinning its capacity to generate ecosystem services. The concepts of 'ecosystem state', 'ecosystem health', 'ecosystem integrity', 'ecosystem quality', and 'naturalness' are closely related to the concept of ecosystem condition.

Ecosystem degradation: A persistent decline in the condition of an ecosystem.

Ecosystem extent: The spatial area covered by an ecosystem or ecosystem type (based on SEEA-EEA, 2012).

Ecosystem service (ES): The contributions of ecosystems to benefits obtained in economic, social, cultural and other human activity (based on TEEB, 2010 & SEEA-EEA, 2012). The concepts of 'ecosystem goods and services', 'final ecosystem services', and 'nature's contributions to people' are considered to be synonymous with ecosystem services in the MAES context.

Ecosystem status: Ecosystem condition defined among several well-defined categories with a legal status. It is usually measured against time and compared to an agreed target in EU environmental directives (e.g. Habitats Directive, Water Framework Directive, Marine Strategy Framework Directive), e.g. "conservation status".

Ecosystem type (ET): A specific category of an ecosystem typology.

Ecosystem typology: A classification of ecosystem units according to their relevant ecosystem characteristics, usually linked to specific objectives and spatial scales.

Habitat: 1. (in a general context): The physical location or type of environment in which an organism or biological population lives or occurs, defined by the sum of the abiotic and biotic factors of the environment, whether natural or modified, which are essential to the life and reproduction of the species (based on EEC, 1992). 2 (in a MAES context): A synonym of 'ecosystem type'.

Human well-being: A state that is intrinsically (and not just instrumentally) valuable or good for a person or a societal group, comprising access to basic materials for a good life, health, security, good physical and mental state, and good social relations (based on MA, 2005).

Indicator: An indicator is a number or qualitative descriptor generated with a well-defined method which reflects a phenomenon of interest (the indicandum). Indicators are frequently used by policy-makers to set environmental goals and evaluate their fulfilment (based on Heink & Kowarik, 2010).

MAES framework: The conceptual framework for the EU Mapping and Assessment of Ecosystem Services (MAES) programme (Target 2 Action 5 of the EU Biodiversity Strategy to 2020). The main elements of the MAES framework are the extent and condition of ecosystem types, and the capacities and flows of ecosystem service types, which need to be valuated with appropriate methods.

Mapping: The process of creating a cartographic representation (map) of objects in geographic space. In the MAES context mapping means a spatially detailed assessment of the elements of the MAES framework, which aims inter alia at creating cartographic representations of the studied elements (based on OpenNESS, 2014).

Pressure: 1 (in a general context): Human induced processes that alter the condition of ecosystems. 2. (in the context of this study): recurrent patterns (regimes) of human land use activities or natural disturbances that can characterize an ecosystem in a particular place.

This glossary of terms is principally based upon **Czúcz & Condé (2017)** and **Maes et al. (2018)**. The definitions for *actual use*, *ecosystem condition* and *pressure* have been adjusted, and the terms *condition aspect* and *MAES framework* are new.

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Annex 4: List of abbreviations

AFOLU	agriculture, forestry and other land use
Art12	Article 12 (assessments of species under the EU Birds Directive)
Art17	Article 17 (assessments of habitats and species under the EU Habitats Directive)
BGR	biogeographic region
CAPRI	Common Agricultural Policy Regionalised Impact
CBD	Convention of Biological Diversity
CICES	Common International Classification of Ecosystem Services
CLC	Corine land cover
Corine	Coordination of Information on the Environment
DB	database
EASIN	European Alien Species Information Network
EBCC	European Bird Census Council
EEA	European Environment Agency
EEC	European Economic Community
EFISCEN	European Forest Information Scenario Model
ES	ecosystem service(s)
ESTIMAP	European Ecosystem Services Mapping tool
ET	ecosystem type(s)
ETC/BD	European Topic Centre on Biological Diversity
ETC/SIA	European Topic Centre for Spatial information and Analysis
ETC/ULS	European Topic Centre on Urban, Land and Soil Systems
ETM	ecosystem type map
EU	European Union
Eurostat	the statistical office of the European Union
FA	availability of floral resources
FSS	farm structure surveys
GIS	geographic information system
HANPP	human appropriation of net primary production
HIPOC	habitat change, invasive species, pollution, overexploitation, climate change (a common list of the main drivers of environmental change)
HNV	high nature value farmland
HSU	homogeneous spatial units (of farmlands)
IAS	invasive alien species
IMAP	Integrated Monitoring and Assessment Programme
InVEST	integrated valuation of ecosystem services and tradeoffs
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IUCN	International Union for Conservation of Nature
JRC	Joint Research Centre
KIP INCA	Knowledge Innovation Project on an Integrated system for Natural Capital and ecosystem services Accounting
LU	livestock units
MAES	mapping and assessment of ecosystems and their services
MS	EU Member States
NS	availability of nesting sites
NDVI	Normalized Difference Vegetation Index

NDWI	Normalized Difference Water Index
NIR	National Inventory Report
NPP	Net Primary Production
NCP	Nature´s Contribution to People
NUTS	nomenclature of territorial units for statistics
OpenNESS	Operationalisation of natural capital and ecosystem services (EU FP7 project)
RL	red list
SEEA-EEA	System of Environmental Economic Accounts - Experimental Ecosystem Accounts
SVL	sparsely vegetated land
TEEB	The Economics of Ecosystems and Biodiversity
UK NEA	UK National Ecosystem Assessment
UNFCCC	United Nations Framework Convention on Climate Change