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Assessing ecosystem condition at the national level in Hungary - indicators, approaches, challenges

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Abstract

The availability of robust and reliable spatial information on ecosystem condition is of increasing importance in informing conservation policy. Recent policy requirements have sparked a renewed interest in conceptual questions related to ecosystem condition and practical aspects like indicator selection, resulting in the emergence of conceptual frameworks, such as the System of Environmental-Economic Accounting - Ecosystem Accounting (SEEA-EA) and its Ecosystem Condition Typology (ECT). However, while such frameworks are essential to ensure that condition assessments are comprehensive and comparable, large-scale practical implementation often poses challenges that need to be tackled within stringent time and cost frames.

We present methods and experiences of the national-level mapping and assessment of ecosystem condition in Hungary. The assessments covered the whole country, including all major ecosystem types present. The methodology constitutes four approaches of quantifying and mapping condition, based on different interpretations of naturalness and hemeroby, complemented by two more using properties that ‘overarch’ ecosystem types, such as soil and landscape attributes. In order to highlight their strengths and drawbacks, as well as to help reconcile aspects of conceptual relevance with practical limitations, we retrospectively evaluated the six mapping approaches (and the resulting indicators) against the indicator selection criteria suggested in the SEEA-EA. The results show that the various approaches have different strengths and weaknesses and, thus, their joint application has a higher potential to address the specific challenges related to large-scale ecosystem condition mapping.

Keywords

ecosystem condition, ecosystem condition mapping, national-scale mapping, naturalness, hemeroby

Introduction

The availability of robust and reliable spatial information on ecosystem condition is important in informing conservation policy (Erhard et al. 2016, Schmidt-Traub 2021). Ecosystem condition forms an essential part of the ecosystem accounts of the United Nations (UN) (Maes et al. 2020, Hein et al. 2020). Action 5 of Target 2 of the EU Biodiversity Strategy to 2020 explicitly required EU Member States to map and assess the ecosystems in their territory, their condition and the status and economic value of the ecosystem services they provide (European Commission 2011). Defining clear conservation objectives and measures and monitoring them is a key commitment of the EU Biodiversity Strategy to 2030 (European Commission 2020). A thorough knowledge of ecosystem condition and its relationship with pressures is necessary to reach the newly-set policy targets (European Environment Agency 2019). Furthermore, the precise nature of relationships between biodiversity, ecosystem condition and ecosystem services (ES) is still not clearly understood (Rendon et al. 2019), despite rapidly increasing research in this field (Smith et al. 2017, van der Plas 2019).

Many attempts have been made to clarify and formulate definitions of ecosystem condition. Two interpretations prevail (Roche and Campagne 2017): the anthropocentric approach considers condition as the quality of ecosystems that underpins ecosystem services supply (Czúcz and Condé 2017), whereas the holistic approach concentrates on the intrinsic values of ecosystems. The latter is related to earlier concepts, such as ecosystem health, ecosystem integrity, ecosystem quality and naturalness (Roche and Campagne 2017, Keith et al. 2020). All these concepts aim to describe the same notion, with a different focus (Winter 2012, Roche and Campagne 2017, Rendon et al. 2019). Nevertheless, they are often used as synonyms and the choice of term may simply be decided by the common terminology of a specific ecosystem type (freshwaters and wetlands: ecosystem condition; forests: naturalness). The term naturalness is a widely applied term in Hungary; it has been used in earlier national-level habitat quality assessment (Bölöni et al. 2008). It implies the comparison of the current ecosystem state with its natural state (Winter 2012, Roche and Campagne 2017).

The determination of naturalness, as well as that of ecosystem condition, is often based on biodiversity indicators (Carignan and Villard 2002, Scholes and Biggs 2005, Erhard et al. 2016). For large-scale assessments, usually some characteristic, easy to assess taxon groups are taken into account and used as proxies for biodiversity in general (e.g. vascular plant species - Schneiders et al. (2012) or birds - Becerra-Jurado et al. (2015)). Biodiversity can be characterised by indicators of structural and functional diversity, for example, the presence/absence or abundance of indicator species (Maes and van Dyck 2005), species richness or composition (Alkemade et al. 2009, Schneiders et al. 2012). Compositional, structural or functional characteristics of certain ecosystem elements (e.g. tree stand attributes in forests or characteristics of semi-natural patches in agricultural landscapes) are sometimes considered better indicators than species, since they determine the processes and characteristics of other components, while being relatively easy to measure (Neumann and Starlinger 2001, Bartha et al. 2006). The above are ‘direct’ ways to measure condition, but there are also ‘indirect’ approaches (Erhard et al. 2016). The concept of hemeroby (Jalas 1955, Sukopp 1976), often considered the reverse of naturalness (Winter 2012), summarises the effects resulting from human intervention in ecosystems. In this case, the habitat studied is classified according to the degree of human impact, with no natural reference (e.g. Grabherr et al. 1988, Csorba et al. 2018, Grantham et al. 2020). Since the effects of human activity are often delayed in time, it is possible to try to describe the effect of past pressure using the degree of the transformation of the vegetation as an indicator. It can be described as the departure of the actual vegetation from the potential natural vegetation (PNV). PNV is the vegetation that ‘would persist under the current conditions, if it was already there’ (Tüxen 1956, Somodi et al. 2012, Somodi et al. 2021). Indicators of current pressure can also be used as proxies for ecosystem condition, especially when other data are scarce. In this case, it is important to take into account that pressures don’t necessarily act immediately (Kuussaari et al. 2009, Rédei et al. 2014) and linearly; the effect also depends on the resilience of the ecosystem (Scheffer and Van Nes 2007, Selmeczy et al. 2019).

Given the number of related concepts, approaches and indicators, the issue of indicator selection has been on the table for a long time (Carignan and Villard 2002, Duelli and Obrist 2003, Molnár et al. 2008, Winter 2012). The current biodiversity crisis and the policy reactions have sparked a renewed interest (Lengyel et al. 2018) and several guidelines have been recently published on both selection criteria (van Oudenhoven et al. 2018, Smit et al. 2021, Czúcz et al. 2021a, Czúcz et al. 2021b) and sets of suitable indicators (Czúcz et al. 2018, Maes et al. 2018). The most recent of these came out as part of a theoretical framework, the System of Environmental-Economic Accounting - Ecosystem Accounting (SEEA-EA; United Nations 2021), developed by the UN for use in National Capital Accounting. The SEEA Ecosystem Condition Typology (SEEA-ECT) defines a hierarchical typology for organising data on ecosystem condition characteristics (United Nations 2021). While conceptual frameworks are essential to ensure that ecosystem condition assessments are comprehensive and comparable, many requirements are difficult to implement in practice. The suggested frameworks or sets of indicators are rarely tested against the specific challenges of large-scale application or in multiple ecosystem types and, thus, may need further refinement and adaptation (Czúcz et al. 2021a). Experiences from national-scale assessments can contribute to successfully meeting policy targets and to the practical implementation of national capital accounting. Matching indicators developed on the basis of practical considerations to theoretical aspects helps to find the balance between theoretical importance and feasibility criteria. Published condition assessments related to the Biodiversity Strategy (Kokkoris et al. 2018, Sopotlieva et al. 2018, Jakobsson et al. 2021) are either regional or deal with only one or a few major ecosystem types; their representation in the literature is spatially and thematically biased (Rendon et al. 2019).

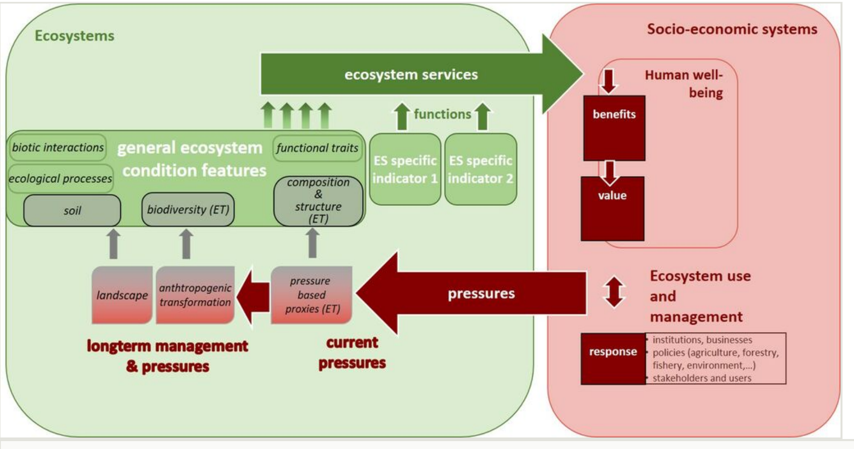

Figure 1.

The different types of ecosystem condition indicators as used in MAES-HU (based on the graphic by Maes et al. (2013), modified) including both ‘general’ and ‘ecosystem service-specific’ condition indicators. The indicators may represent ecosystem condition directly (grey boxes) or indirectly (reddish boxes), the latter quantifying pressures that affect ecosystem condition in the short or the long run. Further types of condition indicators that were not specifically addressed, are shown in light green frames. 'ET' signifies ecosystem type-specific groups of indicators.

In Hungary, a countrywide ecosystem condition assessment took place within the national Mapping and Assessment of Ecosystems and their Services (MAES-HU) between 2016 and 2021. It was conducted in two distinct parts, reflecting the two main interpretations of condition assessments. ‘Service-specific’ condition indicators, which directly determine ecosystem service supply, were selected and assessed by groups of experts for each ES (Kovács-Hostyánszki et al. 2019, Vári et al. 2022). 'General' ecosystem condition indicators aim to describe ecosystem integrity; they reflect the intrinsic values of nature and those aspects of condition, which are hard to directly link to ES supply (Fig. 1). The aim of the latter was to assess the state of all major ecosystem types across the whole country, in order to create indicators and maps that could be used directly for conservation decisions at the national level, including green infrastructure assessments (Szitár et al. 2021). The mapping and assessment of 'general' ecosystem condition was carried out using six approaches. The objectives of this paper are to:

- present the indicator development and the national-scale mapping of ecosystem condition in MAES-HU, focusing on the experiences considered to be of general interest in large-scale ecosystem condition mapping.
- evaluate the MAES-HU results in the light of a recently published theoretical framework, the SEEA-EA, in order to highlight the strengths and limitations of the different mapping approaches.

We present a selection of the most relevant MAES-HU methods and results. Further documentation is available on the project website (Tanács and Standovár 2021, Tanács et al. 2021a).

Material and methods

Indicator selection

As a first step, we conducted an indicator selection in order to find appropriate indicators to describe the condition of the major ecosystems of Hungary. The following expectations, set up at the beginning of the project, defined the choice of methods and the indicator selection for the MAES-HU condition mapping:

- it should be spatially explicit and cover the whole area of Hungary or as much of it as possible;
- it should be based on existing, regularly updated databases - the use of one-off datasets should be avoided;
- data type and quality should be consistent across the mapped area;
- it should comply with the recommendations of the MAES group (e.g. Erhard et al. 2016, Maes et al. 2018).

Indicators were selected and developed in an iterative process. Initial lists, based on available guidelines (Erhard et al. 2016), were discussed and filtered with experts (foresters, scientists, conservation experts) (through consultations and workshops). National and international databases were examined in terms of relevance, availability, quality, spatial and thematic resolution, as well as update frequency and a final list of indicators was proposed. These were later either aggregated into composite indicators or used as stand-alone ones.

Three indicators of ecosystem condition were specifically pre-defined by the project targets: soil fertility, landscape diversity and naturalness/hemeroby. Given the complexity of the term ‘naturalness’, we used various approaches to describe it, highlighting different, but complementary aspects of condition: a direct biodiversity-based approach, one using the anthropogenic transformation of the vegetation and two more using direct or indirect composite indicators specifically developed for each ecosystem type (ET). These were complemented with two more, based on soil and landscape characteristics, which are relevant across all ecosystem types. Thus 'approach' is used here as an umbrella term for the different ways of describing ecosystem condition. Table 1 summarises these along with some examples of indicators. Each mapping approach resulted in either one final indicator or a small set of indicators with similar characteristics.

Table 1.

Different approaches to mapping ecosystem condition in the MAES-HU project.

Approach to map ecosystem condition	**Examples of indicators**
Based on soil characteristics	Soil fertility
Based on the anthropogenic transformation of vegetation *[1]	Departure of the actual vegetation from the potential natural vegetation
Based on direct indicators of biodiversity *[1]	The ratio of the number of bird species present relative to the expected number (based on species list specific for ecosystem types)
Ecosystem-specific evaluation - based on composite indicators (direct) *[1]	Composite indicator of forest condition, based on structural and compositional indices
Ecosystem-specific evaluation - based on composite indicators (indirect) *[1]	Composite indicator of wetlands, based on proxy pressure indicators
Based on landscape-level indicators	Shannon Diversity of ecosystem types within a 1-km radius

Data

MAES-HU did not allow primary data collection; all maps and assessments had to be based on existing national and international databases. Suppl. material 1 summarises the entire range of databases used for the mapping; the most important ones are described in detail.

Mapping method

The mapping methods are described separately according to the six approaches presented in *Table 1*.

Soil characteristics

Only one indicator was chosen within this approach, soil fertility. In order to describe it, we used an already existing national soil fertility map, expressing an overall fertility by scoring units of genetic soil classification (Várallyay et al. 1985). The assessment was originally based on large-scale soil maps. As a result of the evaluation of the country's soil conditions and its agro-ecological potential, a national map was produced which describes the fertility of the national soil cover using a ten-grade version of the original 100-point assessment.

The improvement of the spatial resolution of the original dataset by disaggregation (Pásztor et al. 2013) was made possible by the elaboration of the Digital Kreybig Soil Information System national dataset (Pásztor et al. 2017) and the tools provided by Digital Soil Mapping. The resulting raster dataset comprises ten classes and has a one-hectare spatial resolution.

Anthropogenic transformation of the vegetation

This analysis was carried out only for two major ecosystem types, grasslands and wetlands. As the vegetation category system (Á-NÉR - Bölöni et al. (2011) used by the multiple potential natural vegetation (MPNV) map is more detailed than that of the Ecosystem map of Hungary, a crosswalk between the two had to be created (Suppl. material 2). MPNV estimates were not available for the Á-NÉR equivalents of certain grassland and wetland categories (3500 and 5120), so those were omitted from the analysis along with the non-target ecosystem types (urban areas, agricultural lands, forests and water surfaces). All cells belonging to the omitted types were masked. The map was then overlaid with the MPNV and a corresponding hexagon was assigned to each cell. Then a similarity measure was calculated for each cell, defined as the maximum of the MPNV ranks of all the Á-NÉR categories corresponding to the ecosystem type of the cell. The higher the value, the higher the similarity (and the lower the departure of the actual from the potential vegetation).

Biodiversity-based approach

As a first step, a reference list of bird species was defined for the major ecosystem types, including those species whose presence is presumed in an area considered to be in good condition. In the next step, we differentiated between species, based on what type of observation should be included. To this end, we selected the nesting probability codes under which the species was considered present (Suppl. material 3). Only those squares were included in the analysis where the duration of observation was regarded as sufficient (>60 minutes during the 4-year period). Some rarer species, associated with better ecosystem condition, were given a weight of 2. For each ecosystem type and each 2.5 x 2.5 km square, we calculated the sum of the weights, which was then compared to the expected number of species in the given ecosystem type. The maps created for the different ecosystem types were aggregated using the maximum value.

A biodiversity-based approach was applied also for water bodies, developed within the Water Framework Directive (WFD; European Commission 2003, Padisák et al. 2006, Szilágyi et al. 2008). We used the median of the biological component scores of the six taxa monitored.

Ecosystem-specific evaluation

An important approach to represent ecosystem condition was to design ecosystem-specific composite indicators by combining the relevant individual indicators previously chosen in the selection process (see Suppl. material 4). The process was based mostly on expert knowledge (arable lands, forests, wetlands and urban areas) and, in one case, (grasslands) on using a machine learning method.

In the first case, threshold limits were set for each relevant variable, based on the recommendations of experts and/or the relevant literature and scores were defined for each resulting category. By determining the scores, each variable was also weighted. The scores were then summed and the result was simplified to a 5-level ordinal scale, based on expert knowledge, considering the distribution and, in some cases, the quantiles of the summed scores. The different ecosystem types are, thus, not directly comparable with each other. In the second case (grasslands), a Classification and Regression Tree method (CART) was used. The naturalness maps described in Suppl. material 1 served for training and validation and the remaining area was classified using the obtained model.

The applied methods also differ in terms of indicator type. Structural and compositional indicators were included where possible (forests). Where data were scarce, landscape characteristics and pressure-related variables (e.g. distance to roads) were used as proxies.

For forests, where detailed sectoral data were available, we developed a composite indicator including both structural and compositional components (Suppl. material 5). Sub-indicators describing the composition and structure of the tree stand were aggregated separately. The composition indicators for native and non-native forests differ; the highest possible composition score for non-native plantations is ~70% of the maximum. Some indicators (related to deadwood, presence of game and the herbaceous layer), though considered very important throughout the selection process, had to be omitted due to the lack of adequate data. The final score was calculated as follows: *sum of composition scores*1.5+ sum of structure scores*. Recently cut stands could not be assessed or only in terms of composition.

For wetlands, grasslands and arable lands, where data were particularly scarce, the ecosystem-specific composite indicator was based mainly on proxies (landscape and pressure indicators, most derived from the ecosystem type map and a few from other databases like the OpenStreetMap (OSM) or the Copernicus HRL layer Water and Wetness Probability Index (WWPI) (Langanke et al. 2016). The rules and scores for wetlands are shown in Suppl. material 6 and, for arable land, in Suppl. material 7.

Urban areas were characterised with simple indicators describing the proportion of green surfaces (see Suppl. material 4).

Landscape-level indicators

Landscape-level indicators were calculated using the Ecosystem type map of Hungary, usually for a circle of 1000 m radius. For the indicators measuring change in ecosystem extent over time, the Corine Land Cover database (2000-2018) (Büttner 2014) was used, aggregated to a 1-km grid.

Validation

In order to provide some measure of quality for our result maps, we compared them to habitat maps, where each patch was assigned a naturalness score (modified Németh-Seregélyes /mNS/ naturalness) during field surveys by conservation experts (Török and Fodor 2006, Takács and Molnár 2009). The comparison is based on the overlapping area of the MAES-HU condition categories and the mNS naturalness categories.

Spearman's rho correlations were calculated for the final result of the biodiversity-based approach and

- sampling effort
- the area ratio of major ecosystem types within the squares

in order to see to what extent these variables affect the results.

Evaluation of the six mapping approaches according to the SEEA-EA indicator selection criteria

The six mapping approaches were evaluated against the indicator selection criteria of the SEEA-EA framework (Keith et al. 2020, United Nations 2021, Czúcz et al. 2021b). We chose to compare the mapping approaches rather than the pre-selected individual indicators, because data availability differs across countries, whereas the mapping approaches described here are more universal and can be adapted to the available data.

Results

Ecosystem condition mapping in MAES-HU

Altogether 52 indicators were selected and mapped in order to describe the condition of the major ecosystem types present in Hungary, using the six approaches described under 'Indicator selection'. Suppl. material 4 contains the full list of indicators, along with their corresponding SEEA-ECT type (Czúcz et al. 2021a). Ten of the 52 were used as stand-alone indicators of ecosystem condition, while the rest were combined into composite indicators specifically designed to describe the condition of an ecosystem type. Fig. 2 presents one example map for each of the six approaches. Further details are presented in Suppl. materials 8, 9. All the applied approaches were found to be useful in describing condition, although each has its advantages and limitations (Table 2).

Some examples of validation

Fig. 3 shows an example of the comparison of the MAES-HU results for wetlands with the field-based mNS naturalness maps. Whereas the results of the two independent evaluations are clearly related (the lower categories of one classification mostly overlap with the lower categories of the other and the higher values with the higher), there are also quite a few areas where they significantly diverge (e.g. field-based naturalness score is low but the MAES-HU score is high or vice versa). The distribution of the two types of values are similar in the sample, with the higher scores covering larger areas.

Table 2.

Summary of the main advantages and limitations of the different approaches to map ecosystem condition in MAES-HU.

Approach	**Advantage**	**Limitation**
Based on soil characteristics	- horizontal indicators for terrestrial ecosystems - directly relevant for many ES (→ instrumental relevance)	- resource-intensive data acquisition → wall-to-wall maps based on models (higher uncertainty) → no or less frequent updates
Based on (direct) biodiversity indicators	- sensitive to subtle change - easy to interpret - close to the current, well-established practice of conservation - consistent method and reference state across ecosystem types	- resource-intensive data acquisition - precise choice of taxa and indicators strongly affect the result - difficult to define a reference state - sampling bias issues
Based on the anthropogenic transformation of the vegetation	- can be used as direct input to conservation planning - may be useful in defining the reference state	- PNV not necessarily available at the national level - PNV may differ in (thematic or spatial) resolution from the ecosystem type map - in some cases, PNV is used in ecosystem type mapping to fill in data gaps - nearly impossible to verify the result
Ecosystem-specific evaluation - based on composite indicators (direct)	- easier to measure than biodiversity - most components available from already existing (sectoral) databases at the national scale (→ ensured repeatability)	- all relevant characteristics should be included (in order to define these, a framework like the SEEA-EA ECT can be used) - but existing (sectoral) databases may not hold all necessary information - may yield different results to the biodiversity-based approach → harder to communicate to conservation practice
Ecosystem-specific evaluation - based on composite indicators (indirect)	- better data availability - relatively easy to map at a large scale	- results are rather risk maps, only indirectly reflect condition - may be less sensitive to slow, subtle changes
Based on landscape-level indicators	- easy to map at a large scale (only requires ecosystem type map)	- interpretation in terms of ecosystem condition is not evident - not sensitive to slow, subtle changes

Comparing the departure of the actual from the potential vegetation to field naturalness maps, we also found that areas where there is no or only a small difference are more likely to have higher mNS naturalness values (signifying better condition) (see Suppl. material 8).

The results, based on bird observation data, showed a significant correlation with both the extent of certain ecosystem types (agricultural land: r=-0.187, grasslands and wetlands both: r=0.23) and sampling effort (r=0.537). Only ~40% of all the squares could be evaluated.

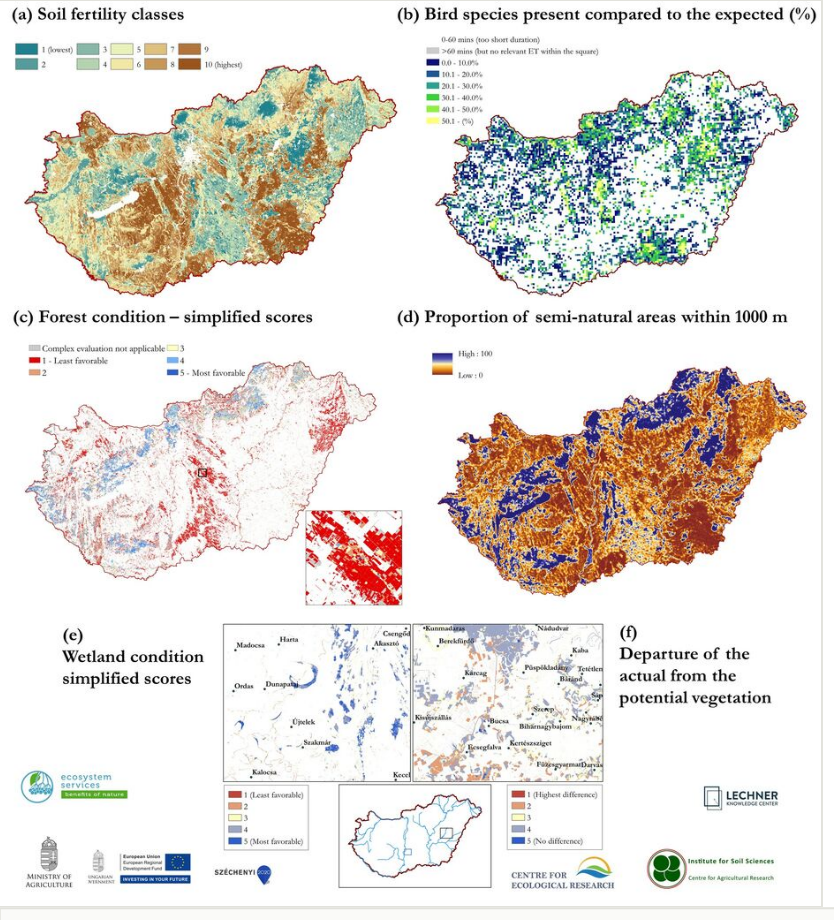

Figure 2.

Example maps for each of the approaches applied to map ecosystem condition in MAES-HU: (a) map of soil fertility (approach based on soil characteristics); (b) percentage of bird species present compared to the expected (biodiversity-based approach); (c) forest condition map with simplified scores (ecosystem-specific approach using direct indicators); (d) proportion of semi-natural areas (approach based on landscape-level indicators); (e) wetland condition map with simplified scores (ecosystem-specific approach using indirect indicators); (f) departure of the potential from the actual vegetation (approach based on the anthropogenic transformation of the vegetation).

Comparison using the indicator selection criteria of the SEEA-EA conceptual framework

Table 3 evaluates the different condition mapping approaches applied in MAES-HU against the indicator selection criteria suggested in the SEEA-EA framework (Czúcz et al. 2021b). In line with preliminary expectations, the applied approaches to condition mapping are complementary; they perform differently against the various relevance criteria.

Table 3.

Evaluation of the mapping approaches applied in MAES-HU against the indicator selection criteria of the SEEA-EA framework (Keith et al. 2020, United Nations 2021, Czúcz et al. 2021b). From '+++': high compliance to '+': low compliance with the criterion and ' -' : not relevant.

SEEA EA - Criterion	Short description	MAES-HU mapping approach					
		Based on soil characteristics	Based on (direct) indicators of biodiversity	Based on the anthropogenic transformation of the vegetation	Based on ecosystem-specific composite indicators		Based on landscape level indicators
					Direct	Indirect	
		Soil fertility	Ratio of the number of bird species present relative to the expected number	Departure of the actual vegetation from the potential natural vegetation	Composite indicator of forest condition, based on structural and compositional indices	For example, composite indicator of wetlands, based on proxy pressure indicators	For example, Shannon diversity of ecosystem types within a 1-km radius
Conceptual criteria							
Intrinsic relevance	Reflective of existing scientific understanding of ecosystem integrity, supported by the ecological literature	++	+++	+++	+++	++	++
Instrumental relevance	Have the potential to be related to the availability of ecosystem services	+++	+	++	++	+	++

SEEA EA - Criterion	Short description	MAES-HU mapping approach					
		Based on soil characteristics	Based on (direct) indicators of biodiversity	Based on the anthropogenic transformation of the vegetation	Based on ecosystem-specific composite indicators		Based on landscape level indicators
					Direct	Indirect	
		Soil fertility	Ratio of the number of bird species present relative to the expected number	Departure of the actual vegetation from the potential natural vegetation	Composite indicator of forest condition, based on structural and compositional indices	For example, composite indicator of wetlands, based on proxy pressure indicators	For example, Shannon diversity of ecosystem types within a 1-km radius
Sensitivity to human influence	Responsive to known socio-ecological leverage points (key pressures, management options)	+	+++	++	+++	++	++
Directional meaning	It should be clear if a change is favourable or unfavourable	+++	+++	+++	+++	++	+
Framework conformity	Differentiated from other components of the SEEA ecosystem accounting framework	+	+++	+++	+++	+	++
Practical criteria							

SEEA EA - Criterion	Short description	MAES-HU mapping approach					
		Based on soil characteristics	Based on (direct) indicators of biodiversity	Based on the anthropogenic transformation of the vegetation	Based on ecosystem-specific composite indicators		Based on landscape level indicators
					Direct	Indirect	
		Soil fertility	Ratio of the number of bird species present relative to the expected number	Departure of the actual vegetation from the potential natural vegetation	Composite indicator of forest condition, based on structural and compositional indices	For example, composite indicator of wetlands, based on proxy pressure indicators	For example, Shannon diversity of ecosystem types within a 1-km radius
Validity	Metrics need to represent the characteristics they address in a credible and unbiased way	++	+	++	++	+++	+++
Reliability	Scientifically valid representation of the characteristics they address	++	+++	++	+++	++	+++
Availability	Cover the studied spatial and temporal extents with the required resolution	++	+	++	++	+++	+++
Simplicity	As simple as possible	+++	++	++	++	+++	+++

SEEA EA - Criterion	Short description	MAES-HU mapping approach					
		Based on soil characteristics	Based on (direct) indicators of biodiversity	Based on the anthropogenic transformation of the vegetation	Based on ecosystem-specific composite indicators		Based on landscape level indicators
					Direct	Indirect	
		Soil fertility	Ratio of the number of bird species present relative to the expected number	Departure of the actual vegetation from the potential natural vegetation	Composite indicator of forest condition, based on structural and compositional indices	For example, composite indicator of wetlands, based on proxy pressure indicators	For example, Shannon diversity of ecosystem types within a 1-km radius
Compatibility	The same characteristics should be measured with the same (compatible) metrics in the different ecosystem types and/or different areas	+++	+++	+++	+	++	-
Ensemble criteria							
Comprehe-nsiveness	The final set of metrics should cover all the relevant characteristics of the ecosystem	+++	+	+	++	++	++
Parsimony	The final set of metrics should be free of redundant (correlated) variables	+++	+++	+++	++	++	+++

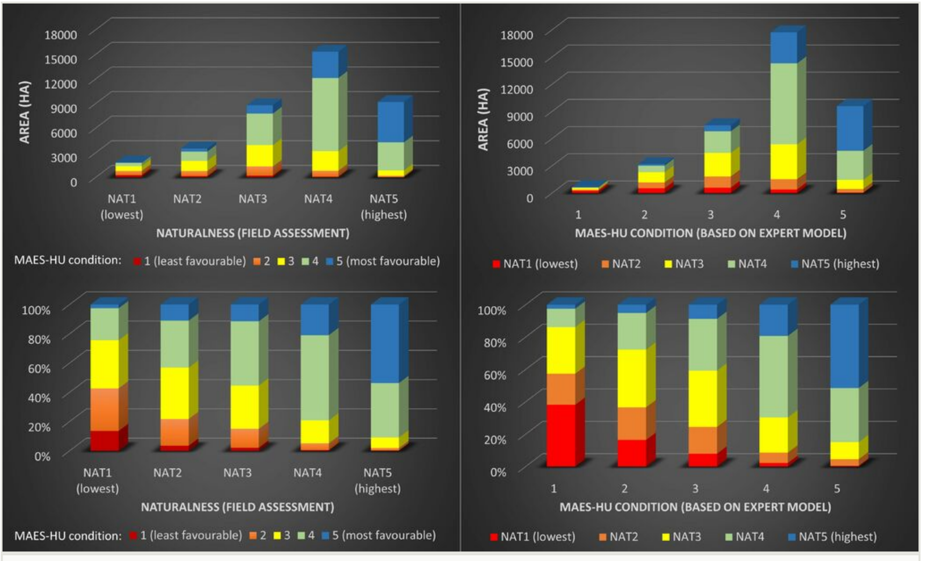

Figure 3.

Comparison of the MAES-HU condition categories (1: least favourable to 5: most favourable) with the field-based modified Németh-Seregélyes naturalness categories (NAT1: lowest naturalness to NAT5: highest naturalness), based on the overlapping area (wetlands).

The soil fertility map, while having the huge advantage of being readily available, scored low on sensitivity to human influence as it is based on a one-off map. The (biodiversity) assessment, based on bird observations, obtained a low score on more than one criteria. Only one group could be examined (comprehensiveness) and the spatial resolution of the data is rather coarse (spatio-temporal reference). The results do not only reflect ecosystem condition, but also ecosystem extent and sampling effort (validity). On the other hand, it has the advantage of being sensitive to change and using the same methodology across ecosystem types (compatibility). Direct (compositional and structural) condition indicators were only available for forests, an ecosystem-specific approach that performed well against several criteria. Since most of these indicators are only relevant in forests, compatibility is not relevant. Some important aspects of forest condition could not be covered with the available database, which affects both comprehensiveness and validity. The approach using indirect (pressure) proxies for data-deficient ecosystem types scored generally high on practical criteria and simplicity, but lower on the conceptual criteria. Finally, landscape indicators are a challenge in terms of directionality, but, since they are calculated from the ecosystem type map, they perform well in all practical criteria.

Discussion

We developed a set of approaches and indicators for Hungary to quantify and map ecosystem condition at the national level, based on the different interpretations of the related concepts of naturalness and hemeroby. These are complementary, grasping different aspects of condition, covering all broad ecosystem types within Hungary and nearly the entire area. Indicators relevant across all ecosystem types, such as the characteristics of soil and landscape, were added to those targeting specific ecosystem types.

Indicator selection

In recent decades, as an answer to the unfolding biodiversity crisis, a multitude of indicators has been designed and published to describe and monitor biodiversity (related to ecosystem integrity/condition) for different scales and ecosystem types (see Feld et al. 2009). The Farmland Bird Index (Gregory et al. 2005) has been used as an official proxy for biodiversity health on farmland (Butler et al. 2010). The Human Appropriation of Net Primary Production (HANPP, Haberl et al. 2007) is a widely used indicator of pressure on biodiversity, although such assessments are often not spatially explicit (Plutzar et al. 2016). A set of Biodiversity Indicators were first proposed in 2005 to monitor the progress of the efforts to halt the loss of biodiversity in Europe (Biała et al. 2012). More recently, Maes et al. (2018) and Czúcz et al. (2018) published whole sets of ecosystem condition indicators for use in national condition assessments. The fast development of remote sensing technology and the increase in the range of available products opens up ever new possibilities in biodiversity monitoring (Petrou et al. 2015), especially if integrated with field-based methods (Cavender-Bares et al. 2022).

In MAES-HU, the available options were overviewed and considered at the indicator selection phase (in 2017). As detailed, high-quality, spatially explicit data were needed for the whole area of Hungary, many otherwise relevant indicators had to be discarded due to data availability (e.g. deadwood) or quality (e.g. grazing/mowing activities in grasslands) issues. Others, especially indicators based on remote sensing data (e.g. grassland management intensity), would have needed a development of new methods or the adaptation of existing methods to the national scale, which was not possible due to time or resource constraints. However, the indicators that were considered important, but needed to be omitted due to such constraints, were highlighted in the project reports (Tanács et al. 2021a) and there are plans to tackle these in a future project.

The different approaches to mapping ecosystem condition

Anthropogenic transformation of the vegetation

In order to describe the anthropogenic transformation of the vegetation, the departure of the actual from the potential natural vegetation was calculated in an experimental manner, for two major ecosystem types (grasslands and wetlands) (see Suppl. material 8).

As potential natural vegetation models are based on the site requirements of vegetation, a PNV is probably the best approximation for 'natural state' and, thus, can have strong implications concerning the sustainability of the present land use (Ricotta et al. 2002, Somodi et al. 2017, Somodi et al. 2021). Bartha et al. (2006) used potential natural forest communities as a hypothetical reference for assessment of the naturalness of forests. PNV has been used for the evaluation of ecosystem health (Jensen et al. 2000) and its use to describe ecosystem condition is suggested by Erhard et al. (2016). This approach is universally applicable for all non-artificial ecosystem types, provided that PNV estimates are available. However, it is important to note that sometimes the PNV (or the somewhat similar concept of predictive mapping) is used in the creation of national ecosystem type maps (Blasi et al. 2017, Tanács et al. 2021b). In this case, the calculation of this indicator becomes either meaningless or the results may reflect the differences in methodology as well as the real differences between the actual vegetation and the PNV.

Biodiversity-based assessment

Whereas the condition map based on bird observations clearly outlines some of the most valuable areas of nature conservation in Hungary, the results reflect a mixed effect of ecosystem extent and condition. Sampling effort (expressed with the duration of observation) also strongly defines the patterns. Unfortunately both condition assessments, based on biodiversity indices (for terrestrial ecosystems and water bodies), display significant data gaps.

Biodiversity-based indicators are amongst the most favoured ones to assess ecosystem condition. They represent a plurality of the values of nature and underpin several ecosystem functions (Carignan and Villard 2002, Scholes and Biggs 2005, Smith et al. 2017, van der Plas 2019, La Notte et al. 2021). Multi-taxa approaches provide a more complete picture, but are also more resource-intensive (Maes and van Dyck 2005). The species richness of one group can indicate that of other groups (e.g. Blair 1999) at certain scales (Carignan and Villard 2002); it is, therefore, often used in large-scale applications (Becerra-Jurado et al. 2015, Erős et al. 2019). Birds are a popular choice for terrestrial ecosystems, because they are relatively easy and efficient to monitor, they appear in all types of habitats and they are sensitive to environmental change (Carignan and Villard 2002, Nagy et al. 2017). However, the precise choice of indicator strongly affects the suitability of the method to predict ecosystem quality (Chin et al. 2015). Nagy et al. (2017) found that the presence of certain bird species showed higher association with the Natural Capital Index than assemblage-level indicators.

As the database we used is mostly derived from a planned survey carried out by volunteers, the strong effect of sampling effort is probably related to factors, such as volunteer density and site popularity, which depend on both site quality and accessibility (Ruete 2015, Johnston et al. 2020, Cretois et al. 2021). Since there is a known measure of sampling effort, some of these effects can be accounted for (Zulian et al. 2021, Cretois et al. 2021) in future analysis.

Ecosystem specific assessment - direct

The large-scale patterns of forest condition, identifiable on the forest condition map developed in MAES-HU (Suppl. material 9), are in line with the findings of earlier related research, based on field surveys (Bartha et al. 2006, Bölöni et al. 2008, Standovár et al.

2016, Standovár et al. 2017). Using stand compositional and structural characteristics is an effective way to describe ecosystem condition in forests (Ćosović et al. 2020). The method, being based on detailed data from a regularly updated sectoral database, allows us to regularly monitor forest condition at the national level in a time- and cost-effective way. However, the results are affected by the characteristics of the underlying database. This includes concerns of data quality related to the varying size of the spatial units and a fluctuation in the level of detail - both of which can affect some of the subscores. Furthermore, the aim of the National Forestry Database (NFD) as a sectoral database is primarily to meet the information needs of the forestry sector; data on certain essential elements of ecosystem condition (e.g. deadwood, game presence, herbaceous layer species) are missing (Tobisch and Kottek 2013). As a consequence, the maps do not entirely reflect conservation experts' views on the value of a specific area. The local importance of a forest area may not be expressed in the results: some valuable remnants of now rare habitat types on the plains, strongly affected by numerous pressures (invasive species, weather extremes, changing water levels), obtained a mediocre overall score. This highlights that, however sound the condition assessment is, local results should be interpreted by taking into account not only the characteristics of the individual stands, but also the landscape context (Wretenberg et al. 2010, Basile et al. 2021).

Ecosystem specific assessment - indirect

In order to validate the expert model developed for wetlands in MAES-HU, we compared the results with field naturalness maps. We found that there is a similar overall tendency, but there are some areas where the results significantly diverge. As the mNS naturalness index strongly relies on indicator species, extinction debt (Kuussaari et al. 2009) may strongly affect the comparison: small wetland fragments surrounded by agricultural land, which score low according to the MAES-HU condition assessment, may still retain valuable or rare species.

The use of easy-to-map pressure proxies is ambiguous. They may not be sensitive to slow, subtle degradation (loss of species or homogenisation of forest structure), only to fast, dramatic changes like habitat fragmentation. According to some preliminary feedback from conservation experts, the divergence of pressure-based condition maps from their perception of the value of a certain area may negatively influence their views and acceptance of large-scale ecosystem condition maps. The recent development of user-friendly GIS tools promotes an increasing use of spatial data by end-users who may not be aware of the underlying concepts, which could lead to misinterpretations (Lecours 2017).

On the other hand, detailed data collection, suitable to support a 'direct' approach to describe ecosystem condition, rarely has nationwide coverage, but usually focuses on protected areas. Yet, dominantly agricultural land, occupying much of the landscape, has its own role in preserving biodiversity (Sutcliffe et al. 2015), therefore ecosystem condition must be, to some extent, described and monitored in such areas as well (Tscharntke et al. 2005). Using pressure proxies with well-established connections to direct measures of condition can be very important in closing the knowledge gaps concerning these areas

(Czúcz et al. 2021a). However, there are some practical considerations related to the use of indicators in Natural Capital Accounting: it is important to avoid double-counting and this should be taken into account when including pressure indicators (Czúcz et al. 2021a).

With regard to the above, the use of pressure proxies must be handled with care and it is especially important to effectively communicate their specific nature to potential users. On the other hand, maps created on the basis of pressure indicators can be used as risk maps and, thus, provide an opportunity for early intervention.

Landscape-level indicators

In MAES-HU, we used several landscape-level metrics (covering indicators irrelevant at the habitat patch level), which, in the SEEA-ECT, are either listed as landscape characteristics, as the ratio of embedded subtypes or as pressure (see Suppl. material 4).

Landscape patterns partly define and partly reflect ecological processes, thus being related to biodiversity (Uuemaa et al. 2013). They have been shown to be linked to the naturalness of the vegetation (Szilassi et al. 2017) and to community integrity (Banks-Leite et al. 2011) at the landscape scale. Yet, we found their use as stand-alone indicators challenging in terms of directionality. Land-use transforms landscapes and the resulting pressures have an impact on biodiversity (Renetzeder et al. 2010, Hudson et al. 2017, Batáry et al. 2020, Davison et al. 2021). However, change often affects both landscape composition and configuration, producing mixed effects (Wilson et al. 2016), which has recently sparked an intensive debate (Fahrig 2017, Miller-Rushing et al. 2019). Furthermore, the usefulness of indicators, like the number or diversity of ecosystem types, is heavily influenced by the thematic resolution of the map serving as a basis of the calculations (Castilla et al. 2009). On the other hand, we found the variables related to ecosystem extent useful proxies in data-scarce ecosystem types (grasslands and wetlands).

Methodological challenges

In the MAES-HU ecosystem condition assessment, reference levels were, in most cases, defined as threshold values for individual variables, based on scientific literature and expert knowledge. In the case of the ecosystem-specific assessments, we used an additive method for the aggregation of variables. The aggregated scores had to be simplified, in part to ensure some measure of comparability, but mostly for easier communication to stakeholders. In order to create these simplified scores, further thresholds were needed, qualifying condition based on all characteristics, including their interactions, for which there is a general lack of empirical evidence (Smith et al. 2017). These thresholds were also defined on the basis of expert decision, albeit considering the distribution of the summed scores. This procedure may have similar limitations as using statistical methods, such as:

1. being arbitrary,
2. being unsuitable to interpret values outside of the originally established range and
3. creating a false sense of consistency.

However, all methods used for defining reference levels have weaknesses (Keith et al. 2020, Jakobsson et al. 2020) and expert knowledge should not be underestimated (Drescher et al. 2013, Roche and Campagne 2019). As there is more empirical evidence on meaningful reference levels for individual variables (e.g. Clapcott et al. 2012, Sály and Erős 2016, Oettel and Lapin 2021), the above issues affect mostly the simplified scores. The individual and summed scores are available to provide a deeper insight for effective decision-making and the thresholds used for simplification can be further adjusted in the future with targeted data collection.

We avoided combining the results of the ecosystem-specific mapping into one map, partly to avoid strengthening the above-mentioned false sense of consistency and partly to avoid misunderstandings about the actual values of different ecosystem types. Arable lands were assigned five classes, the same as forests; however, the term 'most favourable condition' has a different meaning for the two.

The validation of the result maps is a specific challenge. The dataset available for validation is spatially biased, as it mostly covers protected areas. The mNS naturalness we used is itself a composite indicator (Bölöni et al. 2008), a separate condition mapping method in its own right, with its own strengths and limitations. Subjectivity cannot be entirely ruled out from the process. While the classification of the 'worst' and 'best' cases is, in most cases, evident, the boundaries between the middle categories are somewhat fuzzy and subject to individual interpretation (Takács and Molnár 2009).

The assessment was intended as a first attempt, as well as a baseline, using methods and data to ensure future repeatability. Therefore, the results are suitable for studying spatial patterns and relationships between different descriptors and aspects of ecosystem condition, but studying temporal change will need a repeated assessment.

Considerations related to the SEEA-EA conceptual framework

We evaluated and compared the six different condition mapping approaches applied in MAES-HU using the indicator selection criteria introduced within the SEEA-EA framework (United Nations 2021, Czúcz et al. 2021b), in order to compare and highlight their strengths and limitations (Table 3). Although the criteria were originally designed to help select individual indicators to be included in a condition assessment, in this case, we used them for a retrospective evaluation. The evaluation and discussion applies to the actual outcome of the MAES-HU condition assessment; the theoretical potential of the different approaches can be higher.

The aims of MAES-HU included the assessment of ecosystem services as well as ecosystem condition, with the different focuses requiring different considerations and different sets of indicators. Therefore, we differentiated between 'service-specific' condition indicators and 'general' condition indicators. This separation corresponds to the two main strands of ecosystem integrity concepts identified earlier (Roche and Campagne 2017) that relate to two different views and valuations of nature - emphasising the intrinsic values or the instrumental ones (Keith et al. 2020). The SEEA framework of indicator selection

(United Nations 2021, Czúcz et al. 2021b) - while acknowledging the duality of ecosystem condition by differentiating between intrinsic and instrumental relevance - suggests that condition indicators should be relevant in both senses. For our purpose of defining ‘general’ condition indicators, we considered instrumental relevance a bonus, but not a ‘must’.

While there is an evident need to optimise resources, no single set of indicators is suitable for all purposes (Grunewald et al. 2020); robust assessments of ecosystem condition need to cover the various structures and functions of the targeted ecosystem (Jakobsson et al. 2020, Keith et al. 2020). Ignoring the dual nature and complexity of condition-related questions and trying to find a few ‘one fits all’ type of indicators may lead to oversimplification and critical information loss.

Relying on available (and regularly updated) data is time and cost-efficient (Ćosović et al. 2020); it was an important aspect of our choice of indicators. As the real importance of condition assessments lies in enabling the detection of changes in our ecosystem assets and the prevention of further damage, we suggest adding ‘monitoring potential’ to the criteria of indicator selection. This means examining the suitability of databases to assess changes in condition using the same evaluation method at a later time without added data collection effort.

Conclusions

We presented the results of a first wall-to-wall mapping and assessment of ecosystem condition in Hungary. The methods and maps will be further developed in the future, but useful conclusions can be already drawn. A realistic picture of ecosystem condition can only be obtained with the help of data collection that is continuous over time, methodologically well-founded and of sufficient scope, but such spatial databases are not necessarily available. Since a regular wall-to-wall field mapping of ecosystem condition is unlikely, national condition assessments need to be based mainly on existing databases, which will always have shortcomings either in terms of spatial extent, resolution, data quality or data content. However, using complementary approaches with different strengths and weaknesses mitigates the effects of the resulting uncertainty. Comparing the results from direct and indirect approaches allows for a better understanding of the relationship between human pressures and their effects on ecosystem condition, which, in turn, increases our ability to estimate condition in data-scarce regions. The use of multiple approaches also allows for a flexible use of the condition indicators, enabling a change of emphasis on the examined aspects. It helps to satisfy the information needs of both ‘traditional’ conservation and ecosystem accounting. The constant development of new methods, for example, based on remote sensing or citizen science, opens up ever new possibilities. However, the most important data gaps need to be addressed by targeted data collection. Lack of data cannot be a reason to completely ignore any important aspect of ecosystem condition in the long term, especially if the aim is to use the results of these assessments in natural capital accounting systems.

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References

- Alkemade R, van Oorschot M, Miles L, Nellemann C, Bakkenes M, ten Brink B (2009) GLOBIO3: A framework to investigate options for reducing global terrestrial biodiversity loss. Ecosystems 12 (3): 374-390. https://doi.org/10.1007/s10021-009-9229-5
- Banks-Leite C, Ewers R, Kapos V, Martensen A, Metzger JP (2011) Comparing species and measures of landscape structure as indicators of conservation importance. Journal of Applied Ecology 48 (3): 706-714. https://doi.org/10.1111/j.1365-2664.2011.01966.x
- Bartha D, Ódor P, Horváth T, Tímár G, Kenderes K, Standovár T, Bölöni J, Szmorad F, Bodonczi L, Aszalós R (2006) Relationship of tree stand heterogeneity and forest naturalness. Acta Silvatica et Lignaria Hungarica 2: 7-22.
- Basile M, Storch I, Mikusiński G (2021) Abundance, species richness and diversity of forest bird assemblages - The relative importance of habitat structures and landscape context. Ecological Indicators 133: 108402. https://doi.org/10.1016/j.ecolind.2021.108402
- Batáry P, Báldi A, Ekroos J, Gallé R, Grass I, Tscharntke T (2020) Biologia Futura: landscape perspectives on farmland biodiversity conservation. Biologia Futura https://doi.org/10.1007/s42977-020-00015-7
- Becerra-Jurado G, Philipsen C, Kleeschulte S (2015) Mapping and assessing ecosystems and their services in Luxembourg – assessment results. URL: https://www.researchgate.net/publication/298394420_Mapping_and_Assessing_Ecosystems_and_their_Services_in_Luxembourg_-_Assessment_results
- Biała K, Condé S, Delbaere B, Jones-Walters L, Torre-Marín A (2012) Streamlining European biodiversity indicator 2020: building a future on lessons learnt from the SEBI 2010 process. Publications Office, LU. URL: https://data.europa.eu/doi/10.2800/55751

- Blair R (1999) Birds and butterflies along an urban gradient: surrogate taxa for assessing biodiversity? Ecological Applications 9 (1): 164-170. https://doi.org/10.1890/1051-0761(1999)009[0164:BABAAU]2.0.CO;2
- Blasi C, Capotorti G, Alós Ortí MM, Anzellotti I, Attorre F, Azzella MM, Carli E, Copiz R, Garfì V, Manes F, Marando F, Marchetti M, Mollo B, Zavattero L (2017) Ecosystem mapping for the implementation of the European Biodiversity Strategy at the national level: The case of Italy. Environmental Science & Policy 78: 173-184. https://doi.org/10.1016/j.envsci.2017.09.002
- Bölöni J, Molnár Z, Horváth F, Illyés E (2008) Naturalness-based habitat quality of the Hungarian (semi-)natural habitats. Acta Botanica Hungarica 50 (Issue Supplement-1): 149-159. https://doi.org/10.1556/abot.50.2008.suppl.7
- Bölöni J, Molnár Z, Kun A (2011) Magyarország élőhelyei. A hazai vegetációtípusok leírása és határozója. MTA ÖBKI, Vácrátót.
- Butler SJ, Boccaccio L, Gregory RD, Vorisek P, Norris K (2010) Quantifying the impact of land-use change to European farmland bird populations. Agriculture, Ecosystems & Environment 137 (3): 348-357. https://doi.org/10.1016/j.agee.2010.03.005
- Büttner G (2014) CORINE land cover and land cover change products. In: Manakos I, Braun M (Eds) Land use and land cover mapping in Europe.
- Carignan V, Villard M (2002) Selecting indicator species to monitor ecological integrity: A Review. Environmental Monitoring and Assessment 78 (1): 45-61. https://doi.org/10.1023/A:1016136723584
- Castilla G, Larkin K, Linke J, Hay G (2009) The impact of thematic resolution on the patch-mosaic model of natural landscapes. Landscape Ecology 24 (1): 15-23. https://doi.org/10.1007/s10980-008-9310-z
- Cavender-Bares J, Schneider F, Santos MJ, Armstrong A, Carnaval A, Dahlin K, Fatoyinbo L, Hurtt G, Schimel D, Townsend P, Ustin S, Wang Z, Wilson A (2022) Integrating remote sensing with ecology and evolution to advance biodiversity conservation. Nature Ecology & Evolution1-14. https://doi.org/10.1038/s41559-022-01702-5
- Chin AM, Tozer D, Walton N, Fraser G (2015) Comparing disturbance gradients and bird-based indices of biotic integrity for ranking the ecological integrity of Great Lakes coastal wetlands. Ecological Indicators 57: 475-485. https://doi.org/10.1016/j.ecolind.2015.05.010
- Clapcott JE, Collier KJ, Death RG, Goodwin EO, Harding JS, Kelly D, Leathwick JR, Young RG (2012) Quantifying relationships between land-use gradients and structural and functional indicators of stream ecological integrity: Stream integrity along land-use gradients. Freshwater Biology 57 (1): 74-90. https://doi.org/10.1111/j.1365-2427.2011.02696.x
- Ćosović M, Bugalho M, Thom D, Borges J (2020) Stand structural characteristics are the most practical biodiversity indicators for forest management planning in Europe. Forests 11 (3). https://doi.org/10.3390/f11030343
- Cretois B, Simmonds E, Linnell JC, van Moorter B, Rolandsen C, Solberg E, Strand O, Gundersen V, Roer O, Rød JK (2021) Identifying and correcting spatial bias in opportunistic citizen science data for wild ungulates in Norway. Ecology and Evolution 11 (21): 15191-15204. https://doi.org/10.1002/ece3.8200
- Csorba P, Ádám S, Bartos-Elekes Z, Bata T, Bede-Fazekas Á, Czúcz B, Csima P, Csüllög G, Fodor N, Frisnyák S, Horváth G, Illés G, Kiss G, Kocsis K, Kollányi L,

Konkoly-Gyúró É, Lepesi N, Lóczy D, Malatinszky Á, Mezősi G, Mikesy G, Molnár Z, Pásztor L, Somodi I, Szegedi S, Szilassi P, Tamás L, Tirászi Á, Vasvári M (2018) Landscapes. In: Kocsis ,K, Gercsák G, Horváth G, Keresztesi Z, Nemerkényi Z (Eds) National Atlas of Hungary. 2 (Natural environment). Hungarian Academy of Sciences, Budapest. URL: https://www.nemzetiatlasz.hu/en/home.html

- Czúcz B, Condé S (2017) Note on definitions related to ecosystem conditions and their services based on different glossaries. URL: https://www.researchgate.net/publication/323053577_Note_on_definitions_related_to_ecosystem_conditions_and_their_services_based_on_different_glossaries
- Czúcz B, Götzl M, Schwaiger E, Sonderegger G, Condé S (2018) Fact sheets on ecosystem condition: a synthesis. ETC/BD report to the EEA (Task 175A). URL: https://www.eionet.europa.eu/etcs/etc-bd/products/etc-bd-reports/etc-bd-report-12-2018-fact-sheets-on-ecosystem-condition
- Czúcz B, Keith H, Driver A, Jackson B, Nicholson E, Maes J (2021a) A common typology for ecosystem characteristics and ecosystem condition variables. One Ecosystem 6 https://doi.org/10.3897/oneeco.6.e58218
- Czúcz B, Keith H, Maes J, Driver A, Jackson B, Nicholson E, Kiss M, Obst C (2021b) Selection criteria for ecosystem condition indicators. Ecological Indicators 133 https://doi.org/10.1016/j.ecolind.2021.108376
- Davison C, Rahbek C, Morueta-Holme N (2021) Land-use change and biodiversity: Challenges for assembling evidence on the greatest threat to nature. Global Change Biology 27 (21): 5414-5429. https://doi.org/10.1111/gcb.15846
- Drescher M, Perera AH, Johnson CJ, Buse LJ, Drew CA, Burgman MA (2013) Toward rigorous use of expert knowledge in ecological research. Ecosphere 4 (7). https://doi.org/10.1890/ES12-00415.1
- Duelli P, Obrist MK (2003) Biodiversity indicators: the choice of values and measures. Agriculture, Ecosystems & Environment 98 (1): 87-98. https://doi.org/10.1016/S0167-8809(03)00072-0
- Erhard M, Teller A, Maes J, Meiner A, Berry P, Smith A, Eales R, Papadopoulou L, Bastrup-Birk A, Ivits E, Royo Gelabert E, Dige G, Petersen J, Reker J, Cugny-Seguin M, Kristensen P, Uhel R, Estreguil C, Fritz ., Murphy P, Banfield N, Ostermann O, Abdul Malak D, Marín A, Schröder C, Condé S, C G, Evans D, Delbaere B, Naumann S, McKenna D, Gerdes H, Graf A, Boon A, Stoker B, Mizgajski A, Santos Martin F, Jol A, Lükewille A, Werner B, Romao C, Desaulty D, Wugt Larsen F, Louwagie G, Zal N, Gawronska S, Christiansen T (2016) Mapping and assessment of ecosystems and their services: mapping and assessing the condition of Europe's ecosystems: progress and challenges. Publications Office of the European Union, Luxembourg 3.
- Erős T, Kuehne L, Dolezsai A, Sommerwerk N, Wolter C (2019) A systematic review of assessment and conservation management in large floodplain rivers – Actions postponed. Ecological Indicators 98: 453-461. https://doi.org/10.1016/j.ecolind.2018.11.026
- European Commission (2003) Common Implementation Strategy for theWater Framework Directive (2000/60/EC) - Overall approach to the classification of ecological status and ecological potential. European Commission URL: http://bookshop.europa.eu/uri?target=EUB:NOTICE:KH5703758:EN:HTML
- European Commission (2011) The EU biodiversity strategy to 2020. Publ. Office of the European Union

- European Commission (2020) EU Biodiversity Strategy for 2030 - Bringing nature back into our lives. COM/2020/380.
- European Environment Agency (2019) The European Environment State and Outlook 2020. Publications Office of the European Union, Luxembourg.
- Fahrig L (2017) Ecological responses to habitat fragmentation per e. Annual Review of Ecology, Evolution, and Systematics 48 (1): 1-23. https://doi.org/10.1146/annurev-ecolsys-110316-022612
- Feld C, Martins da Silva P, Paulo Sousa J, De Bello F, Bugter R, Grandin U, Hering D, Lavorel S, Mountford O, Pardo I, Pärtel M, Römbke J, Sandin L, Bruce Jones K, Harrison P (2009) Indicators of biodiversity and ecosystem services: a synthesis across ecosystems and spatial scales. Oikos 118 (12): 1862-1871. https://doi.org/10.1111/j.1600-0706.2009.17860.x
- Grabherr G, Koch G, Kirchmeir G, Reiter K (1988) Hemerobie österreichischer Waldöko-Systeme (Hemeroby of Austrian forest ecosystems. Universitätsverlag Wagner
- Grantham HS, Duncan A, Evans TD, Jones KR, Beyer HL, Schuster R, Walston J, Ray JC, Robinson JG, Callow M, Clements T, Costa HM, DeGemmis A, Elsen PR, Ervin J, Franco P, Goldman E, Goetz S, Hansen A, Hofsvang E, Jantz P, Jupiter S, Kang A, Langhammer P, Laurance WF, Lieberman S, Linkie M, Malhi Y, Maxwell S, Mendez M, Mittermeier R, Murray NJ, Possingham H, Radachowsky J, Saatchi S, Samper C, Silverman J, Shapiro A, Strassburg B, Stevens T, Stokes E, Taylor R, Tear T, Tizard R, Venter O, Visconti P, Wang S, Watson JEM (2020) Anthropogenic modification of forests means only 40% of remaining forests have high ecosystem integrity. Nature Communications 11 (1). https://doi.org/10.1038/s41467-020-19493-3
- Gregory RD, van Strien A, Vorisek P, Gmelig Meyling AW, Noble DG, Foppen RB, Gibbons DW (2005) Developing indicators for European birds. Philosophical Transactions of the Royal Society B: Biological Sciences 360 (1454): 269-288. https://doi.org/10.1098/rstb.2004.1602
- Grunewald K, Schweppe-Kraft B, Syrbe R, Meier S, Krüger T, Schorcht M, Walz U (2020) Hierarchical classification system of Germany’s ecosystems as basis for an ecosystem accounting – methods and first results. One Ecosystem 5 https://doi.org/10.3897/oneeco.5.e50648
- Haberl H, Erb K, Plutzar C, Fischer-Kowalski M, Krausmann F (2007) Human appropriation of net primary production (HANPP) as indicator for pressures on biodiversity. In: Hák T, Moldan B, Dahl AL (Eds) Sustainability Indicators: A Scientific Assessment. Island Press, 448 pp. [ISBN 978-1-59726-628-4].
- Hein L, Bagstad KJ, Obst C, Edens B, Schenau S, Castillo G, Soulard F, Brown C, Driver A, Bordt M, Steurer A (2020) Progress in natural capital accounting for ecosystems. Science 367 (6477): 514-515.
- Hudson L, Newbold T, Contu S, Hill SL, Lysenko I, De Palma A, Phillips HP, Alhusseini T, Bedford F, Bennett D, Booth H, Burton V, Chng CT, Choimes A, Correia DP, Day J, Echeverría-Londoño S, Emerson S, Gao D, Garon M, Harrison MK, Ingram D, Jung M, Kemp V, Kirkpatrick L, Martin C, Pan Y, Pask-Hale G, Pynegar E, Robinson A, Sanchez-Ortiz K, Senior R, Simmons B, White H, Zhang H, Aben J, Abrahamczyk S, Adum G, Aguilar-Barquero V, Aizen M, Albertos B, Alcala EL, del Mar Alguacil M, Alignier A, Ancrenaz M, Andersen A, Arbeláez-Cortés E, Armbrecht I, Arroyo-Rodríguez V, Aumann T, Axmacher J, Azhar B, Azpiroz A, Baeten L, Bakayoko A, Báldi A, Banks J, Baral S, Barlow J, Barratt BP, Barrico L, Bartolommei P, Barton D, Basset Y, Batáry P, Bates A,

Baur B, Bayne E, Beja P, Benedick S, Berg Å, Bernard H, Berry N, Bhatt D, Bicknell J, Bihn J, Blake R, Bobo K, Bóçon R, Boekhout T, Böhning-Gaese K, Bonham K, Borges PV, Borges S, Boutin C, Bouyer J, Bragagnolo C, Brandt J, Brearley F, Brito I, Bros V, Brunet J, Buczkowski G, Buddle C, Bugter R, Buscardo E, Buse J, Cabra-García J, Cáceres N, Cagle N, Calviño-Cancela M, Cameron S, Cancello E, Caparrós R, Cardoso P, Carpenter D, Carrijo T, Carvalho A, Cassano C, Castro H, Castro-Luna A, Rolando C, Cerezo A, Chapman KA, Chauvat M, Christensen M, Clarke F, Cleary DR, Colombo G, Connop S, Craig M, Cruz-López L, Cunningham S, D'Aniello B, D'Cruze N, da Silva PG, Dallimer M, Danquah E, Darvill B, Dauber J, Davis AV, Dawson J, de Sassi C, de Thoisy B, Deheuvels O, Dejean A, Devineau J, Diekötter T, Dolia J, Domínguez E, Dominguez-Haydar Y, Dorn S, Draper I, Dreber N, Dumont B, Dures S, Dynesius M, Edenius L, Eggleton P, Eigenbrod F, Elek Z, Entling M, Esler K, de Lima R, Faruk A, Farwig N, Fayle T, Felicioli A, Felton A, Fensham R, Fernandez I, Ferreira C, Ficetola G, Fiera C, Filgueiras BC, Fırıncıoğlu H, Flaspohler D, Floren A, Fonte S, Fournier A, Fowler R, Franzén M, Fraser L, Fredriksson G, Freire G, Frizzo TM, Fukuda D, Furlani D, Gaigher R, Ganzhorn J, García K, Garcia-R J, Garden J, Garilleti R, Ge B, Gendreau-Berthiaume B, Gerard P, Gheler-Costa C, Gilbert B, Giordani P, Giordano S, Golodets C, Gomes LL, Gould R, Goulson D, Gove A, Granjon L, Grass I, Gray C, Grogan J, Gu W, Guardiola M, Gunawardene N, Gutierrez A, Gutiérrez-Lamus D, Haarmeyer D, Hanley M, Hanson T, Hashim N, Hassan S, Hatfield R, Hawes J, Hayward M, Hébert C, Helden A, Henden J, Henschel P, Hernández L, Herrera J, Herrmann F, Herzog F, Higuera-Diaz D, Hilje B, Höfer H, Hoffmann A, Horgan F, Hornung E, Horváth R, Hylander K, Isaacs-Cubides P, Ishida H, Ishitani M, Jacobs C, Jaramillo V, Jauker B, Hernández FJ, Johnson M, Jolli V, Jonsell M, Juliani SN, Jung T, Kapoor V, Kappes H, Kati V, Katovai E, Kellner K, Kessler M, Kirby K, Kittle A, Knight M, Knop E, Kohler F, Koivula M, Kolb A, Kone M, Kőrösi Á, Krauss J, Kumar A, Kumar R, Kurz D, Kutt A, Lachat T, Lantschner V, Lara F, Lasky J, Latta S, Laurance W, Lavelle P, Le Féon V, LeBuhn G, Légaré J, Lehouck V, Lencinas M, Lentini P, Letcher S, Li Q, Litchwark S, Littlewood N, Liu Y, Lo-Man-Hung N, López-Quintero C, Louhaichi M, Lövei G, Lucas-Borja ME, Luja V, Luskin M, MacSwiney G MC, Maeto K, Magura T, Mallari NA, Malone L, Malonza P, Malumbres-Olarte J, Mandujano S, Måren I, Marin-Spiotta E, Marsh C, Marshall EJP, Martínez E, Martínez Pastur G, Moreno Mateos D, Mayfield M, Mazimpaka V, McCarthy J, McCarthy K, McFrederick Q, McNamara S, Medina N, Medina R, Mena J, Mico E, Mikusinski G, Milder J, Miller J, Miranda-Esquivel D, Moir M, Morales C, Muchane M, Muchane M, Mudri-Stojnic S, Munira AN, Muoñz-Alonso A, Munyekenye BF, Naidoo R, Naithani A, Nakagawa M, Nakamura A, Nakashima Y, Naoe S, Nates-Parra G, Navarrete Gutierrez D, Navarro-Iriarte L, Ndang'ang'a P, Neuschulz E, Ngai J, Nicolas V, Nilsson S, Noreika N, Norfolk O, Noriega JA, Norton D, Nöske N, Nowakowski AJ, Numa C, O'Dea N, O'Farrell P, Oduro W, Oertli S, Ofori-Boateng C, Oke CO, Oostra V, Osgathorpe L, Otavo SE, Page N, Paritsis J, Parra-H A, Parry L, Pe'er G, Pearman P, Pelegrin N, Pélissier R, Peres C, Peri P, Persson A, Petanidou T, Peters M, Pethiyagoda R, Phalan B, Philips TK, Pillsbury F, Pincheira-Ulbrich J, Pineda E, Pino J, Pizarro-Araya J, Plumptre AJ, Poggio S, Politi N, Pons P, Poveda K, Power E, Presley S, Proença V, Quaranta M, Quintero C, Rader R, Ramesh BR, Ramirez-Pinilla M, Ranganathan J, Rasmussen C, Redpath-Downing N, Reid JL, Reis Y, Rey Benayas J, Rey-Velasco JC, Reynolds C, Ribeiro DB, Richards M, Richardson B, Richardson M, Ríos RM, Robinson R, Robles C, Römbke J, Romero-Duque LP, Rös M, Rosselli L, Rossiter S, Roth D, Roulston T, Rousseau L, Rubio A, Ruel J, Sadler J, Sáfián S, Saldaña-Vázquez R, Sam K, Samnegård U, Santana J, Santos X, Savage J, Schellhorn N, Schilthuizen M, Schmiedel U, Schmitt C, Schon N, Schüepp C, Schumann K, Schweiger O, Scott D, Scott K, Sedlock J, Seefeldt S, Shahabuddin G, Shannon G, Sheil D, Sheldon F, Shochat E, Siebert S, Silva FB, Simonetti J, Slade E, Smith J, Smith-Pardo A, Sodhi N, Somarriba E, Sosa R, Soto Quiroga G, St-Laurent M, Starzomski B, Stefanescu C, Steffan-Dewenter I, Stouffer P, Stout J, Strauch A, Struebig M, Su Z, Suarez-Rubio M, Sugiura S, Summerville K, Sung Y, Sutrisno H, Svenning J, Teder T, Threlfall C, Tiitsaar A, Todd J, Tonietto R, Torre I, Tóthmérész B, Tscharntke T, Turner E, Tylianakis J, Uehara-Prado M, Urbina-Cardona N, Vallan D, Vanbergen A, Vasconcelos H, Vassilev K, Verboven HF, Verdasca MJ, Verdú J, Vergara C, Vergara P, Verhulst J, Virgilio M, Vu LV, Waite E, Walker T, Wang H, Wang Y, Watling J, Weller B, Wells K, Westphal C, Wiafe E, Williams C, Willig M, Woinarski JZ, Wolf JD, Wolters V, Woodcock B, Wu J, Wunderle J, Yamaura Y, Yoshikura S, Yu D, Zaitsev A, Zeidler J, Zou F, Collen B, Ewers R, Mace G, Purves D, Scharlemann JW, Purvis A (2017) The database of the PREDICTS (Projecting Responses of Ecological Diversity In Changing Terrestrial Systems) project. Ecology and Evolution 7 (1): 145-188. https://doi.org/10.1002/ece3.2579

- Jakobsson S, Töpper JP, Evju M, Framstad E, Lyngstad A, Pedersen B, Sickel H, Sverdrup-Thygeson A, Vandvik V, Velle LG, Aarrestad PA, Nybø S (2020) Setting reference levels and limits for good ecological condition in terrestrial ecosystems – Insights from a case study based on the IBECA approach. Ecological Indicators 116 https://doi.org/10.1016/j.ecolind.2020.106492
- Jakobsson S, Evju M, Framstad E, Imbert A, Lyngstad A, Sickel H, Sverdrup-Thygeson A, Töpper JP, Vandvik V, Velle LG, Aarrestad PA, Nybø S (2021) Introducing the index-based ecological condition assessment framework (IBECA). Ecological Indicators 124 https://doi.org/10.1016/j.ecolind.2020.107252
- Jalas J (1955) Hemerobe and hemerochore Pflanzenarten. Acta Soc Pro Fauna Flora Fenn 72: 1-15.
- Jensen M, Redmond R, Dibenedetto J, Bourgeron P, Goodman I (2000) Application of ecological classification and predictive vegetation modeling to broad-level assessments of ecosystem health. Environmental Monitoring and Assessment 64 (1): 197-212. https://doi.org/10.1023/A:1006479926454
- Johnston A, Moran N, Musgrove A, Fink D, Baillie S (2020) Estimating species distributions from spatially biased citizen science data. Ecological Modelling 422 https://doi.org/10.1016/j.ecolmodel.2019.108927
- Keith H, Czúcz B, Jackson B, Driver A, Nicholson E, Maes J (2020) A conceptual framework and practical structure for implementing ecosystem condition accounts. One Ecosystem 5 https://doi.org/10.3897/oneeco.5.e58216
- Kokkoris I, Dimopoulos P, Xystrakis F, Tsiripidis I (2018) National scale ecosystem condition assessment with emphasis on forest types in Greece. One Ecosystem 3 https://doi.org/10.3897/oneeco.3.e25434
- Kovács-Hostyánszki A, Bereczki K, Czúcz B, Fabók V, Fodor L, Kalóczkai Á, Kiss M, Koncz P, Kovács E, Rezneki R, Tanács E, Török K, Vári Á, Zölei A, Zsembery Z (2019) Nemzeti ökoszisztéma-szolgáltatás térképezés és értékelés, avagy a természetvédelem országos programja. Természetvédelmi Közlemények 25: 80-90.

- Kuussaari M, Bommarco R, Heikkinen R, Helm A, Krauss J, Lindborg R, Öckinger E, Pärtel M, Pino J, Rodà F, Stefanescu C, Teder T, Zobel M, Steffan-Dewenter I (2009) Extinction debt: a challenge for biodiversity conservation. Trends in Ecology & Evolution 24 (10): 564-571. https://doi.org/10.1016/j.tree.2009.04.011
- Langanke T, Moran A, Dulleck B, Schleicher C (2016) Copernicus Land Monitoring Service–High Resolution Layer Water and Wetness Product Specifications Document. Copernicus team at EEA.
- La Notte A, Ferrini S, Pisani D, Grilli G, Grammatikopoulou I, Vallecillo S, Badura T, Turner K, Maes J (2021) How much do Europeans value biodiversity? Publications Office of the European Union.
- Lecours V (2017) On the use of maps and models in conservation and resource management (Warning: Results may vary). Frontiers in Marine Science 4 URL: https://www.frontiersin.org/article/10.3389/fmars.2017.00288
- Lengyel S, Kosztyi B, Schmeller D, Henry P, Kotarac M, Lin Y, Henle K (2018) Evaluating and benchmarking biodiversity monitoring: Metadata-based indicators for sampling design, sampling effort and data analysis. Ecological Indicators 85: 624-633. https://doi.org/10.1016/j.ecolind.2017.11.012
- Maes D, van Dyck H (2005) Habitat quality and biodiversity indicator performances of a threatened butterfly versus a multispecies group for wet heathlands in Belgium. Biological Conservation 123 (2): 177-187. https://doi.org/10.1016/j.biocon.2004.11.005
- Maes J, Teller A, Erhard M, Liquete C, Braat L, Berry P, Egoh B, Puydarrieux P, Fiorina C, Santos F, others (2013) An analytical framework for ecosystem assessments under Action 5 of the EU biodiversity strategy to 2020. Publications Office of the European Union: Luxembourg.
- Maes J, Teller A, Erhard M, Grizzetti B, Barredo J, Paracchini ML, Condé S, Somma F, Orgiazzi A, Jones A, Zulian G, Petersen J, Marquardt D, Kovacevic V, Abdul Malak D, Marin AI, Czúcz B, Mauri A, Loffler P, Bastrup-Birk A, Biala K, Christiansen T, Werner B (2018) Mapping and assessment of ecosystems and their services an analytical framework for mapping and assessment of ecosystem condition. Publications Office of the European Union, Luxembourg.
- Maes J, Driver A, Czúcz B, Keith H, Jackson B, Nicholson E, Dasoo M (2020) A review of ecosystem condition accounts: lessons learned and options for further development. One Ecosystem 5 https://doi.org/10.3897/oneeco.5.e53485
- Miller-Rushing A, Primack R, Devictor V, Corlett R, Cumming G, Loyola R, Maas B, Pejchar L (2019) How does habitat fragmentation affect biodiversity? A controversial question at the core of conservation biology. Biological Conservation 232: 271-273. https://doi.org/10.1016/j.biocon.2018.12.029
- Molnár Z, Horváth F, others (2008) Natural vegetation based landscape indicators for Hungary I.: Critical review and the basic 'MÉTA' indicators. Tájökológiai Lapok 6 (1/2): 61-75.
- Nagy GG, Ladányi M, Arany I, Aszalós R, Czúcz B (2017) Birds and plants: Comparing biodiversity indicators in eight lowland agricultural mosaic landscapes in Hungary. Ecological Indicators 73: 566-573. https://doi.org/10.1016/j.ecolind.2016.09.053
- Neumann M, Starlinger F (2001) The significance of different indices for stand structure and diversity in forests. Forest Ecology and Management 145 (1): 91-106. https://doi.org/10.1016/S0378-1127(00)00577-6

- Oettel J, Lapin K (2021) Linking forest management and biodiversity indicators to strengthen sustainable forest management in Europe. Ecological Indicators 122 https://doi.org/10.1016/j.ecolind.2020.107275
- Padisák J, Borics G, Grigorszky I, Soróczki-Pintér É (2006) Use of phytoplankton assemblages for monitoring ecological status of lakes within the Water Framework Directive: The Assemblage Index. Hydrobiologia 553 (1): 1-14. https://doi.org/10.1007/s10750-005-1393-9
- Pásztor L, Bakacsi Z, Laborczi A, Szabó J (2013) Kategória típusú talajtérképek térbeli felbontásának javítása kiegészítő talajtani adatok és adatbányászati módszerek segítségével. AGROKÉMIA ÉS TALAJTAN 62 (2): 205-218. URL: http://akkrt.hu/9/folyoirat/?gclid=CPPDwIXt5cACFRHLtAodUl0AeA
- Pásztor L, Laborczi A, Takács K, Szatmári G, Fodor N, Illés G, Farkas-Iványi K, Bakacsi Z, Szabó J (2017) Chapter 9 - Compilation of Functional Soil Maps for the Support of Spatial Planning and Land Management in Hungary. In: Pereira P, Brevik EC, Muñoz-Rojas M, Miller B (Eds) Soil Mapping and Process Modeling for Sustainable Land Use Management. URL: https://www.sciencedirect.com/science/article/pii/B9780128052006000098 [ISBN 978-0-12-805200-6].
- Petrou Z, Manakos I, Stathaki T (2015) Remote sensing for biodiversity monitoring: a review of methods for biodiversity indicator extraction and assessment of progress towards international targets. Biodiversity and Conservation 24 (10): 2333-2363. https://doi.org/10.1007/s10531-015-0947-z
- Plutzar C, Kroisleitner C, Haberl H, Fetzel T, Bulgheroni C, Beringer T, Hostert P, Kastner T, Kuemmerle T, Lauk C, Levers C, Lindner M, Moser D, Müller D, Niedertscheider M, Paracchini ML, Schaphoff S, Verburg P, Verkerk P, Erb K (2016) Changes in the spatial patterns of human appropriation of net primary production (HANPP) in Europe 1990–2006. Regional Environmental Change 16 (5): 1225-1238. https://doi.org/10.1007/s10113-015-0820-3
- Rédei T, Szitár K, Czúcz B, Barabás S, Lellei-Kovács E, Pándi I, Somay L, Csecserits A (2014) Weak evidence of long-term extinction debt in Pannonian dry sand grasslands. Agriculture, Ecosystems & Environment 182: 137-143. https://doi.org/10.1016/j.agee.2013.07.016
- Rendon P, Erhard M, Maes J, Burkhard B (2019) Analysis of trends in mapping and assessment of ecosystem condition in Europe. Ecosystems and People 15 (1): 156-172. https://doi.org/10.1080/26395916.2019.1609581
- Renetzeder C, Schindler S, Peterseil J, Prinz M, Mücher S, Wrbka T (2010) Can we measure ecological sustainability? Landscape pattern as an indicator for naturalness and land use intensity at regional, national and European level. Ecological Indicators 10 (1): 39-48. https://doi.org/10.1016/j.ecolind.2009.03.017
- Ricotta C, Carranza ML, Avena G, Blasi C (2002) Are potential natural vegetation maps a meaningful alternative to neutral landscape models? Applied Vegetation Science 5 (2): 271-275. https://doi.org/10.1111/j.1654-109X.2002.tb00557.x
- Roche P, Campagne CS (2019) Are expert-based ecosystem services scores related to biophysical quantitative estimates? Ecological Indicators 106 https://doi.org/10.1016/j.ecolind.2019.05.052
- Roche PK, Campagne CS (2017) From ecosystem integrity to ecosystem condition: a continuity of concepts supporting different aspects of ecosystem sustainability. Current

Opinion in Environmental Sustainability 29: 63-68. https://doi.org/10.1016/j.cosust.2017.12.009

- Ruete A (2015) Displaying bias in sampling effort of data accessed from biodiversity databases using ignorance maps. Biodiversity Data Journal https://doi.org/10.3897/BDJ.3.e5361
- Sály P, Erős T (2016) Ecological assessment of running waters in Hungary: compilation of biotic indices based on fish (Vízfolyások ökológiai állapotminősítése halakkal: minősítési indexek kidolgozása). Pisces Hungarici 10: 15-45.
- Scheffer M, Van Nes EH (2007) Shallow lakes theory revisited: various alternative regimes driven by climate, nutrients, depth and lake size. Hydrobiologia 584: 455-466.
- Schmidt-Traub G (2021) National climate and biodiversity strategies are hamstrung by a lack of maps. Nature Ecology & Evolution 5 (10): 1325-1327.
- Schneiders A, Van Daele T, Van Landuyt W, Van Reeth W (2012) Biodiversity and ecosystem services: Complementary approaches for ecosystem management? Ecological Indicators 21: 123-133. https://doi.org/10.1016/j.ecolind.2011.06.021
- Scholes RJ, Biggs R (2005) A biodiversity intactness index. Nature 434 (7029): 45-49.
- Selmeczy G, Abonyi A, Krienitz L, Kasprzak P, Casper P, Telcs A, Somogyvári Z, Padisák J (2019) Old sins have long shadows: climate change weakens efficiency of trophic coupling of phyto- and zooplankton in a deep oligo-mesotrophic lowland lake (Stechlin, Germany)—a causality analysis. Hydrobiologia 831 (1): 101-117. https://doi.org/10.1007/s10750-018-3793-7
- Smith AC, Harrison PA, Pérez Soba M, Archaux F, Blicharska M, Egoh BN, Erős T, Fabrega Domenech N, György ál, Haines-Young R, Li S, Lommelen E, Meiresonne L, Miguel Ayala L, Mononen L, Simpson G, Stange E, Turkelboom F, Uiterwijk M, Veerkamp CJ, Wyllie de Echeverria V (2017) How natural capital delivers ecosystem services: A typology derived from a systematic review. Ecosystem Services 26: 111-126. https://doi.org/10.1016/j.ecoser.2017.06.006
- Smit K, Bernard AF, Lombard A, Sink K (2021) Assessing marine ecosystem condition: A review to support indicator choice and framework development. Ecological Indicators 121 https://doi.org/10.1016/j.ecolind.2020.107148
- Somodi I, Molnár Z, Ewald J (2012) Towards a more transparent use of the potential natural vegetation concept – an answer to Chiarucci et al. Journal of Vegetation Science 23 (3): 590-595. https://doi.org/10.1111/j.1654-1103.2011.01378.x
- Somodi I, Molnár Z, Czúcz B, Bede-Fazekas Á, Bölöni J, Pásztor L, Laborczi A, Zimmermann N (2017) Implementation and application of multiple potential natural vegetation models – a case study of Hungary. Journal of Vegetation Science 28 (6): 1260-1269. https://doi.org/10.1111/jvs.12564
- Somodi I, Ewald J, Bede-Fazekas Á, Molnár Z (2021) The relevance of the concept of potential natural vegetation in the Anthropocene. Plant Ecology & Diversity 14 (1-2): 13-22. https://doi.org/10.1080/17550874.2021.1984600
- Sopotlieva D, Velev N, Tsvetkova N, Vassilev V, Apostolova I (2018) Ecosystem condition assessment of semi-natural grasslands outside the Natura 2000 network in Bulgaria, using vegetation data. *Tuexenia* 38: 385-404. https://doi.org/10.14471/2018.38.012
- Standovár T, Szmorad F, Kovács B, Kelemen K, Plattner M, Roth T, Pataki Z (2016) A novel forest state assessment methodology to support conservation and forest

management planning. Community Ecology 17 (2): 167-177. https://doi.org/10.1556/168.2016.17.2.5
- Standovár T, Bán M, Kézdy P (Eds) (2017) Erdőállapot-értékelés középhegységi erdeinkben. Duna-Ipoly Nemzeti Park Igazgatóság, Budapest.
- Sukopp H (1976) Dynamik und Konstanz in der Flora der Bundesrepublik Deutschland: Dynamics and constancy in the flora of the Federal Republic of Germany. Bundesamt für Naturschutz.
- Sutcliffe LE, Batáry P, Kormann U, Báldi A, Dicks L, Herzon I, Kleijn D, Tryjanowski P, Apostolova I, Arlettaz R, Aunins A, Aviron S, Baležentienė L, Fischer C, Halada L, Hartel T, Helm A, Hristov I, Jelaska S, Kaligarič M, Kamp J, Klimek S, Koorberg P, Kostiuková J, Kovács-Hostyánszki A, Kuemmerle T, Leuschner C, Lindborg R, Loos J, Maccherini S, Marja R, Máthé O, Paulini I, Proença V, Rey-Benayas J, Sans FX, Seifert C, Stalenga J, Timaeus J, Török P, van Swaay C, Viik E, Tscharntke T (2015) Harnessing the biodiversity value of Central and Eastern European farmland. Diversity and Distributions 21 (6): 722-730. https://doi.org/10.1111/ddi.12288
- Szilágyi F, Ács É, Borics G, Halasi-Kovács B, Juhász P, Kiss B, Kovács T, Müller Z, Lakatos G, Padisák J, Pomogyi P, Stenger-Kovács C, Szabó KÉ, Szalma E, Tóthmérész B (2008) Application of water framework directive in Hungary: development of biological classification systems. Water Science and Technology 58 (11): 2117-2125. https://doi.org/10.2166/wst.2008.565
- Szilassi P, Bata T, Szabó S, Czúcz B, Molnár Z, Mezősi G (2017) The link between landscape pattern and vegetation naturalness on a regional scale. Ecological Indicators 81: 252-259. https://doi.org/10.1016/j.ecolind.2017.06.003
- Szitár K, Csoszi M, Vaszócsik V, Schneller K, Csecserits A, Kollányi L, Petrik O, Lehoczki R, Halassy M, Tanács E, Kertész M, Csákvári E, Somodi I, Lengyel A, Gallé R, Weiperth A, Konkoly-Gyuró É, Máté K, Török K (2021) Az országos zöldinfrastruktúra-hálózat kijelölésének módszertana többszempontú állapotértékelés alapján. TERMÉSZETVÉDELMI KÖZLEMÉNYEK 27: 145-157. URL: http://doi.org/10.20332/tvk-jnatconserv.2021.27.145
- Takács G, Molnár Z (Eds) (2009) National biodiversity monitoring system XI: Habitat mapping (2nd modified ed.). Ministry of Environment and Water, Budapest.
- Tanács E, Standovár T (2021) Az általános ökoszisztéma-állapot indikátorok térképezésének eredményei. A közösségi jelentőségű természeti értékek hosszú távú megőrzését és fejlesztését, valamint az EU biológiai sokféleség stratégia 2020 célkitűzéseinek hazai szintű megvalósítását megalapozó stratégiai vizsgálatok projekt, Ökoszisztéma-szolgáltatások projektelem. Agrárminisztérium, Budapest.
- Tanács E, Bede-Fazekas Á, Standovár T, Pásztor L, Szitár K, Csecserits A, Kiss M, Vári Á (2021a) Az általános ökoszisztéma-állapot indikátorok térképezésének módszertana. A közösségi jelentőségű természeti értékek hosszú távú megőrzését és fejlesztését, valamint az EU biológiai sokféleség stratégia 2020 célkitűzéseinek hazai szintű megvalósítását megalapozó stratégiai vizsgálatok projekt, Ökoszisztéma-szolgáltatások projektelem. Agrárminisztérium, Budapest. URL: 10.34811/osz.allapot.modszer.tanulmany
- Tanács E, Belényesi M, Lehoczki R, Pataki R, Petrik O, Standovár T, Pásztor L, Laborczi A, Szatmári G, Molnár Z, Bede-Fazekas Á, Somodi I, Kristóf D, Kovács-Hostyánszki A, Török K, Kisné Fodor L, Zsembery Z, Friedl Z, Maucha G (2021b) Compiling a high-resolution country-level ecosystem map to support environmental

policy: methodological challenges and solutions from Hungary. Geocarto International1-24. https://doi.org/10.1080/10106049.2021.2005158

- Tobisch T, Kottek P (2013) Forestry-related databases of the Hungarian forestry directorate. In: Tobisch T, Kottek P (Eds) WWW Document National Food Chain Safety Office (NFCSO). URL: https://portal.nebih.gov.hu/documents/10182/862096/Forestry_related_databases.pdf/3ff92716-2301-4894-a724-72fafca9d4fc
- Török K, Fodor L (Eds) (2006) A Nemzeti Biodiverzitás-monitorozó Rendszer eredményei I. Élóhelyek, mohák és gombák. Környezetvédelmi és Vízügyi Minisztérium, Természetvédelmi Hivatal, Budapest.
- Tscharntke T, Klein A, Kruess A, Steffan-Dewenter I, Thies C (2005) Landscape perspectives on agricultural intensification and biodiversity – ecosystem service management. Ecology Letters 8 (8): 857-874. https://doi.org/10.1111/j.1461-0248.2005.00782.x
- Tüxen R (1956) Die Heutige Potentielle Natürliche Vegetation als Gegenstand der Vegetationskartierung. Angewandte Pflanzensoziologie4-42.
- United Nations (2021) System of Environmental-Economic Accounting — Ecosystem Accounting (SEEA EA). White cover publication, pre-edited text subject to official editing. URL: https://seea.un.org/ecosystem-accounting
- Uuemaa E, Mander Ü, Marja R (2013) Trends in the use of landscape spatial metrics as landscape indicators: A review. Ecological Indicators 28: 100-106. https://doi.org/10.1016/j.ecolind.2012.07.018
- van der Plas F (2019) Biodiversity and ecosystem functioning in naturally assembled communities. Biological Reviews https://doi.org/10.1111/brv.12499
- van Oudenhoven AE, Schröter M, Drakou E, Geijzendorffer I, Jacobs S, van Bodegom P, Chazee L, Czúcz B, Grunewald K, Lillebø A, Mononen L, Nogueira AA, Pacheco-Romero M, Perennou C, Remme R, Rova S, Syrbe R, Tratalos J, Vallejos M, Albert C (2018) Key criteria for developing ecosystem service indicators to inform decision making. Ecological Indicators 95: 417-426. https://doi.org/10.1016/j.ecolind.2018.06.020
- Várallyay G, Szücs L, Murányi A, Rajkai K, Zilahy P (1985) Soil factors determining the agro-ecological potential of Hungary. Agrokémia És Talajtan 34 (SUPPL.): 90-94.
- Vári Á, Kozma Z, Pataki B, Jolánkai Z, Kardos M, Decsi B, Pinke Z, Jolánkai G, Pásztor L, Condé S, Sonderegger G, Czúcz B (2022) Disentangling the ecosystem service ‘flood regulation’ - mechanisms and relevant ecosystem condition characteristics. AMBIO.
- Wilson M, Chen X, Corlett R, Didham R, Ding P, Holt R, Holyoak M, Hu G, Hughes A, Jiang L, Laurance W, Liu J, Pimm S, Robinson S, Russo S, Si X, Wilcove D, Wu J, Yu M (2016) Habitat fragmentation and biodiversity conservation: key findings and future challenges. Landscape Ecology 31 (2): 219-227. https://doi.org/10.1007/s10980-015-0312-3
- Winter S (2012) Forest naturalness assessment as a component of biodiversity monitoring and conservation management. Forestry: An International Journal of Forest Research 85 (2): 293-304. https://doi.org/10.1093/forestry/cps004
- Wretenberg J, Pärt T, Berg Å (2010) Changes in local species richness of farmland birds in relation to land-use changes and landscape structure. Biological Conservation 143 (2): 375-381. https://doi.org/10.1016/j.biocon.2009.11.001

- Zulian V, Miller DW, Ferraz G (2021) Integrating citizen-science and planned-survey data improves species distribution estimates. Diversity and Distributions 27 (12): 2498-2509. https://doi.org/10.1111/ddi.13416

Supplementary materials

Suppl. material 1: Appendix 1. doi

Authors: Eszter Tanács, Ákos Bede-Fazekas, Anikó Csecserits, Lívia Kisné Fodor, László Pásztor, Imelda Somodi, Tibor Standovár, András Zlinszky, Zita Zsembery, Ágnes Vári
Data type: list and short description
Brief description: List and short description of the datasets used in the MAES-HU EC mapping.
Download file (327.26 kb)

Suppl. material 2: Appendix 2 doi

Authors: Eszter Tanács, Ákos Bede-Fazekas, Márta Belényesi
Data type: crosswalk table
Brief description: Crosswalk between the categories of the Ecosystem type map of Hungary and the national vegetation classification system (Á-NÉR).
Download file (98.67 kb)

Suppl. material 3: Appendix 3 doi

Authors: András Schmidt, Gergő Gábor Nagy, Mihály Nyúl, Eszter Tanács
Data type: species list
Brief description: The list of bird species used for the MAES-HU biodiversity approach, the nesting probability codes and weights.
Download file (70.84 kb)

Suppl. material 4: Appendix 4 doi

Authors: Eszter Tanács, Ágnes Vári
Data type: list of indicators
Brief description: The final set of indicators developed for the mapping and assessment of ecosystem condition in the Hungarian MAES for the major ecosysytem types (ET), along with their SEEA-ECT condition type.
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Suppl. material 5: Appendix 5 doi

Authors: Tibor Standovár, Eszter Tanács
Data type: indicator scores
Brief description: Summary of the condition assessment of forests in MAES-HU (indicators, scores and threshold values).
Download file (104.82 kb)

Suppl. material 6: Appendix 6 doi

Authors: András Zlinszky, Ágnes Vári, Eszter Tanács
Data type: indicator scores
Brief description: Summary of the condition assessment of wetlands in MAES-HU (indicators, scores and threshold values).
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Suppl. material 7: Appendix 7 doi

Authors: Eszter Tanács
Data type: indicator scores
Brief description: Summary of the condition assessment of arable lands in MAES-HU (indicators, scores and threshold values).
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Suppl. material 8: Appendix 8 doi

Authors: Eszter Tanács, Ákos Bede-Fazekas, Imelda Somodi
Data type: description
Brief description: Further results from the MAES-HU EC assessments - Anthropogenic transformation of the vegetation.
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Suppl. material 9: Appendix 9. doi

Authors: Eszter Tanács, Tibor Standovár
Data type: description
Brief description: Further results of the MAES-HU forest condition assessment.
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Endnotes

*1 *approaches based on different interpretations of naturalness/hemeroby*