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Research Article

Hierarchical classification system of Germany's ecosystems as basis for an ecosystem accounting – methods and first results

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Abstract

Information on changes in the area of different ecosystems is needed in order to establish an accounting system for ecosystem conditions and services. Currently, there are no comprehensive field mappings for the German federal states that obey a uniform mapping system. To create a nationwide "ecosystem accounting", it is necessary to develop a uniform system of ecosystem classifications that can consistently deal with diverse nationwide data sources on the extent and condition of ecosystems, some of which use their own forms of classification. Against this background, we present a concrete proposal on how to combine and blend GIS land-use and ecosystem data that is compatible with EU-wide approaches with other regularly collected data sources, for example, from sample-based surveys, so as to generate a complete, updatable picture of the state of Germany's ecosystems. The area shares of ecosystem types (ETs) can be shown in maps. Allocation tables with different classes or levels (layers) enable an ecosystem extent accounting, which are used to help draw up balances (area balance, status balance, service balance) and can be further detailed, depending on the task at hand. First results and trends of areal changes of main and sub-ecosystem types in Germany, based on the

proposed classification system, are presented and discussed. However, the brevity of the considered timeframe (the three periods 2012-2015-2018) does not yet allow us to pinpoint trends or migratory movements, as these may be masked by methodological changes in the classification of land use and land cover. Nonetheless, the presented system for accounting changes in ecosystem areas should be continued and developed in the future in order to create a useful tool for biodiversity monitoring in Germany.

Keywords

accounting, area changes, biodiversity, classification, CORINE land cover, ecosystem service, federal level, habitat type, monitoring

Introduction

In 2011, the member states of the EU made a commitment to map and assess the state of ecosystems and their services and to integrate the results into European and national reporting systems by 2020 (The Council of the European Union 2011). Target 2 of the EU Biodiversity Strategy also provides for the establishment of “green infrastructure” and the restoration of at least 15% of degraded ecosystems. Corresponding mappings and assessments follow the basic recommendations of the European MAES working group (Mapping and Assessment of Ecosystems and their Services). Aspects of biodiversity as the basis for functioning ecosystems and a high supply of ecosystem services (ES) in connection with human well-being are emphasised (Maes et al. 2013).

The MAES framework provides the following modules for the assessment of ecosystems and their services (Maes et al. 2014), which were then further consolidated by Burkhard et al. (Burkhard et al. 2018):

1. mapping of ecosystems;
2. assessment of ecosystem conditions;
3. assessment of ES;
4. integrated ecosystem assessment with link to national environmental accounting/ natural capital accounting systems.

In accordance with the requirements of the EU Biodiversity Strategy 2020, a system of national initial assessment and evaluation of ES for Germany was first developed and coordinated. The assessment of ecosystem condition comprised mainly pressures, the natural condition of ecosystems and the state of biological diversity. Ecosystem services were measured and evaluated primarily based on land use, official data for agricultural and timber production, water use and population data (Albert et al. 2015, Grunewald et al. 2016, Grunewald et al. 2017, Grunewald et al. 2019).

In addition to the EU Biodiversity Strategy, other international conventions and institutions also address the link between the state of ecosystems, biodiversity and ES, such as:

- CBD (Convention on Biological Diversity; CBD 2000), specified in the so-called "Aichi-targets" (CBD 2010);
- TEEB (The Economics of Ecosystems and Biodiversity; TEEB 2010);
- IPBES (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services; IPBES 2013);
- Ecosystem management approaches of IUCN (International Union for Conservation of Nature; IUCN 2020);
- SEEA EEA (System of Environmental-Economic Accounting, Experimental Ecosystem Accounting; UN - United Nation 2017, UN 2020).

The consideration of ES (and the use of appropriate terminology) is also embedded in other EU policies, such as the Green Infrastructure Strategy, the Forestry Strategy, the Regulation on Invasive Alien Species, the Marine Framework Directive and the Common Agricultural Policy (CAP)/Rural Development (Helming et al. 2013).

In order to create an exhaustive accounting of ecosystem conditions and services, we require a shared informational basis of changes in the spatial extent of diverse ecosystems (i.e. ecosystem extent account). The ecosystems must be classified in such a way as to meet the requirements of the subsequent accounting of their condition and services, which can vary greatly depending on regional and local ecological, economic and social conditions. The aim is to demonstrate the importance of ecosystems for society and to record their changes as a basis for political action. As in other statistically-orientated work (and in contrast to the field of planning), this is done here in the field of SEEA without the development of direct proposals for action.

Currently, Germany's federal states do not follow a uniform mapping system to provide an exhaustive recording of ecosystems. To establish nationwide "ecosystem accounting", it is therefore essential to develop a common structure of ecosystem classifications, with the help of which diverse national datasets on the extent, condition and services of ecosystems (some of which use their own forms of classification) can be consistently integrated to create a standard ecosystem accounting system. With this aim in mind, we present here a concrete proposal on how uniform and spatially accurate national datasets of GIS data on land uses and ecosystems, which are compatible with EU-wide approaches, can be integrated with other regularly updated data sources, including sample-based surveys, so as to generate as complete and up-to-date picture of Germany's ecosystems as possible, that can be filled with the available data on condition and linked with data and required models on ecosystem services.

The challenge to be overcome is to find the degree of thematic detail, especially whether and which functional characteristics should be included in order to support the further accounting steps, e.g. analysis of spatial migration between ecosystems, integrating relevant condition parameters and applying very different models and valuation approaches to assess ecosystem services, including the contribution of the various ecosystems to biodiversity protection on the national scale.

It is important to note at this point that the ecosystem extent account, presented here, was developed in a research project that aimed to develop pilot accounts for three ecosystem services. Criteria for the selection were: a broad spectrum of services, a good data basis and the development of internationally innovative methods, based on German experience. The decision was in favour of the contribution of ecosystems to agricultural production, ecosystem services of urban green spaces and the role of different ecosystem types for conserving biological diversity in Germany.

It is also worth noting that the condition account, which is normally regarded as a necessary link between extent and service account, was skipped against the following background. In Germany (East and West), in the scientific discussion in landscape planning and physical geography in the 1970s, the position gained acceptance that there is neither a single ecosystem classification nor a single set of condition parameters which is suitable for all land use decisions and can therefore guide land use planning in general. Instead, the concept of "Partial Ecosystem Potentials" was developed, where for each type of use, such as agriculture and forestry, groundwater recharge and extraction, recreation or nature conservation, different types of quality and condition parameters are used (Mannsfeld and Grunewald 2015). Thus, in the study carried out, where available, the specific parameters for the condition and suitability of ecosystems for each service were specifically integrated directly into the calculations for the service account. The data used, for example, for the calculation of the ecosystems' contribution to agricultural production, were based on a geo-dataset of the Müncheberger Soil Quality Rating, which in turn is an aggregation of various data on soil, climate, groundwater level, slope inclination etc. (Mueller et al. 2007). The extent account itself can use quite highly aggregated ecosystem classes such as the CLC classes used here, if the detailed service-specific information on the ecosystems is specifically supplemented during the implementation of each service account. With regard to the project objectives, it was decided to wait for the results of further European and international discussions before presenting a separate approach for a general condition account.

In the following, we first discuss the basis for recording data on ecosystems at EU and national level (Sections 2 and 3). Based on this, we present a concrete proposal for processing high-resolution data to classify ecosystems in Germany that is compatible with EU-wide approaches. With the ecosystem contribution to conserve biodiversity as an example, we show how this system can be complemented with detailed special information to assess certain services.

In Section 4, we present first results and trends of areal changes of main and sub-ecosystem types in Germany, based on the proposed classification system. Other area monitoring systems, in particular the area statistics of the Federal Statistical Office (German: *Statistisches Bundesamt* or simply *Destatis*) and the Monitor of Settlement and Open Space Development (IOER Monitor), will also be included to map the ecosystem extent and changes to this over the last years and decades. The paper closes with some conclusions and comments on existing shortcomings, data restrictions and challenges for the future. The use of ETs to assess the condition and services of ecosystems is only

briefly mentioned here, because this can vary greatly from case to case and is not the focus of the paper.

Fundamentals of the systematisation and recording of ecosystems

Ecosystem approach and scaling

Since the middle of the 20th century, 'ecosystem' has been a guiding scientific term for the pragmatic observation of ecological units (Jax 2016). An ecosystem encompasses the structure of relationships between living organisms and their inorganic environment. In a less abstract sense, an ecosystem is characterised by its biocoenosis and associated habitat (assemblage or community of plants and animals with the same or similar ecological demands in a distinct area) (Ellenberg et al. 1992). An ecological system is most frequently defined as "a community of organisms and their physical environment interacting as an ecological unit" (Lincoln et al. 1982). However, this structural view does not describe the substance of the term 'ecosystem', which primarily evolved to describe the functional relations inside ecosystems and within their network, thereby creating the biosphere of the earth (Vačkář et al. 2018). The term 'biotope' is almost synonymous with the term habitat, but while the subject of a habitat is a species or a population, the subject of a biotope is a biological community (Bastian et al. 2020).

Ecosystem research is a conceptual approach particularly identified by natural scientists, since it encompasses the creation of analytical models to examine the structure and dynamics of spatial regions (Grunewald and Bastian 2015). The ecosystem concept comprises several hierarchical levels, not only theoretically, but also from an operational point of view (Blasi et al. 2017). Therefore, in principle, a wide spatial-range of ecosystems can be identified and mapped on levels from biomes and ecoregions to habitats (EEA 2013, EEA 2014a, Klijn and de Haes 1994, Burkhard et al. 2018, Keith et al. 2020).

Ecosystems must be understood holistically. This means that their emergent system properties (interactions between their components) behave in a way that cannot be explained by simply analysing each individual component. Hence, we must attempt a holistic understanding, also in terms of our indicators and mappings. Furthermore, landscapes and ecosystems can be viewed, on the one hand, as the result of influential factors of the natural environment or, on the other hand, as a construct of human perception, i.e. as artificial units, whereby the criteria for the selection of the ecosystem components and their delimitation are determined by the particular interests of the observer (landscape as perceived by people). The Biodiversity Convention (CBD 2018) specifies the ecosystem approach as follows: "[…] the term 'ecosystem' […] can refer to any functioning unit at any scale. Indeed, the scale of analysis and action should be determined by the problem being addressed."

Ecosystem mapping (MAES process of the EU Biodiversity Strategy) in selected EU countries

For land cover mapping at the pan-European level, there exist established data sources such as Corine Land Cover (CLC), Land Use and Land Cover Survey (LUCAS) and the Farm Structure Survey (FSS). New high-resolution Copernicus land-monitoring products can increase the precision and relevance of these data (EEA 2017).

While land cover describes the physical material on the surface of the earth and its characteristics (e.g. grass, asphalt, trees bare ground, water etc.), land use is, by contrast, a description of how people use the land. Examples for land use are urban and agricultural land use, but also institutional land, sports grounds, residential land etc. (Fisher et al. 2005). In practice, ecosystem classifications are enhanced land cover maps and include additional information about abiotic and vegetation characteristics (EEA 2016; Burkhard et al. 2018). The Technical Recommendations in support of the SEEA-EEA indicate that delineation of ecosystem assets (contiguous areas covered by a specific ecosystem) should be based on ecological and ecosystem use factors (UN - United Nation 2017). Ecosystem assets are the primary spatial units for ecosystem accounting (UN 2020).

When classifying ecosystems at national level for ecosystem accounting, EU member states are recommended to use the pan-European CORINE Land Cover (CLC) data on land use (Maes et al. 2014; Erhard et al. 2017). This regularly updated geo-dataset contains spatial information on land cover broken down into 44 classes. CORINE Land Cover data is provided for the years 1990, 2000, 2006, 2012 and 2018. The time series also includes a land-change layer, which highlights changes in land cover and land use. The spatial resolution is at least 25 ha. The European Nature Information System (EUNIS) offers a more detailed typology of ecosystems, taking into account the distribution of species and local spatial characteristics.

The general MAES typology of ecosystems (Maes et al. 2013) is organised into two levels. The first level is defined as “major ecosystem categories” and includes three main classes: 1) Terrestrial; 2) Fresh water; 3) Marine. At the second level, the major categories are subdivided into more detailed subclasses according to the character of their biophysical features. The terrestrial ecosystems are subdivided into seven subclasses: 1) Urban; 2) Cropland; 3) Grassland; 4) Woodland and forest; 5) Heathland and shrub; 6) Sparsely vegetated land; and 7) Wetlands. The fresh-water ecosystem class contains only one subclass, namely Rivers and lakes. Marine ecosystems are subdivided into four subclasses: 1) Marine inlets and transitional waters; 2) Coastal; 3) Shelf; and 4) Open ocean. Annex 2 of the MAES report (Maes et al. 2013) provides a table that links ecosystem types at level 2 with the CORINE Land Cover classification. Some ecosystem types fully correspond to an entire category of CORINE classes. For instance, urban ecosystems correspond to category *1. Artificial surfaces* and include all classes from level one to three, while sparsely vegetated lands correspond to category *3.3 Open spaces with little or no vegetation*. Other ecosystems correspond to classes from different levels of the CORINE classification. For instance, the ecosystem type grassland corresponds to

categories *2.3.1 Pastures* and *3.2.1 Natural* grasslands, which are in different groups at level two of the CORINE classification (Nedkov et al. 2016).

The European Environmental Agency provides a dataset aimed at contributing to a better biological characterisation of terrestrial and marine ecosystems across Europe (EEA-39). It represents probabilities of the presence of EUNIS (European Nature Information System) habitats in terrestrial, freshwater and marine ecosystems. The work supports the Mapping and Assessment of Ecosystems and their Services (MAES), namely Action 5 in Target 2 of the EU Biodiversity Strategy to 2020, established to achieve the Aichi targets of the Convention on Biological Diversity (CBD). Input information and methods are documented in a technical paper (Weiss and Banko 2018).

With regard to the individual approaches of various EU countries in gathering the needed data, we can expect a differentiated picture. This will be outlined below by means of a few examples.

Estonia established a very short project of 18 months, creating a constraint in terms of time and workload (Helm and Prangel 2020). For this reason, it was necessary to prioritise ecosystem types, which was done by the Ministry of Environment, based on relevance for trans-sectoral policies. The following four ecosystems were selected: forest, grassland, agricultural/cropland and wetland. Each ecosystem was assessed by a team of experts, who also determined how to subdivide the ecosystem types, as follows:

- Forest: Subdivided according to the Estonian classification of *site type groups* (primarily based on soil type) to give 10 forest classes;
- Grassland: Initially subdivided according to soil management: Seeded, Permanent, Semi-natural. Semi-natural is further subdivided according to Annex I of the Estonian Habitat Code so that the results can be further "inserted" into the nature conservation policy;
- Agricultural/cropland: Subdivided according to soil fertility;
- Wetland: Subdivided according to soil type.

In **Slovakia**, a generalised nationwide map of ecosystems has been created using agricultural, forestry and environmental data (Černecký et al. 2020). The resulting polygons are classified as ecosystem/habitat types in accordance with the EUNIS classification system. The spatial precision of the data is determined by that of the field data, which was mostly created at scales of between 1:10,000 and 1:5,000. The data are stored in the form of a geo-database containing more than 1,000,000 polygons.

The work in **Poland** was divided into the following stages (Anonymous 2015):

1. Analysis of land cover forms defined according to CORINE Land Cover (CLC level 3) classification with respect to their occurrence on Polish territory;
2. A definition of types of ecosystems occurring in Poland, based on EUNIS ecosystem classification at levels 2 and 3;
3. Defining and delimitation of the basic assessment unit (BAU): basic typological unit representing a given ecosystem type (based on EUNIS classification) taking into

account land cover features (according to CLC). The BAU is simultaneously the basic spatial operational unit for detailed analyses, including the assessment of ecosystem services based on thematic data.

The resolution of the database corresponds to scale 1:100,000. Minimal mapping units are:

- natural and semi-natural non-forested areas (meadows, pastures, wetlands, dunes and sands, sparsely vegetated areas) of size 10 ha;
- remaining areas (e.g. high-density buildings, industrial areas and transport networks, arable lands, forests) of size 25 ha;
- minimum width of the spatial unit: approx. 100 m.

In the **Czech Republic**, a more detailed map of the ecosystems, the so-called Consolidated Layer of Ecosystems of the Czech Republic (CLES), was developed in cooperation with the Czech Nature Conservation Agency. CLES presents a detailed map of the extent of natural, as well as artificial ecosystems in the national territory. It was developed by means of detailed habitat mapping in the Czech Republic, as well as by exploiting other data sources on agricultural land, urban areas and water bodies. The advantage of CLES is the detailed resolution of ecosystems down to the local level. However, in its current form, CLES cannot be used to track changes in the value of ecosystem services (Vačkář et al. 2018).

The **Italian ecosystem types** were identified and mapped by integrating the land cover database with additional spatial datasets that focus on biophysical features of the environment, such as bioclimate and vegetation (Blasi et al. 2017). Consistent with their spatial prevalence, the physiognomic CLC information was enhanced by means of the distinctive compositional, ecological and biogeographical features associated with each Potential Natural Vegetation (PNV). The Ecosystem Map of Italy consists of 84 types, comprising forests and semi-natural areas, wetlands and water bodies, out of a total of 97 legend classes, which also include artificial surfaces and agricultural areas. The typological correspondence with the second level of the EUNIS Habitat classification highlights the relationship, which is often hierarchical, between national ecosystem types and those recognised at the European level (Erhard et al. 2016).

The mapping of ecosystems in **Bulgaria** was based on CLC data and on MAES typology. Drawing on the CORINE dataset, nine main ecosystem types (according to MAES typology) can be delineated in Bulgaria. The scale of the output product was fixed at 1:100,000, giving a spatial precision of the CLC database of 100 m (N).

Proposal for a Systematic Approach to Ecosystem Types (ETs) in Germany

Basic structure of the classification system

The following criteria were determined in developing the typology (classification) of ecosystems:

- clear and consistent classification principle (systematic organisation, cf. Burkhard et al. 2018; Grunewald et al. 2020);
- can be derived from existing data sources;
- compatible with international systems (such as MAES, EUNIS, cf. EEA 2016; IUCN, cf. Keith et al. 2020);
- classes can be illustrated in a spatially explicit manner in order to identify correlations with other locally-collected statistical data;
- data available for regular time periods (monitoring): changes in the various stocks/ changes between classes (migration) quantifiable;
- current and future possibilities for incorporating nature conservation data available throughout Germany (Natura 2000 data, biotope mapping etc.);
- open for further development.

The European CLC classification system was used to define those ecosystem classes that, on the basis of the Digital Land Cover Model for Germany (*Digitales Landbedeckungsmodell für Deutschland* or LBM-DE), can be delimited with sufficient clarity. Of the 44 existing land cover classes for Europe, identified in the CLC nomenclature, 37 are relevant for Germany (Keil et al. 2015). An approach was developed to allow a redundancy-free description of all the land and marine areas under German jurisdiction by means of five main ETs, each of which encompasses three sub-types (or in the case of "forest and woodland", two sub-ETs). This system also takes account of dynamic or complex ETs such as "transitional woodland/shrub" (CLC 3.2.4) (see Table 1).

Table 1.

Proposal for a Systematic Approach to Ecosystem Types (ETs) in Germany (CLC – Corine Land Cover).

Main-ET	Sub-ET	CLC code	CLC class name
1 Semi-natural open areas	11 Natural grassland and heathland	321	Natural grassland
		322	Moors and heathland
	12 Wetlands	411	Inland marshes
		412	Peatbogs
		421	Coastal salt marshes
	13 Open spaces with no or little vegetation	331	Beaches, dunes and sand plains
		332	Bare rock

Main-ET	Sub-ET	CLC code	CLC class name
		333	Sparsely vegetated areas
		334	Burnt areas
		335	Glaciers and perpetual snow
2 Forest and grove areas	21 Forest	311	Broad-leaved forest
		312	Coniferous forest
		313	Mixed forest
	22 Grove	324	Transitional woodland/shrub
3 Agricultural land	31 Arable land	211	Non-irrigated arable land
		221	Vineyards
		222	Fruit tree and berry plantations
	32 Grassland	231	Pasture, meadows and other permanent grasslands under agricultural use
	33 Heterogeneous agricultural area	242	Complex cultivation patterns
		243	Land principally occupied by agriculture, with significant areas of natural vegetation
4 Water	41 Streams	511	Watercourses
	42 Inland water bodies	512	Water bodies
	43 Marine waters	521	Coastal lagoons
		522	Estuaries
		523	Sea and ocean
		423	Intertidal flats
5 Settlement and artificial modified areas	51 Buildings and transportation area	111	Continuous urban fabric
		112	Discontinuous urban fabric
		121	Industrial and commercial units
		122	Road and rail networks and associated land
		123	Port areas
		124	Airports
		133	Construction sites
	52 Mining and dump sites	131	Mineral extraction sites
		132	Dump sites
	53 Urban vegetated areas	141	Green urban area
		142	Sport and leisure facilities

Fig. 1 gives an overview of the proposed classification system. The core of the GIS-based monitoring of the ET areas is the system of CLC classes already defined for Germany. These can be aggregated into the levels of sub- or main ecosystem types. However, these CLC classes are not ideally suited for assessing the state of ecosystems with regard to

nature conservation goals and, specifically, the protection of biodiversity. The requisite refinement of the system is indicated in Fig. 1 (right side) and explained in Section 3.4.

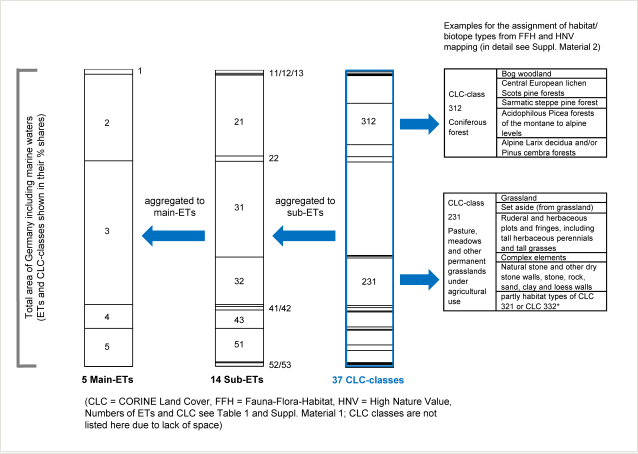

Figure 1.

Schematic diagram of the proposed classification system for ecosystem types (ETs).

The proposed classificatory system has been aligned with the EUNIS classification (EUNIS 2019a) as far as possible with the utilised (land use) data. The 5,284 individual EUNIS habitat types (EUNIS 2019b) were grouped into the 10 main categories of the European ET map (plus habitat complexes), which include both terrestrial and marine types. For the individual habitat types, the EUNIS catalogue (EUNIS 2019a) defines correlations with other classification systems (including FFH types and the above-mentioned CLC classes). These have been largely adopted to enable the correct assignments to be made and thereby ensure a precise and consistent Europe-wide ecosystem accounting (EEA 2014b; Maes et al. 2014; Erhard et al. 2016). The relationship between the ETs and the EUNIS types can be found in Suppl. material 1 (*Table A: Proposal of a classification system for ecosystem types (ETs) in Germany, assignment to the European ecosystem types according to EUNIS and to the CLC types of the database LBM-DE*).

The aggregation of types required by the ET classification system takes account not only of the characteristics of land use and land cover, but also the rules of aggregation and the reliability of the data sources. The rules of aggregation state that small elements must be assigned to that ET of which they can be considered as spatial components (e.g. pastoral forests, hedges or bushes to the open land they are located in, springs to wetlands etc.). In order to keep the number of ETs manageable and to be able to work efficiently with the catalogue, land types that very rarely occur in Germany, which can change with great rapidity or are often recorded incorrectly by remote-sensing methods, were assigned to classes from which they sometimes differ to a large degree. This applies, for example, to glaciers (extremely rare), burnt areas (highly dynamic) or certain natural grassland types (rare and difficult to detect). For the sake of reliability, CLC classes that can hardly be distinguished from one another by analysing the base data, are grouped into relatively

undifferentiated ETs, for example, coniferous, mixed and deciduous forests, as well as wooded dunes, are assigned to the class *forest or wetlands*, which also encompasses lowland moors (undetectable from space). Semantic ambiguity – such as the historically or technically controversial distinction between natural, fortified, straightened, diverted or canalised rivers and their (sometimes more natural but nevertheless artificially created) interconnected millraces and "real" canals – was also avoided in view of the small total extent of running waters. Ultimately, the relatively broad typology was chosen to avoid any unnecessary imprecision through the introduction of uncertainties inherent in finer classifications.

Base data for a detailed spatial presentation and analysis

The specification of EU-wide approaches and data can be realised for Germany by means of the "Digital Basic Landscape Model" (*Digitales Basis-Landschaftsmodell* or Basis-DLM), derived from the "Official Topographic-Cartographic Information System" (ATKIS) and the "Digital Land Cover Model for Germany" (LBM-DE) (Schorcht et al. 2016), which represent the official National Spatial Data Infrastructure. The Basis-DLM contains "areas of actual use" (*Flächen zur tatsächlichen Nutzung* or TN) that are regularly monitored by the surveying authorities of the federal states of Germany in accordance with standard rules and with no spatial overlaps (Krüger et al. 2013; BKG 2016a). The LBM-DE for Germany is provided by the Federal Agency for Cartography and Geodesy (BKG), using classified satellite image data and the ATKIS-Basis-DLM, supplemented by other technical data. It is compatible with CLC data (and obeys the same nomenclature), but has a much more detailed scale of 1:50,000 (minimum mapping unit 1 ha compared to 25 ha for CLC mapping) (BKG 2016b, BKG 2018a, BKG 2019b).

Since 2009, the LBM-DE has been used to derive the CLC dataset for Germany (Hovenbitzer et al. 2014). However, it contains no detailed spatial information on issues that are required to assess ecosystem services, such as the natural contribution to agricultural production (natural soil fertility), flood protection, decomposition of pollutants in watercourses or the service of an ecosystem for nature conservation. Such information has to be integrated into the system from other sources (for agricultural production see the introduction, for nature conservation see 3.4).

Alongside the derivation of CLC, the LBM-DE is favoured as a basis for ET mapping due to the fact that data are regularly updated by the BKG, namely every three years. The LBM-DE records land cover throughout Germany and (in part) marine areas semi-automatically by analysing satellite images (RapidEye), basic DLM and auxiliary data (topographic maps, orthophotos) (BKG 2018a, BKG 2019b). The one-year monitoring period allows the specification of a fixed reference year. The minimum width of elements represented in the digital maps is 15 m and the minimum spatial unit 1 ha. Due to updates, smaller cut areas may exceptionally occur, but these must be at least 0.2 ha in size (BKG 2018a, BKG 2019b). Thus the minimum mapping unit is clearly smaller than the 25 ha indicated for CLC (Keil et al. 2015) or the 10 ha for CLC10 (BKG 2018b) (Fig. 2). The monitoring periods of the base data LBM-DE are the years (2009)/2012/2015/2018. It is recommended not to

use the 2009 time period as methodological refinements (e.g. a distinction between land cover and land use) were introduced into LBM-DE 2012 (BKG 2016b, Hovenbitzer et al. 2014) undermining comparability across all classes.

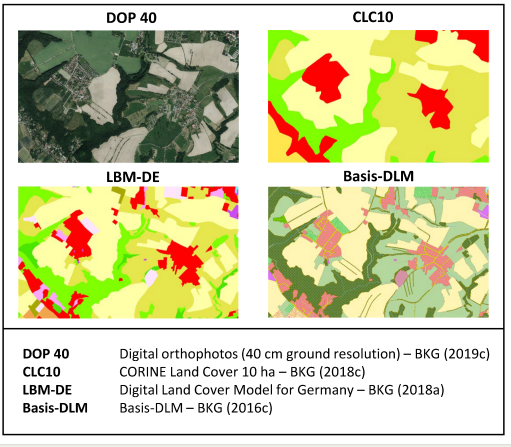

Figure 2.

Example for the spatial resolution of digital landscape models in Germany and aerial photograph reference.

As the reporting in LBM-DE is more finely differentiated than the original CLC system, mixed types such as 242 and 243 (complex parcel structure, as well as agricultural areas with a significant proportion of natural biotopes) do not appear in the LBM mapping. To retain consistency with CLC, some biotope types, for which separate classes might otherwise have been created, had to be assigned to the existing CLC classes. The most prominent example of these are the various small structures and biotopes found in the agricultural landscape (see note in Table B in the supplementary material 2). It is essential that no information is going to be lost when making assignments to superordinate types, but that the ultimate value of each superordinate type is entirely determined by its subtypes.

Since the LBM classification is based, amongst other things, on remote sensing data, there is some uncertainty in the assigned ETs. In order to minimise errors in distinguishing arable land from grassland, satellite data of different vegetation periods over the timeframe of one year were used to generate the LBM-DE (BKG 2019a, Hovenbitzer et al. 2014). High-resolution IMAGE2012 satellite data for the time period 2015 were used to distinguish permanent grassland from temporary grassland (fallow land) (Hovenbitzer et al. 2014). This change in the methodology between the time periods 2012 and 2015 could explain why – according to our observations – areas were converted from "near-natural grassland" to intensively-used grassland ("meadows and pastures") and vice versa from 2012 to 2015. The types of grassland are distinguished by, amongst other things, the form and degree of homogeneity of the area. For example, if the area has a rather irregular shape, is covered with shrubs and perennials and is used as an extensive meadow, it is assigned to CLC

class 321 (BKG 2018a, BKG 2019b). Nevertheless, satellite images cannot reliably differentiate between the two types of grassland.

Linear infrastructure and small structural elements (BKG 2018a) are missing in the LBM-DE, which are therefore not considered in the calculation of areal ratios. However, these missing elements can be taken from the ATKIS-Basis-DLM, as here linear objects narrower than 12 m are featured along with their object axes. These are modelled as buffered areas and introduced into the LBM. SEEA suggested to use the length instead of an estimated area for relatively long and narrow linear elements (e.g. rivers). They dissuade from creating areas by means of width specifications in the dataset, because overlaps with neighbouring areas might be produced (UN 2020). In order to guarantee a clear designation of areas, the resulting overlaps resulting from the linear infrastructure and small structural elements were simply removed. Prioritisation rules were defined for areas of intersection between different ETs, in accordance with the procedures specified by the “Monitor of Settlement and Open Space Development” (IOER 2020a).

The applied widths of spatial elements and the assignment to the CLC classes are shown in Table 2. The widths of railtrack, roads and airport runways, as well as unsurfaced roads and watercourses, are in most cases already supplied as an attribute in the ATKIS basic DLM. A type-specific average width was assumed for linear objects with no previously-assigned values. We assigned a value of 6 m for the width of rock elements (determined by on-site observations in the Erzgebirge). An average width was also assigned to vegetation, determined from HNV farmland data for hedges and tree rows (in Baden-Württemberg, Saxony and Schleswig-Holstein). Linear objects wider than 12 m were adopted unchanged from ATKIS, as these are already modelled as areas. The linear features from ATKIS were omitted in the map of the ETs (1 x 1 km^2 cell size), as they would have increased the blur of the visual representation (cf. Sect. 4.1).

Table 2.

The ecologically valuable small structures and infrastructure from the German official topographic-cartographic information system (ATKIS) added to the digital land cover model of Germany (LBM-DE), their width and CLC-classes.

Small Structures and infrastructures from ATKIS	**Type of geodata in ATKIS**	**Generated widths for linetype geodata**	**CLC-class**
Railway traffic (railway stations, stopping points and operational aboveground railway tracks)	lines/ areas	single / double track	122
standard gauge		7.5 / 10.5 m	
tramway		3 / 6 m	
(Historical) narrow-gauge train		2 / 4 m	
Road traffic (inclusively hard shoulders and adjacent bicycle tracks and sidewalks; in built-up areas, sidewalks were considered by 2.5 m)	lines	according to number of traffic lanes	122
motor-way		5.5 – 17.5 m	

Small Structures and infrastructures from ATKIS	Type of geodata in ATKIS	Generated widths for linetype geodata	CLC-class
miscellaneous roads		4.5 – 12.5 m	
sealed roads (forestal and agricultural purposes)		4.5 – 16.5 m	
Air traffic (footprints, runways)	lines/ areas	5 - 90 m	124
Lanes and paths	lines		122
unsealed roads (forestal and agricultural purposes)		4.5 – 16.5 m	
tracks for bicyling, walking and horse riding, fixed rope routes, steep tracks, footpaths, pedestrian bridges etc. (mostly purpose-built, paved and unpaved)		3 – 25.5 m	
Running waters (perennial and temporäry surface waters)			511
width > 12 m	areas		
width < 12 m	lines	1.5 – 9 m	
Rocks			332
spires, boulders	lines	6 m	
Vegetation	lines		322
tree rows, conifers tree rows, conifers and broadleafs tree rows, broadleafs		6 m	
hedges		6 m	

Raster cells as reference units to calculate ratios and parameters on ecosystem conditions

The cartographic representation of ETs is realised at federal level by means of a 1 km^2 grid, whereby the principle of dominant value is applied. Special evaluations, for example on the hemeroby/natural condition of a landscape section are also often calculated in a 1 km^2 grid. Here the original vector geometries of the LBM-DE are used so as not to distort the original extent of the areas and to ensure the greatest possible accuracy. This is also the case when calculating ratios or changes for individual administrative levels, such as federal states or for the whole German territory.

When determining areal ratios based on the total national territory, it is essential to determine the reference area correctly. Therefore, the entire terrestrial area inclusive inland surface waters of the Federal Republic of Germany (approx. 35,767,570 ha, based on municipal geometries) should be considered to ensure comparability with other statistics. From the point of view of the Ecosystem Extent Account, however, marine and other areas should also be included, as these contain a range of significant biotopes that must be reflected in the analysis. The total area actually represented and investigated therefore currently covers 106.6% of the terrestrial area.

The administrative geometry VG25 of the ATKIS-Basis-DLM includes administrative units that can be simply assigned to the national terrestrial area (municipality geometries) and

other areas (marine areas, Lake Constance, German-Luxembourg border area) (BKG 2017). For all time periods, the most recently available VG25 data from 2016 are taken to determine the base reference areas. This ensures comparability of the areal ratios from the different time periods; otherwise, changes in the administrative units between the different time periods could undermine the reliability of results. This is also in line with the methodology of the Monitor of Human Settlement and Open Space Development (IOER 2020b).

Incorporation of nature conservation data to assess biodiversity and to account for the contribution of ecosystems to conserve biodiversity

Biodiversity is an essential criterion for the condition of ecosystems (CBD 2010, Maes et al. 2018, Geschke et al. 2019). Moreover, the contribution of ecosystems to conserve biodiversity is also an ecosystem service (see CICES 5.1, cultural services 3.2.2.1 and 3.2.2.2)

Therefore, the accounting framework should be structured in a way that all regularly collected data, relevant for the assessment of biodiversity, can be evaluated within the accounting framework in a consistent way. Such data sources are:

- the nationwide reporting on the extent and conservation status of FFH types according to Annex I of the Habitats Directive (Deutschlands Natur 2018),
- the survey of HNV farmland (Hünig and Benzler 2017), which is regularly carried out on more than a thousand sample areas of 1 km² size within the nationwide monitoring of breeding birds,
- the Federal Forest Inventory and
- the classification of the ecological watercourse/body status according to the WFD.

In the near future, it may also be possible to integrate data from the planned sample-based ecosystem-monitoring.

It is obvious that the above-mentioned sample-based data sources cannot deliver spatially explicit data. They can, however, be used to determine average values for the composition of the DLM-classes on the national level (i.e. what is the share of the different FFH-forest ecosystems in the overall forest coverage of Germany). Furthermore, they provide relevant information for biodiversity conservation on the condition of the DLM-classes as a whole (i.e. ecological status of water bodies) or on parts of them (i.e. conservation status of FFH-habitats).

As a basis for the quantitative physical assessment of the contribution of ecosystems to biodiversity, so-called "biotope points" are used. Biotope points consider (average) features of ecosystems like natural condition, age, occurrence of endangered species or degree of the endangerment of the ecosystem itself. They are widely used in Germany to determine the no-net loss under the nature conservation law in cases where impacts on biological diversity have to be compensated for by the upgrading or development of new habitats.

Biotope points can thus be considered as physical exchange values for the function of ecosystems to conserve biodiversity.

We used the current federal list of biotope points (Mengel et al. 2018) that builds on the list of endangered biotope types in Germany (Finck et al. 2017). Despite its name, the list actually comprises all kind of biotope types in Germany, i.e. not only those at risk. It defines average biotope points for about 500 different biotope classes. The scores range from "0" (pavement) to "24" (healthy mires, old (semi-) natural forests). All scores are considered as mean values that can be further increased or reduced by a maximum of three points due to the specific condition. A new list will be published soon which will be even more differentiated, particularly with regard to ocean and shores.

At present, there is no database on the coverage or spatial distribution of these 500 biotopes in Germany. One prerequisite to integrate this list into the accounting system is, therefore, a reference system to assign the categories of the list to the ecosystem classification developed here for accounting purposes. Similar reference systems were developed between the biotope list and the categories used in the above-mentioned surveys and between the survey categories and the CLC-classes used for accounting.

The hierarchical overview of the EUNIS habitat types (EUNIS 2019a) was evaluated as a basis upon which to correlate, i.e. the Red List habitat types with the HNV farmland biotope types and the CLC classes (cf. Section 3.2). As a result, the extended Table B was prepared that is available in Suppl. material 2 (*Table B: Supplementation of ecosystem types (ETs) by more differentiated spatially and non-spatially explicit data (system of assignment of biotope and habitat types relevant for nature conservation to ETs*) . It shows the hierarchical classification system underlying the work described here. In individual cases, double assignments occur in EUNIS (these are asterisked in Suppl material 2, Tab. B). The biotope types in the Red List of Germany's endangered biotopes were assigned to the FFH habitat types according to the highest level of technical agreement. The HNV farmland biotope types were assigned to the corresponding land use types in the CLC legend.

Even for the sample data of the Federal Forest Inventory, ways could be found to interlink between biotope points, inventory data and CLC. If the composition of the forests changes, for example, with regard the age of the tree stocks or the proportion of native tree species, the assignment of the frequencies of combinations of characteristics from the Federal Forest Inventory to biotopes present on the biotope value list enables us to estimate the change in the average biotope value of the forests. Corresponding statements can be made for grassland, for example, if the proportion of HNV grassland changes.

As the biotope values are not understood in a deterministic way, but define an average value as well as an upper and lower value depending on the characteristics, additional information on the condition of ecosystems, habitat types etc. can be used to specify in greater detail their value and the value of aggregates. Information, for example, from the reporting of the Habitats Directive or the WFD on the conservation status or ecological

status, is therefore used to determine the respective assigned biotope value in more detail via additions and deductions in clearly defined calculation steps.

The result of the classification and evaluation system, presented here, are quantitative values for the contribution of the various ecosystems classified by CLC to the conservation of biological diversity. As the values are partly based on random samples, they do not (strictly speaking) apply explicitly to each individual ecosystem, but only to the respective aggregate at the German level. Aggregated values can be calculated not only for the CLC types, but also, for example, for HNV farmland or individual classes of FFH habitats. Although such a system may appear complex and error-prone at first glance, it is precisely the complexity and the resulting need for coherent processing of many different types of information that should make it relatively robust against the incorrect attribution of individual values. In this way, the approach appears suitable for national reporting within the framework of environmental accounting.

Since the above-mentioned information on particular biodiversity relevant issues (FFH-monitoring etc.) is regularly gathered at very different intervals, it is necessary to conduct interpolations and trend updates if results of the ecosystem accounting are to be available continuously at intervals of one or several years.

One shortcoming is the still relatively low level of information on the composition and status of less valuable ecosystems, meaning that the assignment of values in this area is relatively imprecise. However, this weakness should be removed by the implementation of the planned ecosystem monitoring (BfN 2019).

Ecosystem extent account (area changes) in Germany

Overview based on LBM-DE/ATKIS data

The evaluation and presentation of the main and sub-ecosystem types (ETs) in the 1 km² grids according to the dominance principle gives an idea of the distribution of dominant ETs throughout Germany (Fig. 3 and Fig. 4; sub-ET 33 “heterogeneous agricultural land” undocumented by data). Areal ratios should not be derived from this presentation, as the ratios of the dominant ETs are increased by means of this calculation.

For the visual representation of the distribution of ETs at federal level, it makes sense to use grid cells of 1 km x 1 km. At smaller pixel sizes, an excessive number of differently categorised raster cells directly adjacent to one another can prevent the viewer from recognising large contiguous areas. Under the principle of dominant value, the raster cells of 1 km x 1 km are categorised according to the CORINE-Land-Cover (CLC) class with the largest proportionate area within the cell. This is not necessarily the largest undivided area occurring within the 1 km^2 cell. In this way, areas, such as meadows and pastures (CLC 231, sub-ET 32) in the Bergisches Land and in the foothills of the Alps, which are present in large numbers in the LBM-DE (Digital Land Cover Model for Germany), but which in each case often have only a relatively small individual size, can nonetheless determine the categorisation of this sub-ET, since the proportion of such areas is high overall. Similarly,

high ratios of grassland for the above-mentioned regions are also found in the Thünen Atlas (Thünen Institute 2014).

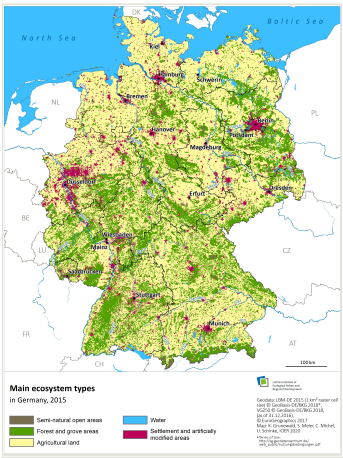

Figure 3.

Main ecosystem types in Germany.

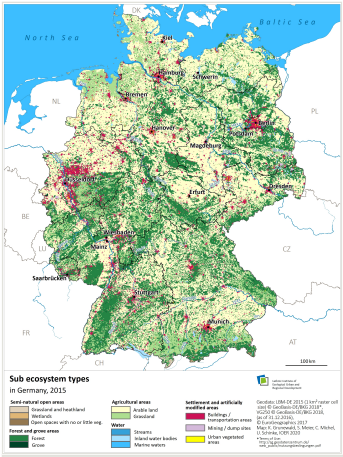

Figure 4.

Ecosystem subtypes in Germany.

The visual representation by the 1 x 1 km^2 raster grid only displays the rough spatial distribution of ET, but it did not serve as a calculation basis for the ET areas. The concrete areal ratios were derived from the vector-based spatial elements of the LBM-DE along with the additional small-scale and infrastructure elements from the ATKIS-Basis-DLM (Digital Basic Landscape Model from the Official Topographic-Cartographic Information System) (Suppl. material 3: *The area and share of main ecosystem types and sub ecosystem types (ETs, see Tab. 1) in the German land cover model (LBM-DE) for the time periods 2012, 2015 and 2018. Linear elements such as small scale structures and infrastructures from*

the topographic-cartographic Information system (ATKIS) were added to the land cover model). One striking fact is that semi-natural open land has a share of less than 2%; accordingly, the areas and ratios of the CLC classes are marginal.

The introduction of linear infrastructures and small structures (Table 2) altered the areal sizes of some CLC classes compared to those given by LBM-DE. The area of the "roadway and rail networks" (CLC class 122) saw the largest increase, namely an additional 1,396,592.61 ha, due to newly-added surfaced and unsurfaced roads. Additionally the area of "watercourses" (CLC class 511) increased by 130,757.41 ha as a result of the additional watercourses. At the same time, other CLC classes decreased in size, especially the "non-irrigated arable land" (CLC class 211), falling by 363,700.13 ha. This was due, amongst other things, to the removal of farm roads from the calculation.

When considering the areal ratios for the year 2018, it becomes clear that the ratios of the main ETs correspond relatively well with known figures from Destatis land use statistics (Destatis 2019, Destatis 2020). Any disparities are largely due to differences in the definition of land use categories between the Destatis statistics and the applied geodata (Krüger et al. 2017). For example, comparing the extent of roads (CLC 122) in LBM-DE with that of Destatis, we note a disparity of approx. 300,000 ha, i.e. an area of 1.80 million ha for Destatis (Destatis 2019, Destatis 2020) compared to 1.54 million ha for the LBM-DE (with added roads, unsurfaced roads and railway lines). This difference could be due, amongst other things, to the fact that the two sources assume different standard widths and take different account of marginal areas, such as railway embankments and roadway verges.

In addition to the reference year 2018, the CLC classes for the years 2015 and 2012 were calculated using the indicated data (LBM-DE/ATKIS) and aggregated to sub-ET or main-ET. However, the relative brevity of the considered timeframe (three time periods) does not allow us to reliably determine any trends or shiftings, as these may be masked by methodological changes in the classification of land use and land cover in the LBM-DE (especially between the reference years 2012 and 2015) (BKG 2019b). Any interpretation of the ETs is also complicated by the fact that, for areas such as grassland, the classification of semi-natural open land changes from one time period to the next, even though no actual change of use has probably taken place (see above). In addition, the ATKIS data serving as a base data for the LBM have been changed by a process of systematisation lasting several years (a task completed in 2014), undermining the temporal comparability (AdV 2019). Thus we find a better agreement of the ET area sizes when comparing the years 2015 and 2018 than when comparing 2012 and 2015.

Extent and changes of main ecosystem types

Main ecosystem types were assessed uniformly at federal level. In cases where it is appropriate and the data situation permits, the spatial framework was extended to the district level. The map representations were limited to the illustrations necessary for understanding.

Agricultural land

Agroecosystems occupy about half of the territory of Germany. Most of this land is used for arable farming, followed by grassland (about two thirds to one third). Approximately 2,300 m² of agricultural land is available per inhabitant, of which 1,500 m² is arable land. The degree of self-sufficiency in Germany is over 100% for many agricultural products (cereals, potatoes, meat), while for fruit and vegetables, it is well below 50% (Destatis 2019).

Official statistics show an ongoing reduction in the extent of land used by Germany's farmers. Whereas in 1990 about 18 million ha were still utilised for agricultural purposes, by 2018 the figure had fallen to only about 16.65 million ha, a decline of approx. 7% (Destatis 2019). The LBM-DE data also show a decrease in the main-ET agricultural land (-147,738 ha from 2012 to 2018). This trend is also found in the two sub-ETs arable land (31) (-50,784 ha) and grassland (32) (-96,954 ha) (Suppl. material 3).

Evaluations, based on the IOER Monitor, also show a clear trend in decreased ratios of agricultural land to total national territory strongly in the period 1995 to 2018. At district level, such ratios fell by up to 16% (Fig. 5). Larger cities and their surrounding areas were most affected. However, a more complex picture emerges for conurbations: while agricultural areas in Berlin, Hamburg or Stuttgart only declined moderately, in the Rhine-Main area or in the Halle-Leipzig region, a strong decrease can be observed. Rural areas are also affected, for example in East Frisia, around the mouth of the Weser or partly in Rhineland-Palatinate (Walz et al. 2018).

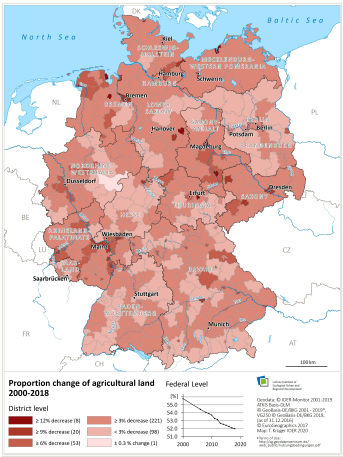

Figure 5.

Ratio of agricultural land to reference area in the period 1995-2018.

With regard to grassland, the IOER Monitor data does not reveal any uniform trend across the country. Some regions, especially along Germany's north-western coast or in Bavaria in the country's south-east, experienced strong decreases. However, we also find sporadic regional increases in grassland ratios, especially in some regions of Bavaria, Baden-Württemberg and the Saarland (Fig. 6). Overall, however, a negative trend can be

discerned. At the same time, it should be noted the IOER Monitor data underlying these evaluations are derived from the Basis-DLM (ATKIS), which, particularly in the case of grassland, does not place a high priority on regular updating. Furthermore, the fact that no statements can be made regarding the quality of grassland is a major drawback, especially with regard to ecosystem services, if we remember that grassland featuring diverse plant species and blossoms has declined significantly in extent (BfN 2009).

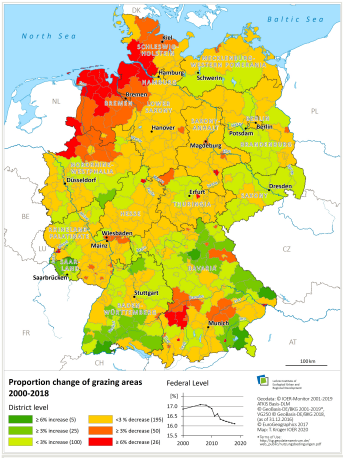

Figure 6.

Ratio of grassland to reference area in the period 2000-2018.

Forest and grove areas

Making up approx. 30% of the national territory, forests and woodlands constitute the second largest form of land use in Germany. Large forest areas are mainly found in the low mountain ranges and on less-favoured soils in the north-east.

In the period 2002-2012, a small increase of 0.4% (50,000 ha) was detected in the extent of land used for forestry. This is the finding of the Federal Forest Inventory 2012 (BMEL 2014), which is carried out every 10 years. The increase in forested area was largely in rural and peripheral areas, mostly at the expense of extensively-used agricultural land of high nature conservation value. In contrast, conurbations saw shrinking areas of forest and groves. The Federal Statistical Office, which estimates the extent of forest according to a different set of parameters than the Federal Forest Inventory, estimated the total area of Germany's forests in 2015 at 109,515 km² (2015), showing a slight upwards trend (Destatis 2019).

The main-ET forest and grove areas calculated from the LBM-DE data show a slight downwards trend from 2012 to 2018 (-0.5%, Suppl. material 3). This may be due to changes in the allocation of area types.

Without human influence, Germany would be predominantly covered by deciduous forest. After various phases of deforestation and special forms of agricultural use that severely decimated the tree population, targeted reforestation began towards the middle of the 19th century, mainly with conifers. The tree species composition is one of the criteria that can be used to classify the condition of forests. Other criteria include the stratification of the forest, the age of the trees or the proportion of old and dead wood.

Today, coniferous forest – as defined by CLC – is the predominant type of woodland (54% of all woodlands in 2015), followed by deciduous (31%) and mixed forests (13%) (Fig. 7). The map does not show the development at district level (as is the case with agriculture), but rather the status quo 2018 at object level. In the case of forests, it is more a question of the overall picture for Germany than of a spatially sharp assessment at local (district) level. The sampling-based Federal Forest Inventory, which uses a different system to distinguish between deciduous and coniferous forests, comes to comparable results (Table 3). The area of deciduous forests and deciduous forests mixed with conifers increased by almost 10% between 2002 and 2012. Compared to potential natural vegetation, however, they are still clearly under-represented.

Figure 7.

Germany's forests in 2018.

Table 3.

Extent and change of the area of different forest types in Germany (source BMEL 2014).

	Area in ha		Change in %	Percentage of total forest area	
	2002	2012		2002	2012
Deciduous forest	2,264,453	2,380,235	5.11	21.04	21.94
Deciduous forest mixed with conifers	1,884,042	2,158,835	14.59	17.50	19.90
subtotal	4,148,494	4,539,070	9.41	38.54	41.85

	Area in ha		Change in %	Percentage of total forest area	
	2002	2012		2002	2012
Coniferous forest	3,324,268	2,961,466	-10.91	30.88	27.30
Coniferous forest mixed with deciduous trees	3,173,922	3,296,067	3.85	29.49	30.39
subtotal	6,498,190	6,257,533	-3.70	60.37	57.69
Equal proportion of deciduous and coniferous trees	117,495	49,837	-57.58	1.09	0.46
Total	10,764,179	10,846,440	0.76	100	100

Settlement and artificially modified areas

Around 13-14% of Germany's landmass was mapped as main-ET "settlement and artificially modified areas" (Suppl. material 3), with the sub-type "buildings and transportation areas" accounting for the largest share of this (96%). From the perspective of ecosystem services, the class "urban vegetated areas" is of particular interest.

Calculations in the LBM-DE showed an increase of 339,374 ha in the main-ET "settlement and artificially modified areas" from 2012 to 2018. This can be attributed to strong growth in the "buildings and transportation areas" (383,700 ha), while in the same period, "urban vegetated areas" decreased by 47,640 ha (Suppl. material 3).

Fig. 8 visualises trends in land conversion between (semi-) natural to urban and other artificial land types in Germany since 2011. The black curve shows the values of the sustainability indicator "increase in settlement and transport areas", based on official land-use statistics adjusted by the Federal Environment Agency. The grey curve shows an equivalent parameter as calculated for the IOER Monitor of Settlement and Open Space Development. These findings are the result of a methodology developed at the IOER to analyse changes in land use, based on the ATKIS Basis-DLM (Schorcht et al. 2016). Both curves show a downward trend in "land take" over the past years. The disparities in the absolute values are due to the disparate base data.

For the new settlement and transport areas added in the period 2013-2018, we can determine the different various ratios of the specific forms of pre- and post-land use. To simplify the model, the previous types of use (or origin) of settlement and transport areas (Fig. 9, left) were roughly divided into three main categories. The category 'other', which includes, for example, 'areas of water' or 'uncultivated soil', shows the smallest ratio of 10%. A further 18% of the newly-added settlement and transport areas were previously forest and grove areas. In contrast, the largest share (72%) was previously agricultural land. At the same time, we can determine the various forms of use of these newly-added settlement and transport areas (Fig. 9, right). Thus, we see that around 18% of new settlement and transport area is, specifically, dedicated to the latter usage, i.e. almost one in five new square metres is used for transportation purposes. The least common usage (only 12%) is open space within settlements, which includes, for example, areas

characterised as non-built-up, such as sports, leisure or recreation areas. The largest share (70%) is made up of built-up areas, including, for example, residential, mixed and industrial areas. A full land use change matrix is presented in Suppl. material 4 (*Table D: Detailed matrix of pre- and post-use of settlement and transportation areas in Germany in the period 2013-2018 in hectare per day (ha/d). (Data source: IOER)*.

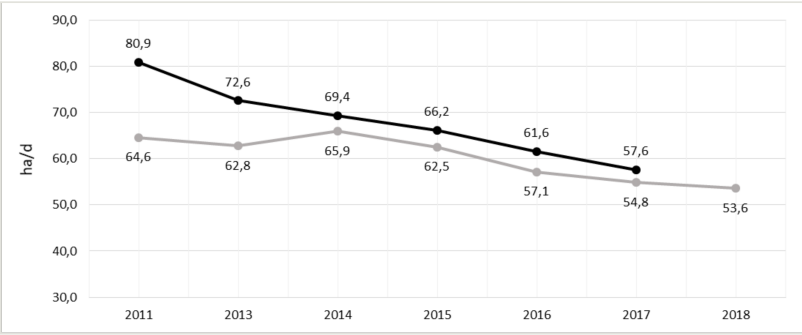

Figure 8.

Development of the indicator "land take". Comparison of figures from the Federal Environment Agency (black line) and the IOER monitor (grey line) (data source: UBA, IOER).

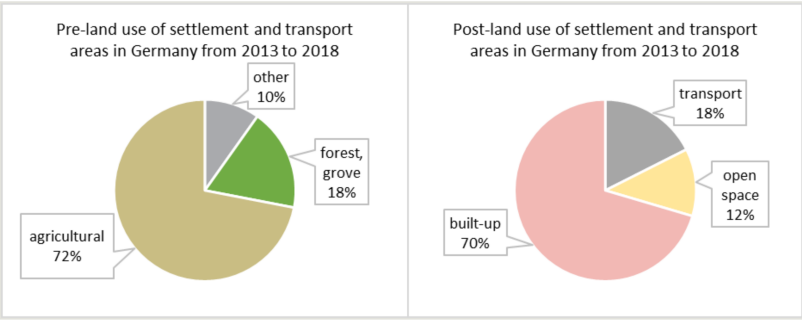

Figure 9.

Pre- and post-use of settlement and transportation areas in Germany in the period 2013-2018 (data source: IOER).

Limiting the growth of settlement an d transport areas continues to be an important goal of the National Sustainability Strategy (German Government 2017). Even though the expansion in settlements and soil sealing has slowed in recent years (Penn-Bressel 2019, UBA 2019), according to Penn-Bressel (Penn-Bressel 2019), great efforts are still needed to maintain this positive trend and avoid a possible return to excessive land consumption.

Waters

According to official statistics, Germany's total surface water is about 8,500 km² or 2.3% of the national territory. The maps of the ecosystem types (Figs. 1 and 2) also encompass the lakes of the Federal Republic, the German part of Lake Constance and the German

Exclusive Economic Zone (EEZ) in the North Sea and Baltic Sea. Together, these bodies of water cover about 3 million ha, with only marginal changes between 2012, 2015 and 2018 (Suppl. material 3).

At the regional level, however, we can detect some transformations in surface waters. For example, Table 4 shows the changes that occurred in the period 2008-2018 due to the flooding of opencast mines in lignite-mining districts of eastern German (“Central German mining area”, “Lusatian mining area”). In the district of Leipzig (Saxony), in particular, the total surface water increased by more than one third over these ten years. The district of Oberspreewald-Lausitz in Brandenburg showed the second largest relative increase in water area. Comparing with the national value for the expansion in water surfaces of 2.8%, we can appreciate the dynamic trends which post-mining landscapes can exhibit with regard to this indicator.

Table 4.

Growth in surface waters in the period 2008-2018 due to the flooding of opencast mines in eastern-German lignite-mining districts (“Central German mining area”, “Lusatian mining area”).

Ligniteregion	**Reporting unit**	**admin. area [km^2]**	**water area [% 2018]**	**water area [km^2 2018]**	**water area [% 2008]**	**water area [km^2 2008]**	**difference (% of adm. area)**	**difference absolute [ha]**	**water surface increase [%]**
Central German	Leipzig (Rural district), Saxony	1651.3	4.0	65.9	2.9	47.9	1.1	1801.4	37.6
	Burgenlandkreis, Saxony-Anhalt	1419.9	0.8	11.5	0.7	9.9	0.1	156.0	15.7
	Leipzig (city), Saxony	297.8	3.0	9.1	2.7	8.0	0.3	105.9	13.2
	Wittenberg, Saxony-Anhalt	1942.8	2.1	41.4	2.0	38.9	0.1	254.3	6.5
Lusatian	Oberspreewald-Lausitz, Brandenburg	1223.0	6.0	73.5	4.8	58.7	1.2	1479.6	25.2
	Bautzen, Saxony	2395.6	4.9	118.3	4.3	103.0	0.6	1529.0	14.8
	Cottbus, Brandenburg	165.6	1.5	2.5	1.4	2.3	0.1	18.1	7.8
	Spree-Neiße, Brandenburg	1657.0	2.4	39.1	2.3	38.1	0.1	99.0	2.6
	Görlitz, Saxony	2111.1	3.3	70.6	3.3	69.7	0.0	93.3	1.3
	Germany	357,680	2.0	6985.3	1.9	6795.92	0.1	18938.0	2.8

Semi-natural open areas

This sub-chapter gives an overview of the remaining terrestrial ecosystems, largely located outside urban areas. The main ET “semi-natural open areas” covers only 1.8% of

Germany's land mass. It is divided into the three subtypes, namely "grassland and heathland", "wetlands" and "open spaces with no or little vegetation", which in 2018 encompassed 418,536 ha, 180,033 ha and 46,976 ha, respectively (Suppl. material 3).

Although highly heterogeneous, these ecosystems have one or more of the following shared characteristics:

- a relatively small total area, as well as small size of each ecosystem;
- low intensity of use or no use at all, often of high nature value;
- in many cases, protected by some kind of national or international regulation or convention (amongst others, national or sub-national regulations on protected biotopes and FFH directives).

So far, no clear trend can be identified from the LBM data for the main-ET "semi-natural open area" (Suppl. material 3). The same applies when we consider hedges, tree rows (from the ATKIS base DLM) and areas of transitional woodland/shrub (CLC 324) (< 1 ha) (from the LBM-DE) in isolation. As groves have only been recorded in the official statistics separately from forests since 2016, it is not yet possible to derive any statements on this feature (Destatis 2019).

Higher-level spatial findings regarding cultural influence

The areal ratios of certain ecosystem types do not yet tell us anything about the composition and structure of larger spatial components, such as administrative districts or larger grid cells (e.g. 10 x 10 km^2). Yet, it is precisely such aspects of the spatial arrangement and composition of the individual elements of land use or ecosystem types that strongly influence the condition of ecosystems, as these influence the inherent functions and processes of each ecosystem (see Sect. 5).

The concept of hemeroby analyses current forms of land use with regard to human impact. For this, the distance between the current vegetation and a constructed final state of self-regulated vegetation in the complete absence of human intervention (so called potential natural vegetation (PNV)) is measured. Hence, the hemeroby is an inverse measure of the closeness to nature (Kowarik 2006). The term hemeroby, which was introduced originally by botanists, is derived from the Greek words hémeros (tamed, cultivated) and bíos (life). Later this concept was applied on whole ecosystems (e.g. Sukopp 1976).

For this purpose, individual objects of the land cover model for Germany (LBM-DE) and the ATKIS-Basis-DLM were each assigned one of the seven hemeroby levels ranging from natural (ahemerobic) to artificial (metahemerobic) (Walz and Stein 2014). Interventions, such as soil sealing or intensification in use, have the effect of increasing, i.e. worsening, the hemeroby level of the respective reference unit. However, since interventions according to German law (German intervention and compensation scheme, Wende et al. 2005, Wende et al. 2018) have to be compensated for (primarily in spatial proximity), an upgrading should simultaneously take place. This means that the values per reference unit should, in theory, scarcely change. If the three hemeroby levels closest to nature are

evaluated (ahemerobic (almost no human impacts) up to mesohemerobic (moderate human impacts)), this gives the ratio of primarily natural areas. A nationwide evaluation at district level (Fig. 10) shows that the ratio of such natural areas often decreases. For Germany in total, there is a slight decrease of -0.1%, but the district values spread from -1.2% to 2.3% in the period 2012-2018.

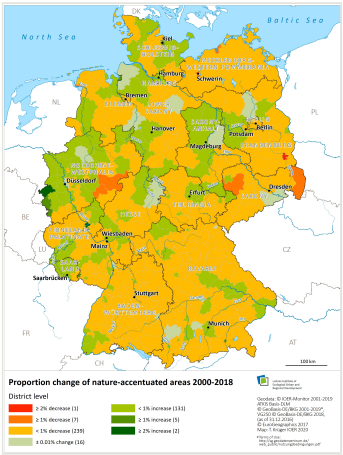

Figure 10.

Ratio of natural areas to total reference area in the period 2012-2018.

Summary of trend developments

Our analyses show that the main trends of land cover change observed in the EU (EEA 2017) can also be identified for the main-ETs in Germany. These are:

- Urban and infrastructure expansion continues to consume areas of productive soil and to fragment existing landscape structure. Of all land cover categories, artificial areas have increased most in terms of both net area and percentage change.
- The extent of agricultural land, often of good quality and in favourable locations, continues to shrink. The fine-grained structure and associated biodiversity of traditional rural landscapes continues to be affected by land take, agricultural intensification and farmland abandonment.
- The extent of forested areas remains more or less stable.
- The area of surface waters also changed only marginally at the federal level between 2012 and 2018, although relevant regional increases were observed in post-mining areas.
- For the few semi-natural areas in Germany, no clear trend of land use change in the observation period could yet be identified. The ration of nature-accentuated areas (estimated by the hemeroby indicator) to total reference area slightly decreased on the federal level (-0.1%) from 2012 to 2018.

Only from the LBM-DE (Suppl. material 3 Table C), however, it is not possible - so far at least - to deduce a definite trend in the changes of most sub-ecosystem types or CLC classes. However, one example should illustrate the potential of such trend analyses. Walz et al. (Walz et al. 2019) assessed the ecosystem services of floodplains of the major river systems in Germany. They found that only 35% of the morphological floodplain still serve for natural flood retention in Germany and that the area for flood retention decreased by a total of 7.3 km² (0.13%) nationwide from 2010 to 2015 due to an increase in the settlement and traffic area.

Discussion and Conclusions

Lesson learned and limitations

A clear delineating of ecosystem types in a reliable manner is important for many current and emerging issues regarding ecosystem assessments and accounting, which ultimately helps to support decision-making. A number of good proposals have been made internationally in this context (Sect. 2), but it is still a dynamic field (Keith et al. 2020).

As discussed and confirmed in the SEEA revision process (UN 2020), the delineation of ecosystem assets should focus on classifying ecosystems from an ecological perspective. The consequence is that land cover alone is not sufficient. However, then the question arises - what kind of characteristics should be considered next in addition to land use? Should it be soils or better, water level or even relief? Soils would be good characteristics if we are looking at the ES for agricultural production; water level is relevant for carbon sequestration in peatlands; relief is of importance for erosion control and for scenic beauty. If we would use all these relevant characteristics for delineation, for each in part it would become important in the further process towards service accounting, then the result would subsequently be an enormous number of very small-scaled homogeneous spatial units.

However, it can be argued tha,t on the one hand, it remains uncertain if the results would have high accuracy, due to different data being collected at very different scales. Often, even they are not available at all or only in very coarse scales for the whole of Germany. On the other hand, all these resulting small homogenous patches would be aggregated again – but in what way – to make any meaningful statements about them with regard to their extent?

To conduct a nationwide analysis of ETs, in our opinion, it is more plausible to reduce the complexity and use ecosystem classifications, like that of the CLC ecosystem types. In general, land cover, in principle, quite accurately reflects the relevant characteristics of the ecosystems (e.g. forests on steep slopes, peat bogs in wet habitats, arable land on fertile soils etc.). If we need to refine the analysis in order to determine ecosystem conditions or services, however, it is reasonable to add additional information: has the land at the urban fringe converted to buildings resulted in higher natural soil productivity than average cropland? Is the water level of a mire ten centimetres higher or lower, which is decisive for

carbon oxidation and greenhouse gas emissions? Is the cropland located on steep slopes so that soil erosion should be reduced by additional hedges or conversion to grassland?

If ecosystem services and ecosystem conditions are in question, additional information is obviously required. However, unlike in the ecosystem extent account, this information can then be used in a very targeted manner, depending on the respective land use, the status parameter under investigation and the ecosystem service that is assessed.

We have shown that the application to the German context, with practical realities considered, has transpired into emerging results. Although we start from the CLC classes, we use the German LBM-DE model, including some more characteristics than just land cover. Additionally, in the geodata system developed here, linear ATKIS elements (e.g. roads, watercourses or even small structures, such as rows of trees and hedges) are converted into polygons by means of buffering and integrating into the polygonal mapped ET and CLC classes. Care has been taken to ensure that no overlapping occurs, thus avoiding potential cases of double recording, thereby confounding the validity of result accuracy (Sect. 3.2).

However, a balance must be achieved between results that are sufficiently ecologically meaningful rather than being simply pragmatic and on which ET classification level this is relevant. We therefore believe that our proposed national system be processed in four levels (Main-ET, Sub-ET, CLC-classes, further subdivision into habitats to integrate biodiversity relevant information, Sect. 3). This would offer a flexible, but also simultaneously best appropriate, approach in this respect.

First evaluations have been realised and discussed (Sect. 4). In addition to the reference year 2018, the CLC classes for the years 2015 and 2012 were also calculated on the basis of the available data (LBM-DE/ATKIS), aggregated to Sub-ET and Main-ET, respectively, giving some results that allow for tentative interpretations. However, the brevity of the timeframe (three reference years) does not yet permit a reliable identification of trends or shiftings. Nevertheless, the results confirm the feasibility of conducting a national spatial monitoring of Germany's ecosystems (Ecosystem Extent Account) in the future and of identifying possible changes on the basis of LBM-DE/ATKIS data.

The CLC classes defined in this way, when combined with other available information, are already sufficient for the evaluation of many ES (e.g. recreation, erosion control) and their conditions (e.g. hemeroby/natural condition,) . For example, in the case of natural soil fertility for the CLC class "arable land", there is a combined analysis possible by overlapping the ETs with a number of other nationally-available datasets (including soil water balance, soil type, climate, slope inclination), which together enable an assessment of natural soil fertility, according to the Müncheberger Soil Quality Rating (SQR) (Mueller et al. 2007, BGR 2013a, BGR 2013b).

The system of ET/CLC classes (Table 1) is further underpinned by biotopes/FFH habitat types, for which extensive classification tables have been devised and developed (for an overview see Tab. B in Suppl. material 2). The recording and assessment of the condition

(here especially biodiversity) of ecosystems can be further supplemented by the spatially explicit and representative data collected for each respective period.

To provide a spatial structuring of ecosystems, 'condition indicators of landscape ecosystems' can be used to measure the ratio of structural elements in the open landscape. This includes, for example, the IOER Monitor indicator "woodland-dominated ecotone density", which reports on the density of linear elements, such as hedges, tree rows, woody plants and forest margins. It is precisely such elements that are of great ecological importance, as they represent transitional areas between ecosystems and are home to special communities of species that are thus particularly significant for the provision of ecosystem services.

Conversely, main roads or railway lines often have negative effects on the condition of ecosystems, as they act as barriers for wildlife and humans, thus impeding or even completely preventing key ecosystem functions. This aspect of the condition of ecosystems can be measured, for example, using indicators on landscape fragmentation as a whole or specifically forest fragmentation (see indicators on landscape fragmentation in the IOER Monitor: https://monitor.ioer.de).

Future work

Besides the classification system for ecosystem types (ETs), the table of the area of various ETs (Suppl. material 3, Table C) is the main result of our work. These datasets can form the basis for the regular reporting on the extent, condition and services provided by Germany's ecosystems at national level. The approach for such an ecosystem accounting is in line with SEEA-EEA requirements (UN 2020). The Federal Statistical Office (Destatis) intends to further develop and implement the national ecosystem accounting system in the future. The recently-published IUCN Global Ecosystem Typology (Keith et al. 2020) will likely be a SEEA Ecosystems "reference classification" and it would be useful to bring our mapping and classification approach in correspondence with this IUCN typology.

Furthermore, we propose that the presented system to record the areal change in ecosystems should be developed into an integral component of biodiversity monitoring in Germany (Geschke et al. 2019). Due to the partial use of representative data, however, it is not suitable as a planning basis for concrete measures. In such cases, local data – for example, from the habitat/biotope mapping of the individual states – should be used (Grunewald et al. 2020).

For the long-term observation of ETs, a consistent and stable data-gathering methodology for the production of the main German data base, the LBM-DE, should be implemented to help realise a representative system of ecosystem monitoring. Only in this case, area changes of land use/land cover types can be mapped in a reliable manner. The results so far, which have been fully calculated for the German state area (terrestrial, inland surface waters, marine) on the basis of available data for the years 2012, 2015 and 2018, are still relatively uncertain with regard to trend developments or shifts, as these may be masked by methodological changes in the classification of land use and land cover (especially

between the time periods 2012 and 2015) (B). There are also challenges in the consistency of the results (How can we deal with significant deviations from existing accounts, for example, forest and agriculture?).

Further challenges to be overcome are related to the degree of thematic detail that can be entailed, especially considering whether, which and with what kind of detail, functional characteristics of ecosystems should be included in order to support the realisation of the respective objectives at the national level (e.g. biodiversity protection, identification of services, prioritisation of damaged ecosystems to be restored, analysis of changes in the extent of specific ecosystems in Germany).

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Conflicts of interest

No conflicts of interest.

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Supplementary materials

Suppl. material 1: Proposal of a classification system for ecosystem types (ETs) in Germany, assignment to the European ecosystem types according to EUNIS and to the CLC types of the database LBM-DE doi

Authors: Karsten Grunewald, Burkhard Schweppe-Kraft, Ralf-Uwe Syrbe, Sophie Meier, Tobias Krüger, Martin Schorcht, Ulrich Walz
Data type: Table
Brief description: Suppl. material 1 contains a table with the proposal of a classification system for ecosystem types (ETs) in Germany, assignment to the European ecosystem types according to EUNIS and to the CLC types of the database LBM-DE.
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Suppl. material 2: Supplementation of ecosystem types (ETs) by more differentiated spatially and non-spatially explicit data (system of assignment of biotope and habitat types relevant for nature conservation to ETs doi

Authors: Karsten Grunewald, Burkhard Schweppe-Kraft, Ralf-Uwe Syrbe, Sophie Meier, Tobias Krüger, Martin Schorcht, Ulrich Walz
Data type: Table
Brief description: Suppl. material 2 contains a table with supplementation of ecosystem types (ETs) by more differentiated spatially and non-spatially explicit data (system of assignment of biotope and habitat types relevant for nature conservation to ETs.
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Suppl. material 3: The area and share of main ecosystem types and sub ecosystem types (ETs, see Tab. 1)) in the German land cover model (LBM-DE) for the time periods 2012, 2015 and 2018. Linear elements such as small scale structures and infrastructures from the topographic-cartographic Information system (ATKIS) were added to the land cover model. doi

Authors: Karsten Grunewald, Burkhard Schweppe-Kraft, Ralf-Uwe Syrbe, Sophie Meier, Tobias Krüger, Martin Schorcht, Ulrich Walz
Data type: Table
Brief description: Suppl. Material 3 contains a table with the area and share of main ecosystem types and sub ecosystem types (ETs, see Table 1) in the German land cover model (LBM-DE) for the time periods 2012, 2015 and 2018. Linear elements such as small scale structures and infrastructures from the topographic-cartographic Information system (ATKIS) were added to the land cover model.
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Suppl. material 4: Tab. D: Detailed matrix of pre- and post-use of settlement and transportation areas in Germany in the period 2013-2018 in hectare per day (ha/d). (Data source: IOER) doi

Authors: Schorcht, M.
Data type: Table
Brief description: The table contains a detailed matrix of pre- and post-use of settlement and transportation areas in Germany from 2013 to 2018.
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