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Mapping ecosystem service supply, demand and budgets

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ABSTRACT

Among the main effects of human activities on the environment are land use and resulting land cover changes. Such changes impact the capacity of ecosystems to provide goods and services to the human society. This supply of multiple goods and services by nature should match the demands of the society, if self-sustaining human–environmental systems and a sustainable utilization of natural capital are to be achieved. To describe respective states and dynamics, appropriate indicators and data for their quantification, including quantitative and qualitative assessments, are needed. By linking land cover information from, e.g. remote sensing, land survey and GIS with data from monitoring, statistics, modeling or interviews, ecosystem service supply and demand can be assessed and transferred to different spatial and temporal scales. The results reveal patterns of human activities over time and space as well as the capacities of different ecosystems to provide ecosystem services under changing land use. Also the locations of respective demands for these services can be determined. As maps are powerful tools, they hold high potentials for visualization of complex phenomena. We present an easy-to-apply concept based on a matrix linking spatially explicit biophysical landscape units to ecological integrity, ecosystem service supply and demand. An exemplary application for energy supply and demand in a central German case study region and respective maps for the years 1990 and 2007 are presented. Based on these data, the concept for an appropriate quantification and related spatial visualization of ecosystem service supply and demand is elaborated and discussed.

1. Introduction

There is no doubt about the increasing popularity of the ecosystem service concept in contemporary science (Seppelt et al., 2011; Fisher et al., 2009). The longer the conceptual orientation phase of the ecosystem service approach has been lasting, the more obvious become the needs for practical applications of the concept (Daily et al., 2009; Burkhard et al., 2010). These applications are necessary in order to improve the concept and make it an acknowledged tool for natural resource management (Kienast et al., 2009). The quantification and implementation of ecosystem goods and services have been among the biggest challenges of current ecosystem science (Wallace, 2007). Monetary approaches like cost-benefit analyses, contingent valuations or willingness-to-pay assessments are useful attempts (Farber et al., 2002) but their outcomes are often disappointing due to the economic focus and the lack of appropriate pricing methods, e.g. for non-marketed goods and services (Ludwig, 2000; Spangenberg and Settele, 2010).

The provision of ecosystem services depends on biophysical conditions and changes over space and time due to human induced land cover, land use and climatic changes. Spatial patterns of land cover and land cover change can be linked to large regions and provide direct measures of human activity (Riitters et al., 2000). Because of the spatial peculiarity of ecosystem services, mapping their distributions and changes over time has the potential to aggregate complex information. This visualization of ecosystem services can be used by decision makers, e.g. land managers, as a powerful tool for the support of landscape sustainability assessments (Swetnam et al., 2010). Unfortunately, there is a clear lack of information relevant to local scale decision making (Turner and Daily, 2008). Therefore, the explicit quantification and mapping of ecosystem services are considered as one of the main requirements for the implementation of the ecosystem services concept into environmental institutions and decision making (Daily and Matson, 2008).

In recent years, many new ecosystem service mapping approaches have been developed and applied at different spatial scales by several authors. For a more detailed review of recent approaches to ecosystem service mapping at different spatial scales we refer to Burkhard et al. (2009). Novel studies and approaches on ecosystem service mapping are presented in this special issue (e.g. Schneiders et al., 2012; Koschke et al., 2012; Haines-Young et al., 2012; Nedkov and Burkhard, 2012; Scolozzi et al., 2012).

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However, the direct comparison of ecosystem service supply and demand in spatially explicit maps is rather rare in spite of the wide agreement about the importance of including the demand side into ecosystem service assessments (van Jaarsveld et al., 2005; McDonald, 2009). Paetzold et al. (2010) note that the status of an ecosystem service is influenced not only by its provision, but also by human needs and the desired level of provision for this service by the society, which connects supply and demand of ecosystem services inseparably (Syrbe and Walz, 2012). Paetzold et al. (2010) developed a framework for the assessment of ecological quality which considers the supply as well as the demand of ecosystem services. van Jaarsveld et al. (2005) present a practical application of ecosystem supply and demand mapping at the subcontinental scale for Africa, whereas (Kroll et al., 2012) provide a method for the quantification and mapping of ecosystem services at the regional scale for a rural-urban region in eastern Germany. These maps can be used by decision makers for the identification of supply–demand mismatches across landscapes and their changes over time (Paetzold et al., 2010). However, caution and patience are still needed as the expectations from practitioners are already very high, but most of the maps might still need further refinement with more detailed spatial data and better socio-economic information (Kienast et al., 2009).

When assessing and mapping ecosystem service supply and demand, the problem of a clear distinction between ecosystem functions, services and benefits is of high relevance (de Groot et al., 2010; Haines-Young and Potschin, 2010; Burkhard et al., 2010). For several practical reasons, the commonly used definition from the Millennium Ecosystem Assessment "ecosystem services are the benefits humans obtain from nature" (MA, 2005) and the related four categories of supporting, provisioning, regulating and cultural services are not always appropriate (Seppelt et al., 2011, 2012; Wallace, 2007). As Fisher and Turner (2008) point out, we have to delineate between *ends* and *means* if we want to operationalize ecosystem services. Therefore, Boyd and Banzhaf (2007) introduced the term *final ecosystem services* which are components of nature directly enjoyed, consumed or used to yield human well-being. Most of the other components and functions of an ecosystem would then be *intermediate products* respectively *intermediate services*. This goes along with Fisher and Turner (2008) who propose that ecosystem services' benefits must have a direct relation to human well-being. For example, nutrient cycling is an ecological function, not an ecosystem service (Boyd and Banzhaf, 2007). However, the distinction between intermediate and final services is often observer-based and depending on rather subjective decisions.

Therefore, we follow a framework which integrates the concept of *ecological integrity* as the base for the supply of regulating, provisioning and cultural ecosystem services (Müller and Burkhard, 2007). Ecological integrity means the preservation against non-specific ecological risks that are general disturbances of the self-organizing capacity of ecological systems. This self-organizing capacity is based on structures and processes in ecosystems, and appropriate indicators for their description have been defined and applied in several case studies (Müller, 2005; Burkhard and Müller, 2008). Land use and related land cover modifications have a strong impact on ecological integrity. Alterations of ecological integrity lead to increasing or decreasing *supplies* of selected or bundles of ecosystem services, on which human societies depend.

If the supply of ecosystem services is changed, human societies' *demands* for ecosystem services might not be fulfilled anymore. However, it is difficult in today's complex and globalized world to follow the tracks and define the origin of goods and services consumed by people in a certain region. Many goods and services are imported from more or less remote places. In this way, the environmental impacts of ecosystem service generation are exported and leave a *biodiversity and ecosystem service footprint* elsewhere (Burkhard and Kroll, 2010). Finding an acceptable and equitable level of ecosystem service footprints and an appropriate balance of local ecosystem service supply and demand are important steps toward sustainability. So far, few approaches exist which deal with the relations between local demands and ecosystem service provision elsewhere (Seppelt et al., 2011).

The following definitions are the conceptual background of our approach:

- Supply of ecosystem services refers to the capacity of a particular area to provide a specific bundle of ecosystem goods and services within a given time period. Here, capacity refers to the generation of the *actually used* set of natural resources and services. Thus, it is not similar to the *potential* supply of ecosystem services in a certain ecosystem, which would be the *hypothetical maximum yield* of selected optimized services.
- Demand for ecosystem services is the sum of all ecosystem goods and services *currently* consumed or used in a particular area over a given time period. Up to now, demands are assessed not considering where ecosystem services actually are provided. These detailed provision patterns are part of the:
- Ecosystem service footprint which (closely related to the ecological footprint's concept; Rees, 1992) calculates the area needed to generate particular ecosystem goods and services demanded by humans in a certain area in a certain time. Different aspects of ecosystem service generation are considered (production capacities, waste absorption, etc.).

According to our definitions, the regional supply of ecosystem goods and services is directly determined by the regional ecological integrity which is influenced by human actions and decisions such as land cover change, land use and technical progress. Human well-being (economic, social and personal well-being) is based on benefits derived from the people's actual use of ecosystem goods and services. This actual use of ecosystem goods and services is the demand side of this supply and demand chain (EEA, 2010). The impacts on the demand side are manifold and can include policies, population dynamics, economic factors, marketing, trends, advertising, cultural norms and governance (Curran and de Sherbinin, 2004). Fig. 1 illustrates the conceptual framework which the ecosystem service supply–demand assessments and mapping have been developed upon.

In this context, the following aims were defined for this paper:

- to present a clear and easy-to-apply concept to map ecosystem service supply and demand as well as supply and demand budgets, to derive a concept that is applicable at different scales for various case study regions and that allows for comparison of different ecosystem services, and
- to support the development of simple tools for landscape managers to support sustainability assessments.

2. Materials and methods

We propose a non-monetary evaluation scheme based on indicators which are categorized and mapped in relation to relative supply/demand scales. The applied method of ecosystem service supply mapping has been presented before in Burkhard et al. (2009). The ecosystem service demand mapping and the final ecosystem service budgeting are added as new components to ecosystem service mapping approaches.

Fig. 1. Conceptual framework linking ecosystem integrity, ecosystem services and human well-being as supply and demand sides in human–environmental systems.

2.1. Indicators for ecological integrity and ecosystem services

The derivation of suitable indicators for the assessment of ecosystem functions and their capacities to supply services is an important step in order to know what will be evaluated. Appropriate ecosystem service indicators need to be quantifiable, sensitive to changes in land cover,[1] temporarily and spatially explicit and scalable (van Oudenhoven et al., 2012).

Ecosystem functionality can be described by ecological integrity and respective indicators have been elaborated in detail in Müller (2005). These indicators describe structures and processes relevant for the long-term functionality and self-organizing capacity of ecosystems. Structures relate to numbers and characteristics of, e.g. selected species (biotic diversity) and physical habitat components (abiotic heterogeneity). Processes refer to ecosystem energy budgets (exergy capture; e.g. biomass production), matter budgets (nutrient storage and loss) and water budgets (biotic water flows and metabolic efficiency). Table 1 provides short rationales and suggests potential indicators to describe and quantify ecological integrity and ecosystem services.

In addition to ecological integrity, regulating ecosystem services relate to ecosystem functions also (see Table 1). As they are difficult to quantify, most assessments are based on model calculations (Jørgensen and Nielsen, 2012). Moreover, some components of regulating services are overlapping with ecological integrity processes; for example processes related to nutrient or water regulation. Therefore, a high risk of merging and double-counting of ecological integrity variables and regulating ecosystem services is inherent. This has to be recognized when interpreting the results.

Production and trade numbers as well as products' market prices are appropriate indicators for provisioning ecosystem services. Hence, provisioning services seem to be relatively easy to quantify but, cornered or changing markets and supplies, resource scarcity or altering production and trade patterns have to be considered.

Assessments of cultural ecosystem services are rather subjective and value-laden as each individual or each group of individuals has different value systems and demands (MA, 2005). Several factors like experience, habits, belief systems, behavioral traditions and judgment as well as lifestyles have to be considered. All of them are related more to the observer than to ecosystem conditions (Kumar and Kumar, 2008; Hansen-Möller, 2009). Nevertheless, there has been a lot of scientific progress with regard to the understanding of landscapes' role for, e.g. cultural identity (Hunziker et al., 2007; Fry et al., 2009). There are also issues of clear conceptual delineation of cultural ecosystem service categories and their proper localization in space (Gee and Burkhard, 2010; Frank et al., 2012). The identification of spatially explicit units for cultural ecosystem services to which functions, benefits and values can be assigned is perhaps more challenging than for the other ecosystem service categories (Haines-Young and Potschin, 2007).

Therefore, we suggest only two classes of cultural ecosystem services here (recreation and aesthetic values and intrinsic value of biodiversity; Table 1) and give space for defining further case study specific cultural ecosystem services. Nevertheless, quantifications based on interviews, questionnaires or additional information sources can provide useful and spatially explicit results (Sherrouse et al., 2010). For certain cultural ecosystem services, for example recreation, tourist numbers or the numbers of overnight stays at particular locations are applied. The intrinsic value of species and biodiversity has been placed within the group of cultural ecosystem services (Table 1). This may not be the most appropriate position for the appreciation of nature and species diversity as such (besides their contribution to human welfare), but in many of the available ecosystem service concepts biodiversity indicators were not considered sufficiently or even not considered at all (TEEB, 2010). Therefore, cultural ecosystem services may be the most suitable of the currently defined ecosystem service categories to reflect the idea of intrinsic values of species and nature.

2.2. Mapping landscape's capacities to supply ecosystem services

Different ecosystems have different functions based on their structures and processes (i.e. their integrity). Consequently, their capacities to supply particular ecosystem services which are used by humans can vary strongly (Bastian et al., 2012). The individual ecosystem capacities to supply services are strongly linked to (a) natural conditions; e.g. natural land cover (vegetation foremost), hydrology, soil conditions, fauna, elevation, slope and climate as well as (b) human impacts; mainly land use but also emissions, pollution, etc. All this information and related data should be as detailed as possible, in a relevant resolution and at an appropriate scale when defining the capacities of different ecosystems to supply services. Land cover information from remote sensing, land survey, simulation models, and statistical data are appropriate starting points. By integrating these features with further data, the state of ecosystems and their capacities to supply ecosystem services can be assessed and transferred to maps of different spatial and temporal scales. The results reveal patterns of natural conditions and human activities over time and the capacities of different ecosystems to supply ecosystem services considering current states and real or potential changes in land use.

To start mapping ecosystem service capacities, we used satellite-based CORINE land cover data from the European Union. CORINE provides classified spatial land cover data in GIS format ready for use. The hierarchically organized three-level CORINE nomenclature (EEA, 1994) was used to define the different European land cover types in the sense of service providing ecosystems. The CORINE system includes 44 land cover classes grouped into (1) artificial surfaces, (2) agricultural areas, (3) forests and semi-natural areas, (4) wetlands, and (5) water bodies. The GIS data in the European CORINE data base contain a minimum mapping unit (MMU) of 25 ha. Additional national datasets are available on a 100 m grid, a 250 m grid and a 1 km grid for the years 1990, 2000

[1] *Land cover* refers to features that cover the earth's surface whereas *land use* documents how people are using the land (NOAA, 2009). Remote sensing data, for example, provide a logical combination of land cover and land use as it can be tracked from space. This latter combination of *land cover* and *land use* was used under the term "land cover" in the following.

Table 1
List of ecological integrity and ecosystem service components with rationales and potential indicators.

	Rationales	Potential indicators
Ecological integrity		
Abiotic heterogeneity	The provision of suitable habitats for different species, for functional groups of species and for processes is essential for the functioning of ecosystems.	Abiotic habitat components' diversity indices; Heterogeneity indices, e.g. humus contents in the soil; Number/area of habitats
Biodiversity	The presence or absence of selected species, (functional) groups of species, biotic habitat components or species composition.	Indicator species representative for a certain phenomenon or sensitive to distinct changes
Biotic water flows	Referring to the water cycling affected by plant processes in the system.	Transpiration/total evapotranspiration
Metabolic efficiency	Referring to the amount of energy necessary to maintain a specific biomass, also serving as a stress indicator for the system.	Respiration/biomass (metabolic quotient)
Exergy capture	The capability of ecosystems to enhance the input of usable energy. Exergy is derived from thermodynamics and measures the energy fraction that can be transformed into mechanical work. In ecosystems, the captured exergy is used to build up biomass (e.g. by primary production) and structures.	Net primary production; Leaf area index LAI
Reduction of nutrient loss	Referring to the irreversible output of elements from the system, the nutrient budget and matter flows.	Leaching of nutrients, e.g. N, P
Storage capacity	Is referring to the nutrient, energy and water budgets of the system and the capacity of the system to store them when available and to release them when needed.	Solved organic matter; N, C_{org} in the soil; N, C in biomass
Regulating ecosystem services		
Local climate regulation	Changes in land cover can locally affect temperature, wind, radiation and precipitation.	Temperature, albedo, precipitation, wind; Temperature amplitudes; Evapotranspiration
Global climate regulation	Ecosystems play an important role in climate by either sequestering or emitting greenhouse gases.	Source-sink of water vapour, methane, CO_2
Flood protection	Natural elements dampening extreme flood events	Number of floods causing damages
Groundwater recharge	The timing and magnitude of runoff, flooding, and aquifer recharge can be strongly influenced by changes in land cover, including, in particular, alterations that change the water storage potential of the system, such as the conversion of wetlands or the replacement of forests with croplands or croplands with urban areas.	Groundwater recharge rates
Air quality regulation	The capacity of ecosystems to remove toxic and other elements from the atmosphere.	Leaf area index; Air quality amplitudes
Erosion regulation	Vegetative cover plays an important role in soil retention and the prevention of landslides.	Loss of soil particles by wind or water; vegetation cover
Nutrient regulation	The capacity of ecosystems to carry out (re)cycling of, e.g. N, P or others.	N, P or other nutrient turnover rates
Water purification	Ecosystems have the capacity to purify water but can also be a source of impurities in fresh water.	Water quality and quantity
Pollination	Ecosystem changes affect the distribution, abundance, and effectiveness of pollinators. Wind and bees are in charge of the reproduction of a lot of culture plants.	Amount of plant products; Distribution of plants; Availability of pollinators
Provisioning ecosystem services		
Crops	Cultivation of edible plants.	Plants/ha; kJ/ha
Livestock	Keeping of edible animals.	Animals/ha; kJ/ha
Fodder	Cultivation and harvest of animal fodder.	Fodder plants/ha; kJ/ha
Capture fisheries	Catch of commercially interesting fish species, which are accessible for fishermen.	Fishes available for catch/ha; kJ/ha
Aquaculture	Animals kept in terrestrial or marine aquaculture.	Number of animals/ha; kJ/ha
Wild foods	Harvest of, e.g. berries, mushrooms, wild animal hunting or fishing.	Plant biomass/ha; Animals available/ha; kJ/ha
Timber	Presence of trees or plants with potential use for timber.	Wood/ha; kJ/ha
Wood fuel	Presence of trees or plants with potential use as fuel.	Wood or plant biomass/ha; kJ/ha
Energy (biomass)	Presence of trees or plants with potential use as energy source.	Wood or plant biomass/ha; kJ/ha
Biochemicals and medicine	Production of biochemicals, medicines.	Amount or number of products; kg/ha
Freshwater	Presence of freshwater.	Liters or m^3/ha
Cultural ecosystem services (*selection*)		
Recreation & aesthetic values	Refers specifically to landscape and visual qualities of the resp. case study area (scenery, scenic beauty). The benefit is the sense of beauty people get from looking at the landscape and related recreational benefits.	Number of visitors or facilities; Questionnaires on personal preferences
Intrinsic value of biodiversity	The value of nature and species themselves, beyond economic or human benefits.	Number of endangered, protected or rare species or habitats

Based on de Groot et al. (2010), Burkhard et al. (2009), Müller and Burkhard (2007) and MA (2005).
+ further case study specific cultural ecosystem services and indictors.

Table 2
List of established ecosystem service case studies used as information source for the derivation of the ecosystem service supply and demand assessment; including spatial scales, relative data availability (+++ = excellent, ++ = good, + = sufficient) and References.

Study site	Spatial scale	Data availability	References
Finnish Lapland	Regional	++	Vihervaara et al. (2010)
Malki Iskar basin, Bulgaria	Regional	++	Nedkov and Burkhard, 2012
German North Sea	Regional	+++	Lange et al. (2010); Gee and Burkhard (2010)
Schleswig-Holstein (Kielstau, Bornhöved, Ritzerau, Sylt), Germany	Local – regional	++	Schmidt (2008)
Leipzig-Halle, Germany	Regional	+++	Kroll et al. (2012)
Himalaya, Nepal	Regional	++	Tamang (2011)
Thailand	Regional	+++	Graterol (2011)
Three Gorges Dam, China	Local – regional	+	Still to be written
South East Asia (Vietnam, Malaysisa, Philippines)	Local – regional	+	Still to be written

and 2006. Basic CORINE data can be downloaded for free from the EEA website (http://dataservice.eea.europa.eu/). Data with higher resolution can be purchased at marginal costs. For the mapping approach presented in this paper, CORINE data sets in ArcGIS polygon format with 25 ha MMU were applied.

One main problem in almost all ecosystem service evaluations is the identification of appropriate indicators and data to quantify the broad range of ecosystem services (Seppelt et al., 2011; Wallace, 2007). One solution can be to make use of expert evaluations in order to gain an overview and see trends for ecosystem service assessments (Burkhard et al., 2009; Scolozzi et al., 2012; Busch et al., 2012). The general assessment approach presented here is based on values which were derived mainly by the authors as hypotheses linking different land cover types with ecosystem service supply capacities and demands for ecosystem services. In subsequent analyses, the expert evaluation values can successively be replaced by data from monitoring, measurements, computer-based modeling, targeted interviews or statistics. This has been done successfully in several case studies on regional scales; like the example presented in Section 2.5, in Vihervaara et al. (2010), Nedkov and Burkhard (2012) or Burkhard et al. (2009). Table 2 provides an overview on the case studies where comparable ecosystem service assessments have been carried out. Maes et al. (2011) applied a similar approach on a continental scale, developing an ecosystem service atlas for whole Europe.

We suggest a matrix linking 7 ecological integrity indicators and 22 ecosystem services (on the x-axis) to 44 land cover types (on the y-axis). The selection of the ecological integrity indicators was based on Müller (2005); because these indicators represent the main components of ecosystem functionality. Our selection of ecosystem services is based on a combination of different ecosystem service lists provided in recent literature (de Groot et al., 2010; TEEB, 2010; Müller and Burkhard, 2007; MA, 2005). The 44 land cover classes originate from the CORINE nomenclature (EEA, 1994). At the intersections (altogether 1276), the different land cover types' capacities to support ecological integrity or to provide particular services were assessed (first qualitatively; in the following case study also quantitatively) on a scale consisting of: 0 = no relevant capacity of the particular land cover type to support the selected ecological integrity component or to supply the selected ecosystem service, 1 = low relevant capacity, 2 = relevant capacity, 3 = medium relevant capacity, 4 = high relevant capacity and 5 = very high relevant capacity (Fig. 2).

The matrix values are based on experience from different case studies in different European regions (see list in Table 2) and have to be considered as hypotheses of possible capacities of ecosystem service provision (Burkhard et al., 2009). Naturally, there is a high dependence on the observer's experience, knowledge and objectivity which service supplies are supposed to be relevant and how to value them. However, this relative 0–5 scale offers a way of evaluating alternatively to monetary accounting or value-transfer methods. Nevertheless, the values will be checked carefully in further case studies and substituted by numbers from respective research, monitoring or statistics whenever available.

Fig. 2 reveals rather high capacities of many near-natural land cover types (forests, wetlands, water bodies, green urban areas, certain agricultural areas) to support ecological integrity. High capacities to provide several ecosystem services can be found for the different forest land cover types, peatlands, moors and heathlands. The highly human-modified land cover types (urban fabric, industrial or commercial areas, mineral extraction and dump sites) have very low or no relevant capacities to support ecological integrity or to provide regulating and provisioning ecosystem services. A similar trend was found for cultural ecosystem services which is consistent with several studies on human perception and preferences of landscapes. For instance, Hartig and Staats (2006) carried out experiments on human preferences of landscapes for recreation (i.e. recovery, reflection and social stimulation). They found a clear preference of natural landscapes (forests in their study) compared to urban areas. Palmer (2004) applied landscape metrics (landscape composition and configuration) to predict people's perception of landscapes, thus adding behavioral and perceptual components into landscape pattern analyses. The results showed a clear preference of "natural-appearing" landscapes with complex patterns of edges.

By linking the 0–5 values to appropriate spatial data in GIS, estimates of ecosystem service supply can be mapped in spatially explicit units of similar biophysical settings (e.g. land cover types in combination with soil types, hydrological and climatic conditions). In the GIS, the ecosystem service supply matrix (Fig. 2) was joined with the polygon attribute table using the CORINE land cover code field as common identifier field. The following case study application will apply the procedure described above for an example of energy provisioning ecosystem services.

2.3. *Mapping human demands for ecosystem services*

By definition, an ecosystem service is only a service, if there is a (human) benefit. Without human beneficiaries, ecosystem functions and processes are not services (according to Fisher et al., 2009). In other words, there must be a certain demand by people to use a particular ecosystem service. To assess demands for ecosystem services, data on their actual use are needed. This information can be derived from statistics, modeling, socio-economic monitoring or interviews. A matrix similar to the one for the ecosystem service supply assessment was derived, showing initial hypotheses on demands for ecosystem services (Fig. 3). The different (CORINE) land cover types are again shown on the y-axis. On the x-axis, the regulating, provisioning and cultural ecosystem services are listed. Note that ecological integrity components are not included in the demand matrix. Ecological integrity indicates ecosystem functions which do not support human well-being directly (Fig. 1). The values in the demand matrix (Fig. 3) indicate: 0 = no relevant demand from people within the particular land cover type for the selected ecosystem service; 1 = low relevant demand; 2 = relevant demand;

CORINE land cover type:	Ecological Integrity Σ	Abiotic heterogeneity	Biodiversity	Biotic waterflows	Metabolic efficiency	Exergy Capture (Radiation)	Reduction of Nutrient loss	Storage capacity (SOM)	Regulating services Σ	Local climate regulation	Global climate regulation	Flood protection	Groundwater recharge	Air Quality Regulation	Erosion Regulation	Nutrient regulation	Water purification	Pollination	Provisioning services Σ	Crops	Livestock	Fodder	Capture Fisheries	Acquaculture	Wild Foods	Timber	Wood Fuel	Energy	Biochemicals and Medicine	Freshwater	Cultural services Σ	Recreation& Aesthetic Values	Intrinsic Value of Biodiversity
Continuous urban fabric	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Discontinuous urban fabric	7	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	3	1	0	1	0	0	1	0	0	1	0	0	0	0	0
Industrial or commercial units	2	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Road and rail networks	4	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Port areas	2	1	1	0	0	0	0	0	3	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0
Airports	7	1	1	1	1	1	2	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Mineral extraction sites	4	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0
Dump sites	8	2	1	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Construction sites	3	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Green urban areas	18	3	3	2	1	4	3	2	11	2	1	0	2	1	2	1	1	1	2	0	0	0	0	0	1	0	1	0	0	0	3	3	0
Sport and leasure facilities	16	2	2	2	1	4	3	2	9	1	1	0	2	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	5	5	0
Non-irrigated arable land	22	3	2	3	4	5	1	4	5	2	1	1	1	0	0	0	0	0	21	5	5	5	0	0	0	0	0	2	1	0	1	1	0
Permanently irrigated land	21	3	2	5	2	5	1	3	5	3	1	1	0	0	0	0	0	0	18	5	5	2	0	0	0	0	0	1	1	0	1	1	0
Ricefields	20	3	2	5	1	5	1	3	4	2	0	0	2	0	0	0	0	0	7	5	0	2	0	0	0	0	0	0	0	0	1	1	0
Vineyards	14	3	2	3	1	3	0	2	3	1	1	0	1	0	0	0	0	0	5	4	0	0	0	0	0	0	1	1	0	0	5	5	0
Fruit trees and berries	21	4	3	4	2	3	2	3	19	2	2	2	2	2	2	1	1	5	13	5	0	0	0	0	0	4	4	1	0	0	5	5	0
Olive groves	17	3	2	3	2	3	1	3	7	1	1	0	1	1	1	1	1	0	12	4	0	0	0	0	0	4	4	1	0	0	5	5	0
Pastures	24	2	2	4	5	5	2	4	8	1	1	1	1	0	4	0	0	0	10	0	5	5	0	0	0	0	0	1	0	0	3	3	0
Annual and permanent crops	18	2	2	3	2	4	2	3	7	2	1	1	1	1	1	0	0	0	20	5	5	5	0	0	0	0	0	1	1	0	1	1	0
Complex cultivation patterns	20	4	3	3	2	4	1	3	5	2	1	1	1	0	0	0	0	0	9	4	0	3	0	0	0	0	0	1	2	0	2	2	0
Agriculture& natural vegetation	19	3	3	3	2	3	2	3	13	3	2	1	2	1	3	0	1	0	21	3	3	2	0	0	3	3	3	2	1	0	5	2	3
Agro-forestry areas	27	4	4	4	3	4	4	4	13	2	1	1	1	1	2	1	1	3	14	3	3	2	0	0	0	3	3	2	0	0	3	3	0
Broad-leaved forest	31	3	4	5	4	5	5	5	39	5	4	3	2	5	5	5	5	5	21	0	0	1	0	0	5	5	5	1	5	0	10	5	5
Coniferous forest	30	3	4	4	4	5	5	5	39	5	4	3	2	5	5	5	5	5	21	0	0	1	0	0	5	5	5	1	5	0	10	5	5
Mixed forest	32	3	5	5	4	5	5	5	39	5	4	3	2	5	5	5	5	5	21	0	0	1	0	0	5	5	5	1	5	0	10	5	5
Natural grassland	30	3	5	4	4	4	5	5	22	2	3	1	1	0	5	5	5	0	5	0	3	0	0	0	2	0	0	0	0	0	6	3	3
Moors and heathland	30	3	4	4	5	4	5	5	20	4	3	2	2	0	0	3	4	2	10	0	2	0	0	0	1	0	2	2	0	0	10	5	5
Sclerophyllous vegetation	21	3	4	2	3	3	4	2	7	2	1	1	1	0	0	0	0	2	8	0	2	0	0	0	1	0	2	0	3	0	6	2	4
Transitional woodland shrub	21	3	4	2	3	3	4	2	3	1	0	0	0	0	0	0	0	2	5	0	2	0	0	0	1	0	2	1	0	0	4	2	2
Beaches, dunes and sand plains	10	3	3	1	1	1	0	1	6	0	0	5	1	0	0	0	0	0	2	0	0	0	0	0	0	0	0	1	0	0	7	5	2
Bare rock	6	3	3	0	0	0	0	0	3	0	0	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	4	4	0
Sparsely vegetated areas	9	2	3	1	0	1	1	1	3	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Burnt areas	6	2	1	0	0	0	0	3	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Glaciers and perpetual snow	3	2	1	0	0	0	0	0	10	3	3	0	4	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	5	5	5	0
Inland marshes	25	3	2	4	4	4	3	5	14	2	2	4	2	0	0	4	0	0	7	0	2	5	0	0	0	0	0	0	0	0	0	0	0
Peatbogs	29	3	4	4	4	4	5	5	24	4	5	3	3	0	0	3	4	2	5	0	0	0	0	0	0	0	0	2	0	0	8	4	4
Salt marshes	23	2	3	4	3	3	3	5	8	1	0	5	0	0	0	2	0	0	2	0	2	0	0	0	0	0	0	0	0	0	3	3	0
Salines	2	1	1	0	0	0	0	0	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	0
Intertidal flats	13	2	3	0	2	1	4	1	7	1	0	5	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	4	4	0
Water courses	18	4	4	0	3	3	3	1	10	1	0	2	1	0	0	3	3	0	12	0	0	0	3	0	4	0	0	3	0	5	10	5	5
Water bodies	23	4	4	0	4	4	3	4	7	2	1	1	2	0	0	1	0	0	12	0	0	0	3	0	4	0	0	0	0	5	9	5	4
Coastal lagoons	25	4	4	0	5	5	3	4	5	1	0	4	0	0	0	0	0	0	16	0	0	0	4	5	4	0	0	1	0	0	9	5	4
Estuaries	21	3	3	0	5	5	3	2	9	0	0	3	0	0	0	3	3	0	17	0	0	0	5	5	4	0	0	2	0	0	7	4	3
Sea and ocean	15	2	2	0	3	3	4	1	13	3	5	0	0	0	0	5	0	0	11	0	0	1	5	5	0	0	0	3	0	0	6	4	2

scale for assessing capacities:
0 = no relevant capacity
1 = low relevant capacity
2 = relevant capacity
3 = medium relevant capacity
4 = high relevant capacity
5 = very high relevant capacity

Fig. 2. Assessment matrix illustrating the capacities of different land cover classes to support ecological integrity (column at the left side) and to supply ecosystem services (the three columns at right). The values/colors indicate the following capacities:0/rosy = no relevant capacity; 1/grey green = low relevant capacity; 2/light green = relevant capacity; 3/yellow green = medium relevant capacity; 4/blue green = high relevant capacity; and 5/dark green = very high relevant capacity (after Burkhard et al., 2009).

3 = medium relevant demand; 4 red = high relevant demand; and 5 = very high relevant demand.

The matrix of Fig. 3 clearly shows that demands for ecosystem services are highest in human-dominated land cover types (in the upper part of the matrix). The highest demand values can be found in the urban, industrial and commercial areas. The more near-natural land cover types are characterized by generally lower population numbers and less ecosystem service-consuming activities and consequently, lower demand rates. The agricultural land cover types show characteristic high demands for regulating ecosystem services (e.g. nutrient regulation, water purification, pollination). Using similar spatially explicit units as during the ecosystem service supply assessment, respective maps of ecosystem services demands can be produced.

2.4. Mapping budgets of ecosystem services' supply and demand

For analyzing source and sink dynamics and to identify flows of goods and services, the information in the matrixes and maps of ecosystem service supply and demand can be merged. Supply and demands have to be quantified in the same units in order to be comparable. If the same units are not applicable, different units need to be reclassified into the relative 0–5 scale. As a result we get budgets of ecosystem service supply and demand. Fig. 4 shows the corresponding matrix of ecosystem service budgets within the different land cover classes. Each field in the budget matrix was calculated based on the corresponding field in the supply (Fig. 2) and the demand matrix (Fig. 3). The scale ranges from −5 = demand exceeds supply significantly = strong undersupply; via 0 = demand = supply = neutral balance; to 5 = supply exceeds the demand significantly = strong oversupply. Empty fields indicate that there is neither a relevant supply of nor a relevant demand for the particular ecosystem service. For more detailed information on actual supply–demand patterns including specific areas of supply and demand, an ecosystem service footprint could be calculated.

The pattern emerging in Fig. 4 indicates that there is an obvious undersupply of ecosystem services in the human-dominated land cover types, especially in the urban, industrial or commercial areas. The more near-natural land cover types again, and especially the forested areas, are characterized by many ecosystem services' supplies exceeding their demands.

2.5. Exemplary quantification of energy supply and demand in the rural-urban region Leipzig-Halle

As an example for a detailed quantitative assessment of ecosystem service supply and demand, we calculated the provisioning ecosystem service "energy" for the rural-urban region Leipzig-Halle in Eastern Germany. Rural-urban regions reflect today's complex interactions and dependencies between different spatial categories within urban agglomerations. They are defined as being composed of the urban area, the peri-urban area and the rural hinterland (Ravetz et al., 2010). Being situated in the former German Democratic Republic, the Leipzig-Halle region experienced severe societal, economic, demographic and land use related changes during the post-socialist transition period after

CORINE land cover type:	Regulating services	Local climate regulation	Global climate regulation	Flood protection	Groundwater recharge	Air Quality Regulation	Erosion Regulation	Nutrient regulation	Water purification	Pollination	Provisioning services	Crops	Livestock	Fodder	Capture Fisheries	Acquaculture	Wild Foods	Timber	Wood Fuel	Energy	Biochemicals / Medicine	Freshwater	Cultural services	Recreation& Aesthetic Values	Intrinsic Value of Biodiversity
Continuous urban fabric		5	3	4	5	5	1	1	1	3		5	5	1	5	5	5	3	2	5	5	5		4	2
Discontinuous urban fabric		5	3	5	5	5	1	2	2	4		4	4	2	4	4	4	3	3	4	5	5		4	3
Industrial or commercial units		1	5	4	5	5	1	3	3	4		5	5	5	4	4	4	5	5	5	5	5		1	1
Road and rail networks		2	4	4	1	4	3	0	0	1		0	0	0	0	0	0	2	0	4	0	1		2	0
Port areas		2	3	5	2	2	4	0	3	1		2	2	2	2	2	1	5	2	5	1	3		2	1
Airports		2	5	1	1	4	1	1	2	0		2	2	0	1	1	1	1	0	5	1	3		1	0
Mineral extraction sites		0	0	2	4	0	4	0	0	0		0	0	0	0	0	0	2	0	3	0	2		0	0
Dump sites		2	2	0	2	3	0	0	2	0		0	0	0	0	0	0	0	0	1	0	2		0	0
Construction sites		2	0	2	0	1	2	2	2	0		0	0	0	0	0	0	4	0	4	0	2		0	0
Green urban areas		2	0	0	1	1	0	0	0	2		1	1	0	0	0	0	0	0	1	0	2		4	1
Sport and leasure facilities		2	0	0	2	3	0	0	1	0		2	2	1	2	2	2	1	1	3	3	3		3	0
Non-irrigated arable land		2	2	2	0	1	2	3	0	3		1	0	0	0	0	0	0	0	1	1	0		0	0
Permanently irrigated land		2	2	2	5	1	2	3	5	3		1	0	0	0	0	0	0	0	2	1	5		0	0
Ricefields		3	4	5	5	1	5	3	5	1		1	0	0	0	0	0	0	0	2	1	5		0	0
Vineyards		5	2	0	3	1	5	3	4	2		1	0	0	0	0	0	1	0	2	2	4		0	0
Fruit trees and berries		2	1	0	3	1	1	3	2	5		1	0	0	0	0	0	1	0	2	2	3		0	0
Olive groves		2	1	0	1	1	0	2	2	2		1	0	0	0	0	0	0	0	1	2	1		0	0
Pastures		1	3	1	0	0	0	1	2	0		0	1	3	0	0	0	1	0	1	1	2		0	0
Annual and permanent crops		1	1	1	1	1	1	5	2	2		1	0	0	0	0	0	0	0	2	1	1		0	0
Complex cultivation patterns		1	1	1	1	1	1	5	2	3		1	0	0	0	0	0	0	0	2	1	1		0	0
Agriculture & natural vegetation		1	2	0	1	1	1	3	2	2		1	0	0	0	0	0	0	0	2	1	2		0	0
Agro-forestry areas		1	1	0	1	1	0	3	2	2		1	0	0	0	0	0	0	0	1	1	2		0	0
Broad-leaved forest		0	0	0	0	0	0	0	0	0		0	0	0	0	0	1	1	1	0	0	0		0	0
Coniferous forest		0	0	0	0	0	0	0	0	0		0	0	0	0	0	1	1	1	0	0	0		0	0
Mixed forest		0	0	0	0	0	0	0	0	0		0	0	0	0	0	1	1	1	0	0	0		0	0
Natural grassland		0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0		0	0
Moors and heathland		0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0		0	0
Sclerophyllous vegetation		0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0		0	0
Transitional woodland shrub		0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0		0	0
Beaches, dunes and sand plains		0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0		1	1
Bare rock		0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0		0	0
Sparsely vegetated areas		0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0		0	0
Burnt areas		0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0		0	0
Glaciers and perpetual snow		0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0		0	0
Inland marshes		0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0		0	0
Peatbogs		0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0		0	0
Salt marshes		0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0		0	0
Salines		0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0		0	0
Intertidal flats		0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0		0	0
Water courses		0	0	0	0	0	0	0	0	0		0	0	0	1	0	0	0	0	0	0	0		0	0
Water bodies		0	0	0	0	0	0	0	0	0		0	0	0	1	0	0	0	0	0	0	0		0	0
Coastal lagoons		0	0	0	0	0	0	0	0	0		0	0	0	1	0	0	0	0	0	0	0		0	0
Estuaries		0	0	0	0	0	0	0	0	0		0	0	0	1	0	0	0	0	0	0	0		0	0
Sea and ocean		0	0	0	0	0	0	0	0	0		0	0	0	1	0	0	0	0	0	0	0		0	0

scale for assessing demands:

- 0 = no relevant demand
- 1 = low relevant demand
- 2 = relevant demand
- 3 = medium relevant demand
- 4 = high relevant demand
- 5 = very high relevant demand

Fig. 3. Assessment matrix illustrating the demands for ecosystem services of humans living within the different land cover classes. The values/colors indicate the following demands: 0/rosy = no relevant demand; 1/dark rosy = low relevant demand; 2/light red = relevant demand; 3/red = medium relevant demand; 4/dark red = high relevant demand; and 5/brown red = very high relevant demand.

1990 (Nuissl and Rink, 2005). Land use changes include increasing housing, industrial and traffic areas at the cost of agricultural land and the increase of semi-natural areas, forests and water bodies due to the restoration of several huge lignite open mining pits (see land cover maps in Figs. 5 and 6; top left).

We quantified the supply and demand of energy as well as the budgets of both for the years 1990 and 2007. In doing so, we linked spatial and statistical data of energy supply and demand to CORINE land cover maps of the respective years (German Federal Environment Agency, 2004, 2006) (Figs. 5 and 6; top left). The energy supply was calculated in GJ final energy per hectare land cover type during the respective year. For that, the different energy resources used in the region in 1990 and 2007 were identified and assigned to the corresponding land cover types that were responsible for the energy provision. The identified energy resources, corresponding land cover types, scales of quantification and data sources used are summarized in Table 3.

The energy demand was calculated in the same unit as the supply (GJ final energy per hectare per year) in order to guarantee the direct comparability of supply and demand. For that purpose, statistical data on energy demands of households, the service sector, industry, traffic, mining and agriculture were applied and values of energy demand per hectare of the respective land cover types were calculated. The calculated energy demand and supply values per hectare land cover type and (where appropriate) per municipality or Federal State, were linked to the CORINE land cover

Table 3
Energy resources, corresponding land cover types, scales and data sources used for the quantification of energy supply in the case study region Leipzig-Halle.

Energy resources	Land cover type	Quantification scale	Data sources
Solar energy	Urban and industrial area	Municipality	Vattenfall Europe AG (2009)
Wind energy	Agricultural area	Municipality	Vattenfall Europe AG (2009)
Energy crops	Agricultural area	Federal State	Ministry for Agriculture and Environment Saxony-Anhalt (2002, 2007), Saxon State Ministry of the Environment and Agriculture (2007), Institute for Energy and Environment (2007)
Lignite	Mineral extraction sites	Mineral extraction site	Saxon State Department of the Environment and Geology (2004), Saxon Upper Mining Authority (2002, 2007)

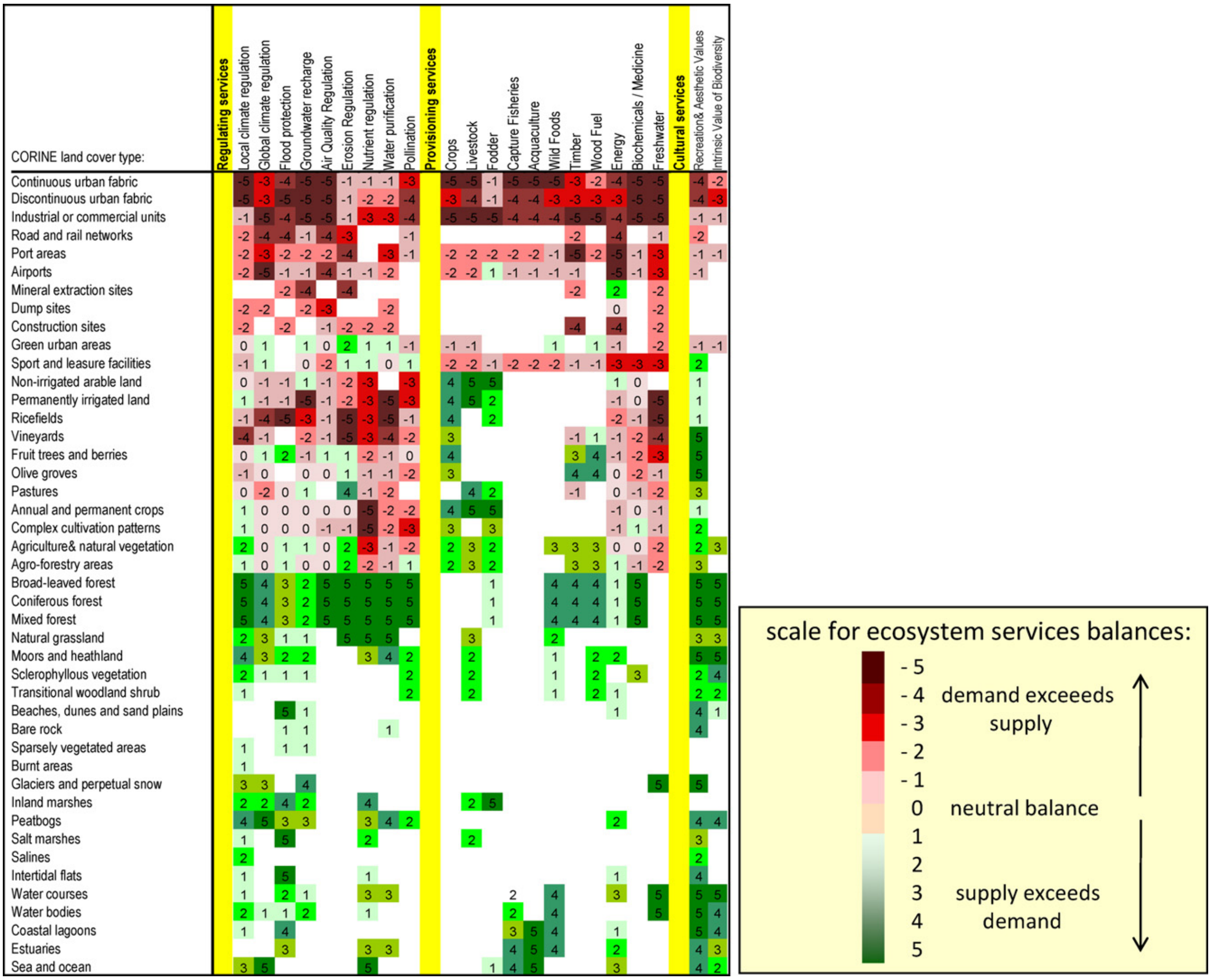

Fig. 4. Assessment matrix illustrating budgets of ecosystem services' demand and supply (matrices in Fig. 2 and Fig. 3) within the different land cover classes. The values/colors indicate budgets from −5/brown red = demand exceeds supply significantly = undersupply; via 0/rosy = demand = supply = neutral balance; to 5/dark green = supply exceeds the demand significantly = oversupply. Empty fields indicate neither relevant supply of nor relevant demand for the particular ecosystem service.

maps of the years 1990 and 2006 in order to produce comparable maps of energy supply and demand. CORINE data for the year 2007 are not available. Hence, there is one year difference between the CORINE data and the statistical data from 2007, which seems to be acceptable. The resulting values were then grouped into the above described classes ranging from 0 (no relevant capacity/no relevant demand) to 5 (very high relevant capacity/very high relevant demand).

Subsequently, the maps of energy supply and demand were intersected and spatially explicit energy budget maps were computed by subtracting energy demand values from energy supply values of each land cover polygon. The resulting values were grouped into classes ranging from −5 (demand exceeds the supply significantly) to +5 (supply exceeds the demand significantly). Values near 0 indicate a balanced budget, i.e. the supply fits the demand. For a more detailed description of energy supply and demand quantifications, data sources used for energy demand calculations as well as further ecosystem service quantifications see (Kroll et al., 2012).

3. Results

The resulting maps of the Leipzig-Halle case study area show the spatial distribution of the provisioning ecosystem service energy supply, related demands for energy and respective energy supply/demand budgets for the years 1990 and 2007 (Figs. 5 and 6). The units in all six ecosystem service maps are final energy in GJ per hectare per year. The legends were classified according to the 0–5 classes used in the ecosystem service matrices (Figs. 2–4). On the figures' top left are the CORINE land cover maps from the years 1990 and 2006 which provided the spatial reference and basic land cover information. Within the EU project PLUREL[2], further ecosystem service supply and demand in the Leipzig-Halle region were calculated and mapped; including food provision (supply and demand in GJ/ha per year), global climate regulation (supply and demand of CO_2 sequestration in t CO_2/ha per year) and water supply and demand (m^3/ha per year); see (Kroll et al., 2012) and www.plurel.net. In the following we will focus on examples from energy provisioning ecosystem services.

3.1. Capacities to supply energy provisioning ecosystem services

The energy supply map for the year 1990 (Fig. 5; top right) shows that exclusively the large lignite open mining pits were used as energy sources in that period. They provided a vast amount

[2] http://www.plurel.net/

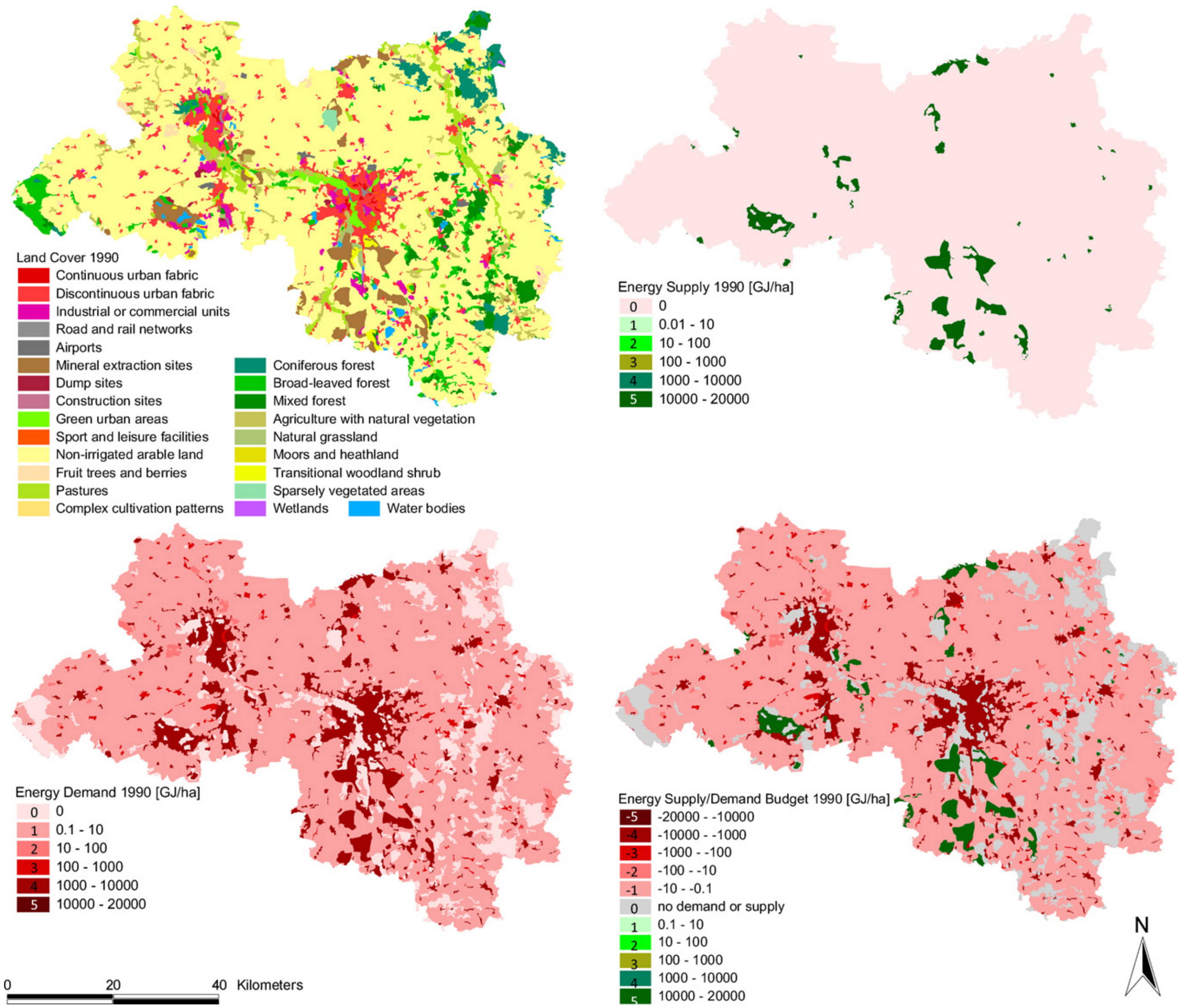

Fig. 5. CORINE land cover map 1990 (top left); maps of energy supply (top right) and energy demand (bottom right); and budget map of energy supply and demand (bottom right) for the rural-urban region of Leipzig-Halle, Germany in the year 1990 (energy data in GJ/ha/year).

of 20,000 GJ of final energy per hectare and year. This number decreased by almost two thirds until 2007 due to a reduction in mining areas and a reduced amount of extracted lignite (map in Fig. 6; top right). Additionally, the use of the renewable energy sources like wind, biomass, water and sun has appeared in the region during the years until 2007. Wind energy was the most important renewable energy source. All renewable energy sources contributed less than 7% of the total final energy supply in the region in 2007. In contrast to the locally discrete lignite mining areas, renewable energy facilities occur area-wide. This becomes very clear when comparing the maps from 1990 and 2007. In 1990, only the two extreme capacity classes are present, showing the maximum capacity (5) in the lignite pits and no relevant capacity (0) in all other areas. In 2007, a broad range of capacities is distributed more or less equally over the whole area. Of course, renewable energy facilities are locally discrete phenomena in reality as well. During the mapping process their locations have been joined to the land cover classes' polygons and thus, their attributes were extrapolated to larger spatial extensions. Moreover it has to be noticed that most changes in energy provision were not related to relevant changes in land cover types. Most of the existing land cover types did not change between 1990 and 2007. Instead, the actual land use was modified by adding renewable energy facilities on for example existing arable land.

3.2. Human demands for energy provisioning ecosystem services

The energy demand data show a different picture: the highest values can be found in industrial and commercial units, followed by urban fabric and traffic areas as well as mineral extraction sites. As the energy demand per hectare urban area depends on the population density, it was the highest in the city centers of Leipzig and Halle. The respective maps (Figs. 5 and 6; bottom left) show the area-wide occurrence of energy demand and its concentration in the areas mentioned above. Energy demand decreased by almost 20% from 1990 to 2007 due to declining population, decline of energy-intensive industrial activities as well as more energy-efficient technologies. Nevertheless, the temporal changes in the demand maps are not as obvious as in the supply maps.

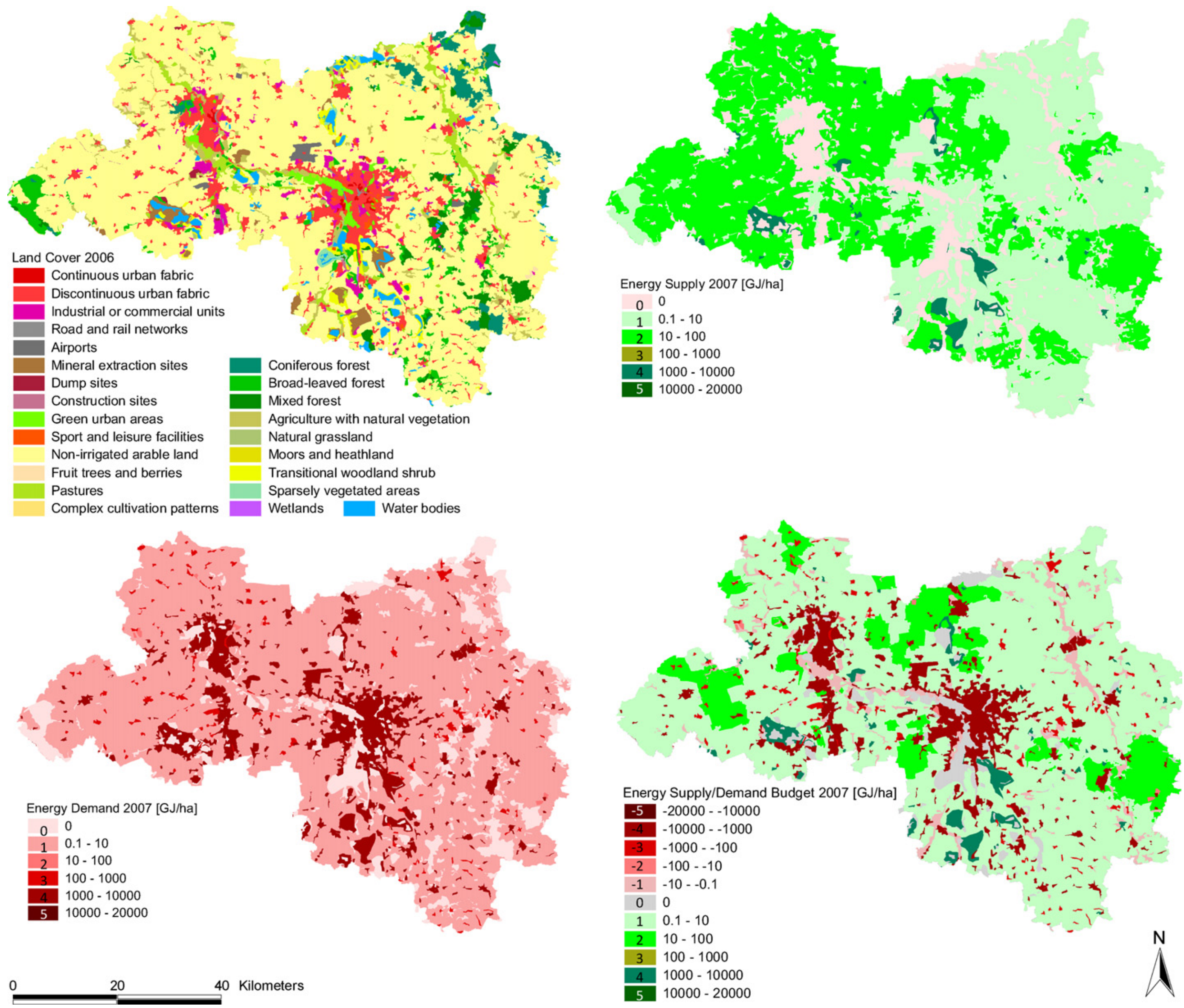

Fig. 6. CORINE land cover map 2006 (top left); maps of energy supply (top right) and energy demand (bottom right); and budget map of energy supply and demand (bottom right) for the rural-urban region of Leipzig-Halle, Germany in the year 2007 (energy data in GJ/ha/year).

3.3. Budgets of energy provisioning ecosystem services' supply and demand

The energy provisioning ecosystem services supply–demand budget maps indicate dynamics in the production-consumption respectively source-sink patterns. In the year 1990 (Fig. 5; bottom right), when lignite was the only energy supplier in the region, all areas in the region (except the mineral extraction sites) can be characterized as sinks of energy provisioning ecosystem services. Especially the urban, industrial and commercial areas but also the rural regions were dependent on flows of energy supplied in only one land cover type. A different pattern emerges for the year 2007 (Fig. 6; bottom right). Even though the urban, industrial and commercial areas are still remarkable sinks of energy provisioning services, the amount and spatial extension of areas with oversupply of energy have been increasing significantly due to the area-wide use of renewable energy sources. In combination with decreasing energy demands, the former dependence on only one source of energy supply could be reduced on the one hand. On the other hand, several open pit mining areas were closed down between 1990 and 2007 (compare the CORINE land cover maps in Figs. 5 and 6; top left), reducing the energy supply by lignite.

4. Discussion

The maps illustrate the temporal dynamics of the spatial supply and demand distributions in the case study area using the example of energy provisioning ecosystem services for 1990 and 2007. For some land cover types, the case study capacity values do not match exactly with the initial hypotheses values provided for energy provision in the ecosystem service supply matrix (Fig. 2; for example green urban areas). However, the majority of hypotheses values were corroborated.

Supplementary data from statistics can improve the interpretation of the maps. For example, calculations of supply/demand ratios for the energy provisioning ecosystem services provide information on the total budget and the energy self-sufficiency of the whole case study region. The supply/demand ratio was above 1 in 1990, indicating that the energy supply (solely based on lignite) in the region was higher than the demand (data references can be found in Table 3). Then, several open pit mining areas were closed down between 1990 and 2007 (compare the CORINE land cover maps in Figs. 5 and 6; top left) and the lignite output has been reduced. As a consequence, the whole case study region's supply/demand ratio declined to 0.5, indicating a clear dependence on energy imports (data references in Table 3).

There is an ongoing debate within the ecosystem service research community on whether natural resources are to be denoted as ecosystem services or not. Lignite (fossil fuels in general), wind as well as solar energy have for example been denoted as usually non-renewable abiotic resources which can neither be attributed to specific ecosystems nor be called ecosystem services (de Groot et al., 2002). We do not agree with this as wind and solar energy are renewable inexhaustible natural services. In the case of fossil fuels we conclude that it is actually depending on the temporal perspective (exchangeable by or in combination with higher temperature and pressure), whether a resource is called renewable or not. The production function "raw materials" was defined by de Groot et al. (2002; p. 396) as "the conversion of solar energy into biomass for human use", which is exactly what initially took place during fossil fuel formation. Therefore we suggest denoting all goods and services provided by every natural system to benefit human well-being as ecosystem goods and services.

Looking at our ecosystem service mapping approach in general, several points worth discussing emerge. One major issue, not really addressed yet, refers to questions related to spatial and temporal scales. Considering our approach to be a generic conceptual model, it can be applied at any scale and would use data appropriate to the scale of analysis. Nevertheless, resolutions reflecting peculiarity of the given habitats and temporal dynamics have to be chosen. It seems like the CORINE data set and statistics based on annual values are suitable starting points. For more detailed analyses, further data with higher spatial (e.g. land survey data, airphotos, topographic maps) and temporal (seasonal or monthly) resolution could be used. With regard to the values in the matrices (Figs. 2–4), it has to be taken into account that no real weighting system between the different services was applied. Therefore, also the calculated sums for the different ecosystem service groups in the matrices provide only an overview on total service provision with only limited accuracy when used for detailed interpretation.

One major shortcoming in the maps presented for our case study is the inherent scale mismatch between supply and demand. On the one hand, the supply of energy provisioning ecosystem services could explicitly be related to respective supplying spatial units. The demand for energy on the other hand was based on data on spatially explicit final energy consumption but did not consider where this energy was actually generated. Hence, real energy flows between areas of supply and demands cannot be calculated based on this information. Especially with today's globalized trade systems including intercontinental cables, pipelines and trade routes, origins and transport paths of a broad range of ecosystem services are difficult to track. This is especially the case for provisioning ecosystem goods and services (food, energy, material). Ecosystem functions (ecological integrity) and regulating services are often characterized by more or less physically connected areas of supply and demand. Most of these functions and services have to be utilized or consumed at the same or a nearby locality from where they are supplied, e.g. biomass production based on exergy capture, large scale soil formation, (natural) pollination, nutrient regulation, erosion control or flood regulation; (Nedkov and Burkhard, 2012).

Nevertheless, there are also regulating ecosystem services with scale mismatches and delocalized causes and effects. One prominent example is global climate regulation, where a global demand is supplied by local ecosystem functions. Another tricky point is the proper assessment of cultural ecosystem services. Despite the rather common (but nevertheless still not solved) difficulties inherent to all intangible service assessments (Vejre et al., 2010; Gee and Burkhard, 2010), we encountered additional problems when defining spatial units of actual cultural ecosystem service "consumption". Are benefits like recreation, education or spiritual enrichment consumed immediately at the place of their supply or are they taken home to the place where people live for the most time of the year? For the moment we decided to apply a consistent way of thinking as for the other ecosystem services. Thus, people's home places are defined as spatial units of ecosystem service benefits, also with regard to cultural ecosystem services.

5. Conclusion

Mapping ecosystem service supply and demand and especially the quantifying information behind these maps are important contributions toward the applications of the ecosystem service approach in science as well as in practice. Today's ecosystem service demand and consumption are far from being driven by actual supply; maps can help to visualize this mismatch. Certainly the demand side has been neglected in most ecosystem service studies so far, perhaps as data on demands are more difficult to collect than data on production or costs (Ellis and Fisher, 1987). By adding ecosystem service demand and budget matrices and corresponding maps to our approach on ecosystem service supply maps presented before (Burkhard et al., 2009), we hope to initiate further discussions and to foster the development of appropriate tools.

Starting with matrices (as presented above) which are filled by expert evaluations provides a rather easy tool to begin the ecosystem service assessments with. Expert hypotheses deliver a good overview and "even imperfect measures of their [ecosystem services] value, if understood as such, are better than simply ignoring ecosystem services altogether, as is generally done in decision making today" (Daily, 1997, p. 8). Levels of complexity and data accuracy can then be increased successively. By using a "neutral" relative scale (0–5), value-laden units (such as monetary terms) can be avoided and a variety of data sources (e.g. monitoring, statistics, expert judgment, literature review, on-site assessment) can be harmonized.

The selection of appropriate temporal and spatial scales as well as appropriate system borders is crucial for ecosystem service assessments. For mainly imported services (e.g. in urban regions), a concept of ecosystem service footprints should be developed. For local or regional decision making, trade-offs between the particular services can be calculated. For example in our Leipzig-Halle case study, the increase of energy crop cultivation negatively impacts the regional food production. The decreased lignite extraction again negatively influences the energy, but positively influences the water supply (Kroll et al., 2012).

Besides the case study presented here, this assessment and mapping approach has already been applied in further case studies (see Table 2). These applications showed that one main obstacle in the evaluation of ecosystem services is the lack of appropriate data for the quantification of the individual services' supply and demand. Therefore, the development of corresponding research projects, monitoring schemes, capacity building and further national ecosystem service assessments is suggested in order to implement the concept of ecosystem services as a solution for human–environmental problems and to provide a better data base for the mapping of ecosystem services.

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