Ecosystem Services xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Ecosystem Services

journal homepage: www.elsevier.com/locate/ecoser

Integrating ecosystem service bundles and socio-environmental conditions – A national scale analysis from Germany

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A R T I C L E I N F O

Article history:
Received 30 September 2016
Received in revised form 20 July 2017
Accepted 11 August 2017
Available online xxxx

Keywords:
Hot spots
Landscape stratification
Self-organizing maps
Spatial analysis
Spatial clustering
Trade-offs

A B S T R A C T

Understanding the relationship and spatial distribution of multiple ecosystem services (ES) in the context of underlying socio-environmental conditions is an essential element of national ecosystem assessments. Here, we use Germany as an example to present a reproducible blueprint approach for mapping and analysing ecosystem service bundles (ESB) and associated socio-environmental gradients. We synthesized spatial indicators of eleven provisioning, regulating and cultural ES in Germany and used the method of self-organizing maps (SOM) to define and map ESBs. Likewise, we collated data from 18 covariates to delineate socio-environmental clusters (SEC). Finally, we used an overlap analysis to characterise the relationship between the spatial configuration of ESBs and co-occurring SECs. We identified and mapped eight types of ESBs that were characterized to varying degrees by provisioning, cultural and regulating/maintenance services. While ESBs dominated by provisioning ES were linked to regions with distinct environmental characteristics, cultural ESBs were associated with areas where environmental and socio-economic gradients had similar importance. Furthermore, spatial stratification of ESBs indicated hot spots where more detailed analysis is needed within national assessments. Our approach can serve as a blueprint for ESB analysis that can be reproduced in other geographical and environmental settings.

1. Introduction

Since the *Millennium Ecosystem Assessment* (MA, 2005), ecosystem services (hereafter ES) have received increasing attention in science and public to safeguard human livelihood and biodiversity. This is reflected in *The Strategic Plan for Biodiversity 2011–2020* of the *Convention on Biological Diversity* (CBD, 2010), e.g. in the Aichi target goal D aiming to "enhance the benefits to all from biodiversity and ecosystem services" on a global scale. Furthermore the *Intergovernmental Platform on Biodiversity and Ecosystem Services* (IPBES, 2017) was founded to improve the science-policy exchange and to support assessments in this area. At the European scale the *EU Biodiversity Strategy to 2020* (European Commission, 2011) declares the aim of maintaining and restoring ecosystems to ensure the continuous provision of ecosystem services. Specifically, Action 5 of Target 2 requires EU member states to "map and assess the state and economic value of ecosystems and their services" and to "promote the recognition of their economic worth into accounting and reporting systems across Europe". Thus, spatially-explicit mapping of ecosystem services and a comprehensive synthesis of ES information in the context of the underlying environmental and socio-economic conditions are required by policy makers to tackle future challenges.

Several European countries have either initiated or compiled (sub-)national ecosystem assessments (eight of which are reviewed in Schröter et al., 2016). These efforts range from the collection of suitable ES indicators in Germany (Albert et al., 2015; Rabe et al., 2016) and Switzerland (Staub et al., 2011), to the completion of full ecosystem assessments (e.g. UK NEA, 2011). These programs differ widely regarding the aims, political context, spectrum of methods and level of implementation (Schröter et al., 2016). Maes et al. (2016) developed a conceptual framework for ecosystem assessments in the EU to support future national mapping efforts and to allow comparability among member states. This framework proposes a typology of available ES indicators based on the *Common International Classification of Ecosystem Services* (CICES; Haines-Young and Potschin, 2013), while taking into account data availability at the European level and the ability to convey information to policy and decision makers.

(Sub-)national assessments, which are a time-consuming endeavour (e.g. the UK National Ecosystem Assessment involved more than 600 authors and took two years), should synthesise information on ES for decision makers (Maes et al., 2013). Analys-

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http://dx.doi.org/10.1016/j.ecoser.2017.08.007
2212-0416/

ing ecosystem service bundles (hereafter ESB), defined as "sets of services that appear repeatedly together" (Raudsepp-Hearne et al., 2010), is an efficient way to compile and convey such information. ESBs allow a systematic and synoptic description of landscapes based on the importance and co-occurrence of different ES. This provides insights regarding differences in ES provision and use across space (e.g. Turner et al., 2014; Queiroz et al., 2015) and time (Renard et al., 2015). Furthermore, the consideration of multiple ES is essential to obtain a greater understanding of how ES trade-offs and synergies (*sensu* Raudsepp-Hearne et al., 2010) may change within and between regions. However, ESB studies rarely include a thorough analysis of environmental and socio-economic covariates to understand how the composition of ESBs is linked to nature and society (but see Renard et al., 2015; Crouzat et al., 2015).

Given the current diversity of methods for analysing associations between ES (Mouchet et al., 2014), our goal here is to present a transferable and widely applicable blueprint for analysing ESBs at regional to national scales. The key component is the application of self-organizing maps (SOM, Skupin and Agarwal, 2008), an unsupervised clustering technique based on artificial neural networks, that was recently featured by Mouchet et al. (2014) as an efficient way to delineate ESBs. SOM reduce high-dimensional data by grouping observations based on their similarities while it preserves topological properties of input data (Skupin and Agarwal, 2008) and thus it is suitable for spatially-explicit mapping of co-occurring ES. The ability of SOM to visualize clustered patterns in complex data is widely acknowledged in environmental sciences, e.g. in studies of ecological communities (Giraudel and Lek, 2001), in water related applications (Kalteh et al., 2008) or in mapping of European and global land systems (Levers et al., 2015; Václavík et al., 2013).

Focusing on Germany as a case study, we propose a reproducible approach which integrates ESBs with socio-environmental conditions and can assist other EU member states in fulfilling the basic requests of the *EU Biodiversity strategy to 2020* (European Commission, 2011). This approach comprises a series of steps. First, we start with the collection and harmonization of spatial data on ecosystem service indicators as well as socio-environmental covariates. Second, we delineate ecosystem service bundles and socio-environmental clusters (SEC; see Section 2.5 for details) using the SOM method. Finally, we describe the relationship between the spatial configuration of ESBs and SECs based on an overlap analysis. To illustrate the main outcomes, we present spatially-explicit maps that highlight the regional patterns in ecosystem service provisioning and underlying socio-environmental gradients. This approach allows us to answer the following questions, relevant to science, policy and management, and partly raised also in recent ES studies (Bennett et al., 2009; Raudsepp-Hearne et al., 2010; Turner et al., 2014; Schmidt et al., 2016):

Q1 Which ecosystem services are most important for a specific region and form ecosystem service bundles? How are these bundles distributed in space?
Q2 Which regions provide a multitude of ecosystem services potentially indicating multifunctionality?
Q3 Which are the focus areas (hot spots) to be studied in more detail within a national ES assessment and to pinpoint future research and management questions?
Q4 How is the composition of existing ecosystem service bundles linked to social and environmental gradients?

2. Materials and methods

2.1. Study area

Germany, being the fourth largest country within the European Union by area (Eurostat, 2014), underwent far-reaching land-use changes after the Second World War. This process characterized by land-use intensification, further mechanisation and specialisation of agricultural systems together with industrial livestock farming and intensive grassland management (e.g. Antrop, 2005) changed the provisioning of and demand for various ES. These factors led to major trade-offs, e.g., agricultural production vs. water purification (Berka et al., 2001) or biodiversity conservation (Flynn et al., 2009). Forest areas, mainly located in Southwestern and Southern Germany at higher altitudes as well as Eastern Germany, account for 34% of the total land area. Cropland occupies 33% of the total land area, mainly located in Central and Northeastern Germany as well as in the lowlands of Southern Germany. Grasslands are mainly located in Northern and Northwestern Germany as well as at average heights in the hilly and mountainous regions and account for 23% of the total land area. Both cropland and grassland area are above the European average. Germany has a coast line with the Baltic Sea and the North Sea in the North whereby Mountainous regions characterize Southern Germany. Even though the German reunification took place more than 25 years ago, socio-economic differences between the eastern and western part are still apparent today (Damm et al., 2015). Due to the organization of farmers in agricultural cooperatives in former German Democratic Republic (GDR), differences in the current land-use can also be detected, e.g. leading to variations in average field sizes ranging from 55 to 232 ha in Western and Eastern Germany, respectively (Gurrath, 2011). The sovereignty of the 16 federal states poses large challenges regarding the collection and harmonization of spatial environmental data.

2.2. Ecosystem service indicators

Following the framework of Maes et al. (2016), who proposed 27 indicators for mapping 21 ES in terrestrial and freshwater ecosystems throughout Europe, we collected 12 indicators representative for eleven ES (see Table 1 and Appendix A.1). The main criteria for selecting ES indicators were also data availability and geographical coverage which in turn were strongly affected by the federal German system. Seven out of the eleven ES employed in our analysis have been identified as being of high importance for Germany (see Table A3 in Rabe et al., 2016). To ensure comparability with other ES studies in Germany (Albert et al., 2015; Rabe et al., 2016) and enhance reproducibility of our approach in other countries, we applied the hierarchical CICES system (Haines-Young and Potschin, 2013) as typology. The mapped indicators refer to ES potential, supply or demand depending on the specific ES (see Maes et al., 2016).

The indicators used here result either from primary data or from different types of models and refer to different spatial scales or units (e.g., districts, regular grids, river basins; see Table 1). To harmonize the various data sets, we resampled all indicators to a regular grid of 10×10 km using the standardized European equal-area reference system developed for statistical mapping (ERTS89). This reference grid, representing a compromise between the fine and coarse-scale data available, was also used to aggregate the analysed environmental and socio-economic covariates. To improve downscaling of district level data, we employed high resolution land-use data (GeoBasis-DE/BKG, 2010) and calculated the exact proportion of individual land-use categories for each reference grid cell. For example, we used the proportion of grassland per grid cell to spatially allocate estimates of the total number of livestock units per reference cell based on data about average numbers of livestock units per hectare available only at district level (see Appendix A.1). For data at finer resolution than 10×10 km, the average value per reference grid cell was calculated. As urban ecosystems and their ES have special characteristics and cannot be assessed easily with the same indicators as non-urban ecosys-