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Mapping social–ecological systems: Identifying 'green-loop' and 'red-loop' dynamics based on characteristic bundles of ecosystem service use

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ABSTRACT

We present an approach to identify and map social–ecological systems based on the direct use of ecosystem services by households. This approach builds on the premise that characteristic bundles of ecosystem service use represent integrated expressions of different underlying social–ecological systems. We test the approach in South Africa using national census data on the direct use of six provisioning services (freshwater from a natural source, firewood for cooking, firewood for heating, natural building materials, animal production, and crop production) at two different scales. Based on a cluster analysis, we identify three distinct ecosystem service bundles that represent social–ecological systems characterized by low, medium and high levels of direct ecosystem service use among households. We argue that these correspond to 'green-loop', 'transition' and 'red-loop' systems as defined by Cumming et al. (2014). When mapped, these systems form coherent spatial units that differ from systems identified by additive combinations of separate social and biophysical datasets, the most common method of mapping social–ecological systems to date. The distribution of the systems we identified is mainly determined by social factors, such as household income, gender of the household head, and land tenure, and only partly determined by the supply of natural resources. An understanding of the location and characteristic resource use dynamics of different social–ecological systems allows for policies to be better targeted at the particular sustainability challenges faced in different areas.

1. Introduction

Addressing the pressing challenges of global change and sustainable development demands a better understanding of the complex interactions between humans and their environment (Future Earth, 2013; Griggs et al., 2013). Consequently, there has been a growing interest in the study of dynamic social–ecological systems and the ecosystem services (ES) they generate (Berkes et al., 2003; Carpenter et al., 2009; Millennium Ecosystem Assessment, 2005). While recent years have seen a concerted research effort into the spatial exploration and mapping of ES (Kareiva et al., 2011; Martínez-Harms and Balvanera, 2012), maps of social–ecological systems are much harder to find. Part of the challenge of mapping social–ecological systems is the complex nature of interactions between biophysical and social system components acting at different scales, which makes it difficult to assign clear spatial boundaries (Cilliers, 2001; Folke, 2007). Yet in the context of sustainability it is crucial to understand what kinds of systems are present in a landscape, as different configurations of societal interactions with nature are characterized by different resource use patterns, human well-being outcomes, development trajectories, and potentials for environmental traps or collapse (Cumming et al., 2014; Ostrom, 2007).

Cumming et al. (2014) recently identified two archetypal social–ecological systems with substantively different sustainability challenges and governance needs. Rural agricultural or 'green-loop' systems are characterized by high direct dependence on local ecosystems, and little or no external economy through which to secure natural resources from elsewhere. In these systems there is a direct feedback between human well-being and the degradation of the environment. On the other hand, in urban industrialized or 'red-loop' systems, almost all individuals in society secure their basic needs for food, water and other materials through markets supplied by distant ecosystems, resulting in a society that is largely disconnected from its local environment. These two system types face very different sustainability challenges. In the green-loop system, the challenge – especially in the face of growing

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populations – is to avoid a 'green trap' of ongoing poverty and excessive local degradation of ecosystems. In the red-loop system the challenge is to avoid overconsumption fuelled by increasing wealth and the disconnect between people and the environment, leading to over-exploitation of multiple, distant ecosystems, or the so-called 'red trap'. An ability to identify countries or parts of countries that are in these different social–ecological configurations, or in transition between them, is therefore essential in tailoring policies to manage the particular resource use and human well-being challenges in different areas.

To date, studies that have mapped social–ecological systems have typically relied on combining separate social and ecological data, either at a local scale based on surveys of human-perceived landscape value overlaid with biophysical information to identify 'social–ecological hotspots' (Alessa et al., 2008); or at a global scale by combining population data with land use and land cover information to create 'anthropogenic biomes' (Ellis and Ramankutty, 2008). However, given that social–ecological systems are complex adaptive systems (Levin et al., 2013), we expect that these systems are shaped by the interaction of social and ecological factors, which means that the emergent system boundaries are likely not simply additive combinations of social and ecological boundaries (Folke et al., 2007).

In this paper we explore characteristic bundles of ES use to identify and map social–ecological systems. A bundle of ES comprises a group of interacting services that co-occur in time and space (Bennett et al., 2009). The ES that make up a bundle arise from the interaction of social and ecological factors (Reyers et al., 2013). Crop production, for example, results from an interplay of seeds, soil, water and pollinators, but also depends on a farmer's skill, equipment and fertilizer subsidies. Different combinations of these factors could reflect different underlying social–ecological systems, which would lead to different levels of crop production, and therefore different ES bundles. However, not all definitions of ES found in the literature reflect the influence of social factors, as ES may be defined anywhere along a spectrum from ecological stocks (e.g. wetlands), to flows (e.g. water purification), to benefits (e.g. clean drinking water) that people make use of in support of human well-being (Nahlik et al., 2012). Here, we focus on ES in the form of locally available natural resources that are directly used by a household (e.g. firewood for cooking, subsistence crops, freshwater collected from a spring or river). We do not include ES that are produced far away from the household, and are potentially transported, processed, traded, and then used. We argue that the bundle of locally available ES that are directly used by households in a certain area is an integrated expression of how connected people are to their environment, and therefore a suitable metric for identifying that area's underlying social–ecological system, specifically whether it is a green-loop or red-loop type system.

The objective of this study is to develop and test an approach to mapping social–ecological systems based on characteristic bundles of direct ES use, to be used as a tool for identifying different system types in order to better target governance interventions in support of sustainability. We build upon an earlier study by Raudsepp-Hearne et al. (2010) who used a mix of ES indicators, ranging from ecological stock to use values, in mapping the distribution of ES bundles in a Canadian landscape. We examine whether this method can be adapted to map social–ecological systems at a national scale in South Africa, using ES bundles that reflect people's direct use of locally available ES. South Africa is an interesting case study because of its high biological, cultural, and socio-economic diversity which potentially generates different types of social–ecological systems alongside one another. We compare the resulting social–ecological systems with the anthropogenic biomes (or 'anthromes') developed by Ellis and Ramankutty (2008) to examine whether there are notable differences between the systems identified by our approach and those resulting from an overlay of social data and land use/cover data. Finally, we assess key predictor variables that explain the distribution of the social–ecological systems we have identified.

2. Methods

We mapped the direct use of six provisioning ES across South Africa, and performed a cluster analysis on ES bundles at different scales. Distinct ES bundle types were used to identify and map social–ecological systems. These systems were compared to anthromes, and analysed to find key predictors of their distribution.

2.1. Study area

South Africa has a population of 52 million people, and a total land area of 1,221,037 km^2 (Appendix A, Fig. A1). It is divided into three main tiers of government, from largest to smallest: provinces, district municipalities (here referred to as districts), and local/metropolitan municipalities (here referred to as municipalities). In total, there are 234 municipalities, 52 districts, and nine provinces. We chose municipalities as our focal unit of analysis as they are the most important spatial planning units for government in South Africa. The average size of the municipalities is 5217 km^2, ranging from 252 to 36,128 km^2. The average number of households per municipality is 61,753, ranging from 1784 to 1,434,856. The average district size is 23,477 km^2 with an average of 277,888 households.

2.2. Mapping direct use of ecosystem services

We evaluated six provisioning ES: animal production (livestock and poultry), crop production, use of freshwater from a natural source (a river or spring), use of firewood for cooking, use of firewood for heating, and use of natural building materials. We chose these ES based on their importance in providing the basic needs of people (food, water, fuel, shelter), as well as data availability. The level of direct use of each ES was measured as the percentage of households in the municipality (or district) that indicated using the particular ES sourced directly from their local environment. Therefore, if 20% of households stated that they used wood as cooking fuel in a given municipality, then 20% was the use value assigned to that ES for that particular administrative area. These data were derived from the 2011 national population census (Stats SA, 2012) in which about 15 million households were surveyed (data available at www.statssa.gov.za). The census was primarily designed to assess the distribution of government services across the country, but many questions included response variables that relate to the direct use of local natural resources by households (Appendix A, Table A1). Due to the design of the survey questions, it was not possible to combine the two uses for firewood (energy for cooking or heating) into one ES and they were evaluated as separate services.

All data were spatially depicted and analysed using ArcGIS 10.0 (ESRI, 2011). The most recent shapefiles for the different administrative boundaries were downloaded from the South African Municipal Demarcation Board (SAMDB, 2013). Spatial clustering of all services was determined using spatial autocorrelation (Global Moran's I statistic (Moran, 1950)). As the data were found to be non-normally distributed (based on Shapiro–Wilk tests and QQ plots), correlations were tested using Spearman's rank correlation coefficient for non-parametric data. All statistical analyses in this study were performed in R statistical software (R Development Core Team, 2012).