Global Environmental Change 34 (2015) 218–226

Contents lists available at ScienceDirect

Global Environmental Change

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

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

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ARTICLE INFO

Article history:
Received 16 January 2015
Received in revised form 12 June 2015
Accepted 17 July 2015
Available online xxx

Keywords:
Ecosystem services
Land use planning
Natural resource management
Human well-being
Sustainability
South Africa

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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http://dx.doi.org/10.1016/j.gloenvcha.2015.07.008
0959-3780/

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).

2.3. Mapping social–ecological systems

To identify municipalities in South Africa that share a similar bundle of direct ES use, a *k*-means cluster analysis was performed on all ES using the Hartigan–Wong algorithm (Hartigan and Wong, 1979) with 25 random starts and a maximum of 10,000 iterations to find the cluster solution with the lowest within-cluster sum of squares. The analysis was performed in R using the *k*-means function from the *stats* package (R Development Core Team, 2012). *K*-means clustering was deemed appropriate after results were verified using the *clValid* package in R, which lets a user determine the most appropriate method and an optimal number of clusters for a given dataset by comparing different clustering algorithms, validation measures (e.g. internal and stability measures), as well as different numbers of clusters (Brock et al., 2008). *K*-means clustering scored highest in the stability measures for the municipal dataset, and there was support for two or three clusters. The optimal number of clusters was set to three after a leveling of the decline in eigenvalues was confirmed at that point in a scree plot, though a two cluster analysis was also performed for comparison. ES bundles were visualized using star plots in R. The resulting clusters were mapped in ArcGIS to depict the distribution of areas sharing similar bundles of direct ES use. To explore the effect of scale in mapping social–ecological systems, we first varied the resolution (i.e. municipalities vs. districts) and then the extent of the analysis (i.e. national vs. provincial).

2.4. Comparison of social–ecological systems and anthromes

Anthropogenic biomes (v1)(Laboratory for Anthropogenic Landscape Ecology, 2010) were compared to the social–ecological systems we identified by calculating anthrome areas in each municipality using ArcGIS. The anthromes are derived from an overlay of population, land use and land cover data. Percentage covers were determined for each anthrome type in each of the system types we identified, as well as in South Africa as a whole.

2.5. Identifying predictors of social–ecological systems

Potential social and ecological predictor variables were calculated from census data or existing biophysical datasets and models based on land cover, rainfall etc. (Appendix A, Table A2). Predictors were chosen based on variables identified in the literature that may contribute to the use of natural resources at the household level. For example, there is much evidence for the influence of household income and gender of the household head on patterns of resource use, especially in southern Africa (Cavendish, 2000; Cocks et al., 2008; Shackleton and Shackleton, 2006). Similarly, the role of land tenure and access to common pool resources in determining natural resource use has long been thought to be important (Barbier, 1997; Hardin, 1968; Shackleton et al., 2001), and is included in this study as the amount of land under traditional authority rule (in other words, the amount of communal land). Population density and distance to a city are variables representing the rural–urban gradient, and have been shown to be significant factors in land use change and resource use (Irwin and Geoghegan, 2001; Pfaff, 1999). The ecological predictors have previously been used as proxy indicators for the potential supply of ES in landscapes (Egoh et al., 2008; O'Farrell et al., 2011; Reyers et al., 2009; SAfMA, 2004), and were chosen to test the influence of supply on the patterns of ES use in the different social–ecological systems.

To identify the most important predictors of the spatial pattern observed in the distribution of ES bundle types, a multinomial logit model was run on the results of the cluster analysis and the predictor variables (standardized to *z*-scores) at the municipal level. The analysis was performed in R using the *mlogit* package (Croissant, 2013) to calculate the log-odds (the log of the odds ratio) of a municipality in a reference category (in this case 'high direct use') changing membership to a different category (i.e. 'low direct use' or 'medium direct use') as a function of social and ecological predictor variables. A principal component analysis (PCA) was also run on the municipal data to analyse the variation in

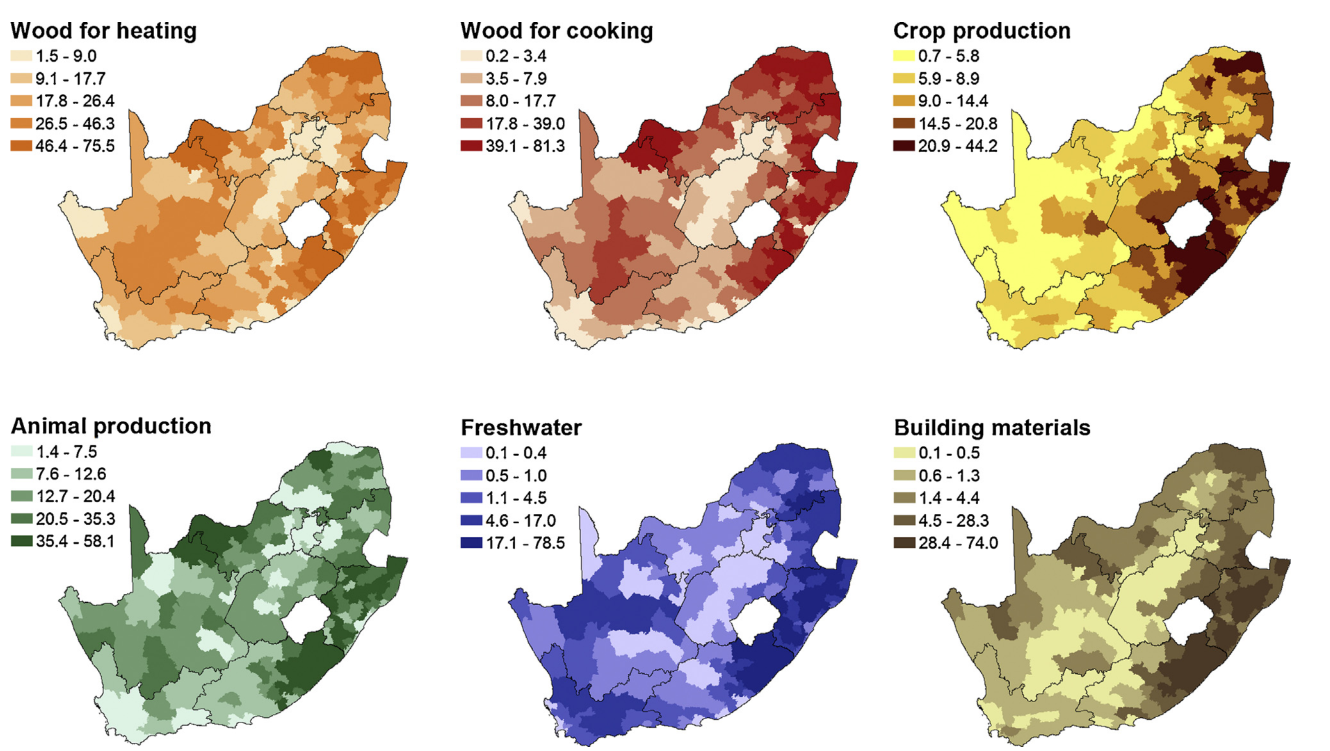

Fig. 1. Distribution of the direct use of six locally available ecosystem services in South Africa. Values represent the percentage of households per municipality using a local natural resource, and are categorized in quintiles. Provincial borders are shown.

all ES and predictor variables, after applying a square root transformation and scaling the data to z-scores, since the data were non-normally distributed.

3. Results

3.1. Individual ecosystem service use

High levels of direct use of all services tend to occur in the east of the country, with a more mixed pattern apparent in the rest of South Africa (Fig. 1). Use of each ES was significantly spatially clustered in the landscape (Moran's I, $p < 0.01$). Correlation analysis between pairs of ES revealed that they were all positively and significantly ($p < 0.01$) correlated (Appendix A, Table A3). Use of wood for cooking and wood for heating were most correlated ($r_s = 0.92$), while animal production was also highly correlated with use of fuelwood. In contrast, crop production generally exhibited the weakest correlations with the other services.

3.2. Distribution of bundles and social–ecological systems

The cluster analysis resulted in three distinct ES bundles representing low, medium and high relative levels of direct use of local ES among households (Fig. 2). Use of building materials and freshwater from a natural source declined most notably between areas of high and medium direct use. Taking these bundles types as representing distinct social–ecological systems and mapping them across South Africa resulted in 152 municipalities in the low direct use system; 50 municipalities in the medium direct use system; and 32 municipalities in the high direct use system (Fig. 3a). This corresponded to 75.8%, 18.2%, and 6.0%, respectively, of the total land surface area, and 78.2%, 14.4%, and 7.3% of the total number of households in the country.

3.3. Effect of scale

Bundle types were similar when clustering ES based on data at municipal and district levels (Fig. 2). At the district resolution, we found that 28 districts made up the low direct use system (61.0% of

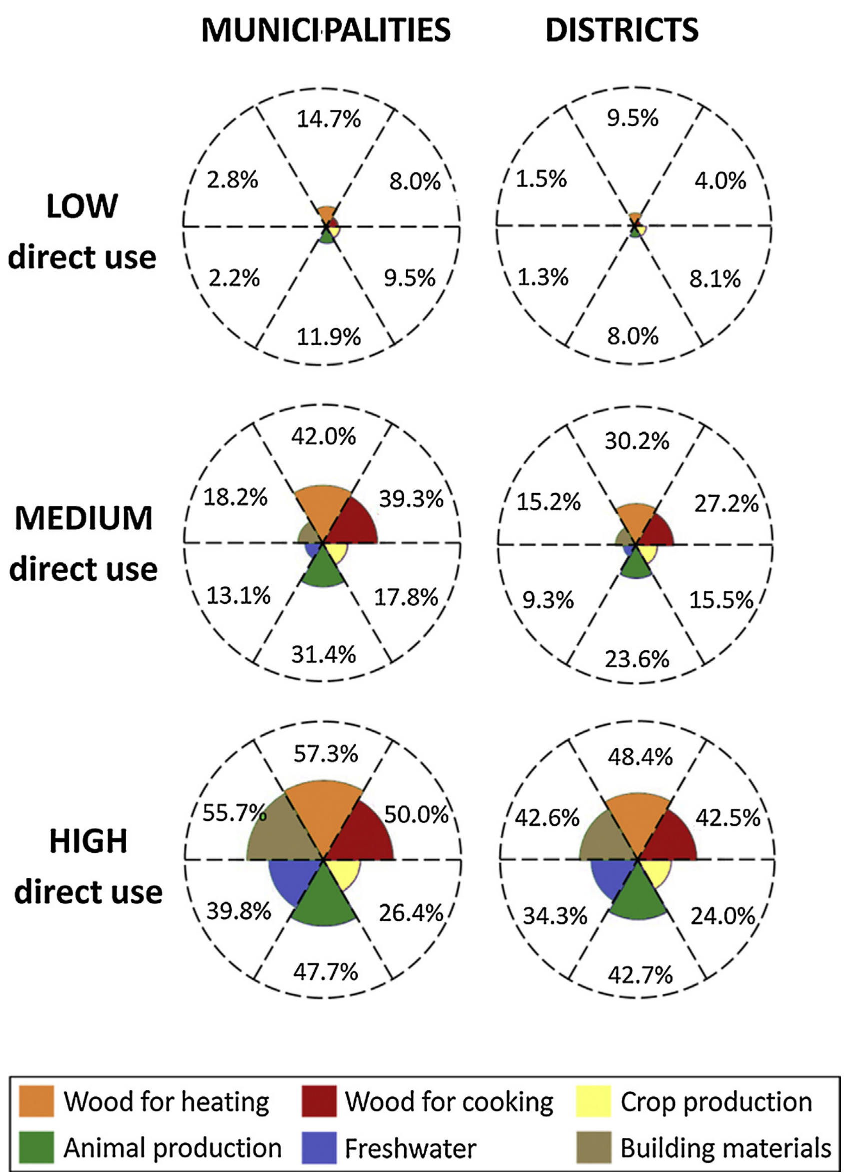

Fig. 2. Typical bundles that characterize high, medium and low direct use of locally available ecosystem services among households. Petal length indicates the average percentage of households using each ecosystem service (maximum 100%) within each use category and at either municipal or district scale.

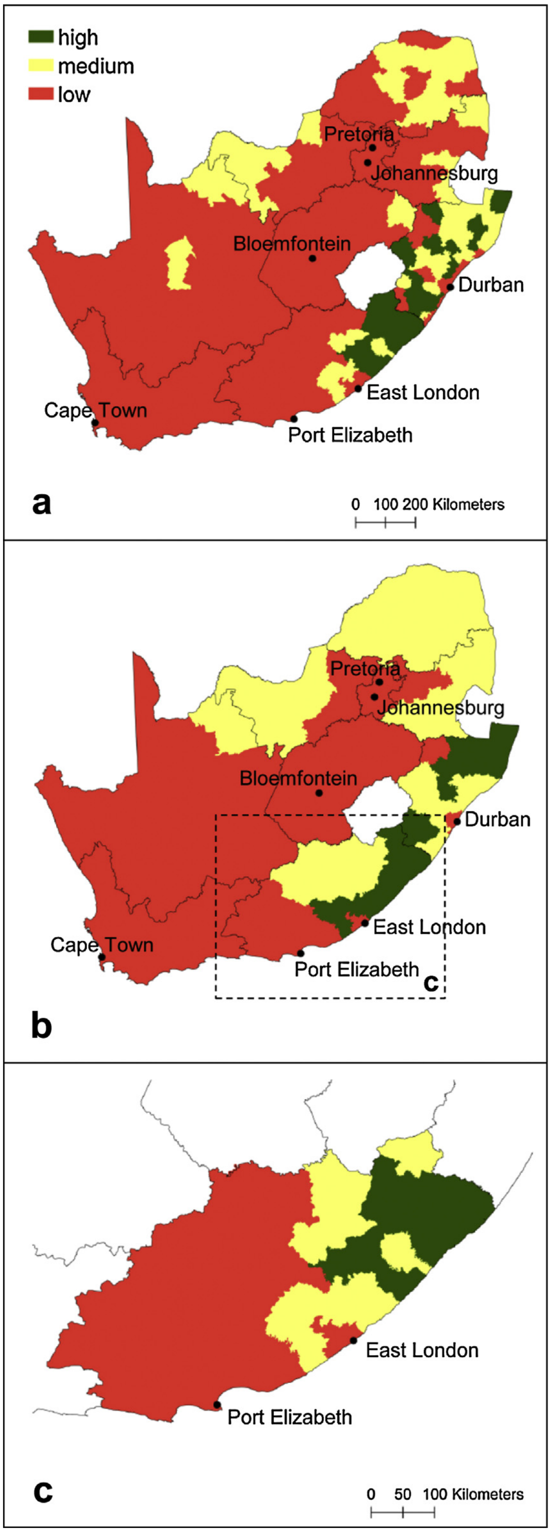

Fig. 3. Distribution of social–ecological systems in South Africa, characterized by high, medium and low direct ecosystem service use, which can be interpreted as an expression of 'green-loop', 'transition', and 'red-loop' dynamics (Cumming et al., 2014), respectively. Systems were identified by clustering ecosystem service bundles found in the country's (a) municipalities and (b) districts, as well as (c) municipalities of the Eastern Cape Province. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

total land area; 65.2% of total households); 17 districts made up the medium direct use system (31.4% of total land area; 26.4% of total households); and 7 districts made up the high direct use system (7.6% of total land area; 8.4% of total households) (Fig. 3b). The high direct use system therefore covered a similar area at both resolutions, while the medium direct use system increased as the low direct use system decreased in the district analysis.

To examine the effect of varying the extent of the analysis, we repeated the clustering at the municipal level for the highly diverse Eastern Cape Province (total area = 169,000 km^2) (Fig. 3c). The observed pattern was similar to that of the national analysis, though two municipalities (of a total of 39) switched from the low to medium direct use system, as did two municipalities from the high direct use system, resulting in 9.9% of the province being reclassified. In all analyses the resulting regions were significantly clumped in space (Moran's I, $p < 0.01$).

When only two clusters were identified during k-means clustering at municipal scale for the whole country, all of the high direct use system plus 62% of the medium direct use system were grouped into one cluster, with the remaining area being grouped as a second cluster representing a social–ecological system with comparatively lower levels of direct ES use.

3.4. Comparing social–ecological systems and anthromes

A comparison of the social–ecological systems we identified with the anthromes for South Africa revealed that the low and medium direct use systems are dominated by rangeland anthromes (Fig. 4). The high direct use system exhibited the highest percentage of village-type anthromes, as well as a relatively high proportion of croplands. There were no dense settlements or wildlands in the high use system. Overall, the low and medium direct use systems displayed a similar pattern of anthrome categories, except that the low direct use system included almost all the dense settlements. The different social–ecological systems do not coincide neatly with certain anthrome types, nor with some unique combinations of anthromes.

3.5. Predictors of social–ecological systems

Table 1 shows that an increase in the percentage of land under traditional authority significantly decreases the log-odds of a municipality being characterized as a medium or low direct use social–ecological system. The same pattern held as the percentage of female-headed households increased. In contrast, an increase in average annual household income of the municipality led to a significant increase in the log-odds of the municipality falling into the medium or low direct use social–ecological system. Similarly, an increase in population density led to a significant increase in the

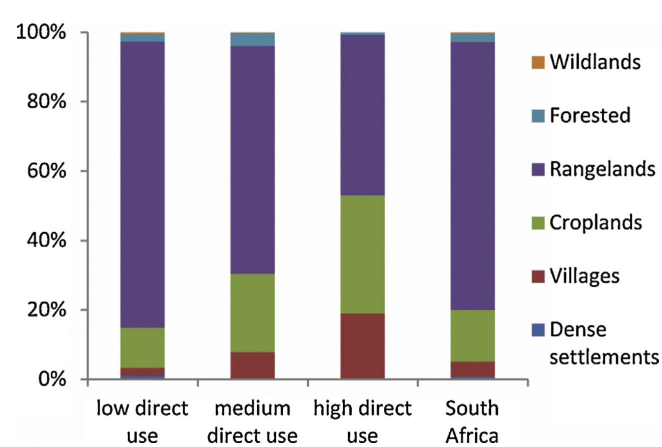

Fig. 4. Relative percentages of anthromes in social–ecological systems, and in South Africa as a whole. Anthromes are sorted in order of population density (wildlands = lowest densities; dense settlements = highest densities).

Table 1
Estimated model coefficients (Coef) and their standard errors (SE) for changes in the category of direct ecosystem service (ES) use of municipalities in South Africa in response to social and ecological predictor variables. Significance denoted by * at $p < 0.05$.

Predictor	Direct ES use	Slope		
		Coef	SE	*p*-value
Traditional Authority	high → med	−1.701	0.712	0.017*
	high → low	−4.783	1.263	0.000*
Female household Head	high → med	−2.075	1.234	0.093
	high → low	−4.560	1.472	0.002*
Household income	high → med	4.461	1.824	0.014*
	high → low	5.281	2.008	0.009*
Population density	high → med	5.574	5.580	0.318
	high → low	20.527	7.200	0.004*
Distance to city	high → med	−0.058	0.729	0.936
	high → low	−0.627	0.838	0.454
Wood supply	high → med	−1.535	0.657	0.019*
	high → low	−2.037	0.730	0.005*
Mean annual runoff	high → med	−1.765	0.855	0.039*
	high → low	−3.834	1.040	0.000*
Grazing potential	high → med	−2.056	0.923	0.026*
	high → low	−1.641	1.001	0.101
Arable land	high → med	−0.337	0.777	0.665
	high → low	−0.362	0.904	0.689

log-odds of a municipality being classified as a low direct use rather than a high direct use system. High direct use systems are therefore characterized by lower average household income and population density, and are more likely to be headed by females or located in communal areas. In the case of ecological variables such as wood supply and mean annual runoff, a unit increase led to a significant decrease in the log-odds of a municipality being classified as a low or medium direct use system, relative to the reference category of high direct use. This pattern indicates that as the supply of these ES increases, use of locally available ES overall also increases. A correlation analysis of the predictors (Appendix A, Table A4) showed strongest correlations between the percentage of total municipal area under traditional authority and the percentage of female-headed households ($r_s = 0.82$). Average annual household income per municipality, on the other hand, was strongly negatively correlated with the percentage of female-headed households ($r_s = -0.78$).

A principal component analysis of all ES and predictors showed that most of the variation between municipalities could be explained along gradients of poverty and wealth, as well as the urban–rural divide. Principal component 1 corresponded to an axis that varied from high natural resource use in traditional areas with many female-headed households to high income areas and explained 49% of the variance. Principal component 2 explained a further 19% of the variance and ranged from areas far from urban centers to highly populated urbanized areas. The rest of the components explained less than 8% each of the remaining variance.

4. Discussion

Social–ecological systems are units in which distinctive human–environment interactions take place, yet much research is still needed to identify and map these systems in order to improve their management for sustainable human well-being outcomes. In this study we present an approach to mapping social–ecological systems based on bundles of direct ES use, derived from national development data. When mapped, different bundle types formed spatially clustered and coherent areas (Fig. 3) with different characteristic social and ecological features (Table 1). We argue that these areas correspond to three distinct social–ecological systems in South Africa, and can be categorized as green-loop, transition and red-loop systems as identified by Cumming et al. (2014). This approach demonstrates a new way of capturing emergent social–ecological dynamics that are not reflected in additive combinations of separate social and biophysical datasets, such as used to derive anthromes (Ellis and Ramankutty, 2008), and can help target governance interventions for sustainability across diverse social–ecological landscapes. Below we discuss four key insights from our analysis.

4.1. Bundles of direct ecosystem service use represent a practical approach to identify and map social–ecological systems

Our analyses revealed distinct clusters of ES use among households in South Africa. We had no a priori expectations as to the number of clusters that would be identified, nor their characteristic features. We found three clusters which were characterized by different levels of ES use, and – upon further examination – related strongly to the system types described by Cumming et al. (2014). We therefore argue that the high, medium and low direct ES use clusters we identified reflect social–ecological systems that can be categorized as green-loop, transition, and red-loop systems, respectively. These systems do not merely represent areas in which average ES use among households differs – they represent entities that differ fundamentally in the way people relate to the environment. As highlighted by Cumming et al. (2014), societies that make direct use of ES they collect from or grow in their local environment (green-loop systems) are embedded in social and economic structures that differ profoundly from communities that obtain ES through other means (red-loop systems). High levels of direct use of local ES is typically associated with communities that have limited access to market economies (Godoy et al., 2005; Sierra et al., 1999), high income-defined poverty rates (Cavendish, 2000; WRI, 2005), and strong spiritual and cultural ties to nature (Berkes et al., 2000; Godoy et al., 2005). As communities become richer and more urban, they tend to disengage from the direct procurement of provisioning ES and cover their basic needs by buying these services, which may have been produced in faraway systems (Cumming et al., 2014; Folke et al., 1997; Folke et al., 2011; Grimm et al., 2008). However, this requires the establishment of complex larger-scale social and economic structures to ensure the procurement of these services, and exposes these societies to different kinds of sustainability challenges and risks, including a vast spatial expansion of their ecological footprint or area of ES procurement. This means that while the level of direct use of locally sourced ES in red-loop systems may be low (Fig. 2), total ES use in absolute terms may be very high, with resources largely sourced from areas very distant from the place of consumption.

A significant addition that our analysis makes to the original model proposed by Cumming et al. (2014) is to highlight that red-loop (low direct use) systems are not exclusively urban but include relatively wealthy rural communities, which likely constitute most rural areas in developed countries. Also, transition (medium direct use) systems are mostly highly heterogeneous regions including a patchwork of low and high ES use areas, rather than being homogeneous medium use entities. However, their overall trajectory is still likely to be towards the red-loop system, since development of rural areas (e.g. electrification, improved sanitation, and government housing programmes) is continually taking place in South Africa and many other developing countries, thus reducing the level of households' direct use of basic, locally sourced provisioning services.

To our knowledge, this is the first time that census data on resource use have been used to identify and map social–ecological systems at national level. We suggest that this presents a practical and meaningful approach which could be implemented in other countries and regions with existing data. The comparison of our approach with the anthromes suggests that the systems we identified based on direct use of local ES reflect emergent social–ecological processes that are directly relevant for sustainability policy but may be missed by approaches that identify systems through overlays of social and ecological data. Neither do simple indicators like income or population density reflect the distribution of the social–ecological systems we identified. For example, large parts of the low ES use areas are rural and sparsely populated, while some of the high use areas include densely populated, peri-urban settlements.

Furthermore, the approach we present here for mapping social–ecological systems is robust to variations in the scale of the input data, with very similar patterns emerging at the municipal and the district scale. However, the district resolution is very coarse, and likely to be less useful in a management context. Future work would benefit from further disaggregation of the ES use data into ward-level units (i.e. below municipal level), which would allow for a more comprehensive exploration of the scale at which social–ecological systems emerge as cohesive units in space. Unfortunately, there is currently no data on animal or crop production available at that level, which means a comparative, finer scale analysis is not possible.

4.2. Social factors are key determinants of social–ecological dynamics

Our results indicate that the spatial location of different social–ecological systems, specifically green- vs. red-loop systems, is heavily influenced by social factors. The system in which households rely most heavily on resources they garner from their local environment is characterized by low average household income, as well as high proportions of female headship and land under communal tenure (which is mostly rural) (Table 1). This system is mainly located in former homeland areas of the Eastern Cape and KwaZulu-Natal provinces (Fig. 3), which have historically experienced a lack of government support and remain comparatively underdeveloped in terms of services like water and electricity supply (Department of Cooperative Governance and Traditional Affairs, 2009; Nnadozie, 2011). Our results show that as household income increases, use of locally available natural resources, and therefore reliance on local ES, decreases. This pattern of declining dependence on locally available natural resources as income rises is commonly observed in the poverty–environment literature (Cavendish, 2000; Reddy and Chakravarty, 1999; Vedeld et al., 2007), and has been documented in numerous South African case studies, though only at the local scale (Jogo and Hassan, 2010; Shackleton and Shackleton, 2006; Thondhlana et al., 2012; Twine et al., 2003). Our results are also consistent with previous findings on gender differences in resource dependence, as well as the importance of communal land and its 'invisible capital' in South Africa (Cousins, 1999; Shackleton et al., 2001; Twine, 2013). Those households that are both headed by a woman and are located in communal areas face the added difficulty that, due to South African customary law, women's rights of access to land in these areas is insecure, making these particular households especially vulnerable (Meer, 1997; Rangan and Gilmartin, 2002).

The principal component analysis (PCA) further supported a significant influence of income and the rural–urban gradient on the variation between municipalities. Both the PCA and regression analysis suggest that poor households with overall high levels of ES use are generally found in areas of low to medium population density. Meanwhile, municipalities in which households had high annual incomes and low overall use of ES occurred in both relatively unpopulated rural areas far from cities, but also in densely populated urban centers. This suggests that just because households are situated in a rural environment does not mean that they rely heavily on direct use of ES. Households in commercial farming districts, for example, may well be involved in crop or animal production, but live in modern brick houses, source their energy from the national electricity grid and draw their freshwater from groundwater reserves through boreholes or from municipal water supplies – in short, they are relatively disconnected from their natural resource base and operate within red-loop dynamics (Cumming et al., 2014).

4.3. Ecosystem service use is only partly linked to supply

We also tested ecological predictors that have previously been used as proxies for the supply of ES (Egoh et al., 2008; Reyers et al., 2009; SAfMA, 2004) to assess whether the potential of a landscape to provide services predicts the level of ES use among the population. Our results showed that high direct use (green-loop) systems also exhibited high levels of mean annual runoff and wood supply. This suggests that the landscape's ability to provide easily accessible fresh water and fuelwood plays a role in determining to which degree people rely on those ES. In contrast, grazing potential was only significant in distinguishing between medium and high direct use areas, while the amount of arable land in a municipality did not appear to be an influential driver of the social–ecological system type. This may indicate a mismatch between supply and demand, since more than 47.7% and 26.4% of households in high use areas engage in animal and crop production, respectively, even though the land in these areas is not necessarily more conducive to those activities than elsewhere. Our results therefore emphasize that ES potential or production in an area does not necessarily translate into ES use, a fact that is increasingly acknowledged in multi-indicator ES assessments (Burkhard et al., 2012; Crossman et al., 2013). In the context of increasing research and policy attention on the links between ES and human well-being, particularly in poor regions of the world (e.g. ESPA, 2015), our results underscore the importance of assessing actual ES use, not simply ES production, in order to understand these linkages.

4.4. Management implications and research needs

Managing for sustainable resource use and human well-being outcomes requires tailored strategies that focus on avoiding ecological degradation driven by either poverty or overconsumption. By highlighting where in South Africa red-loop versus green-loop dynamics are at play, policies can be better targeted to address the particular sustainability challenges faced in different areas, i.e. resource degradation due to lack of alternative options for securing basic needs (green-loop systems), versus resource degradation due to burgeoning demands from a complex, often opaque economic system driven by wealthy consumers that are disconnected from environmental feedbacks (red-loop systems). These differing challenges demand different policy interventions. In green-loop areas the primary focus might be on supporting growth and access to the economy in order to secure basic needs, and reducing the vulnerability of the most marginalized, through social grants for instance. In red-loop areas, sustainability policy might rather focus on 'reconnecting' society to their local environment and limiting over-/extractive consumption from distant places, for example through urban farming projects and sustainable seafood initiatives (Battersby and Marshak, 2013; Jacquet and Pauly, 2007).

Knowing where low, medium and high ES use systems are located is especially important in the context of land use planning and natural resource management. The national government strategy on biofuels in South Africa, for example, focuses on former homeland areas to increase biofuel crop production since these areas are considered 'underutilized' (Department of Minerals and Energy, 2007). Yet our results show that provisioning services in these areas are, in fact, heavily utilised by households, which may explain why there has been strong community resistance to the introduction of large-scale biofuel production facilities in some of the former homeland areas (Amigun et al., 2011).

Our approach explores a practical way of mapping green-loop versus red-loop dynamics at different scales, using readily available data, and moving beyond the usual set of indicators used (such as income and land use) to identify new, emergent social–ecological boundaries that can inform targeted decision-making. While we feel our study represents a significant advance, we emphasize that other conceptualizations of social–ecological systems are possible, and different approaches and data may be needed to map these. For example, social–ecological systems can be conceptualized and modeled without specific consideration of ES (Schlüter et al., 2012). Furthermore, additional research is needed to determine whether the distribution of social–ecological systems mapped here is maintained if other non-subsistence provisioning services, as well as regulating and cultural services are included in the ES bundles, and whether such an approach is conceptually consistent with the approach adopted here. It will be challenging to find indicators that measure the use of regulating services among households, in a way that mirrors the kind of indicator used for provisioning services in this study. Cultural services, on the other hand, may be more easily expressed in terms of use of local services at the household level (e.g. engaging in nature-based spiritual activities), and their inclusion might result in some regions currently classified as low ES use areas (red-loop systems) being re-categorized as medium or high use areas (transition or green-loop systems), or some completely new category of system. It would also be interesting to investigate whether there are characteristic trade-offs between provisioning, regulating and cultural services associated with green-loop or red-loop dynamics. However, more scientific effort is needed to develop use-based metrics of all ES that could potentially be included in future surveys or census questionnaires.

5. Conclusions

This study has demonstrated an approach to identify and map social–ecological systems as emergent patterns in a landscape based on direct use of ES. The approach builds on an understanding of household-level use of ES – and particularly provisioning services – as an integrated expression of underlying social–ecological systems with distinct dynamics and characteristics, and differs from other mapping exercises that combine separate social and biophysical data to identify social–ecological systems. The approach presented here may be a practical tool, that can be implemented using available data, to identify where fundamentally different underlying human–environment interactions are at play, and enable us to better tailor sustainability policies to these differing contexts. Of course the full complexity of social–ecological systems can never be captured by static maps, but ES use bundles and the social–ecological interactions they represent may take us a step further to mapping systems that have direct policy and decision-making relevance for sustainable resource management and land use planning.

Acknowledgements

We thank Statistics South Africa for their helpful assistance with data acquisition, and Gretchen Daily, Stuart Kininmonth and Kristoffer Hylander for their constructive reviews. This work was supported by a grant from the Swedish International Development Cooperation Agency (Sida) and the Swedish Research Council (VR). RB is supported by a Branco Weiss Society in Science Fellowship. BR received support from the WISER project (NE/L001322/1) funded by the Ecosystem Services for Poverty Alleviation program (ESPA). ESPA receives its funding from the Department for International Development (DFID), the Economic and Social Research Council (ESRC) and the Natural Environment Research Council (NERC).

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.gloenvcha.2015.07.008.

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