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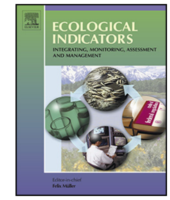

Bundles of ecosystem (dis)services and multifunctionality across European landscapes

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ABSTRACT

We present an assessment of the spatial pattern of ecosystem services (ES) associations across Europe based on models of eleven ES and one dis-service, mapped at the extent of twenty-seven Member States of the European Union (EU27) on a 1 km^2 grid. We isolated three clusters of cells sharing common features in multi-ES supply associated with the main land-use-land-cover types such as forests and agricultural lands. Confronting these spatial patterns with biophysical and socio-economic drivers revealed two strong gradients structuring European ES bundles, climate and land use intensity. Variations in the diversity of ES bundles provided across administrative units (NUTS 2), quantified by the Shannon diversity index, tend to be higher in forested regions (e.g. SE Romania) and in the mosaic landscapes in the central EU27 (from eastern France to Austria). Lower diversity prevails in areas of homogeneous terrain and land use in north-western Europe (e.g. Western France). Our findings illustrate that ES trade-offs and bundles cannot be reduced to land use conflicts but also depend on climate and, for a specific bundle, to biodiversity.

1. Introduction

At the European Union (EU) level, the spatial quantification of ES has become one of the milestones of the EU 2020 Biodiversity strategy. Target 2 of the EU Biodiversity Strategy makes explicit reference to ES by advocating for the restoration of at least 15% of degraded ecosystems to sustain the supply of services (European Commission, 2011). Reaching Target 2 (Action 5) requires efforts from each EU Member State to map and assess the state of ecosystems and their services. Combining national assessments into a consolidated view of European ecosystems would support the review and improved targeting of EU environmental policies, subsequently constraining the national environmental policies. However, national assessments are often based on different methodologies and approaches limiting the possibilities for EU wide harmonised assessments.

Because ES do not vary independently of each other, but rather respond to climate and land use as "bundles" (Raudsepp-Hearne et al., 2010), management targeted at improving the supply of a given ES must also consider the sustainability of the provision of other ES (Bennett et al., 2009) and their response to environmental changes. A few ES mapping studies have incorporated multiple services and an analysis of the corresponding trade-offs, but these assessments regarded the national (e.g. UK, Bateman et al., 2013; Denmark, Turner et al., 2014) or regional (e.g. Ruijs et al., 2014; Crouzat et al., 2015) scale. Even fewer have mapped the supply (actual or potential) of multiple ES across land use types over large geographic scales (but see Maes et al., 2015; Stoll et al., 2015). To our knowledge to date no study has attempted to identify the drivers of ES bundles at these scales, and specifically in the EU.

Macro-scale land use patterns and climate influence one another through biophysical and socio-economic mechanisms, e.g. temperature and precipitation shape land cover and land use which, in return, may alter ES supply (Mitchell, 2013). As a consequence,

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future changes in European land use are expected to alter the supply of ES (Metzger, 2008; Rounsevell et al., 2010; Verkerk et al., 2014). This paper presents a spatially explicit assessment of current ES supply and associations among a broad selection of ES across the diversity of land uses in Europe. Our analysis proceeded in three steps: (i) assessing ES supply, (ii) detecting ES bundles and (iii) investigating drivers of ES bundles. Finally, our analysis aimed to assess the diversity of ES supply across the EU to identify multifunctional regions.

2. Material and methods

2.1. Assessing ecosystem services supply

We quantified eleven ES provided by the EU ecosystems at the continental level as part of the EU project VOLANTE (FP7-ENV-2010-265104; http://www.volante-project.eu). ES indicators are summarized in Table 1. We also quantified one dis-service relating to invasive species. Each ES was quantified in a spatially explicit fashion, data layers were georeferenced to the standard INSPIRE reference grid for Europe at 1 km^2 based on the ETRS89 LAEA projection (Supplementary material). Alien threat score and regulation of wind disturbance were assimilated to a semi-quantitative variable ranging from 1 to 4 (4 being the highest value) and from 0 to 5 (5 being the highest value), respectively. All ES indicators, except for the relative water retention index (already standardized), were standardized by subtracting the minimum value observed and then dividing by the difference between the maximum and the minimum values observed (Paracchini et al., 2011). To ease the interpretation of our analyses, both wind disturbance and fire risk indicators were converted using the formula *1-x* (*x* being the indicator value), thus indicating the regulation of wind disturbance and fire risk.

2.2. Detecting ecosystem service bundles and multifunctionality

In our study, the bundling of ES was markedly driven by the tight relationship of several ES to land-use land-cover (hereafter "LULC") classes (e.g. dead wood and wood supply in forests, nitrogen retention capacity in water bodies). However, not all ES were LULC-dependant and other factors may influence the bundling of ES. Consequently, we applied the self-organizing map (hereafter "SOM") method (Kohonen, 1982) on the twelve (dis-)ES values to objectively cluster locations (i.e. 1 km^2 cells) according to their similarity in their multi-ES supply, using the "kohonen" R package. The SOM algorithm was parametrized to build two to twenty clusters and we then used the silhouette width index (Rousseeuw, 1987) to determine the optimal number of clusters. Three clusters provided the highest silhouette width value (e.g. 0.35). Finally, we investigated the multifunctionality of European regions, i.e. the ability of NUTS 2 administrative levels to provide more than one ES bundle. We estimated the equiprobability of SOM clusters within each NUTS 2 using Shannon's diversity index (following the formula given by Jost (2007) based on Hill numbers). Shannon's index equals 0 when all pixels of a given NUTS 2 region belong to the same cluster, and is maximal when all pixels of a region are evenly distributed across the three clusters (e.g. each cluster represents a third of the pixels in the region).

2.3. Investigating drivers of ecosystem service bundles

We selected potential drivers of ES supply within each ES cluster that satisfy the compromise between relevance and data availability at the extent and resolution required (Table 2). These potential drivers include variables that were directly used in the modelling of the ES supply (land cover, topography and climate factors) to account for their influence on the clustering of cells, and also independent variables that may be associated with the occurrence of bundles of ES supply (land use intensification, potential primary production, biodiversity, population and economic densities). Then, we analysed the co-variation of ES indicators within each SOM cluster using a Redundancy Analysis (RDA), a canonical analysis method appropriate to regress several explanatory variables (i.e. the forteen drivers) against multiple response variables (i.e. the twelve ES indicators). For each cluster, a RDA combined with a (forward) stepwise procedure was used to select the model with the combination of variables with the highest R^2 and p-value (Legendre and Legendre, 2012). With this, we were able to isolate variables significantly affecting the co-variation of multiple ES, partialling out land cover classes. Both RDA and the stepwise selection of variables were performed using the "vegan" R package.

3. Results

As expected, the clustering of cells into typical ES bundles was strongly driven by LULC (Fig. 1). Clusters can be described according to broad common trends in ES bundles (Fig. 1A):

- Cluster A (30.1% of all pixels): a stronger supply of forest-related services (i.e. dead wood and wood supply), carbon sequestration, regulation of flood, but a lower alien threat and almost no supply of energy from agricultural biomass or nitrogen retention capacity. 99.6% of these cells overlapped with the "forest" class in the LULC map and were mainly located in central and northern Europe.
- Cluster B (68.2% of all pixels): a higher supply of biocontrol, pollination, regulation of wind disturbance and flood, energy output from agricultural biomass and alien threat, but a lower supply of nitrogen retention capacity, regulation of fire risk, dead wood and wood. Mainly situated in Mediterranean areas and Western Europe, most cells were classified as non-irrigated arable lands (42.2%), pasture (19.5%) and (semi-)natural areas (16.1%).
- Cluster C (1.7% of all pixels): the highest multifunctionality, with nitrogen retention capacity, biocontrol of pests, alien threat, regulation of wind disturbance, recreational potential and energy output from agricultural biomass, being strongest This high multifunctionality was associated to a high level of alien threat and almost no dead wood or wood supply. Cells were sparsely distributed from Spain to Romania and across LULC classes (26.6%, 20.9%, 14.9%, 11.2% and 9.5% of cells overlapped non-irrigated arable lands, pasture, built-up areas, forests and water and coastal flats, respectively).

With a few exceptions (e.g. Greece, UK, Baltic States or Denmark), bundles were quite evenly represented within each NUTS 2 region as visible from the fine grain of their distribution map (Fig. 1B) and suggested by the intermediate to high values of Shannon's diversity index (Fig. 2).

Multi-ES patterns in clusters A and B were strongly associated to three drivers related to climate (i.e. annual mean temperature) and biodiversity (cluster A) or HANPP (cluster B) (Table 3). In contrast, multi-ES patterns in cluster C were more evenly associated with seven variables (Annual mean and range temperature, biodiversity, land cover, aridity, HANPP and population density). Economic density was not relevant for any of the three clusters (Table 3).

4. Discussion

In line with previous assessments (e.g. Kienast et al., 2009; Maes et al., 2012; Stoll et al., 2015), we show that most European ecosystems provide a variety of ES. One step further, we