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

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Highlights

-A spatially explicit assessment of eleven ecosystem services and one dis-service across the European Union (EU)

-Three bundles of ecosystem services related to climate and land use intensity were identified

-Ecosystem service diversity and multifunctionality are strongly variable across EU

Keywords: bundles, drivers, ecosystem services, Europe, indicator, supply, trade-off

Abstract

We present an assessment of the spatial pattern of ecosystem services (ES) associations across Europe based on models of 11 ES and 1 dis-service, mapped at the extent of 27 Member States of the European Union (EU27) on a 1km² 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., 2013; 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 et al., 2013). As a consequence, future changes in European land use are expected to alter the supply of ES (Metzger et al., 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 1km² 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 12 (dis-)ES values to objectively cluster locations (i.e. 1km^2 cells) according to their similarity in their multi-ES supply, using the "kohonen" R package. The SOM algorithm was parametrized to build 2 to 20 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 unit 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 14 drivers) against multiple response variables (i.e. the 12 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 show that these patterns of ES supply follow regional and especially climate-related latitudinal patterns that reflect the nature of European landscapes and the spatial distribution of land use types, i.e. a contrast between the areas of Central and Northern Europe associated with forest-related ES, and Mediterranean areas associated with biotic regulation services (biocontrol by vertebrates and pollination), but a lower regulation of fire risk (a higher fire risk). Our analysis also captures the leading contrast between the most productive and highly populated regions, and the less productive ones. Our results outline the dichotomy between ES trade-offs arising from the ability of different land uses to provide specific ES (e.g. forests do not provide cereals) and trade-offs arising from conflicting uses for a given land use (e.g. logging *vs* sequestering carbon in forests).

The levels of ES supply in the identified clusters also indicate that within each of the main land use types, multiple services are (potentially) supplied, indicating high multifunctionality, even discounting for the high level of the dis-service. This multifunctionality occurs at two levels: within clusters (i.e. at least half of the ES are supplied in each cluster) and within European regions (i.e. in many regions the three clusters are rather evenly represented). European forested regions in particular tend to be those with more remaining natural habitats in general, thus providing a broad range of ES (incl. pollination, flood regulation and outdoor recreation). The composition and configuration of landscapes are crucial elements to explain the overall spatial variation in ES (Laterra et al., 2012). The landscape heterogeneity of the Alpine and Mediterranean regions, which are mosaics of mountainous, built-up, (semi-)natural and agricultural areas most likely explained the balanced representation of bundles. In more homogeneous regions with large patches of pastures and arable lands (e.g. Central to Western regions of France), a single bundle was over-represented (i.e. cluster B). The intermediate level of evenness in the forest-dominated regions from northern Scandinavia, however, suggests that the potential of one land cover type to provide many ES may be as important as landscape complexity in the establishment of multifunctionality, as previously shown by Crouzat et al. (2015) for mountain regions.

An important consideration in the interpretation of our results is the influence of our choice of ES and indicators on the results. The number, types and spatial distribution of ES bundles are sensitive to the individual ES selected and the input data available to define these services. Outcomes from our assessment converge with Maes et al. (2015) for the high multifunctionality in forested regions (e.g. Austria, SE Romania, SW France) but diverge in coastal regions (e.g. Italy) because we did not assess ES specifically provided by coastal areas. Such sensitivity does not invalidate our results but rather highlights the complementarity in ES assessments. An important caveat in exiting large-scale ES assessments regards the evaluation of their uncertainties. Schulp et al. (2014) discussed the uncertainty of 5 ES assessment at the EU-scale, including climate and flood regulation, recreation and pollination, to conclude that the lack of observed data hampers any independent validation. Implementing the EU 2020 Biodiversity strategy entails a compromise between delivering EU and national scales ES assessments now and waiting to have enough observed data for a proper validation process.

This first conjoint analysis of patterns of drivers and of multiple ES at continental scale showed that broad patterns of ES associations driven by land use are modulated by bioclimatic factors (mean annual temperature, temperature range and aridity). This analysis highlighted two strong, but nested, gradients structuring European landscapes: climate and land use intensification, especially for the bundles related to agricultural areas. The influence of land use is partly embedded in climatic gradients through land cover's dependency on climatic conditions. Similarly, land use and socio-economic conditions are often strongly co-determined and not independent. Nevertheless, and in spite of our inclusion of socio-economic and land use-related drivers in the analyses, their contribution tended to be secondary to that of climate. In addition, our analyses revealed that multi-ES patterns spatially co-vary with biodiversity patterns, acknowledged to be driven by climate as well (e.g. Gaston, 2000). While our analysis cannot explicitly shed light on the direct causal relationships between ES and biodiversity, it suggests that spatial congruency between ES and biodiversity patterns likely emerges from common drivers (e.g. temperature). Overall, our results confirm a latitudinal climatic gradient of ES supply in Europe, modulated by a longitudinal gradient of human modification, particularly in mid-latitude Europe, decreasing from France to Romania (Jepsen et al., 2015). If climate is the primary driver of ES supply at the macro-scale, then environmental policies focusing solely on LULC conflicts to mitigate trade-offs among ES might fail to foster supply of multiple ES in the long term.

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Table 1. Overview of ecosystem services assessed in this study. Models are presented in Mouchet et al. (2013) but the detailed description of the quantification of services is given in the cited references.

CICES section	CICES group	Indicator	Code	Description	Unit	References
Cultural	Physical and experimental interactions	Recreation potential index	RPI	Potential provided by ecosystems related to the presence of certain ecosystems (i.e. forest, coastline), certain ecosystem characteristics (i.e. naturalness) and their accessibility	Adimensional continuous index	Paracchini et al., 2014
Provisioning	Biomass (nutrition, materials, energy)	Energy output from agricultural biomass	ECO	Energy content of agricultural production	MJ/ha	Perez-Soba et al., 2015
	Biomass (materials, energy)	Wood supply	WS	The volume of stemwood extracted from forests for material and energy use	m^3/ km^2 forest/yr	Nabuurs et al., 2007
Regulating and maintenance	Mediation of flows	Fire risk index*	Fire	Estimated on the vegetation vulnerability to wildfires, climatic conditions and topography	Probability	Mouchet et al., 2013
	Mediation of liquid flows	Flood regulation supply indicator	IFS	Related to flood regulation. Based on the variability of the peak discharge at the outlet of a catchment in dependence of land use and soil distribution	Adimensional continuous index	Stürck et al., 2014
	Mediation of air flows	Wind disturbance risk in forests*	Wind	Based on the vulnerability of forest to wind disturbance	Adimensional index	Schelhaas et al., 2010
	Climate regulation	Carbon sequestration	Cseq	Amount of carbon that is sequestered from land use, land use change and forestry	C/km²/yr	Schulp et al., 2008
	Water conditions	Nitrogen retention capacity	NRC	Amount of nitrogen retained in water bodies	Ton of nitrogen removed/km/yr	
	Pest control	Species providing natural control of invertebrate and rodent pests	BC	Based on the overlaid distributions of species providing pest control	Number of species	Following Civentos et al., 2012
	Lifecycle maintenance, habitat and gene pool protection	Relative pollination potential	RPP	Related to the availability of floral resources, bee flight ranges and the availability of nesting sites	Adimensional continuous index	Zulian et al., 2013
		Dead wood	DW	Indicator for biodiversity in forests Related to the resource availability and species richness	Mg dry matter/km^2 forest	Verkerk et al., 2011
Dis-service$	Invasive species	Alien threat score	Alien	Based on the ecological impact and the invasive potential of species	Scores	Adapted from Molnar et al., 2008

* Wind disturbance risk and fire risk indices are related to the vulnerability of an ecosystem to wind or fire. Consequently, the higher the value, the higher the vulnerability. To assess the corresponding services (i.e. regulation of wind disturbance and fire risk), we used the formula *1-x* (*x* being the indicator value).

$ Dis-services are not part of the CICES typology of ES.

Table 2. Overview of potential drivers of ES bundles.

Potential driver	Code	Description	Unit	Source
HANPP	HANPP	Land use intensity (Human appropriation of NPP) for the year 2006	% of NPP0	Haberl et al., 2007
NPP0	NPP0	Potential NPP	$tC/m^2/yr$	Haberl et al., 2007
Agricultural land use intensity	agriLUI	Agricultural intensity characterized by 5 classes (extensive arable, moderately intensive arable, intensive arable, extensive grassland, intensive grassland)	Categorical variable	Overmars et al., 2014, Temme and Verburg, 2011
Degree of soil sealing	SSeal	Soil sealing depending on built-up areas	%	EEA database
Population density	PopDens	Distribution of population disaggregated with CLC2000	$Inhabitants/km^2$	EEA database
Biodiversity	Biodiv	Overall diversity of amphibians, birds, mammals and reptiles	Species richness	Maiorano et al., 2013
Economic density	EcoDens	Income generated per $1km^2$, calculated as the product of NUTS 3 GDP and population density	kEuro	Van Eupen et al., 2012
Land cover classes	LCC	Classes simulated using Dyna-CLUE model	Categorical variable	Verburg and Overmars, 2009
Terrain ruggedness	TRI	Topographic heterogeneity based on amount of elevation difference between adjacent cells	m	Riley et al. 1999
Aridity	Arid	The aridity index is based on precipitation, temperature and potential evapo-transpiration. It increases with humidity level.	Categorical variable	CGIAR-CSI
Annual mean temperature	Bio1	Annual mean temperature for the 1950-2000 period	°C	WorldClim Global Climate Data Hijmans et al., 2005
Annual temperature range	Bio7	Given by subtracting the minimum temperature of the coldest month of the maximal temperature of the warmest month for the 1950-2000 period	°C	WorldClim Global Climate Data Hijmans et al., 2005
Annual precipitation	Bio12	Annual trends of precipitation for the 1950-2000 period	mm	WorldClim Global Climate Data Hijmans et al., 2005
Precipitation seasonality	Bio15	Coefficient of variation of annual precipitations for the 1950-2000 period	Categorical variable	WorldClim Global Climate Data Hijmans et al., 2005

Table 3. Outcomes of the variable selection procedure for potential drivers by clusters. The R^2 of the selected model are given as well as the F values for each variable (i.e. driver) selected. “**-**“: unselected variable. All model and F values are significant.

Cluster	*R²*	HANPP	NNP0	agriLUI	SSoil	PopDens	Biodiv	EcoDens	LCC	TRI	Arid	Bio1	Bio7	Bio12	Bio15
A	*0.24*	33,454.3	4,889.7	4,352.2	-	3,281.1	76,014.7	-	-	19,571.2	82,589.4	**104,943.6**	17,372.8	9,521.5	6,741
B	*0.4*	165,566	6,619.1	26,553	-	37,919.7	56,138	-	8,744.6	-	-	**266,932.7**	114,221.4	-	-
C	*0.44*	2,489.9	386.8	1,126	591,5	2,010	**3,303.4**	-	2,030.2	-	3,162.04	2,444.5	2,055.3	-	232

Fig. 1. Spatial clusters of ES associations given by the Self Organizing Map method. A) ES profiles of clusters and B) the spatial distribution of the clusters. A) Each slice of a pie chart represents an ES. The size of the slices indicates the weight of the variables (i.e. ES) in the generation of clusters. It symbolizes how each ES relatively affects each cluster. B) Cells belonging to cluster A are colored in green, cells related to cluster B in light orange and cluster C in dark blue (illustrated by the focus).

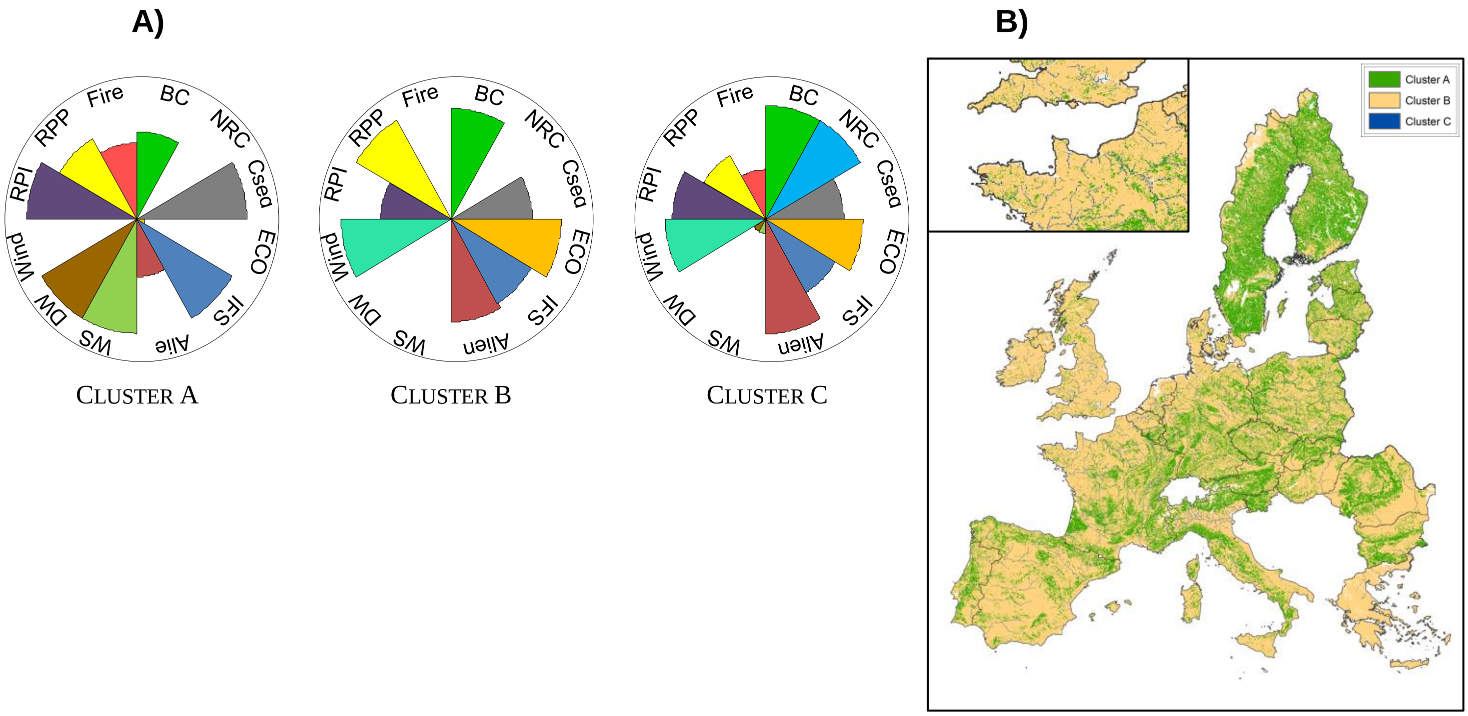

Fig. 2. Relative representation of ES bundles at NUTS2 level estimated using the Shannon's diversity index. NUTS 2 regions dominated by one bundle exhibit low values of the Shannon's diversity index. NUTS 2 regions with equal shares of the three bundles exhibit high values.