Clustering Spatially Explicit Bundles of Ecosystem Services in A Central European Region

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Abstract. Ecosystem Services (ES) are classified into three main categories: regulating, provisioning and cultural. However, spatially explicit bundles of ES may not necessarily conform to these groups. In this study, bundles of ES were explored in a central European region to identify spatial associations. We estimated the provisions of 31 ES using the CORINE land use land cover dataset and assessed the clustering using principal component analysis. Five clusters of ES were identified and did not completely represent the three traditional groups. Our results suggest that clustering should consider geographical features to identify ES bundles that work together independently. The spatially explicit characterisation of ES bundles is fundamental to determine the trade-offs and synergies to support adequate policy making.

1. Introduction

Ecosystem services (ES) are essential to human life, livelihoods and wellbeing. National policies and international agreements include goals to assess ES [1]. Decision-makers must understand the extent and condition of ecosystems for adequate management [2], [3]. ES modelling can support policy-making and provide insight into the impact of alternative policies or management decisions on the provisions of ES [4]. Good data quality is mandatory. However, in many countries, acquiring ES data is both costly and scarce [2], [5]. Good quality, spatially explicit data are required to perform sound analysis and modelling, which are lacking in several regions of the world [6]. Therefore, indirect approaches, including the use of proxies, are of particular relevance for exploratory assessments and policy design. ES mapping using land use land cover (LULC) types as a proxy has become a powerful tool to support decision making [2], [5], [7].

The bundling of ES remains a fundamental challenge for advancing the ES framework to include natural and social capital to sustain wellbeing [8]. Current classification systems such as the Mapping and Assessment of Ecosystems and their Services (MAES), The Common International Classification of Ecosystem Services (CICES) and The Economics of Ecosystems and Biodiversity (TEEB) divide ES into three main categories: regulating (RES), provisioning (PES) and cultural (CES). These classifications enable a priori discussions to identify ES, directly and indirectly, which can benefit society. Current approaches for ES bundling tend to respect the divisions between RES, PES and CES. Although these categories greatly facilitate the a priori conceptualisation of ES, they do not necessarily reflect the particular ways in which ES interact within space and time and in defined geographical locations. Indeed, “the connections between ecosystem process, functions and benefits to humans are complex, nonlinear and dynamic… complex interactions and feedbacks are required among built, human, social and natural capital to produce ES”; therefore, the “relative rates of production of each
service vary from system-to-system, site-to-site, and time-to-time”, [8]. Thus, ES are intricately entangled with built, social and natural capital [9].

In this study, we performed a cluster analysis of ES to explore and ascertain ES bundles. We compared this ES cluster with the standard RES, PES and CES categories and assessed the differences between the standard categories and our ES bundle.

2. Materials and methods

We performed the analysis in the cross-boundary region of Upper Silesia, located between Poland and the Czech Republic. Formerly a unitary socio-cultural region, Silesia was split between the two countries after the WW2. This region has served as a case study to assess ES in related research [10].

Following [2] and [11], a LULC-based estimation of 31 ES was performed using the CORINE dataset (Copernicus 2018). This dataset provides several land cover types and has been used for similar purposes [11]. A total of 17 LULC classes were used for the assessment.

The calculations were performed over a cell environment using a 100 ha hexagonal grid, which allowed for the analysis of the ES spatial structure. This cell size ensured an appropriate representation of the analysed landscape [10]. ES were accounted and weighted in each cell using Equation 1.

\[ E_j = \frac{\sum_{i=1}^{n} c_i \times P_i}{100} \]  

Where \( E_j \) is the total amount of ES per cell, \( c_i \) is the land use type according to CORINE and \( P \) is the potential provision of the LULC types. We used \( P \) values following [11]. We report the ES provisions in the standard grouping of RES, PES and CES as a basis for comparison to the identified bundles.

2.1. Bundling of ES using PCA

To bundle the ES provisions we used principal component analysis (PCA). This statistical technique groups variables that converge into a certain number of principal components (PC) using the intrinsic statistical numerical variability of variables.

We used Kaiser's rule as a criterion for the selection of PCs and only retained components with eigenvalues larger than 1. To enhance the statistical performance of the PCA, we used varimax (orthogonal) rotation. We used factor loadings after rotation to maximise the interpretation of the results. Further calculations were performed over normalised rotated factor scores. We performed PCA over the entire study area and over each region separately to ascertain the agreement in the convergence of the PCs.

We mapped and analysed spatial patterns using Local Moran's I statistic of spatial association [12]:

\[ I_i = \frac{x_i - X}{S_i^2} \sum_{j=1, j\neq i}^{n} \omega_{ij} (x_j - X) \]  

Where \( x_i \) is the ES of cell i, \( X \) is the mean of ES, \( \omega_{ij} \) is the spatial weight between cells i and j, and:

\[ S_i^2 = \frac{\sum_{j=1, j\neq i}^{n} w_{ij}}{n-1} - X^2 \]  

Where \( n \) equates to the total amount of analysed cells.
3. Results and discussion
Both regions performed slightly differently regarding RES, PES and CES (Fig. 1) and followed their different LULC spatial structures. In Ostrava, 45.8% of the land area provided low values for RES, 18.2% provided medium values and 14.3% provided very high values. The CES provisions were similar, with a higher medium provision (25%) and small very low provision (1.5%). In contrast, the PES were highly concentrated in low (89.7%) and very low provisions (10.3%). The RES in Katowice were predominantly low (34.5%) and very low (30.2%), indicating that this region performed worse than Ostrava. The differences between medium, high and very high RES provisions were similar, reaching 13.3%, 10.4%, and 11.5%, respectively. The PES shares concentrated around low (65.9%) and very low (34.1%) provisions. In both regions, areas depicting medium, high and very high PES provisions were absent. CES in Katowice clustered into low values (52.1%), followed by medium (17.1%), high (13.3%) and very high (11.5%), whereas very low CES provisions reached 6%, which was four times larger than in Ostrava. Overall, the performance of Katowice was worse than Ostrava, which resulted from the scattered LULC pattern and the fragmented structure of urban land uses (Table 1).

Table 1. RES, PES and CES in both analysed regions.

|          | Regulating | Provisioning | Cultural |
|----------|------------|--------------|----------|
|          | Regulating | Provisioning | Cultural |
| Very low | 10.0%      | 10.3%        | 1.5%     | 30.2% | 34.1% | 6.0% |
| Low      | 45.8%      | 89.7%        | 45.9%    | 34.5% | 65.9% | 52.1% |
| Medium   | 18.2%      | 0%           | 25%      | 13.3% | 0%    | 17.1% |
| High     | 11.7%      | 0%           | 13.5%    | 10.4% | 0%    | 13.3% |
| Very high| 14.3%      | 0%           | 14%      | 11.5% | 0%    | 11.5% |

Clusters of RES and CES were similar. The forest areas were concentrated with high-high values of RES and CES in both regions. The urban areas in Katowice were concentrated with low-low values for RES and CES, whereas in Ostrava, agricultural areas were concentrated with low-low values (Fig. 1). In contrast, the PES had low and very low values, and were larger in Katowice than in Ostrava. Clusters of low-low values mirrored urban areas in Katowice, whereas in Ostrava, high-high values were also concentrated in agricultural areas in the north and east of the region. Despite these differences, both regions behaved similarly.

3.1. Bundles of ES
Our data indicated a strong convergence of ES towards the first PC. This trend was consistent at all tested spatial aggregations, as shown by the PCA (Table 2). We identified 5 PCs for the combined regions, Ostrava and Katowice, which explained 98%, 97.6% and 97.8% of the total variability, respectively. The first PC grouped 20 ES into the entire study area and 21 into each separate region. Biochemicals & medicine converged towards PC2 for the separate regions. However, the difference in the factor loadings between the PC1 and PC2 was very small (Table 2). PC1 explained 66.1% of the total variability for the entire study area, and 61.3% and 63.2% for Ostrava and Katowice, respectively. The ES comprising PC1 included RES and CES, in addition to timber, wood fuel and wild foods & resources. These 21 ES were considered fundamental and we termed them “primal ES”.

Figure 1. Spatial distribution of regulating, provisioning and cultural ecosystem services and their respective spatial clusters of high-high (HH) and low-low (LL) values. Low-high and high-low values are absent. P values are calculated at the 0.05 confidence level.
PC2 explained 13%, 16.8% and 15.1% of the total variability of the combined regions, Ostrava and Katowice, respectively. PC2 contained a cluster of five ES for the whole region, including crops, biomass for energy, fodder, fiber and biochemicals & medicine. For the separated regions, PC2 grouped four ES, which excluded biochemicals & medicine, as the factor loadings for these ES were slightly higher than in PC1 (0.708 vs 0.665 in Ostrava and 0.653 vs 0.646 in Katowice). From a statistical perspective, the numerical differences between these factor loadings are so small that this ES could be grouped into the first or second PC. We called PC2 a “commodity-based ES”.

PC3 explained 9.8%, 10.6% and 10.2% of the total variability of the combined regions, Ostrava and Katowice, respectively. This PC consistently grouped three ES, including fish, seafood & edible algae, aquaculture and freshwater. We termed PC3 the “blue ES”. Interestingly, this PC grouped ES including material goods, but excluded the regulation of water functions (water flow regulation and water purification), which are represented in PC1 with strong factor loadings (Table 2).

PC4 explains 5.7%, 5.6% and 6% of the total variability for the combined regions, Ostrava and Katowice, respectively. PC4 grouped livestock and abiotic energy sources. PC5 explained 3.2% of the total variability for the three analysed spatial units. This PC had only one ES, mineral resources. The PCA results show a simple structure and clear convergence of this ES into particular components. Only one ES, biochemicals & medicine, converged into two PCs. For all other cases, the differences in the factor loadings between components were very large, which allowed for a straightforward and consistent interpretation of ES bundles.

### 3.2. Discussion

In this study, we bundled ES to aid in the development and application of ES frameworks. This approach is valuable in contexts where a lack of quality data hinders the assessment of trade-offs between ES.

The five ES bundles were highly consistent at different spatial aggregations. More than half of the ES clustered around the first component, demonstrating the close relationships between these ES. These data indicate fundamental ecosystem functions and processes, which should be carefully managed. Therefore, although these ES belong to different standard groups, i.e., regulating, provisioning and cultural, the decisions that affect their provisions will affect them as a bundle. ES bundles may vary across geographical settings, from system-to-system, from site-to-site, and from time-to-time [8]. Therefore, it is important to perform similar quantitative analyses before assessing the ES trade-offs.

We found an asymmetric behaviour of particular sets of ES in the two analysed regions. This behaviour was particularly evident in PC4 (Fig. 2). Such differences in performance may have relevance for policy-making, which are obscured when the standard regulating, provisioning and cultural categories are used (Fig. 1).

### 3.3. Bundles of ES and LULC

As bundles of ES are heavily driven by LULC [13], the LULC analysis provides relevant information for policymakers, especially when high quality data are lacking [5], [6]. Our results pinpoint the multifunctionality of particular LULCs, which tend to be thematically and spatially clustered. Indeed, the LULC-based ES assessment considers the spatial structure of ecosystems as a fundamental input. This is especially relevant considering that trade-offs between ES are a zero sum game, where gains in some ES occur at the expense of others.
Table 2a) The sets of ES that clustered into principal components, were highly consistent at the three tested spatial units

| Eigenvectors | PC1 | PC2 | PC3 | PC4 | PC5 | PC1 | PC2 | PC3 | PC4 | PC5 |
|--------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Eigenvalue   | 20.51 | 4.052 | 3.045 | 1.791 | 0.999 | 19.00 | 5.217 | 3.294 | 1.748 | 1.013 |
| Variability (%) | 66.17 | 13.07 | 9.823 | 5.777 | 3.223 | 61.31 | 16.82 | 10.626 | 5.639 | 3.267 |
| Cumulative % | 66.17 | 79.24 | 89.07 | 94.84 | 98.07 | 61.31 | 78.14 | 88.766 | 94.40 | 97.67 |

| Factor loadings | Study area | Ostrava |
|-----------------|------------|---------|
| 1 Global climate regulation | 0.964 | 0.252 | -0.058 | 0.021 | -0.005 | 0.992 | -0.084 | -0.062 | 0.006 | -0.012 |
| 2 Local climate regulation | 0.984 | 0.024 | -0.027 | 0.147 | -0.007 | 0.983 | 0.139 | -0.012 | -0.093 | -0.013 |
| 3 Air quality regulation | 0.952 | 0.180 | -0.085 | 0.225 | -0.003 | 0.975 | -0.051 | 0.113 | -0.177 | -0.010 |
| 4 Water flow regulation | 0.913 | -0.273 | 0.248 | 0.141 | -0.012 | 0.867 | 0.338 | 0.340 | -0.053 | -0.019 |
| 5 Water purification | 0.924 | 0.337 | -0.001 | 0.155 | -0.002 | 0.956 | -0.239 | 0.007 | -0.159 | -0.006 |
| 6 Nutrient regulation | 0.963 | 0.227 | 0.022 | 0.128 | -0.004 | 0.990 | -0.080 | 0.054 | -0.085 | -0.008 |
| 7 Erosion regulation | 0.863 | 0.474 | -0.086 | 0.114 | -0.011 | 0.878 | -0.413 | -0.144 | -0.143 | -0.042 |
| 8 Natural hazard regulation | 0.965 | 0.180 | 0.042 | 0.150 | -0.003 | 0.992 | -0.019 | 0.093 | -0.061 | -0.009 |
| 9 Pollination | 0.916 | 0.232 | -0.108 | 0.278 | -0.010 | 0.946 | -0.074 | -0.155 | -0.217 | -0.026 |
| 10 Pest and disease control | 0.976 | 0.111 | 0.008 | 0.031 | -0.022 | 0.977 | 0.080 | 0.044 | -0.021 | -0.055 |
| 11 Regulation of waste | 0.925 | 0.097 | 0.107 | -0.236 | -0.011 | 0.928 | 0.120 | 0.192 | 0.239 | -0.020 |
| 12 Recreation & tourism | 0.831 | 0.492 | 0.083 | 0.125 | -0.024 | 0.789 | -0.418 | 0.129 | -0.126 | -0.084 |
| 13 Landscape aesthetics & inspiration | 0.894 | 0.420 | 0.040 | 0.093 | -0.016 | 0.927 | -0.273 | 0.082 | -0.054 | -0.047 |
| 14 Knowledge systems | 0.948 | 0.234 | 0.038 | 0.115 | 0.007 | 0.956 | -0.045 | 0.087 | -0.053 | 0.033 |
| 15 Religious & spiritual experience | 0.777 | 0.529 | 0.017 | 0.269 | -0.016 | 0.745 | -0.491 | 0.025 | -0.259 | -0.056 |
| 16 Cultural heritage & diversity | 0.964 | -0.124 | -0.031 | -0.022 | -0.035 | 0.918 | 0.294 | 0.013 | 0.071 | -0.083 |
| 17 Natural heritage & diversity | 0.905 | 0.363 | 0.041 | -0.011 | -0.004 | 0.957 | -0.241 | 0.072 | -0.057 | -0.002 |
| 18 Crops | -0.499 | -0.849 | -0.046 | 0.118 | -0.012 | -0.363 | 0.918 | -0.056 | -0.054 | -0.034 |
| 19 Biomass for energy | -0.303 | -0.946 | -0.028 | 0.072 | -0.008 | -0.070 | 0.989 | 0.000 | 0.026 | -0.019 |
| 20 Fodder | -0.331 | -0.832 | -0.086 | -0.332 | -0.013 | -0.075 | 0.898 | -0.068 | 0.399 | -0.032 |
| 21 Livestock (domestic) | -0.108 | 0.213 | -0.021 | -0.967 | -0.015 | -0.052 | -0.062 | -0.023 | 0.990 | -0.026 |
| 22 Fiber | -0.219 | -0.951 | -0.068 | 0.131 | -0.009 | 0.025 | 0.984 | -0.069 | -0.068 | -0.018 |
| 23 Timber | 0.922 | 0.324 | -0.069 | 0.194 | 0.000 | 0.958 | -0.217 | -0.095 | -0.150 | -0.004 |
| 24 Wood fuel | 0.918 | 0.332 | -0.070 | 0.196 | 0.001 | 0.960 | -0.209 | -0.097 | -0.142 | 0.001 |
| 25 Fish, seafood & edible algae | 0.002 | 0.055 | 0.998 | 0.004 | -0.002 | 0.024 | 0.060 | 0.998 | -0.004 | 0.010 |
| 26 Aquaculture | 0.002 | 0.055 | 0.998 | 0.004 | -0.002 | 0.024 | 0.060 | 0.998 | -0.004 | 0.010 |
| 27 Wild foods & resources | 0.967 | 0.239 | 0.051 | 0.013 | -0.005 | 0.990 | -0.066 | 0.107 | 0.012 | -0.011 |
| 28 Biochemicals & medicine | 0.596 | -0.615 | -0.132 | 0.448 | -0.003 | 0.708 | 0.665 | -0.129 | -0.179 | -0.016 |
| 29 Fresh water | 0.002 | 0.055 | 0.998 | 0.004 | -0.002 | 0.024 | 0.060 | 0.998 | -0.004 | 0.010 |
| 30 Mineral resources | -0.032 | 0.020 | -0.006 | 0.005 | 0.999 | -0.060 | 0.063 | 0.027 | 0.012 | 0.996 |
| 31 Abiotic energy sources | -0.555 | -0.302 | -0.022 | -0.716 | 0.026 | -0.489 | 0.394 | 0.020 | 0.747 | 0.101 |

1 after Varimax rotation.
Table 2b) The sets of ES that clustered into principal components were highly consistent at the three tested spatial units

| Eigenvectors | PC1       | PC2       | PC3       | PC4       | PC5       |
|--------------|-----------|-----------|-----------|-----------|-----------|
| Eigenvalue   | 19.60     | 4.70      | 3.16      | 1.86      | 1.00      |
| Variability (%) | 63.25    | 15.16     | 10.21     | 6.07      | 3.22      |
| Cumulative % | 63.25     | 78.41     | 88.62     | 94.63     | 97.86     |
| Factor loadings<sup>1</sup> | Katowice |           |           |           |           |
| 1 Global climate regulation | 0.982   | -0.167    | -0.062    | 0.003     | -0.010    |
| 2 Local climate regulation  | 0.988   | 0.069     | -0.233    | 0.109     | -0.013    |
| 3 Air quality regulation    | 0.966   | -0.115    | -0.100    | 0.199     | -0.008    |
| 4 Water flow regulation     | 0.890   | 0.324     | 0.288     | 0.082     | -0.020    |
| 5 Water purification        | 0.942   | -0.288    | 0.000     | 0.149     | -0.005    |
| 6 Nutrient regulation       | 0.981   | -0.152    | 0.034     | 0.104     | -0.007    |
| 7 Erosion regulation        | 0.869   | -0.452    | -0.114    | 0.124     | -0.025    |
| 8 Natural hazard regulation | 0.981   | -0.103    | 0.064     | 0.111     | -0.006    |
| 9 Pollination               | 0.936   | -0.155    | -0.132    | 0.246     | -0.019    |
| 10 Pest and disease control | 0.982   | -0.010    | 0.023     | 0.017     | -0.043    |
| 11 Regulation of waste      | 0.932   | 0.021     | 0.147     | -0.240    | -0.018    |
| 12 Recreation & tourism     | 0.810   | -0.474    | 0.104     | 0.131     | -0.056    |
| 13 Landscape aesthetics & inspiration | 0.913 | -0.357 | 0.057 | 0.076 | -0.032 |
| 14 Knowledge systems        | 0.962   | -0.130    | 0.058     | 0.075     | 0.020     |
| 15 Religious & spiritual experience | 0.763 | -0.518 | 0.019 | 0.265 | -0.036 |
| 16 Cultural heritage & diversity | 0.943 | 0.221 | -0.011 | -0.054 | -0.066 |
| 17 Natural heritage & diversity | 0.935 | -0.292 | 0.051 | 0.000 | -0.005 |
| 18 Crops                    | -0.422  | 0.892     | -0.051    | 0.082     | -0.028    |
| 19 Biomass for energy       | -0.173  | 0.980     | -0.017    | 0.014     | -0.020    |
| 20 Fodder                   | -0.193  | 0.876     | -0.076    | -0.365    | -0.028    |
| 21 Livestock (domestic)     | -0.060  | -0.130    | -0.025    | -0.983    | -0.025    |
| 22 Fiber                    | -0.084  | 0.978     | -0.070    | 0.084     | -0.020    |
| 23 Timber                   | 0.940   | -0.276    | -0.082    | 0.174     | -0.001    |
| 24 Wood fuel                | 0.938   | -0.280    | -0.084    | 0.175     | 0.002     |
| 25 Fish, seafood & edible algae | 0.010 | -0.060 | 0.998 | 0.006 | 0.008 |
| 26 Aquaculture              | 0.010   | -0.060    | 0.998     | 0.006     | 0.008     |
| 27 Wild foods & resources   | 0.983   | -0.152    | 0.075     | -0.005    | -0.009    |
| 28 Biochemicals & medicine  | 0.653   | 0.646     | -0.130    | 0.327     | -0.012    |
| 29 Fresh water              | 0.010   | -0.060    | 0.998     | 0.006     | 0.008     |
| 30 Mineral resources        | -0.056  | -0.053    | 0.020     | 0.001     | 0.997     |
| 31 Abiotic energy sources   | -0.517  | 0.350     | -0.002    | -0.732    | 0.061     |

<sup>1</sup> after Varimax rotation.

The bundles of ES differ in the two regions, reflecting the differential spatial structure of the LULC types. Although the observed bundles differ, there is some consistency between the two regions. This observation indicates the differential performance of ecosystems regarding the flow of ES towards society, and may also reflect the different intensities of the built and natural capital in these ecosystems.
Figure 2. Spatial distribution and clusters of PCs. The differential performance of both regions is evident when mapping bundles of ES.
4. Conclusions
In this study, ES bundles were explored with a spatially explicit analysis using PCA and a LULC-based method. Our findings show that ES analysis should be performed in bundles, where several ES converge in their provision. The bundles were spatially determined and do not necessarily follow the a priori RES, PES and CES classifications. Further research might explore how ES bundles vary across different spatial and temporal scales for analysing explicit trade-offs and synergies.

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