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Ecosystem Services and Urbanisation. A Spatially Explicit Assessment in Upper Silesia, Central Europe

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Abstract. Urbanisation is a complex spatiotemporal process taking place across landscapes even in areas far beyond urban cores; therefore, directly and indirectly affecting the functions, processes and services of ecosystems. Urbanisation is a difficult process to monitor, quantify and plan. Landscape areas located outside of urban cores are heavily affected by urbanisation, yet they provide fundamental ecosystem services (ES). To date, the evidence of the spatial variability of the relationship between ES and urbanisation is scarce. In this contribution, a spatial analysis was carried out in Upper Silesia, central Europe, to explore the provision of ES and the levels of urbanisation to advance the use of ES in planning. The potential provision of ES was assessed using an approach based on land use land cover. The technomass indicator was used to assess urbanisation as a continuous variable. To ascertain the spatial variability between urbanisation levels and ES provision across the landscape, a geographically weighted regression model was used. The results show a statistically significant variability across the landscape for several ES, showing that this relationship does not remain constant. The spatial variability of urbanisation affects ES in a differentiated manner. The proposed method allows for the direct use of the ES framework in landscape planning to assess the impacts of urbanisation outside of urban areas.

1. Introduction

Cities depend on persisting flows of goods and services coming from other neighbouring non-urban ecosystems to sustain fundamental urban functions [1], [2]. Urbanisation both directly and indirectly affects the functions and processes of ecosystems [3], [4], thus compromising the generation, provision, and flow of ecosystem services (ES) to sustain life and functions in urban areas [5].

The ES framework provides analytical tools and empirical evidence for valuing the tremendous contributions of ecosystems towards the development of society [6]. Such conceptual and operational contributions have been realised in different geographical contexts and scales, such as land management [7], environmental impact assessments [8], and land use planning [9], to mention a few. Recently, the ES framework has landed in the urban arena where issues of scale and spatial complexity are challenging its successful application [10]. Research on urban ES has become a hot topic used to address green infrastructure [11], cultural ES and urban planning [10].

To account for the contributions of ES, spatially explicit quantitative methods based on GIS and remote sensing techniques are highly promising [12]–[14]. Such methods can enhance the transferability of results to practical applications of ES in spatial planning [7]. However, a stronger effort has to be made to put the framework of ES into practice using adequate indicators [7], [10].

The relationship between urbanisation and ES has been mostly concerned with the impacts of urbanisation on natural resources, looking at ES and biodiversity [15]–[17] and global urbanisation and ES [16], [18]. From the social sciences side, recent research on ES has paid attention to the perceptions and preferences of people for different types of green urban areas [19]–[23]. The direct links between the levels of urbanisation and ES provision remain unexplored. To date, most research on urbanisation has used demographically based approaches, considering urbanisation as a categorical variable [24]. In contrast, urbanisation is a tetra-dimensional continuous process, taking place in three spatial and one temporal dimensions. Therefore, analysing urbanisation as a continuous variable can greatly help to establish links between ecological functions and ES [24].

The objectives of this contribution are, therefore, three-fold. The first objective is to estimate the levels of urbanisation and the provision of ES at the landscape scale in a highly urbanised area. The second objective is to analyse the spatial variations of ES provision. The final objective is to perform a quantitative exploration of the relationship between ES provision and level of urbanisation.

2. Material and Methods

The study area is located in Upper Silesia, central Europe, belonging to the Czech Republic and Poland. We used functional urban zones (FUZ) (Copernicus 2018) to identify the extension of the studied area in both countries.
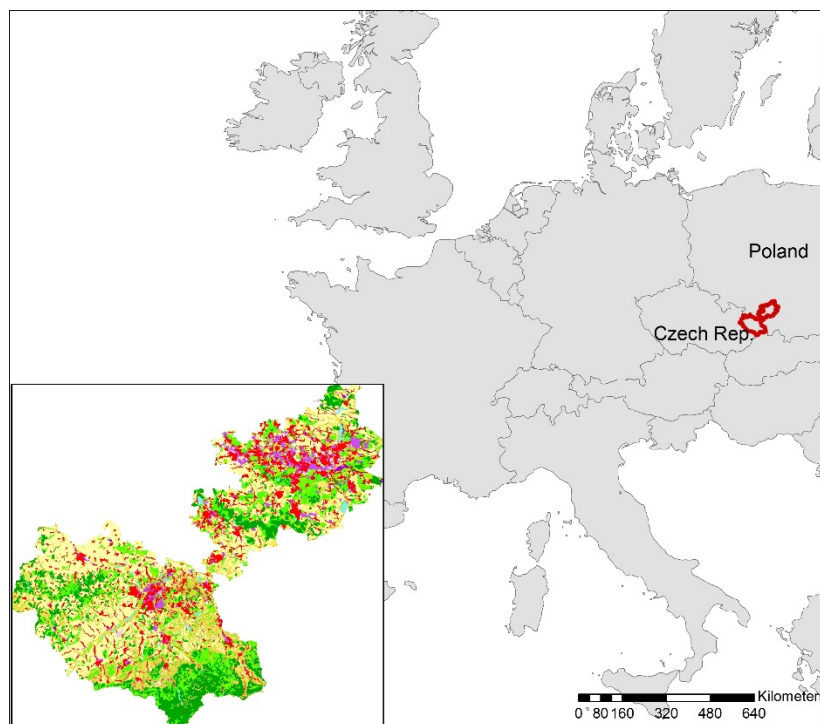
Figure 1. Location of the study area within Europe. The small box shows the CORINE land cover classes in the study area.

The CORINE land cover data set (Copernicus 2018) was used to determine the potential provision of ES, using equation (1):

$$E_j = \frac{\sum_{i=j}^{n} c_i^j * P_i}{100} \tag{1}$$

Where:

E_j = Ecosystem service provision of cell j

c^j_i = Surface of land cover i in cell j

P_i = Potential provision of ecosystem service of land cover i

The CORINE dataset allows for direct links between the land cover classes and the estimated potential provision of ES to be made following the methods in [25]. In table 1, we present the respective values used in the ES calculation, divided into 11 regulating, 14 provisioning and 6 cultural ES.

Table 1. Land cover classes from CORINE and the respective values for 31 ES used in the calculation. Source for ES values [25]

Code	Land cover class	Regulating											Provisioning														Cultural					
		Global climate regulation	Local climate regulation	Air quality regulation	Water flow regulation	Water purification	Nutrient regulation	Erosion regulation	Natural hazard regulation	Pollination	Pest and disease control	Regulation of waste	Crops	Biomass for energy	Fodder	Livestock (domestic)	Fibre	Timber	Wood Fuel	Fish, seafood & edible algae	Aquaculture	Wild foods & resources	Biochemicals & medicine	Freshwater	Mineral resources*	Abiotic energy sources*	Recreation & tourism	Landscape aesthetics & inspiration	Knowledge systems	Religious & spiritual experience	Cultural heritage & cultural diversity	Natural heritage & natural diversity
1	Continuous urban fabric	0	0	0	0	0	0	2	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3	3	2	2	1	0
2	Discontinuous urban fabric	0	0	0	0	0	0	1	0	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	3	2	2	2	2	0
3	Industrial or commercial units	0	0	0	0	0	0	2	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	2	0
4	Road and rail networks and associated land	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
5	Port areas	0	0	0	0	0	0	3	3	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	0	0	1	0
6	Airports	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	Mineral extraction sites	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	3	0	0	0	2	0	1
8	Dump sites	0	0	0	0	0	0	0	0	0	0	2	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	Construction sites	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0
10	Green urban areas	2	2	2	2	2	2	1	2	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	1	0	2	1
11	Sport and leisure facilities	1	1	1	1	1	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	1	0	0	1	0
12	Non-irrigated arable land	1	2	1	2	0	1	0	1	1	2	2	5	5	5	0	5	0	0	0	0	1	3	0	0	2	1	1	1	2	0	1
16	Fruit trees and berry plantations	2	2	2	2	1	2	2	2	5	3	2	4	1	0	0	0	0	2	2	0	0	2	0	0	0	3	2	2	0	4	1
18	Pastures	2	1	0	1	0	1	1	1	0	2	4	0	1	5	5	0	0	0	0	0	2	0	0	0	5	2	2	2	0	3	1
20	Complex cultivation patterns	1	2	1	1	0	1	1	1	2	3	2	4	2	2	1	4	0	1	0	0	1	2	0	0	1	2	2	2	0	3	0
21	Land principally occupied by agriculture, with significant areas of nat	2	3	2	2	2	2	1	2	3	2	3	3	3	2	2	4	1	1	0	0	2	1	0	0	1	2	2	3	1	3	3
23	Broad-leaved forest	5	5	5	5	5	5	4	4	4	4	0	0	1	1	0	1	5	5	0	0	5	3	0	0	0	5	5	5	3	4	4
24	Coniferous forest	5	5	5	3	5	5	5	4	4	4	0	0	1	1	0	1	5	5	0	0	5	3	0	0	0	5	5	5	3	4	4
25	Mixed forest	5	5	5	3	5	5	5	4	4	5	0	0	1	1	0	2	5	5	0	0	5	3	0	0	0	5	5	5	3	4	5
29	Transitional woodland-shrub	2	2	1	1	1	2	1	1	2	2	3	0	2	1	1	1	2	0	0	1	1	0	0	0	1	2	3	4	1	2	2
32	Sparsely vegetated areas	0	1	0	1	1	1	1	1	1	0	1	0	0	0	1	0	0	0	0	0	1	0	0	0	2	1	1	3	0	2	1
35	Inland marshes	2	2	0	3	2	4	1	4	1	2	3	0	0	4	2	0	0	0	0	0	1	0	0	0	0	1	2	3	0	2	2
40	Water courses	0	1	0	3	3	3	0	3	0	3	5	0	2	0	0	0	0	3	0	4	0	5	0	3	4	4	4	4	2	3	3
41	Water bodies	1	2	0	5	2	3	0	3	0	3	5	0	1	0	0	0	0	0	4	5	4	0	5	0	1	5	4	4	2	3	3

The levels of urbanisation were measured using the technomass indicator on a hexagonal grid basis, following [24], [26]. Technomass is a spatially explicit indicator that can reduce the high complexity of the built environment to one single measure of the weight/volume per unit of surface [1].

To ascertain the spatial variability between the levels of urbanisation and ES, we used a geographically weighted regression (GWR) model. GWR accounts for the spatial variability in the quantitative relationship between factors. GWR is an advanced spatial statistical method allowing for the exploration of the presence of spatial variability in the relationships between dependent and independent variables in a much more robust manner that ordinary least squares (OLS). GWR calibrates a separate model at each location, including only the data that are located in the neighbouring area of the calibration point in the estimation. Indeed, every point is calibrated and weighted according to the geographic distance from every other data point in a way that data closer to the calibration point are given higher importance than data further away. The result is a set of local models, one at each point, which capture any spatial variability in the relationships [27]. The GWR model used equation (2):

$$y_i = \beta_{0i} + \beta_{1i} x_{1i} + \beta_{2i} x_{2i} + e_i \qquad (2)$$

where y is the dependent variable (ES provision), urbanisation is the independent variable, B is the respective coefficient at points $x_1 \dots x_n$ and e accounts for the error in the model, which has to be randomly distributed to ensure the robustness of the model without spatial bias. The GWR model performance will be compared with the results of an ordinary least squares (OLS) model.

3. Results and discussions

There are relevant differences in the spatial distribution of areas providing relevant regulating, provisioning and cultural ES (Figure 2). Very high and high values for provisioning and cultural ES are concentrated in forest areas in the southern part of Ostrava and the middle part of Katowice. There are spatial coincidences in the areas with very low provision of the three groups of ES where urban areas are allocated.
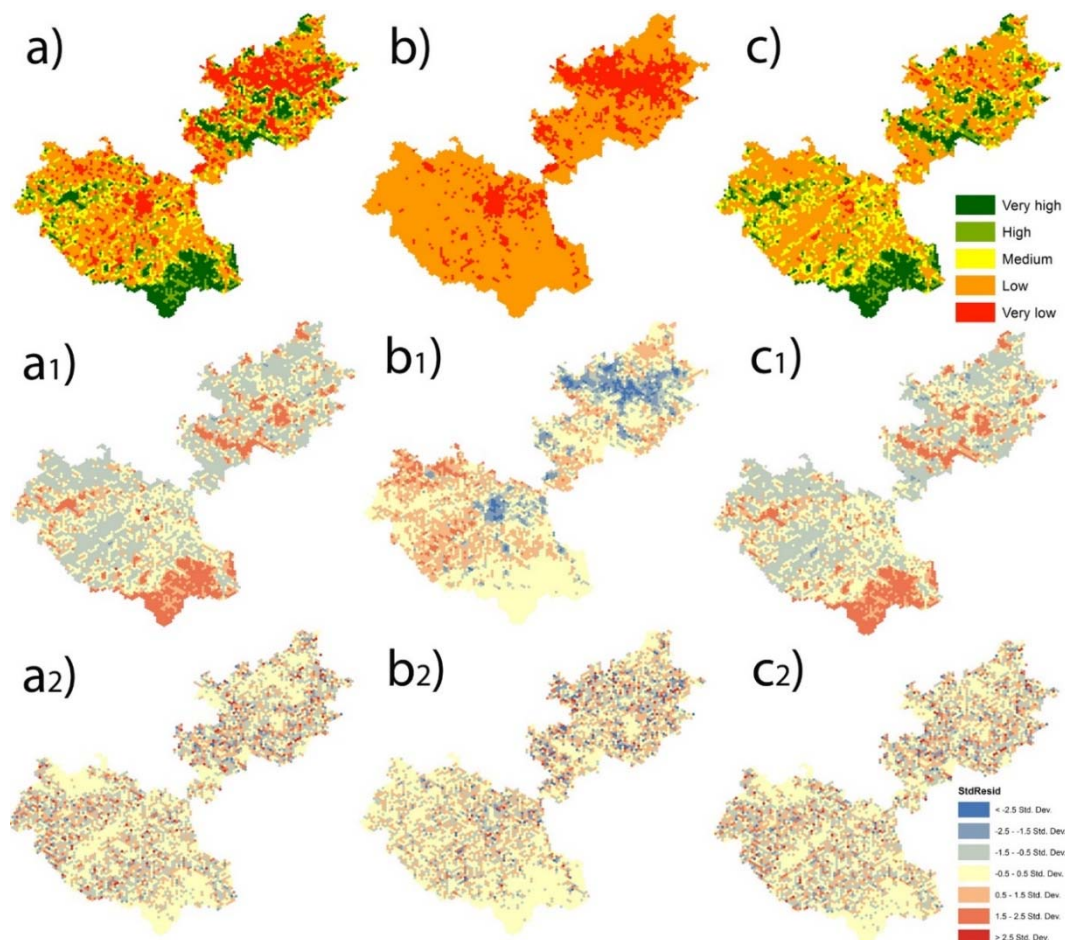
Figure 2. Results of regulating (a), provisioning (b) and cultural (c) ES and the respective OLS (1) and GWR (2) models

When comparing the spatial distribution of residuals, it is clear that the GWR model exhibits better performance. The three OLS models overestimate and underestimate residuals in particular areas. This clustering of residuals is evidence of the strong limitations of OLS in depicting the spatial variability between ES and urbanisation. In contrast, in the case of the GWR model, the patterns of the distribution

of residuals are random. We tested for the presence of statistically significant clusters in the residuals using Moran's I from Anselin [28] for the GWR. We did not find significant spatial clusters.

Our results from the GWR show that there is a clear spatial non-stationary [27] between the provision of ES and the level of urbanisation. Standard OLS regression is incapable of modelling these geographically varying relationships. To further explore the varying spatial relationship between ES and urbanisation, multi-level modelling is necessary to account for both spatial autocorrelation and non-stationarity.

4. Conclusions

Increasing degrees of urbanisation affect the provision of ES. These relationships are not linear; rather they vary across space. In some cases, the relationship between the amounts of technomass and ES is quadratic (environmental Kuznets curve). Certain amounts of technomass help enhance the provision of ES from particular areas until a certain threshold when diminishing returns begin to dominate. Analysing such non-linear relationships helps to set maximum thresholds of anthropogenic stocks to maximise ES returns from landscapes, a task that can be pursued by using differentiated types of technomass, as proposed by [1]. Ecosystem services are the benefits to humans from nature. For ES to flow towards society, natural capital needs to interact with social, human and built capital. Such interaction is highly complex and driven by flows of energy, matter and information [1], [6]. At the same time, it is necessary to use adequate spatiotemporal representations of the built capital, which is the built environment compounded by all kinds of human artefacts. The built dimension is not necessarily equal to sealed surfaces or other indicators that poorly represent the material side of society [1], [24]. In this contribution, we have used a novel indicator, the technomass, to account for the built dimension, understanding that it is determinant in the provision of ES. We have proven that the interaction between the levels of urbanisation, i.e., the intensity of the built environment, and the ES provision does not remain constant; rather, it varies across space. Determining the drivers of this spatial variability is fundamental for maintaining the provision of ES for sustainable development.

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