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Assessment and Spatial Distribution of Urban Ecosystem Functions Applied in Two Czech Cities

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Highlights:

What are the main findings?

- Surprisingly, ecosystem services can be provided at relatively high levels even in medium-sized cities of regional importance.
- Contrary to expectations, the level of ecosystem service provision is unevenly distributed and does not exactly follow the urban-rural gradient, with very good performance in peri-urban areas compared to rural areas.

What are the implications of the main findings?

- The uneven distribution of ecosystem service provision requires a more detailed analysis for urban planning and achieving the goals of adaptation strategies.
- Consequently, more focus on key areas is needed, rather than assuming provision of ecosystem services along an urban-rural gradient.

Featured Application: The method can serve as a useful tool to quickly identify valuable urban habitats that are strong providers of ecosystem functions and ecosystem services (EFs/ESs) and advocate for their protection or, on the contrary, identify places with low values of EFs/ESs which should be prioritized and sorted in urban adaptation strategies toward global climate change.

Abstract: As urban areas expand worldwide, the importance of ecosystem services provided by urban and peri-urban areas (ESs) increases, especially those that mitigate the effects of ongoing climate change. We present a relatively simple method to assess the performance of three ecosystem functions (EFs: evapotranspiration, carbon production, and habitat- and landscape-level biodiversity) in urban and peri-urban areas, indicating their capacity to provide relevant regulative ESs. The method was applied to two Czech foothill cities, Liberec and Děčín, and the results showed that the EFs of both cities were at comparable or even higher levels than the average values for the whole Czech Republic. The peri-urban area showed surprisingly high values for all EFs and habitat connectivity. The urban–rural gradient of EFs also showed higher values for EFs in the peri-urban area than in the adjacent rural (forest and agricultural) landscape. The method can serve as a useful tool to quickly identify valuable urban habitats (strong ESs providers) to support their protection or to identify places with low functional values that should be considered and sorted in urban adaptation strategies to global climate change to support the creation of functional green infrastructure.

Keywords: urban ecosystem functions/services; climate change mitigation; green infrastructure; connectivity; urban–rural gradient

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1. Introduction

1.1. Functions and Services of Urban Ecosystem Climate Change Mitigation

Urban vegetation provides unique ecosystem services that enhance environmental conditions in cities [1,2]. Global climate change is expected to have a particularly adverse effect on the urban environment, particularly highlighting the problems with the "urban heat island" [3], as well as the problems with the reduction in biodiversity and, thus, the adaptive capacity of the landscape to the expected changes [4]. To mitigate these problems, green spaces in urban areas must be carefully planned to create what is known as green infrastructure, "an interconnected network of green spaces that maintains the values and functions of natural ecosystems and provides corresponding benefits to human populations" [5]. The TEEB report for cities [6] suggests that ESs could be used to support the opportunity to make positive changes, save municipal costs, support the local (green) economy, and improve quality of life.

From the variety of ecosystem services that urban green areas provide, this paper focuses on three selected services which are most related to adaptation of cities to global climate change: climate change mitigation at the local scale, climate change mitigation at the regional scale, and biodiversity/habitat provision. Instead of the actual flow of ESs, the capacity of ecosystems to provide them [7] is examined, according to the idea of an "ecosystem service cascade" by Potschin and Haines-Young [8], who summarized the ESs paradigm as a "production chain" starting as ecological and biophysical structures which support processes and these ensure ecosystem functions (EFs), on the basis of which ESs are produced and finally become benefits expressed as values.

1.2. Assessment of Urban Ecosystem Functions and Services

A number of articles devoted to the evaluation of urban ESs have been published recently, assessing the full range of ESs (see refs. [9–14]). On the other hand, Marando et al. [15] focused on climate regulation, Davies et al. [16] developed an expert method for mapping carbon storage, and Baró et al. [17] studied bundles of ESs in an urban–rural gradient. Projects with the theme of mapping and assessment of urban ESs were also addressed, ESMERALDA (Enhancing Ecosystem Services Mapping for Policy and Decision Making) being among the most prominent, creating ESs mapping and assessment strategies for all 28 EU Member States, plus Norway, Switzerland, and Israel, including a case study from the Czech Republic [18].

While culture ESs are mostly assessed using sociocultural methods [19], regulation and supporting ESs assessment mostly involve biophysical/indicator-based methods which is also recommended by European Commission [20] and used by many authors (see refs. [12,14,21,22]). Other option is using models (see refs. [11,13]).

Indicators are numerical values that describe the state of a phenomenon or environment, summarizing the state of an ecosystem [23]. They can combine measurable structural features, such as habitat or landscape patterns, with inherent ecosystem functions and services [24].

1.3. Assessment of Individual Ecosystem Functions

1.3.1. Biodiversity: Habitat Provision

Climate change endangers biodiversity due to a change in natural conditions, habitat loss, migration barriers, etc. [25]. Simultaneously, biodiversity serves as a precondition of stability that helps to reduce abrupt ecosystem shifts [26]. Urban areas often constitute barriers to the migration of organisms [27]; however, on the other hand, the urban environment can also host a variety of native and non-native species [28,29], as well as even support endemic and protected native species [30]. In particular, spontaneously vegetated areas (e.g., brownfields, roadsides, and railway sides) have a high potential for urban nature conservation [31].

Assessing urban biodiversity is, thus, crucial for planning and protection of valuable habitats in the urban environment. Its quality depends on the correctly selected map base, ideally based on a field survey. Jarvis and Young [32] listed options for mapping green infrastructure in cities: (i) mapping species based on a field survey; (ii) using land-use and land-cover maps, which usually lack the necessary detail; (iii) using habitat maps; (iv) mapping tree cover and street trees using aerial photography; (v) using remote sensing methods. Many authors believe that habitat mapping is best suited for biodiversity assessment in urban areas, as it can be utilized to protect native species and rare habitats, delineate conservation zones and design corridors to connect habitats [33,34]. Several habitat assessment methods have been developed to evaluate urban green spaces (see refs. [32,35–37]).

For the connectivity assessment at the landscape scale, landscape metrics describing the spatial structure of habitats and connectivity are used. A rapid assessment of structural connectivity, so-called "distance to nature", was proposed in ref. [38]. Functional connectivity [39] is related to specific organisms and depends on the ability of organisms to move, the spatial distribution of suitable habitats, and the permeability of the landscape matrix [40]. Functional connectivity, using graph theory, was also used for the assessment of urban areas (see refs. [41–43]).

1.3.2. Climate Regulation at the Local Level: Evapotranspiration

Vegetation can significantly cool the environment through shading [44,45] and evapotranspiration [46–48]. A large number of studies used evapotranspiration as an indicator for the cooling effect of vegetation [22,49–51]. The cooling effect of vegetation in cities can be assessed by measuring and comparing the temperature in vegetated and non-vegetated areas, using land surface temperature [3,52], air temperature [53,54], or bioclimatic indices to capture human perception of temperature comfort [55]. These methods are more appropriate for the microscale or local scale. For larger areas, airborne remote sensing methods using satellite imagery [56,57] or aircraft/airship thermal scans of surface temperature [58] are more suitable. However, data processing and interpretation can be challenging. Therefore, a habitat-based approach may be easier to apply in some cases, such as urban planning or assessment of ESs [59]. Examples of habitat-based assessment of cooling function exist in Berlin (Biotope Area Factor [60]) and Malmö (Green Space Factor [61]).

1.3.3. Climate Change Mitigation: Carbon Production, Storage, and Sequestration

Urban vegetation, mainly urban forests, stores carbon during biomass growth [62] and into soil complexes [63], contributing to climate change mitigation and adaptation [64,65]. Both carbon stock and carbon production are part of a sequestration process and are important factors influencing climate change mitigation, even though the amount of carbon stored by urban vegetation is still quite small compared to the annual CO_2 emissions from cities [66].

Most methods for estimating carbon stocks in urban greenery use estimations based on information about the greenery/trees, increasingly using remotely sensed data, and allometric equations adapted to urban space [67]. Carbon sequestration is typically assessed using models (e.g., UFORE, i-Tree Eco and Streets, and CUFR Tree Carbon Calculator).

For a large-scale assessment of carbon storage or production, the lookup table method is also appropriate and provides adequate results, especially when using high-quality data for land use and habitats [68,69]. Due to the large heterogeneity of urban vegetation, its correct mapping is a crucial part of carbon stock assessment.

1.4. Distribution of EFs in a City

The structure and urban form of a city (whether its compact or more scattered) is closely related to EFs/ESs provision [70]. Most cities exhibit a typical scheme; the urban core is surrounded by a suburban part, where discontinuous development prevails, sometimes interspersed with other habitat types, followed by a peri-urban landscape that represents an interface between the countryside and the city [71]. In peri-urban areas, there is a complex mosaic of land-cover transitions composed of low-density residential areas next to agricultural land, sometimes with remnants of highly sensitive biodiversity hotspots [72]. Urban landscapes vary from sprawling areas to high-rise cities with large public parks. Although there is no consensus on which variant is better, evidence suggests that, at the regional level, concentrated cities with bigger parks are preferable for maintaining EFs/ESs [73] and for biodiversity conservation [74], whereas, at the local level, a more scattered city is preferable for improving urban living conditions [75] and enabling better habitat connectivity [76]. Development approaches should aim to optimize the distribution of urban intensity rather than focus on polarized options [73]. The concept of blue–green infrastructure can contribute to the urban environment with multiple benefits: water supply, flood mitigation, terrestrial biodiversity, urban cooling, resilience to climate change effects, urban agriculture, and human wellbeing [77].

1.5. Objectives

There is a need for a clear, simple, and effective method to assess the ability of urban and peri-urban areas to perform EFs. We focused on three selected EFs relevant to climate change adaptation: evapotranspiration, carbon production (which are thought to demonstrate the capacity of ESs most relevant to climate change adaptation and mitigation at local and regional scales), and habitat- and landscape-level biodiversity. The method should be able to use widely available data without the need for time-consuming mapping and field measurements. It should be applicable not only to urban core areas, but also to peri-urban areas to assess connectivity with the surrounding landscape and the gradient of EFs from the urban core to peri-urban and landscape areas.

Our aim was to (i) develop a method that uses created habitat mapping data to quantify and spatially distribute selected EFs, (ii) verify the method on the example of administrative territory of two distinct Czech foothill cities (Liberec and Děčín), comparing their relative EFs performance and comparing their average values with the average value of the Czech Republic, and (iii) assess the urban–rural gradient of the selected EFs.

2. Materials and Methods

2.1. Location

The analysis was carried out for two cities in the northern part of the Czech Republic, Liberec and Děčín. Despite their rather industrial character, they have a large proportion of green areas and relatively high proportion of valuable habitats. They are situated on the border of protected landscape areas; the administrative territory of Liberec extends into the Jizera Mountains Protected Landscape Area in the northeastern part, while the Děčín administrative territory lies entirely in the nature protection regime, with the northern part in the Labské Pískovce Protected Landscape Area and the southern part in the České Středohoří Protected Landscape Area (Figure 1).

The two cities have a similar administrative territory, but they differ significantly in the number of inhabitants, being more than double in Liberec, which also has higher population growth. The geomorphological conditions are also different; Liberec is situated in a depression surrounded by hills with many small, radially oriented watercourses, while Děčín is situated in a narrow valley carved into the sandstone rock by the Elbe River and the Jílovský Brook, with the southeastern part of the valley merging into a wider floodplain with the Ploučnice tributary, surrounded by a hilly landscape. The detailed characteristics are described in Table 1.

Table 1. Characteristics of two administrative territories—Liberec and Děčín.

Name of the Administrative Territory	Liberec	Děčín
Area (km^2)	106.1	117.7

Table 1. *Cont.*

Name of the Administrative Territory		Liberec	Děčín
Elevation min–max (m a.s.l.)		296–1012	115–708
Elevation mean (m a.s.l.)		469	331
Predominant geological subsoil		Granite, silt, marble	Sandstone, impure carbonate sedimentary rock, basanite
Predominant soil types		Cambisols, Leptosols, Podzols, Stagnosols, and Retisols	Podzols, Cambisols, Leptosols, Stagnosols, and Luvisols
Annual average daily temperature (°C)		7.4	8.2
Annual average total precipitation (mm·year^{-1})		890	640
CORINE LC (class level 1) 2018 (%)	Artificial surfaces	31.5	12.5
	Agricultural areas	27.4	21.7
	Forest and seminatural areas	41.2	64
	Water bodies	0	1.8
Number of citizens (1 January 2021)		104,261	47,951

Data sources: Czech Geological Survey [78,79]; Czech Hydrometeorological Institute [80,81]; Czech Statistical Office [82,83]; European Environment Agency [84].

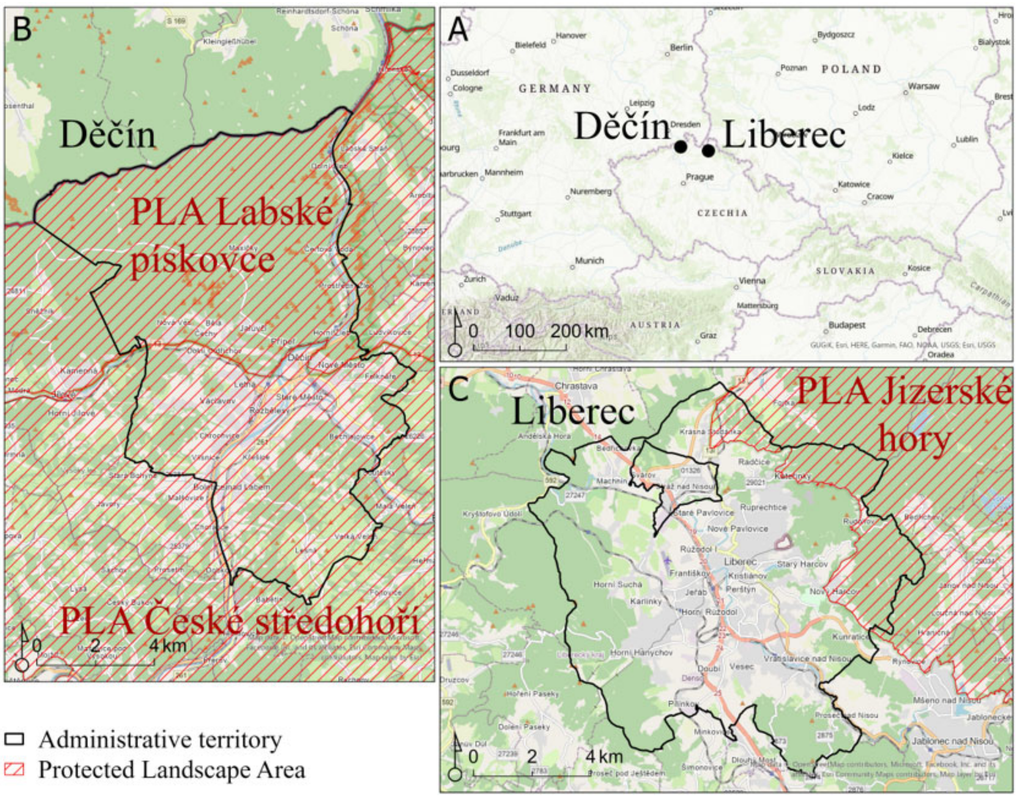

Figure 1. (**A**) Location of Liberec and Děčín, Basemap: World Hillshade [85], World Topographic Map [86]; (**B**,**C**) administrative territory of Děčín and Liberec and protected landscape areas [87], Open Street map [88].

2.2. Map Data and Habitat Types

As a map base for this study, we used a detailed habitat layer that was created by combining two map layers: (i) the modified consolidated layer of ecosystems (© CzechGlobe © NCA CR, 2013) which distinguishes 41 categories with a mapping grain close to that of field mapping [89], and (ii) the habitat mapping layer [89], based on a detailed mapping of plant communities in the field for the purpose of mapping natural and near-natural habitats across the Czech Republic [90]. For more information about composition of the detailed habitat layer, see ref. [91]. The final map was further specified using the latest aerial photographs where necessary. All mapped habitats were expressed as 138 natural and near-natural habitats, according to Catalog of habitats in the Czech Republic [90], and 38 degraded habitats, according to Seják [36]. Map layers were created and edited in GIS using ArcMap 10.2.1 (see Figure 2).

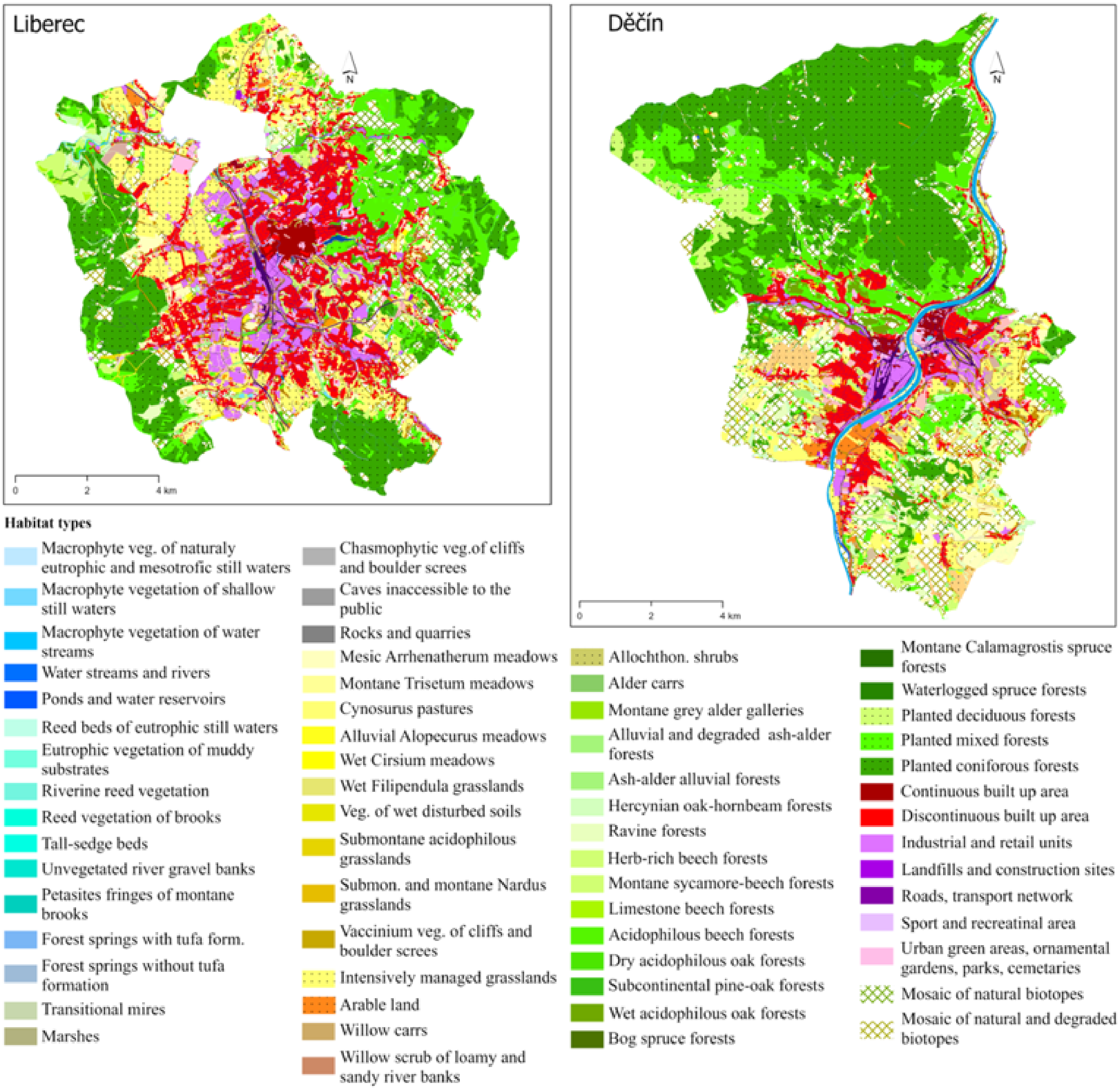

Figure 2. Spatial distribution of habitat types in administrative territories of Liberec and Děčín. For clarity of this image, some categories of habitat types are combined. However, the methodology considered all habitat types according to the list of habitats (see Table S1, Supplementary Materials).

2.3. *Assessment of EFs Performance Indicating Habitat Capacity to Provide ESs*

We opted for an assessment based on biophysical values using the quantification of biotic and abiotic configurations related to their capacity of ESs provision [18]. For assessment of regulation services, biophysical values are more suitable [20] and can combine measurable habitat patterns with inherent ecosystem functions and services [24]. In the administrative territories studied, the assessment of the degree of performance of ecosystem functions was used as an indicator of the capacity to provide the corresponding ecosystem services according to the ”ecosystem service cascade” of Potschin and Haines-Young [8]. The capacity of three key ecosystem services was assessed: provision of habitat/biodiversity, climate regulation at the local level, and climate regulation at the regional level. Habitat/biodiversity provision was assessed using habitat-level biodiversity and habitat connectivity at the landscape level, which allows an assessment of relationships between habitats. Climate regulation at the local scale was represented by an estimation of evapotranspiration, which is often used indicator in various urban ESs assessment studies (see ref. [22,49–51,92,93]). Climate regulation at the regional scale was assessed using the carbon production indicator. As suggested in the recent IPBES document [94], ecosystem uptake of greenhouse gasses is an appropriate indicator of climate regulation services; carbon storage was also used by ref. [14,16], while carbon sequestration or carbon production was used by ref. [10,11,13,95]. Values for the performance of individual ecosystem functions were assigned to the habitat types (for habitat-level biodiversity) or their functional groups (for evapotranspiration and carbon production) in the study area (lookup table approach) to produce a map of ecosystem functions. Habitat connectivity was assessed by analyzing the distances and spatial arrangement of natural and near-natural habitats.

2.3.1. Biodiversity Assessment at Habitat Level

The assessment was carried out using the habitat valuation method (HVM), a systematic method for establishing a list of national habitat types, classifying them according to their plant composition, and assessing their habitat provision value on the basis of an expert valuation of eight ecological criteria [36,96]. Habitats from this list of national habitat types for the Czech Republic were categorized according to their naturalness: natural and near-natural habitat types identified in the habitat mapping level (© NCA CR, 2015) and described in the Catalog of Habitats of the Czech Republic [90], as well as degraded habitat types divided into three naturalness levels (distant natural, unnatural, and human-made habitat groups) defined for the purposes of the HVM method [36,91,97]. Each habitat type was assigned a habitat provision value. A detailed description of the habitat classification method can be found in [98]; the list of habitat types and their point values are provided in Table S1 (Supplementary Materials).

2.3.2. Habitat Connectivity Assessment at the Landscape Level

The modified distance to nature method, introduced by Rüdisser [38], was used as an indicator of connectivity at the landscape level. It assesses the distribution of valuable habitats and the distance to the nearest valuable habitat in the landscape. The habitat types from the HVM method and their five levels of naturalness were used for the analysis: the two best degrees of naturalness (natural and near-natural) for identification of valuable habitats, and the three remaining levels of degraded habitat types (distant natural, unnatural, and human) for resistance of habitats, forming a matrix for the dispersal of organisms. The Euclidean distance to the closest natural or near-natural habitat patch, multiplied by resistance values of the matrix, was calculated and expressed in the form of a continuous raster map, on the basis of which the mean values for reporting units were estimated. Values were normalized and scaled along a range from zero (no distance) to one (habitat completely far from natural habitat). For a more detailed description of the method, see [38]. To adapt the original method for use in urban landscapes, it was modified to consider roads and contiguous built-up areas larger than 0.25 ha as a total barrier to organism dispersal.

2.3.3. Assessment of Evapotranspiration

The method was developed in 2007–2009 by Seják [97,99]. It classifies the vegetation according to the annual transpiration. Transpiration assessments were conducted for 22 functional groups of habitats, into which the 193 HVM habitat types were grouped. For these groups, an expert estimate of average annual evapotranspiration was made, based partly on field measurements [99] and partly on findings and results from the work of the

Botanical Institute of the Czech Academy of Sciences and others [100–102]. The functional groups of habitats and their estimated values of evapotranspiration are listed in Table 2.

Table 2. EFs performance values estimated for functional groups of habitats in the CR according to [99].

No.	Functional Group	Area (km^2)	Evapotranspiration ($L{\cdot}m^{-2}{\cdot}year^{-1}$)	Biomass Prod. ($kg{\cdot}m^{-2}{\cdot}year^{-1}$)
1	Water bodies	675	600	1.67
2	Peatbogs	23	750	0.2
3	Other wetlands	364	750	2.03
4	Extensively managed mesic meadows and pastures	2601	550	1.05
5	Intensively managed mesic meadows and pastures	5579	500	1.39
6	Degraded mesic meadows, pastures, and heathlands	4609	400	0.8
7	Dry dense grasslands	40	300	0.7
8	Dry open grasslands	172	300	0.4
9	Xerophilous scrubs	426	300	0.8
10	Mesic scrubs	1959	400	1.06
11	Wet scrubs	17	600	1.16
12	Dry pine forests	298	300	0.9
13	Other coniferous forests	6050	500	1.56
14	Damaged coniferous forests	8222	400	1.25
15	Deciduous forests	6636	700	1.79
16	Degraded deciduous forests, culticenosis	1632	500	1.28
17	Alluvial forests	924	800	2.03
18	Solitary trees, alleys	1276	500	1.43
19	Arable land: habitats of cereals and root-crops	27,605	300	0.9
20	Arable land: habitats of fodder crops and perennial plants	141	350	1.98
21	Areas without vegetation	2938	100	0
22	Rocks habitats	113	200	0.2
23	Other natural and near-natural habitats	3780	569	1.51
24	Other more anthropic affected habitats	2787	342	0.96

2.3.4. Assessment of Carbon Production

The net annual production of above- and belowground biomass, i.e., the amount of dry matter in kg per m^2 per year, was determined for the same functional groups as for evapotranspiration. These values were transferred from available literature sources, and repeated biomass sampling was carried out within the Czech Carbo project (see, e.g., ref. [103]). The detailed method was published in refs. [97,99,103]. The main functional groups of habitats and their estimated values of carbon production are presented in Table 2.

2.4. Parametrization and Relative Comparison of Values

In order to be able to assess and compare the relative performance of ecosystem functions, the values were parametrized into a uniform scale using Equation (1).

$$y_i^* = (y_i - y_{min})/(y_{max} - y_{min}), \quad (1)$$

where y_i^* is the parameterized value of the selected EFs, y_i is the value of the selected EFs in relevant units, y_{max} is the maximal value of the selected EFs in relevant units, and y_{min} is the minimal value of the selected EFs in relevant units.

The three assessed EFs (biodiversity expressed by HVM, evapotranspiration, and carbon production) were merged into a single aggregated EFs performance by an average of the three parameterized values.

2.5. Assessment of Urban–Rural Gradient of EFs

We distinguished several levels of urban intensity: (i) the urban core, characterized by continuous development; (ii) the suburban area, where discontinuous development predominates, sometimes interspersed with other habitat types; (iii) the peri-urban area, which is an interface between the rural and the urban space, where there is an even smaller proportion of built-up areas; (iv) adjacent rural landscapes.

The spatial analysis of the urban–rural gradient of assessed ecosystem function was carried out using the buffer gradient analysis method, which is based on a series of equidistant buffer zones established starting from a circle in the urban core. The city center was defined as the geometric center (centroid) of the polygon of urban core area, which is identical to the historical city center. In Liberec, it was possible to identify only one centroid. In Děčín, due to the historical development that took place on both banks of the Elbe River, it was necessary to identify two focal points. A concentric buffer with 0.5 km intervals was created around the urban core area. In each ring section, the values of individual EFs were calculated.

Since Děčín does not have a typical city center, and the built-up areas are located in a narrow strip along the river, the gradient analysis was also carried out between the river and the outer landscape. A buffer of 0.5 km was created around the part of the Elbe (in Děčín) and the Neisse (in Liberec) to form the central river polygon. Equidistant buffer zones with a distance of 0.5 km were established around these river polygons. In each section, the values of individual EFs were calculated.

Spatial data analysis and map outputs were processed in the ArcGIS environment (ArcGIS Desktop 10.7.1 ESRI, 2019 and ArcGIS Pro 2.8.0 ESRI, 2021).

3. Results and Discussion

3.1. Results and Discussion of Method Application

3.1.1. Values of EFs in Liberec and Děčín

Layers of habitats and their EFs, biodiversity (habitat assessment and structural connectivity), evapotranspiration, and annual carbon production were prepared for the administrative territories of Liberec and Děčín. The representation of habitat types, for which the ecosystem functions were quantified, is shown in Figure 3. Only habitats with more than 1% of the area are shown in the graph.

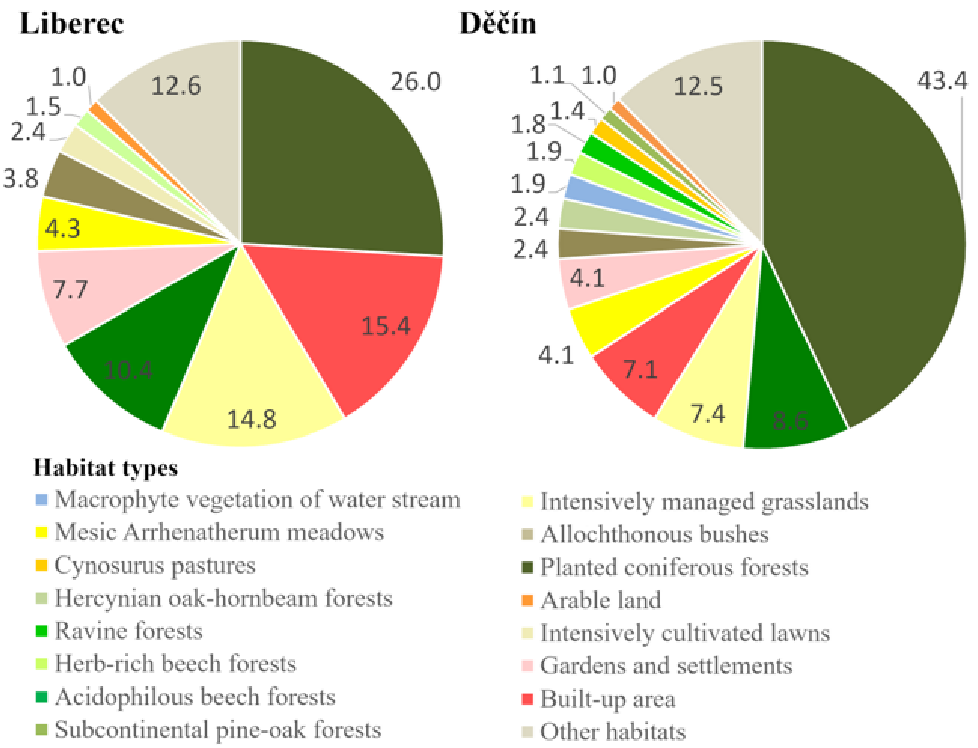

Figure 3. Representation of habitat types in administrative territory of Liberec and Děčín.

An overview of the results for the entire administrative territory of Liberec and Děčín is given in Table 3.

Table 3. Assessment of ecosystem functions: aggregate values for the whole administrative territories of Liberec and Děčín (∑) and average values per area unit (Ø). Biodiversity expressed in HVM (points·m^{-2}) [36], evapotranspiration (L·m^{-2}·year^{-1}), and annual carbon production (tC·ha^{-1}·year^{-1}) [99].

Administrative Territory	Area	Biodiversity		Evapotranspiration		Carbon Production	
		∑	Ø	∑	Ø	∑	Ø
	(km^2)	(million Points)	(points·m^{-2})	(million L·year^{-1})	(L·m^{-2}·year^{-1})	(tC·year^{-1})	(tC·ha·year^{-1})
Liberec	106	2005	18.9	49,080	463	559,582	5.27
Děčín	118	2659	22.6	59,035	502	689,099	5.85

The average biodiversity score (HVM) was 19 points·m^{-2} in Liberec and 23 points·m^{-2} in Děčín. This is 2.15% (in Liberec) and 23.7% (in Děčín) more than the average HVM score for the Czech Republic, which is 18.6 points·m^{-2} [99]. Connectivity has extremely low values in the urban core area, which is considered almost entirely a barrier, and low values in the suburban area, especially in Liberec, where urban development is greater. According to Rüdisser [38], good connectivity corresponds to values up to 0.06, expressed on the map (Figure 4) by green and yellow color, covering 61% of the administrative territory in Liberec and 66% in Děčín. In Liberec, the good connectivity tends to be situated near the borders of administrative territory, especially in the area that is part of the PLA Jizerské hory. In Děčín, connectivity was good, especially in the peri-urban area of the city and on the steep slopes near the river Elbe, most of which are covered with natural and near-natural habitats. In the areas close to the northern boundary of the administrative territory, connectivity decreased due to large areas covered by planted, low-diversity spruce forests. The graphical representation of connectivity shows corridors that consist of well-connected habitats. Both cities contain watercourses that are indispensable natural corridors for the movement of organisms and for the flow of materials and energy. Supporting and further connecting these corridors, especially in areas with lower connectivity, is a land-use planning task to create a functioning blue and green infrastructure. This connectivity has positive impacts, especially on biodiversity [104].

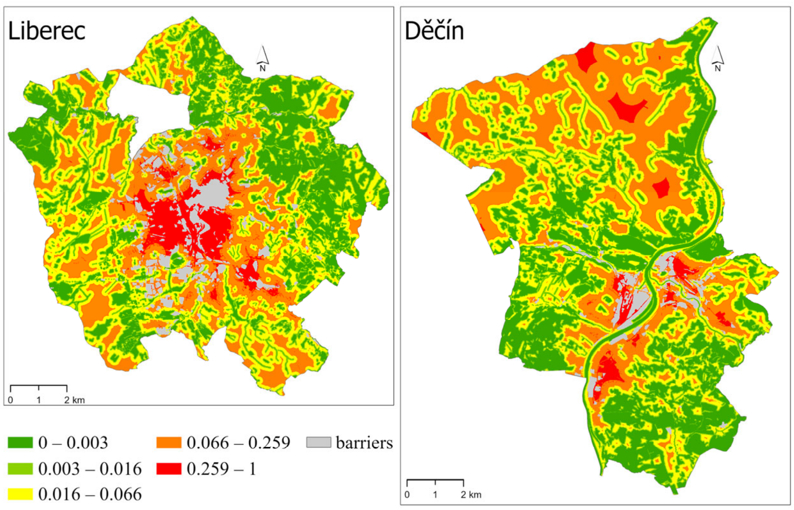

Figure 4. Habitat connectivity calculated for Liberec (**on the left**) and Děčín (**on the right**). Euclidean distance to the closest natural or semi-natural habitat patch was calculated and is expressed in the form of a continuous raster map (10 m pixel). Values are scaled along a range from 0 to 1; 0 indicates natural/no distance, 1 represents completely artificial/far from natural habitat, and barriers refer to roads and contiguous built-up areas larger than 0.25 ha.

For connectivity planning, the selection of appropriate data is crucial. As already stated, standard land-use and land-cover data are not detailed enough for the urban administrative territory level [32], and remote sensing data, which have recently become widely available, may be sufficient for carbon storage and possibly for estimating evapotranspiration but do not contain sufficient information on species and habitats for biodiversity assessment (although there is ongoing progress in this area; see ref. [105]). Therefore, the use of more detailed habitat mapping data using the lookup table approach seems to be the simplest way to obtain results on the distribution of EFs and biodiversity in urban administrative territories.

The average value of evapotranspiration was 463 $L \cdot m^{-2} \cdot year^{-1}$ in Liberec and 502 $L \cdot m^{-2} \cdot year^{-1}$ in Děčín. Comparing these values with the average value for the Czech Republic, 421.4 $L \cdot m^{-2} \cdot year^{-1}$ published by Seják [99], they are higher by 9.9% and 19.1%, respectively. The amount of carbon production was 5.3 $t \cdot ha^{-1} \cdot year^{-1}$ in Liberec and 5.9 $t \cdot ha^{-1} \cdot year^{-1}$ in Děčín, which exceeds the average value for the Czech Republic of 5.1 $t \cdot ha^{-1} \cdot year^{-1}$ published by Seják [99] by 3.9% and 15.7%, respectively. The values of carbon production also significantly exceed the published values of average carbon sequestration in urban areas in various cities in Asia and North America, which ranged from 2.16 to 3.06 $t \cdot ha^{-1} \cdot year^{-1}$ [64,106,107]. The results clearly show that EFs related to climate change mitigation can be performed better in very heterogeneous urban administrative territories with urban forests, parks, and other green spaces than in common landscapes. In particular, peri-urban areas of cities located near (or within) protected landscape areas, as in the case of Liberec and Děčín, can have a high value of EFs.

3.1.2. Comparison of Liberec and Děčín

Although Liberec and Děčín are comparable in terms of area, ecosystem function values differ substantially. Habitat-level biodiversity, expressed in HVM values, was almost 33% higher in Děčín than in Liberec, as was the average connectivity value, which was 22% higher. Annual carbon production was 23% higher and evapotranspiration was 20% higher than in Liberec. These differences can be attributed mainly to the stronger population growth and the related faster development of the built-up area in Liberec, while, in Děčín, the number of inhabitants (similar population to 100 years ago, Czech Statistical Office, 2006) and the development of the city have more or less stagnated; consequently, the current built-up area in Liberec is twice as large as in Děčín. Accordingly, the share of forests in Liberec is lower (only 24%), while, in Děčín, forests cover almost half of the administrative territory. However, the protection regime probably had a dominant influence on the fact that ecosystem functions in the territory of Děčín reached significantly higher values than in Liberec, as most of the cadaster of Děčín falls within two PLAs, while, in the case of Liberec, only a small percentage of the administrative territory belongs to the PLA.

3.1.3. Relative Comparison of Values of Individual EFs

A comparison of the relative parameterized values of the ecosystem functions assessed (see Figure 5A–F) shows that the lowest values apply to habitat-level biodiversity (HVM), especially in the urban core and suburban area and, in the case of Děčín, also near the northern boundary, where there are large stands of planted spruce forests. The other two functions, evapotranspiration and especially production, have relatively higher values and, unlike biodiversity, are also located to a limited extent in the suburban area.

The disparate results (especially lower biodiversity compared to other EFs) are consistent with findings that certain habitat features are important for maintaining biodiversity but are not as critical for maintaining other ecosystem functions. Species diversity in urban vegetation depends on diverse vegetation structure and vertical complexity [108,109], the naturalness of the habitat [110], and eventually, the proportion of native trees [111] and the intensity of management [29]. Some of these characteristics are not as important for the other two functions (carbon production and evapotranspiration), as these depend mainly on the vegetation biomass [112] and LAI values [54], as well as, in the case of evapotranspiration, physiological characteristics such as tree-level transpiration [113]. These results suggest that certain habitats with average and sometimes rather low biodiversity values (mainly planted spruce forests but also urban parks and other urban green spaces) can, due to their high biomass, provide ecosystem services that contribute notably to cooling of the urban environment through evapotranspiration and to mitigating climate change through carbon sequestration.

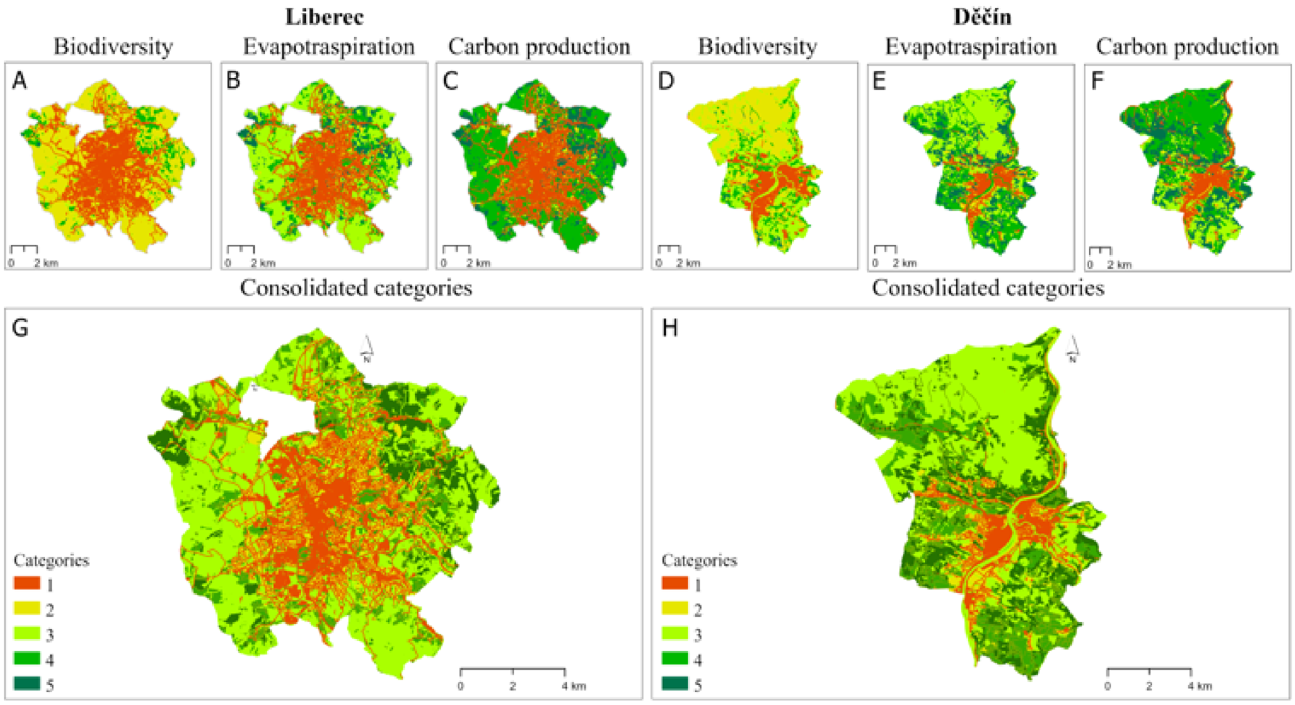

Figure 5. Map visualization of (**A**–**F**) indicating the comparison of the performance of EFs in relative values parameterized on a scale of 0–1 and divided into five categories (1 for the worst value, 5 for the best value; the legend is the same as for maps (**G**,**H**)). Maps (**G**,**H**) merge the three assessed EFs values into a single aggregated performance of EFs value.

Merging of the three EFs into one value (Figure 5G,H) shows the location of area of the best EFs performance. In Liberec, they are situated mostly near the border of the administrative territory, especially where the PLA is defined; however, there are some habitats of relatively high EFs performance situated in the suburban area. In Děčín, the peri-urban area has a very high EFs performance. On the contrary, the worst values of EFs were found in the urban core areas, which are almost devoid of vegetation, and in the suburban areas, where discontinuous development predominates.

3.1.4. The Urban–Rural Gradient

The urban–rural gradient shows how much the composition of habitats differs (see Figure 6) and how the values of EFs change depending on the distance (a) from the center in the case of a city with typical urban core, or (b) from the river in the case of a city with development situated around the river (see Figure 7).

In the case of Liberec, it is noticeable that the values of EFs increase relatively gradually with increasing distance from the center. Only evapotranspiration increases sharply at a distance of 5 km, before decreasing and starting to increase again; this may be due to the relatively large area of alluvial and deciduous forests, as well as wet meadows in this area. The prevailing gradual pattern of EFs increase is also supported by geomorphological conditions. Liberec lies in a valley whose slopes gradually rise to the foot of the Jizera Mountains in the northeast and the Ještěd Mountain in the southwest; the city grows on all sides relatively evenly. In Liberec, the center with very low values of all EFs spreads across a diameter of about 5–6 km; in Děčín, this area with low EFs extends cross a diameter of only 2–3 km, corresponding to the different size of urbanized area. In Děčín, the gradient is very uneven, as values increase at much shorter distances from the center but decrease again when reaching 5 km from the center (in the case of HVM value and carbon production) or 8 km in the case of evapotranspiration caused by river Elbe influence and high share of deciduous forests. This situation is supported by a particular geomorphology. At a certain distance from the urban core (and from the river), there are steep slopes carved by the river in the sandstone rock, which are not suitable for urban or agricultural use and are, therefore, mainly covered by natural and near-natural habitats. The plateau that continues above these slopes is dominated by planted spruce forests; thus, the biodiversity value decreases at greater distances. A similar trend in urban–rural gradient was described by Baró [17] for EFs/ESs in Barcelona, where it was found that areas closer to the city had higher values than the surrounding agricultural landscape. From Figure 2, it is apparent that, especially in the case of Děčín, the peri-urban area is covered by diverse habitats with relatively high proportion of natural and near-natural habitats.

Figure 6. Representation of habitats in individual intervals representing distance to (**A**) city center (upper part) and (**B**) dominant river of the city (lower part). For the sake of clarity of the graph, habitats are grouped into categories based on land use, but the division into natural (N) and degraded (D) habitats is retained.

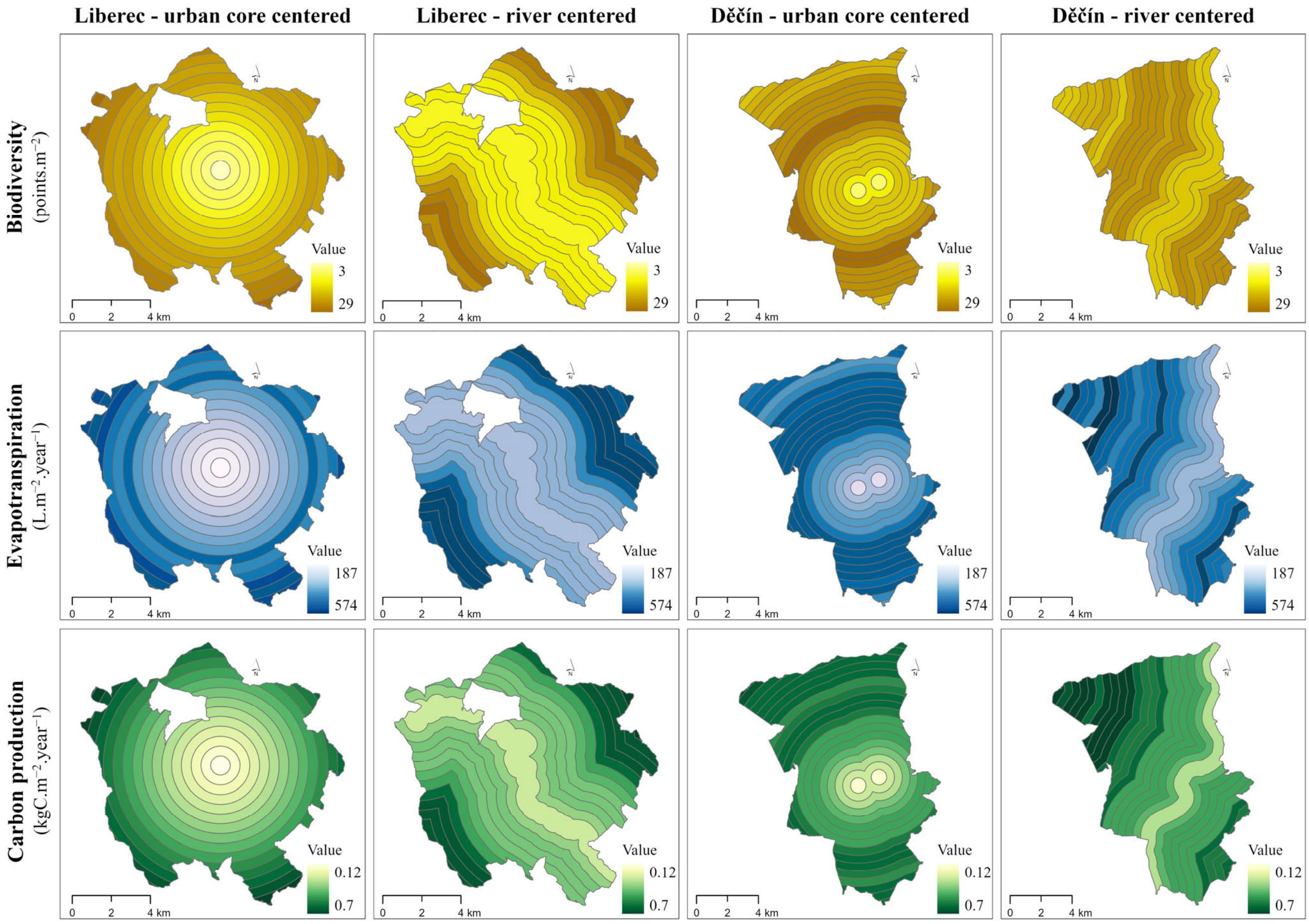

Figure 7. Urban–rural gradients of three EFs (biodiversity, evapotranspiration, and carbon production) and their gradient related to the distance from the center of urban core area and main watercourse visualized for Liberec and Děčín administrative territories.

The highly urbanized area is, especially in Děčín, concentrated around a large watercourse and creates a narrow strip of development in the valley along the river. To visualize the specific gradient, a buffer around the river was created, revealing that, instead of forming blue and green infrastructure of high habitat quality, areas around watercourses are of the lowest value concerning studied EFs. A suitable strategy would be the development of blue and green corridors for pedestrian and animal movement, biodiversity, and ecosystem service support [75].

3.2. Discussion of the Method Choice

We chose the biophysical (also called indicator-based [114]) method to avoid underestimation, to which the use of sociocultural methods (according to ref. [20]) could lead. Studies comparing biophysical and sociocultural values to assess local climate change mitigation services are rare (e.g., ref. [115]). Biophysical values quantify biotic and abiotic configurations related to the provision of ESs [18]. For our three selected ESs, we sought suitable indicators that have been recommended in official reports or used in a number of other studies (see Section 1.3). From the range of suitable indicators, we selected those suitable for the scale of the entire urban administrative territory and in the lookup table approach, which we preferred because of its ease of use in practice. The methods and data used for their quantification were based on the results of previous projects of the Czech Ministry of Life Environment (Czech Carbo, Czech Terra, habitat valuation of the Czech Republic, and valuation of ecosystem functions and services of the Czech Republic) and the Interreg project Bidelin, in which the authors of this paper participated.

Because the urban administrative territory consists of clearly definable segments to which the values and approaches apply, the performance of ecosystem functions can be calculated for each segment. Although most lookup table methods use land-cover data as a basis [116], in most cases, these data are not detailed enough to assess EFs at the urban administrative territory level [32]. In this case, the European Commission suggests using maps created by combining land-cover maps with habitat databases [20]; we used this principle to create a detailed habitat layer and augmented it with other data sources, some of which were results from the Czech case study involved in the ESMERALDA project [117] to make it more precise. To capture the influence of a higher hierarchical level of landscape structure and its complexity, we calculated the connectivity indicator, which indicates the distance (within the urban area structure) to the nearest natural habitat within which the EFs are performed without negative human influence. Ecosystem function values are assigned to individual habitat types or their groups, which makes the method easily applicable and allows transferring the values to other European countries with similar climatic conditions (and, thus, habitat types).

4. Conclusions

We presented a method for assessing three EFs of urban and peri-urban habitats (biodiversity, evapotranspiration, and carbon production) indicating their capacity to provide associated ESs (habitat provision and climate regulation at local and regional scales). The simplicity of application of the lookup table approach based on values associated with habitat types makes it suitable not only for urban areas but also for the adjacent rural landscape and enables analysis of the urban–rural gradient of EFs values. The values assigned to habitat types can be transferred to other European countries with similar climatic conditions and, thus, habitat types.

The application of the method to the administrative territories of two cities, Liberec and Děčín, revealed high performance of EFs, which was even higher than the average for the whole country. Urban and suburban areas had the lowest values, but the peri-urban areas had surprisingly high values for habitat connectivity and other EFs, especially in Děčín, where the special conditions led to a concentration of valuable habitats in this area. The urban–rural analysis also supported this result, showing higher values for biodiversity and connectivity in peri-urban areas than in the adjacent rural landscape. The lowest values of the three studied ESs were obtained for habitat-level biodiversity, especially in the urban core and suburbs and near the boundary of the administrative territory. This indicates that many habitat types typical of urban and peri-urban areas may perform climate-regulating functions relatively well, but do not support biodiversity to the same extent. Therefore, promoting biodiversity should be a priority in urban adaptation plans.

This method can serve as a useful tool to quickly identify valuable urban habitats (strong EFs providers) and advocate for their protection or, on the contrary, identify places with low values of EFs. In particular, low values of evapotranspiration in the central area of cities and the low connectivity of valuable habitats are situations that should be prioritized and sorted in urban adaptation strategies toward global climate change.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/app13095759/s1, Table S1. Habitat types and their relative point values according to ref. [36].

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Abbreviations

CR	Czech Republic
EFs	Ecosystem function
ESs	Ecosystem services
HVM	Habitat valuation method
LAI	Leaf area index
NCA CR	Nature Conservation Agency of the Czech Republic
NDVI	Normalized difference vegetation index
PLA	Protected landscape area
TEEB	The Economics of Ecosystems and Biodiversity

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