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Research Article

Mapping and assessment of urban ecosystem condition and services using integrated index of spatial structure

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Abstract

Urban ecosystems are the areas where built infrastructure covers a large proportion of the land surface but the main source of ecosystem services provision is the green infrastructure. This provision is very much dependent on the particular combination of green spaces such as parks or vegetation belts and paved areas such as buildings and streets. The spatial arrangement of these elements is an important parameter which could be used for the assessment of the ecosystem condition in the urban areas. An integrated index of spatial structure is proposed which incorporates built types and land cover from the Local Climate Zones (LCZ) concept with urban ecosystems' classes developed on the basis of MAES typology. An algorithm has been developed for index generation using an urban ecosystems' database and remote sensing data. The index is used to define vegetation cover in urban ecosystems and assess their condition as a part of the assessment framework. It is also applied in the assessment of several ecosystem services through quantification of ecosystem services' indicators or as an indicator in a complex assessment. The results show that, although most urban ecosystems in Bulgaria are assessed as moderate and good condition, very few of them have very good condition and about 3.5% have very bad condition. The highest scores are defined for urban green areas while the lowest are for transport networks. The use of an integrated index in urban ecosystem services' assessment is represented by examples for global and local climate regulation. The results are used to develop maps of ecosystem services supply capacity for selected cities. The overall analysis indicates that the urban ecosystems in Bulgaria have a moderate to good capacity for local climate regulation and moderate to low capacity for global climate regulation. The integrated index of spatial structure provides an appropriate basis for characterisation and assessment of the urban ecosystems condition and ecosystem services following the requirements of the EU Biodiversity Strategy and the MAES process. The proposed approach enables the internal heterogeneity of the urban ecosystems at national level to be defined, this being one of the main challenges in studying urban ecological systems.

Keywords

Urban ecosystems, MAES, green infrastructure, land cover, built type, carbon storage, climate regulation

Introduction

Ecosystem services (ES) are defined as “the contributions of ecosystem structure and functions, in combination with other inputs, to human well-being” (Burkhard et al. 2012) and this contribution is highly dependent on the condition of the ecosystems. The natural ecosystems such as forest or freshwater are usually regarded as the main sources of services but the urban areas can also be treated as ecosystems with their own structure and function which provide a certain range of ecosystem services (Haase et al. 2014a). Urban ecosystems are the areas where built infrastructure covers a large proportion of the land surface and include also blue and green spaces such as parks, cemeteries, yards and gardens, urban allotments, urban forests, wetlands, rivers, lakes and ponds. (Gómez-Baggethun et al. 2013). These spaces are described with the terms “green and blue infrastructure", which are defined as the main source of services is urban ecosystems (Andersson et al. 2014). On the other hand, the built structures are the places where people live and spend most of their time. In order to benefit from the services provided by green spaces, they need easy and comfortable access to them. Therefore, the provision of ecosystem services is very much dependent on the particular combination of green spaces such as parks or vegetation belts and paved areas such as buildings and streets. The spatial arrangement of these elements is an important parameter which could be used for the assessment of the ecosystem condition in the urban areas. The EU Biodiversity Strategy to 2020 requires Member States to map and assess the condition of ecosystems and their services in their national territory. The working group on Mapping and Assessment of Ecosystems and their Services (MAES) delivered a methodological framework for this process which contains a coherent typology to be used for the different types of broad ecosystems to be considered in the assessment to ensure consistency across Member States (Maes et al. 2013). It defines nine types of ecosystems including urban which “represent mainly human habitats but they usually include significant areas for synanthropic species, which are associated with urban habitats” (Maes et al. 2013). This ecosystem type not only covers building areas but also covers industrial, commercial and transport areas, urban green areas, mines, dumping and construction sites. Therefore, further division of the urban ecosystem type and study on the spatial arrangement of its elements is necessary for the assessment and mapping of ecosystem services provided by them.

Following the MAES framework, a methodology for mapping and assessment of urban ecosystems and their services in Bulgaria was developed (Zhiyanski et al. 2017). It consists of three main parts: mapping of ecosystem types; assessment of ecosystems condition and assessment of ecosystem services. For the mapping of ecosystem types, a third level of MAES typology was developed. It is based on EUNIS habitat classification (Davies et al. 2004) and includes 10 classes that represent the variety of urban areas in the Bulgarian territory. The ecosystem types were delineated using different sources of spatial data and a GIS polygon dataset was created. The ecosystems condition is assessed by a set of indicators representing biotic diversity, abiotic heterogeneity, water, energy and matter cycling. One of the most important indicators is the vegetation cover which represents the percentage of green areas within each polygon of the dataset. As the green areas are the main sources of benefits for people in the cities, the calculation of this indicator is vital for further ecosystem services' assessment. The methodological framework addresses the assessment of 25 ecosystem services defined after the CICES classification (Haines-Young and Potschin 2013) and adapted for the specifics of urban ecosystems in Bulgaria.

However, the implementation of the methodology in practice encounters particular problems related to the identification of vegetation cover and the availability of spatial data. Firstly, the applied ecosystem classification does not reveal some important spatial aspects of the urban ecosystems. For instance, the class "urban green areas" covers all urban green spaces larger than 0.25ha, but they can be urban tree park, grass field or a meadow in the suburban area. These three kinds of green area are characterised by different structures and functions as well as by the services they provide which could not be differentiated using the existing classification. Secondly, most spatial data sources for the assessment of ecosystem condition and services are referred to small scale which could not reveal the heterogeneity of the urban ecosystems. Furthermore, the vegetation cover indicator could not be calculated as there are tens of thousands of individual polygons in the database.

One possible solution for solving these problems is to include an additional spatial index which is based on urban morphology and can reveal the internal heterogeneity of the urban ecosystems. Urban morphology is the application of a diverse range of scientific approaches, aimed at creation of a particular thematic land cover classification and providing specific spatial information in support of urban management and planning.

Taubenbock and Roth (2007) applied the segmentation process to achieve an object-orientated analysis and classification of predominant shape features to support further analysis of city patterns and urban zoning, based on density measures. Herold et al. (2003) relied on spatial matrix and texture measures to describe spatial urban morphology and structure and identified and mapped urban land use classes. Banzhaf and Hofer (2008) applied a transferable methodology to monitor urban dynamics and structure on a local level, with the accent on the environmental performance of urban land cover types, for urban environmental planning purposes. Their urban structure classification identified different types of buildings and open spaces, as well as their structural combinations. Several studies clarified the relationship between urban spatial heterogeneity and ecological outcomes (Band et al. 2005, Cadenasso et al. 2007, Douglas and James 2015), including investigations in relation to air pollution and acoustic noise (Weber et al. 2014), green infrastructure and climate adaptation (Koc et al. 2016) and plant species diversity (Čeplová et al. 2017). Other research directly focused on ecosystem services in urban areas positing that "The most salient thrust of current research activities in the field of urban ecology is the emerging urban sustainability paradigm which focuses on urban ecosystem services and their relations to human well-being" (Wu 2014). Oke (2005), Oke (2004a) proposed the concept of "Urban climate zones" which was further developed into "Local climate zones" classification (LZC) (Stewart and Oke 2012). The latter attempted to reflect urban heterogeneity by taking into account such factors as morphology, surface cover and land use. LCZ mapping has the potential to yield valuable information on the basic physical properties of any urban area (Bechtel et al. 2015). As Geletič and Lehnert (2016) pointed out, the first LCZ mapping methods created by Bechtel and Daneke (2012) and Lelovics et al. (2014) moved the LCZ concept towards a generally recognised regional typology. This concept serves as a basis for extensive investigations (Geletič and Lehnert 2016, Koc et al. 2016, Kaveckis and Bechtel 2014) which aim to improve metadata of urban settings and their properties. The recently designed World Urban Database and Access Portal Tool (WUDAPT project, Mills et al. 2015) uses the LCZ classification framework as the starting point for characterising cities in a consistent manner and for providing open access to this dataset to be used for applications ranging from climate and weather modelling to energy balance studies (http://www.wudapt.org/). Nowadays, the LCZ concept is recognised as a focus of general interest within the field of urban climate and is used to compile a worldwide urban morphological and urban metabolic database (Bechtel et al. 2015).

The spatial heterogeneity in urban systems is an important issue as the urban land cover is clearly heterogeneous and the heterogeneity itself is a core ecological concept and plays a role in the functioning of the systems (Cadenasso et al. 2007, Gómez-Baggethun et al. 2013). Therefore, the assessment of urban ecosystems needs to include an indicator that can reveal this heterogeneity in an appropriate manner. The combination of built structures and green spaces determines the flows of energy and matter which are vital for the ecosystem functions. Dense and high buildings with limited green areas form a spatial structure that does not facilitate a healthy environment therefore the ecosystem condition is bad. Open arrangements of low buildings with a variety of green spaces would provide a healthy environment and a good ecosystem condition respectively. The above mentioned

LCZ classification scheme allows the representation of such spatial arrangements in an appropriate system which can reveal the heterogeneity of urban ecosystems and give solid arguments for assessment of their condition. Therefore, it was decided to develop an integrated index of spatial structure in urban ecosystems which builds on the Stewart and Oke (2012) LCZ scheme by integrating built and land cover types with urban landscape typology. The LCZ scheme has a universal meaning and provides a much needed context to standardise the classification of landscapes (Bechtel et al. 2015). The system is accessible and reproducible (Lotfian 2016) and facilitates intra-urban and inter-urban cross comparisons (Unger et al. 2015), as well as transferability of results and global exchange of urban environmental observations. Based on the above, this approach not only adopts the main criteria of Stewart and Oke (2012) for describing and classifying urban heterogeneity, but applies them for analysis of urban ecosystem types. This interpretation aims at national assessment of the urban ecosystems' ecological condition and their potential to provide ecosystem services. The proposed index is concordant with the classification criteria of Stewart and Oke (2009) and meets the requirements of the ecosystem services' concept which include: 1) logical and consistent representation of the surface properties of urban ecosystem types; 2) clear identification of the urban green infrastructure composition and configuration; 3) highly informative character, relevant for urban studies spatial scales (Oke 2004b, Muller et al. 2013) and 4) easily repeatable, measurable and compatible with the landscape matrix indices.

In this context, the following main objectives were defined for this paper:

- to present a new indicator for urban ecosystem assessment – integrated index of spatial structure
- to assess the condition of urban ecosystems in Bulgaria using this index
- to test its application in urban ecosystem services' assessment

Material and methods

Mapping and assessment of urban ecosystems in Bulgaria - approach and data

The methodology for mapping and assessment of urban ecosystems is part of the national methodological framework which aims to streamline the national ecosystems and ecosystem mapping and biophysical assessment processes in Bulgaria (Zhiyanski et al. 2017). It delivers a practical step-by-step guidance for delineation of urban ecosystems, assessment of their condition and assessment of the services they provide. Urban ecosystems are considered as "areas where most of the human population lives and it is also a class which is significantly affecting other ecosystem types" (Zhiyanski et al. 2017). For delineation of urban ecosystems, the typology of MAES (Maes et al. 2013) at first and second level was further developed at a third level (sub-types) for the territory of Bulgaria (Table 1). The spatial representation of ecosystems is based on land cover/land use types. It was considered that they do not fully correspond to the term ecosystem from ecological point of view, but for the mapping purposes it is necessary to use spatially explicit data and this is the most appropriate source at both national and European level. The urban subtypes were defined in correspondence with the National Concept for Spatial Development for the period 2013 – 2025 and EUNIS habitat classification (Davies et al. 2004). For instance, the class *Residential and public areas of cities and towns (J1)* includes the cities from level one (the capital Sofia), level two (large cities, centres of national significance for the territory of the regions) and level three (medium-size cities, centres of regional significance for the area of the districts). This class corresponds to J1 (J1.1, J1.2, J1.3, J1.5, J1.6), X2.4, X2.5 of EUNIS classification. More detail about the other subtypes are given in Suppl. material 4.

Table 1.

Typology of urban ecosystems in Bulgaria (Zhiyanski et al. 2017).

Level 1	Terrestrial
Level 2 (Type)	Urban
Level 3 (subtype)	J1. Residential and public areas of cities and towns
	J2. Suburban areas
	J3. Residential and public low density areas
	J4. Recreation area outside cities and towns
	J5. Urban green areas (incl. sport and leisure facilities)
	J6. Industrial sites (incl. commercial sites)
	J7. Transport networks and other constructed hard surfaced sites
	J8. Extractive industrial sites (incl. active underground mines and active opencast mineral extraction sites and quarries)
	J9. Waste deposits
	J10. Highly artificial man made waters and associated structures

The assessment of an ecosystem condition is measured by a set of indicators which are organised in a system based on the concept of ecosystem integrity. It is defined as "supporting and maintaining a balanced, integrated adaptive community of organisms having a species composition, diversity and functional organisation comparable to that of a natural habitat of the region" (Jørgensen and Müller 2000). The indicators classification system is organised in four levels. At the first level, there are two main categories - ecosystem structure and ecosystem processes. At the second level, the ecosystem structure indicators are divided into biotic diversity and abiotic heterogeneity, while the ecosystem processes are divided into energy budget, matter budget and water budget. Each of these is further divided to form an operational set of 37 indicators at the fourth level. Each indicator has its own parameter, measurement unit and measurement approach. The assessment scale for all indicators is unified in a five-level scoring system: 1 – very bad; 2 – bad; 3 – moderate; 4 – good; 5 – very good (Zhiyanski et al. 2017). The scores are defined according to the analyses of measured parameters and are individual for each indicator.

The final step of the whole process is the assessment of ecosystem services in urban areas. The identification of ecosystem services is based on CICES classification (Haines-Young and Potschin 2013) by selection of those which are relevant to urban ecosystems and can be supported by the appropriate dataset for the assessment. The selection led to identification of 25 services which have to be assessed by using appropriate indicators for their quantification. Although the methodology proposes one set of recommended indicators, there is an option to develop new indicators during the assessment process. The methodological framework for ecosystem services' assessment is based on the “matrix approach” proposed by Burkhard et al. (2010), Burkhard et al. (2012), Burkhard et al. (2014) with a relative six-level scale ranging from 0 to 5. This approach enables integration of the ecosystem condition assessment result for the services which could be measured by similar indicators.

Study Area

The assessment of ecosystems in Bulgaria under the Biodiversity Strategy and MAES process is implemented through a funding scheme with two main lines, one of them being directed to NATURA 2000 zones and the other for the rest of the country. As the current study is part of the mapping and assessment activities outside NATURA 2000 zones, the mapping is performed in all urban ecosystems outside protected areas. The delineation of urban ecosystems was performed in two steps. Firstly, the extent of urban ecosystems, corresponding to level 2 of the typology, was outlined and then the resulting polygons were divided into ecosystem subtypes corresponding to the more detailed level 3 of the classification. This process necessitates detailed spatial data which is not available as one single database; therefore different data sources were used. The restored property plan database was used as a main source for delineation of ecosystems at level 2. This is the most precise spatial database for the land use types in urban areas available for the whole country, therefore it was used as a reference layer to delineate the extent of urban ecosystems in Bulgaria. Then, the NATURA 2000 areas were excluded from the database. Thus, the area for the current study was defined to 5301.7km2, which is about 94% of all urban areas in the country. It includes 235 cities and towns, 4555 villages and 59 other places such as resorts, holiday villages, open-pit mines etc. For delineation of the ecosystems at level 3, a flexible spatial approach was developed (Nedkov et al. 2016). It uses multiple data sources such as digital cadastre of the cities, restored property plans, digital orthophoto maps of Bulgaria and incorporates several GIS tools and analyses. The Digital Cadastre of the settlements in Bulgaria is the most useful spatial data source but it is available only for some big cities. It was used as a complementary data for validation and update. The outline of each ecosystem subtype requires specific data therefore it necessitates a unique set or procedures incorporated in a common spatial analyses scheme. For urban ecosystems in the cities with available digital cadastres, they were delineated using the information for the land use part of this database. The polygons were classified into ecosystems at level 3 and then they were aggregated in order to meet the requirement of the methodology. The cities and villages without digital cadastres were mapped using the Restored Property Plan database and Digital orthophoto maps of

Bulgaria as a complementary source. The output vector dataset containing the graphical representation of the ecosystem subtypes was prepared in scale 25 000, while the minimum mapping area was fixed at 0.25ha. The data was organised in ArcGIS Personal GeodataBase format with a uniform structure containing a polygon feature class for all mapping units, ecosystem type table linking them to the ecosystem classification, metadata table and validation table. The validation was performed for the thematic accuracy of the data. As there were more than 70 000 polygons in the database, it was performed both on the field and by reference data. The overall thematic accuracy of the dataset was 92%.

Integrated index of spatial structure in urban ecosystems

As mentioned above, the assessment of the urban ecosystems' condition is based on a set of indicators which represent different aspects of the ecosystem integrity. Ecosystem structure indicators are divided into biotic and abiotic. The latter consists of several groups including soil heterogeneity, hydrological heterogeneity, air heterogeneity, geomorphological heterogeneity, disturbance regime and other abiotic heterogeneity indicators (Zhiyanski et al. 2017). Each of these is focused on a particular abiotic component (such as water, air etc.) or a process but there is also spatial heterogeneity which is an important issue of the urban ecosystems. Therefore, the integrated index of spatial structure is included in the group of other abiotic heterogeneity indicators. It is developed in order to reveal the spatial arrangements of the building elements in the urban systems and builds on the LCZ scheme proposed by Stewart and Oke (2012).

LCZ is based on the assumption that each city is unique with respect to its geographical location and setting, cultural history and architectural expression (Oke 2005). Urban systems' investigations and the application of such knowledge to the improvement of human settlements are objects of interdisciplinary interactions and collaborations within the natural, social and applied sciences. Challenges to better communications in the field of urban climate observations motivated Oke (2005) to assert the necessity for a common scientific language, in terms of standardisation of the terminology and adoption of generally recognised principles for urban cities' description and classification. He proposed a simplified classification of “Urban climate zones” (Oke 2004a) which became the basis for development of a further “Local climate zones” classification (Stewart and Oke 2012). There are 17 standard LCZs which are divided into 10 “built types” and 7 “land cover types” Table 2. New descriptors provide a precise view on local-scale site properties and, therefore, represent an effective research framework for climate observations, especially for urban heat island studies (Emmanuel and Krüger 2012, Alexander and Mills 2014, Lehnert et al. 2014, Leconte et al. 2015). However, this scheme is quite general and could effectively be implemented in more complex research such as ecosystem studies. The typology of urban ecosystems at level 3 (Table 1) provides an appropriate functional classification scheme which could be integrated with built and land cover types of the LCZ scheme to develop an index representing the spatial structure in more details. The correspondence was analysed between the urban ecosystem sub-types (Table 1) and the LCZs in selected representative areas using the vector dataset of urban ecosystems (see previous subsection). The analysis revealed that some built types were closely related to particular ecosystem sub-types while the land cover types were randomly distributed. For example, built types from 1 to 3 are typical in J1 ecosystems, while 4 to 6 are better represented in J2 and J3. On the other hand, there is no single polygon that represents a pure built type or land cover type. They were always in combination. Therefore, these two elements (built and land cover types) should be included as separate parts of the index. Thus, it was composed of three elements that integrate the ecosystem sub-type code (J1 – J10 in Table 1), built type code (1 -11 in Table 2) and land cover code (A – G in Table 2). As there were some ecosystem sub-types such as urban green areas which have no buildings, an additional class 11 was added to the built type scheme (see Table 2). Furthermore, the analysis revealed that there was usually more than one land cover type in a single polygon. For instance, some polygons in residential areas of the cities (J1) have open mid-rise buildings (5), scattered trees (B), grass (C) and streets (E). Therefore, it was decided to form a composite land cover part of the index which means that, for the above-mentioned example, it would be J15BCE.

Table 2.

Built types and land cover types (after Stewart and Oke 2012 with modification according to national specifics).

Built Types	Definition	**Land cover types**	Definition
1. Compact high-rise	Dense mix of tall buildings to tens of storeys.	A. Dense trees	Heavily wooded landscape of deciduous and/ or evergreen trees.
2. Compact mid- rise	Dense mix of mid-rise buildings (3–9 storeys).	B. Scattered trees	Lightly wooded landscape of deciduous and/ or evergreen trees.
3. Compact low-rise	Dense mix of low-rise buildings (1–3 storeys).	C. Bush, shrub	Open arrangement of bushes, shrubs and short, woody trees.
4. Open high-rise	Open arrangement of tall buildings to tens of storeys.	D. Low plants	Featureless landscape of grass or herbaceous plants/crops.
5. Open mid-rise	Open arrangement of midrise buildings (3–9 storeys).	E. Bare rock or paved	Featureless landscape of rock or paved cover.
6. Open low-rise	Open arrangement of low-rise buildings (1–3 storeys).	F. Bare soil or sand	Featureless landscape of soil or sand cover.
7. Lightweight low-rise	Dense mix of single-storey buildings.	G. Water	Large, open water bodies such as seas and lakes, or small bodies such as rivers, reservoirs and lagoons.
8. Large low-rise	Open arrangement of large low-rise buildings (1–3 storeys).		
9. Sparsely built	Sparse arrangement of small or medium-sized buildings in a natural setting.		
10. Heavy industry	Low-rise and mid-rise industrial structures (towers, tanks, stacks).		
11. No buildings	Open areas with no built structures		

Algorithm for index generation

The application of the integrated index of spatial structure in mapping and assessment of urban ecosystems necessitates generation of the index for each polygon of the database i.e. for each single urban ecosystem in Bulgaria. The generation of the spatial index is a result of several repetitive procedures including GIS-based analyses and visual interpretation of orthophoto images (Fig. 1 and Fig. 2). The spatial basis for this process is the urban ecosystems GIS database (see the first subsection). It includes a vector polygon layer with urban ecosystems at level 3 containing various attribute data including the sub-type codes (J1 – J10) that form the first element of the integrated index. The identification of built types and land cover types was performed through visual interpretation of orthophoto images which is a time-consuming labour-intensive process. It necessitates employing several operators who have to identify the built and land cover type polygon by polygon. In order to unify this process and reduce the uncertainty related to the subjective interpretation of the different individuals, preliminary interpretation and classification was performed in case study areas. It resulted in development of catalogues for land cover and built types which contain pictures and orthophoto screenshots of representative polygons for each respective land cover and built type. Examples from built types and land cover types catalogues are given in Suppl. material 1. The built types within polygons were identified using the approach of dominance, hence the built type in the spatial index represents the predominant built pattern. For land cover identification, all types presented within a polygon were checked and the predominant type was placed first. For instance, index J1BCE5 means that the predominant land cover type was scattered trees (B) followed by grass (C) and paved areas (E).

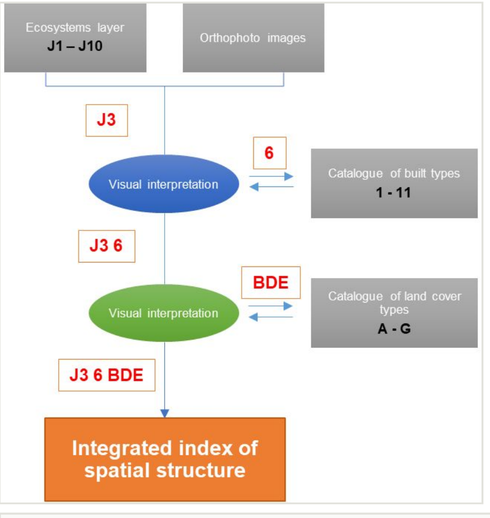

Figure 1.

Conceptual scheme for index generation. The digits in red are examples corresponding to Fig. 2.

Figure 2.

Example of index generation: 1 - delineation of ecosystem subtypes; 2 - visual interpretation and definition of built types; 3 - visual interpreation and definition of land cover types; 4 - generation of spatial index. The digits in red correspond to the example digits in Fig. 1.

The process of land cover and built types identification was performed using ArcGIS software and the ecosystems database. The codes of built and land cover types were stored in separate columns in the attribute table. Thus, the three elements of the integrated index (ecosystem sub-type, built type and land cover type) were recorded in the database and then it was generated using a Python string script. This structure enables easy and repetitive verification of the index's elements which is very important for such extensive databases. The data verification was performed by a field study in representative sites where all three elements were checked. As a result of these procedures, 532 different combinations of the index were identified. As some of them were represented in a single or limited number of polygons with limited area, a generalisation procedure was performed. All indices found in less than 5 polygons and with an area less than 5ha were selected and analysed. Most of them were transformed to indices with similar structure and only combinations that represent specific urban ecosystems were left. For instance, the indices of waste deposits (J9) were left because they were represented in limited areas and most of them had unique land cover which could not be easily attributed to another index.

Mapping and assessment of ecosystem condition using integrated index of spatial structure

The urban ecosystem condition is assessed by a set of indicators whose parameters should be measured by particular quantitative units. As some of these indicators have not been supplied by an appropriate dataset at national level, other approaches were needed. The integrated index of spatial structure could be used as an appropriate tool for generation of the necessary data. The vegetation cover is one of the most important ecosystem condition indicators representing the plant diversity group of the biotic heterogeneity. It is measured as the percentage of green areas (green infrastructure) within the urban ecosystems which means that it should be defined for each polygon of the database (Nedkov et al. 2016, Zhiyanski et al. 2017). As the green spaces in the urbanised areas are essential and indispensable sources of benefits for people, this indicator is very important for further ecosystem services' assessment. The identification and mapping of green infrastructure is usually undertaken by using remote sensing data. The most convenient method is through extraction of NDVI index (Myneni et al. 1995). It necessitates the choice of satellite images with high resolution to ensure a precise outline of the mapped units. This approach could be performed in case study areas but it is not convenient for a national scale study due to the higher cost of the high resolution satellite images. Therefore, an approach has been developed that combined calculation of green areas in case studies with representative urban ecosystems (Fig. 3) which enabled average values for the integrated index to be defined. These values were then transferred to the ecosystems' database to define the vegetation cover for each polygon. The calculation of green area was performed in selected case studies which represent the whole range of combinations of the integrated index and representative polygons for each index were selected. The number of representative polygons per index was chosen in relation to their number in the database. For example, 50 representative polygons were chosen for the indices with more than 1000 polygons in the database, 25 for the indices which had between 500 and 999 polygons etc. Two different methods were used: i) delineation of green areas from high resolution satellite images through the NDVI index; ii) delineation of green areas through visual interpretation of orthophoto images. The first approach was performed in the Pleven case study using the WorldView-2 satellite image. The NDVI index was calculated using the third and fourth bands and by appropriating a value of 0.43 as a threshold between green vegetation and non-vegetated areas (Nedkov et al. 2016). The resulting raster images with spatial resolution of 2m were reclassified into two classes corresponding to green and non-green areas and later converted into a GIS vector layer. Further GIS analysis and spatial overlay procedures were performed in order to define the vegetation cover for each representative polygon. The second approach was performed in seven smaller case studies located in different types of urban areas. Orthophoto images were used for visual interpretation and manual delineation of the green areas. Then the same procedure for calculation of vegetation cover was undertaken. The results from both approaches were analysed in order to define the percentage of green areas for each combination of integrated index (Fig. 3).

The integrated index of spatial structure, as a part of the ecosystem condition assessment framework, is an indicator that represents the abiotic heterogeneity of the urban ecosystems. The indicators of ecosystem condition should illustrate the cumulative effect of pressures on ecosystems over time (Erhard et al. 2016). In this case, the pressures were represented by different kinds of land use intensities and building structures. The land cover types represent different land use practices in the urban areas. Urban parks with dense trees (A) are examples of low intensity land use, thus allowing an ecosystem function which is close to the natural forest ecosystems. Therefore, their condition is good and they can offer various services to people. Grass urban areas (D) represent higher intensity land use as they are highly cultivated and regularly cut while paved areas (E), such as streets or parking lots, have highest intensity where no natural elements remain, therefore their condition is bad. Built structures represent different kind of pressure as they not only totally modify the landscape, but also affect the surrounding ecosystems by the pressure from the people living there. Therefore, higher and denser (built type 1) buildings will generate more pressure and consequently a lower condition. As spatially explicit information about cumulative pressures and how these affect ecosystem functioning is crucial for decision-making to secure sustainability (Erhard et al. 2016), the data of integrated index of spatial structure could be effectively used to define the urban ecosystem condition. The pressures generated by different land use intensities and built structures and the resulting condition can be measured by different indicators such as air pollution (PM10, NO_2, O_3), population density and species diversity (Maes et al. 2016), but they need much more data which is not available in such details (as required for this study) at national scale. In this case, multiple pressures can be assessed by a composite indicator, where each pressure is normalised on a qualitative scale and then weighted and summed. This kind of assessment should rely on expert opinion as quantitative data on relative impact is not available (Erhard et al. 2016). An example of such an approach is the aggregated indicator for management intensity on the impact of multiple pressures on cropland as a combination of land management and crop yield (EEA 2015). In this case, a similar qualitative scale from 1 (very bad) to 5 (very good) to define the condition of urban ecosystems was used. The assumption is that higher pressure results in a worse condition and vice versa. Furthermore, the “good condition” of a city reflects a “good” or “desired” balance between green and built infrastructure which can be measured by a selection of indicators (Maes et al. 2016). The meaning of the categories “bad” or “good” in thisour case is comparable only to urban areas in Bulgaria. For instance, very good condition, according to a particular indicator, is assigned to the ecosystems in the database with the highest score. The integrated index represents various mixtures of built and green types combined with the functional aspects of the urban ecosystem sub-types (e.g. J1, J2, J3 different kinds of residential areas, J6 industrial areas). Therefore, the built types and land cover types using the 5-level qualitative scale, following the above-mentioned assumptions, were assessed. The assessment scores were made by eight experts engaged in the project “Toward better understanding of ecosystem services in urban environments through mapping and assessment (TUNESinURB)”. They have expertise in urban planning, forestry, landscape ecology, regional planning and hydrology. Each of them assessed all built and land cover type combinations. Subsequently, the average scores were input to a table which represented the different combinations between built and land cover types (Table 3).

The impact of different funtional aspects of the ecosystem sub-types was added through weighted coefficients which range from 1 for J5 (green areas functioning as closest to natural) to 0.6 for J6 (functioning industrial areas generate highest pressure). Furthermore, weighted coefficients were assigned to different land cover combinations in order to reflect different proportions of green and paved areas. Thus, combination EBD gets a lower weighting than BDE because the share of green areas in the first is lower. The final assessment of each index is calculated through the formula:

$$Asp = ((\sum a, b, c \ldots n/n * WLc))We$$
(1)

where: *Asp* - ecosystem condition assessment; *a, b, c* - urban land cover types for particular build type from Table 3; *n* – number of land cover types; *Wlc* – weighted coefficient of land cover combination; *We* – weighted coefficient of ecosystem sub-type.

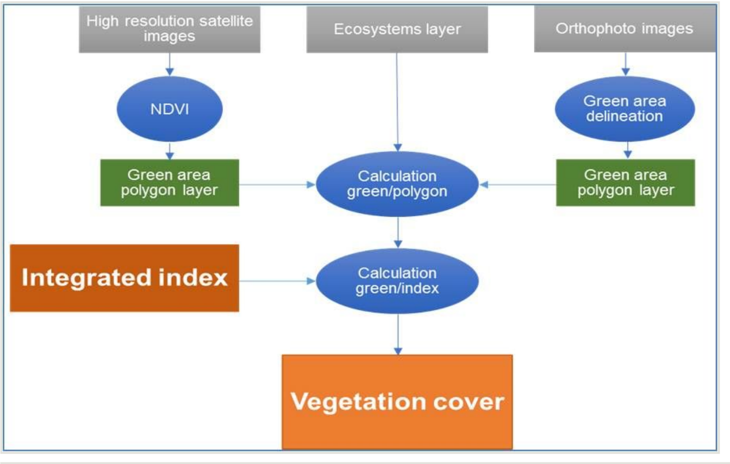

Figure 3.

Conceptual scheme for calculation of vegetation cover.

Table 3.

Expert assessment scores of the urban ecosystem condition as a combination of built types and urban land cover (built type and land cover codes are given in Table 2; built type 1 not presented in the database)

Built types	Urban land cover						
	A	B	C	D	E	F	G
2		3	2	2	1	1	2
3		3	2	2	1	1	2
4	4	3	2	2	1	1	2
5	4	3	2	2	1	1	2
6	4	3	2	2	1	1	3
7		3	2	2	1	1	
8	3	3	2	2	1	1	2
9		3	2	2	1	1	3
10		3	2	2	1	1	3
11	5	4	3	3	1	2	4

The condition of ecosystems is a key component for their potential to deliver economic benefits to people. However, the regions for which ecosystems provide benefit for both biodiversity and ecosystem services cannot be identified unless the ecosystem condition and services can be quantified and their areas of production mapped (Naidoo et al. 2008). Maps of ecosystems, their condition and services for national assessment should be prepared for the whole country on the same scale using an appropriate sequence of the map sheets. Therefore, the European Environmental Agency (EEA) reference grid at 50km was selected to arrange the map sheets. Maps scale 1:125 000 and size A2 were chosen in order to ensure appropriate representation of the content within the 50km map sheets. The spatial units for the mapping were the urban ecosystems outlined in the GIS database. The ecosystem condition was represented through the attributed data generated after the assessment. Thus, a series of maps can be produced using ArcGIS map generating techniques. For visualisation of the ecosystem condition, a graduated colour scheme from blue (very bad) to green (very good) was used. Additionally, maps for areas of interest such as selected cities can be generated in a larger scale in order to represent such areas in more detail.

Assessment of ecosystem services using integrated index of spatial structure

Ecosystem services' provision depends on the physical, chemical and biological condition of an ecosystem and one of the important further steps in the MAES framework is to devise a method for linking the condition of the ecosystem types to the supply of ecosystem services (Erhard et al. 2016). The integrated index of spatial structure provides appropriate information for different aspects of urban ecosystems which refer both to their structure and function. The land cover part of the index, which contains data on vegetation types, combined with vegetation cover data, could be used as a proxy to generate important parameters such as above-ground biomass, carbon storage, air pollutants capture etc. Thus, the indicator, in combination with other parameters, could be used for quantification of ecosystem services' indicators (Table 4). The first two columns of the table show examples of ecosystem services and indicators, in which the index of spatial structure is used to quantify elements of these indicators. The second part of the of the table presents examples of the index's application as one of the indicators in complex assessment.

Table 4.

Application of the index in ecosystem services assessment.

Quantification of ES indicators		**Indicator in complex assessments**	
Ecosystem services	**Indicators**	**Ecosystem services**	**Indicators for complex assessment**
Fibres and other materials	Above-ground biomass	Cultivated crops	Soil productivity, environmental condition, **integrated index of spatial structure**
Air quality regulation	Air pollutants capture	Surface water for non-drinking purposes	Precipitation, potential evapotranspiration, **integrated index of spatial structure**

Global climate regulation	Above ground carbon storage	Erosion regulation	Vegetation cover, soil sealing, **integrated index of spatial structure**
		Flood regulation	Vegetation cover, urban runoff index, soil moisture, **integrated index of spatial structure**
		Pest and disease control	Vegetation cover, **integrated index of spatial structure**, risk to atmospheric drought
		Local climate regulation	**integrated index of spatial structure**, vegetation cover, water bodies
		Soil formation and composition	**integrated index of spatial structure**, climate, topography, vegetation cover, organic matter etc.

Although global climate regulation can be assessed using different indicators, the common indicators are carbon storage and carbon sequestration (Fisher et al. 2009, Groot et al. 2010, Burkhard et al. 2014). Carbon storage is the amount of carbon stored in the vegetation and soil measured in tC/ha, while carbon sequestration is the amount of carbon taken up by these agents measured in tCO_2/ha per year. For calculation and mapping of carbon storage of urban ecosystems in Bulgaria, an approach was developed which combines land cover data from the integrated index of spatial structure, vegetation cover of the urban ecosystems and, soil organic matter data in the GIS environment. The amount of carbon in the biomass in different kinds of vegetation was estimated from literature sources using the value transfer method while, for the soil, carbon direct measurement combined with value transfer from literature sources was used (Nedkov et al. 2016). The amount of carbon for each polygon of the urban ecosystems database was calculated through an algorithm that included the following steps: 1) calculation of green area per polygon using the vegetation cover index (in percentages) and the area of the polygon (in ha); 2) differentiation of green areas into grass, scrub and tree parts using the data from the land cover part of the index; 3) calculation of carbon in grass, shrub and trees using reference values from literature sources; 4) calculation of soil carbon using a digital soil map and reference values from literature sources; 5) calculation of tC per polygon and 6) calculation of tC/ha per polygon. The carbon stock in above-ground tree biomass from urban forest parks (J5) is based on these calculations and is defined as 36.5tC/ha. The carbon storage in the urban forest parks (land cover class A) was assumed as 41tC/ha (C stock in trees and forest floor) based on the calculation of Zhiyanski et al. (2015). The carbon in the scattered urban trees class (B) was estimated using the calculation of Nowak and Crane (2002) which is defined as 25tC/ha. The carbon stock in urban grasslands based on field measurements is estimated at 2tC/ha (Zhiyanski et al. 2013). The carbon stock in soils is estimated for the upper 30cm of soils, using the information for soil types from Koynov et al. (1998) for natural soils and Zhiyanski et al. (2013), Zhiyanski et al. (2015) for urban soils.

Another application of the proposed index is in the complex ecosystem services assessment (Table 4) where the condition score (see previous subsection) was applied in combination with other indicators using a similar normalised assessment scale. This was most evident in the case of the complex assessment of the potential for urban ecosystems to regulate climate at regional and local scale. Such an approach focuses on the spatial structure of urban ecosystems and on the elements of the green infrastructure which determines the climate parameters' local regimes and their spatial pattern including modification of temperature, humidity, wind flow and its intensity and air quality. The procedure for complex assessment of urban ES capacity for climate regulation (regional to local) was based on the sum of the following three indicators: 1) "Integrated Index of Spatial Structure" - on a scale from 1 to 5 (1 - very low capacity, 2 - low capacity, 3 - average capacity, 4 - high capacity, 5 - very high capacity) – which represents the capacity of the indicator to influence the urban ecosystem state; 2) "Vegetation Cover" - using the same scale from 1 to 5 – which shows the capacity of the indicator to influence the urban ecosystem state and 3) "Water bodies" – with a value of 0 or 1 (0 - absence / 1 – presence of water bodies in the unit/polygon of the urban ecosystem types). Visualisation of areas of different capacity to supply the respective ES followed GIS spatial analysis of the integrated assessment's results of each unit/polygon of the urban ecosystem types on a scale from 1 to 5 (1 - very low capacity, 2 - low capacity, 3 - average capacity, 4 - high capacity, 5 - very high capacity). The meaning of the capacity categories in thisour case is comparable only to urban areas in Bulgaria. For instance, very high capacity according to a particular indicator is assigned to the ecosystems in the database with the highest score for this indicator.

Maps of ecosystem services were produced using the same general approach presented in the previous section. The capacities of the ecosystems to deliver ecosystem services were assessed on a relative scale ranging from 0 to 5 (after Burkhard et al. 2010, Burkhard et al. 2012). The supply capacities of the ecosystems, defined through the assessment, were assigned to each unit in their databases. Then, the map series of ecosystem services capacity was produced for each cell of the EEA 50km grid.

Results

Integrated index of spatial structure of urban ecosystems in Bulgaria

The application of the proposed approach for the urban ecosystems outside NATURA 2000 zones in Bulgaria resulted in identification of the spatial index for each single polygon in the database. The results show that there are 364 unique combinations of the index (see appendix 2), which are not equally distributed amongst different ecosystem subtypes (Table 5). The highest number of combinations is in industrial ecosystems (J6) although they occupy much less area and number of polygons than residential low density areas (J3). The lowest number is represented by transport ecosystems (J7), which are the most homogeneous ecosystem type. The number of combinations per ecosystem subtype depend more on the number of the polygons than on the area of the respective subtype. The correlation coefficient between the number of combinations and the number of polygons is 0.69, while for the area it is 0.55. The different ecosystem subtypes have their own combinations of built types. Some of them have various built structures while the others are dominated by two or three. The ecosystems with the highest variety of built types are both residential and public areas (J1 and J3) which have 9 different building structures. They are the same for both ecosystems but vary in the area distribution. J1 is dominated by open midrise and have also more compact built structures while J3 is dominated by open low-rise and other less built structures such as large low-rise and sparsely built. The ecosystem subtypes with the lowest variety of built structures are waste deposits (J9) and urban waters (J10) with only two built types. The most common land cover type by far is the combination scattered trees –low plants – paved (BDE).

Table 5.

Distribution of spatial index combinations in urban ecosystem subtypes.

Ecosystem sub-types	**Number of combinations**	%	**Number of polygons**	%	**Area (ha)**	%
J1	41	11.3%	1684	2.1%	27796.4	5.2%
J2	16	4.4%	376	0.5%	8486.5	1.6%
J3	60	16.5%	28326	35.6%	311697.0	58.8%
J4	22	6.0%	460	0.6%	3276.7	0.6%
J5	57	15.7%	17059	21.4%	50113.0	9.5%
J6	89	24.5%	14007	17.6%	82761.8	15.6%
J7	13	3.6%	8511	10.7%	22548.6	4.3%
J8	25	6.9%	304	0.4%	20127.1	3.8%
J9	27	7.4%	247	0.3%	2163.2	0.4%
J10	14	3.8%	451	0.6%	1199.7	0.2%

The most common index combination by far is J36BDE (Table 6). It represents residential and public low density areas with open low-rise built type and scattered trees –low plants - paved land cover. This is typical spatial structure in small towns and villages of the country and the corresponding subtype covers 59% of the whole urban ecosystem area. The most common buildings are two-storey family houses usually in a yard with fruit trees and low plants which are a mixture of grass and agricultural plants. Paved areas are the streets between yards which are usually combined by scattered park trees. The vegetation cover is relatively high (about 60%) and diverse which ensures various ecosystem services supply. The next of the most common combinations have far less share of the urban ecosystems in the country which vary between 1 and 7% (Table 6). The combination with the second largest area is J68BDE (7.5%) which is presented by relatively large low-rise buildings surrounded by open space and scattered trees. These are the industrial parcels of the former agricultural cooperatives formed during the communist periods (1944-1989) which are present in almost all villages in Bulgaria. They are located in the outskirts of the villages and their normative land use (according to the cadastre) is industrial and, therefore, they are identified as an industrial ecosystem subtype. The vegetation cover is also relatively high with an average of 55% per polygon. This kind of industrial sites is represented by another index (J68DE) in the top 10, which differs from the previous only by the lack of trees. The heavy industry sites (J610BDE) with scattered trees – low plants - paved land cover are also well represented. The extractive industrial sites (J811DF) are also amongst the most common indexes although they have relatively low number of polygons. This is mostly due to the large open coal mines in the southeast part of the country. One of the most common indexes is J711E which represents the transport network that contains only paved surfaces.

Table 6.

Distribution of the most common indices in Bulgaria.

Index	Number of polygons	Area (ha)	Average area of polygon (ha)	Percent
J36BDE	13861	233386.29	16.84	44.02%
J68BDE	5264	39801.85	7.56	7.51%
J39BDE	3693	23276.43	6.30	4.39%
J36BD	3307	22335.06	6.75	4.21%
J711E	7366	16029.30	2.18	3.02%
J68DE	3238	13722.85	4.24	2.59%
J15BDE	544	12794.87	23.52	2.41%
J511BD	5530	12706.89	2.30	2.40%
J811DF	49	12089.57	246.73	2.28%
J511BDE	4037	11152.94	2.76	2.10%
J39BD	3951	9513.28	2.41	1.79%
J610BDE	246	6894.74	28.03	1.30%
J26BDE	228	6816.01	29.89	1.29%
J16BDE	401	5547.18	13.83	1.05%

Urban ecosystems condition based on the integrated index of spatial structure

The generation of the index of spatial structure and the identification of green areas for each index combination enable the vegetation cover for each polygon of the database to be defined. The results showed that most of the urban ecosystems in Bulgaria have vegetation cover above 50% (Table 7) which corresponded to good and very good condition according to the assessment scale proposed by Zhiyanski et al. 2017. Only 3.7% were areas with no vegetation and 4% with limited vegetation cover (between 1 and 25%). The areas with vegetation cover above 75% were the second largest (24.1% of the whole area) but the number of polygons were much higher than the others (Table 7). This meant that the smaller polygons, in general, had a higher percentage of vegetation cover. The main reason was due to the smaller area of urban green polygons (J5) compared to residential and public areas (J1 and J3). The average percentage of vegetation cover was the highest in the J5 ecosystem subtype which had 95% followed by J4 with 72%. The residential and public areas had 48% in J1 and 67% in J3 respectively, while suburban areas (J2) had 59%. Industrial ecosystems had relatively high vegetation cover of 58% but this was mainly due to the larger areas of J68BDE which had 59%, while the heavy industry areas had less than 20%. The extractive industrial sites (J8) and waste deposits (J9) also had lower vegetation cover of 24% and 22% respectively. Transport ecosystems (J7) had the lowest vegetation cover with an average of only 2%.

Table 7.

Distribution of vegetation cover of urban ecosystems in Bulgaria.

Vegetation cover (%)	Number of polygons	Area (ha)	Percent
0	8073	20041.1	3.7%
1 - 25	1567	21273.7	4.0%
25-50	5350	45782.7	8.6%
51-75	21840	315210.2	59.4%
76-100	34595	127861.9	24.1%

The condition of urban ecosystems measured by the integrated index of spatial structure represents a complex assessment of an ecosystem's characteristics related to the spatial arrangements of built and land cover types in combination with particular ecosystem subtype. The calculation of formula 1 in GIS resulted in generation of an assessment score for each polygon in the database. The results show that most urban ecosystems in the country are assessed as moderate (score 3) and good (score 4) condition (Table 8). Very few ecosystems (1.3% of the whole area) have very good condition, while very bad condition is evident for 3.4% of the ecosystems.

Table 8.

Urban ecosystems condition based on the integrated index of spatial structure.

Condition	Area (ha)	Percent
1 – very bad	18071,7	3,4%
2 – bad	46133,7	8,7%
3 - moderate	398330,4	75,1%
4 – good	60245,8	11,3%
5 – very good	7388,0	1,3%

The condition of the ecosystem subtypes is calculated as the average score of all polygons from their respective subtypes and the results are presented in Table 9. The threshold value between condition classes was defined at 0.49, therefore scores 2.5 and 3.4 fall in the range of moderate condition while 3.6 is defined as good condition. Urban green areas (J5), recreational areas (J4) and urban waters (J10) had good average condition but the absolute figures were below 4.0 which refers to the transitional score between good and moderate. The residential areas are assessed as moderate condition but the figures vary from 2.5 for J1 to 3.4 for J2. Bad condition is assigned to extractive industrial sites (J8) and waste deposits (J9) while the transport network (J7) had a very bad condition.

Table 9.

Condition of urban ecosystem subtypes based on the integrated index of spatial structure.

Ecosystem sub-type	J1	J2	J3	J4	J5	J6	J7	J8	J9	J10
Condition	Moderate	Moderate	Moderate	Good	Good	Moderate	Very bad	Bad	Bad	Good
	2.5	3.4	3.2	3.6	3.9	2.8	1.2	2.1	1,6	3,8

Maps of the urban ecosystem condition at scale 1:125 000 have been prepared for the whole country using the GIS database of the ecosystem subtypes and assessment results (Fig. 4). There are 61 map sheets which cover all urban ecosystems outside NATURA 2000 zones. These maps give a general view of the ecosystem condition at national level. Additionally, larger scale maps of selected cities have been generated in order to visualise the spatial aspects in more detail for large urbanised areas.

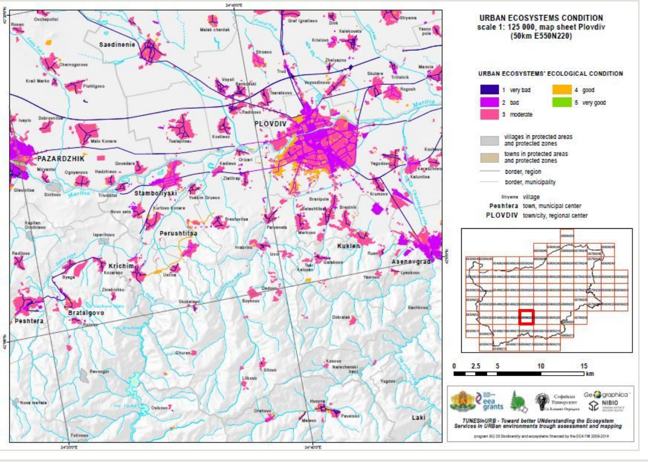

Figure 4.

Map of the urban ecosystem condition based on the integrated index of spatial structure (Note: this is a low quality copy, the original map being given in Suppl. material 3)

The maps in Fig. 5 show how the urban ecosystem condition is distributed in four cities in the country representing a large capital city (Sofia), a large city (Varna), a medium size city (Pleven) and a small city (Karlovo). There are some similarities and differences in the ecosystem condition pattern in the different cities. All of them have a mixture of ecosystems with moderate and low condition in their central parts. The large cities have a well formed periphery of good condition ecosystems which is located in one or two directions from the city centre (south – southwest in Sofia, north – northeast in Varna). In the medium size city (Pleven), this periphery is not so clear while, in the small one (Karlovo), it is not present. Ecosystems in good condition are generally rare but, in Sofia, they are more and evenly distributed than in the other cities, while in Varna, they are almost absent.

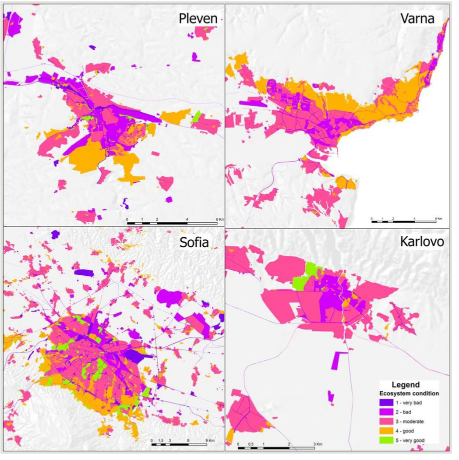

Figure 5.

Ecosystem condition based on integrated index of spatial structure of selected cities.

Integrated index of spatial structure of urban ecosystems in Bulgaria

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The most common index combination by far was J36BDE (Table 6). It represented residential and public low density areas with open low-rise built type and scattered trees – low plants - paved land cover. This is a typical spatial structure in small towns and villages of the country and the corresponding subtype covers 59% of the whole urban ecosystem area. The most common buildings were two-storey family houses usually in a yard with fruit trees and low plants which are mixture of grass and agricultural plants. Paved areas are the streets between yards which were usually combined with scattered park trees. The vegetation cover was relatively high (about 60%) and diverse which ensured various ecosystem services supply. The next of the most common combinations have far less share of the urban ecosystems in the country and these varied between 1 and 7% (Table 6). The combination with the second largest area was J68BDE (7.5%) which is presented by relatively large low-rise buildings surrounded by open space and scattered trees. These were industrial parcels of former agricultural cooperatives formed during the communist periods (1944-1989) and which are present in almost all villages in Bulgaria. They were located in the outskirts of the villages and their normative land use (according to the cadastre) was industrial therefore they were identified as industrial ecosystem subtype. The vegetation cover was also relatively high with an average of 55% per polygon. This type of industrial site is represented in the top 10 by another index (J68DE), which differs from the previous only by the lack of trees. The heavy industry sites (J610BDE) with scattered trees – low plants - paved land cover were also well represented. The extractive industrial sites (J811DF) were also amongst the most common indices although they had relatively low number of polygons. This was mostly due to the large open coal mines in the south east part of the country. One of the most common indices was J711E which represented the transport network that contained only paved surfaces.

Mapping and assessment of ecosystem services using integrated index of spatial structure

The urban ecosystem services assessment framework in Bulgaria developed by Zhiyanski et al. (2017) relies on a set of indicators for quantification of ES supply and implementation of the matrix approach (Burkhard et al. 2010, Burkhard et al. 2012). The integrated index of spatial structure was used in the assessment of several services for quantification of the indicators or as an indicator in complex assessment (Table 4). Two examples (one for each of the two cases) are presented here for global and local climate regulation.

The global climate regulation ecosystem service is represented by the carbon storage capacity of urban ecosystems. The overall analysis at national level indicates an even distribution of the areas with low, moderate and high capacities which cover respectively 25%, 28% and 31% of whole urban ecosystems area. Only 5% have no capacity, 2% have very low cpacity and 9% have very high capacity. Urban green areas (J5) have the highest capacity of 4.0, followed by low density residential areas (J3) with 3.3 and recreation areas outside cities (J4) with 2.9. The lowest average score (0.2) is for transport networks (J7). Extractive sites and waste deposits have very low capacity of 1.4 and 1.3 respectively. The selected cities (Fig. 6) show quite different patterns in the distribution of carbon storage capacity. Sofia is very similar to the general distribution in the country with a balance between low, moderate and high capacity, 23%, 36% and 20% respectively. Pleven and Varna have a higher percentage of low capacity areas (76% and 53% respectively) and low percentage of high capacity areas (4% in both cities). Karlovo has more areas with high (40%) and moderate (37%) capacity and less (10%) with low capacity.

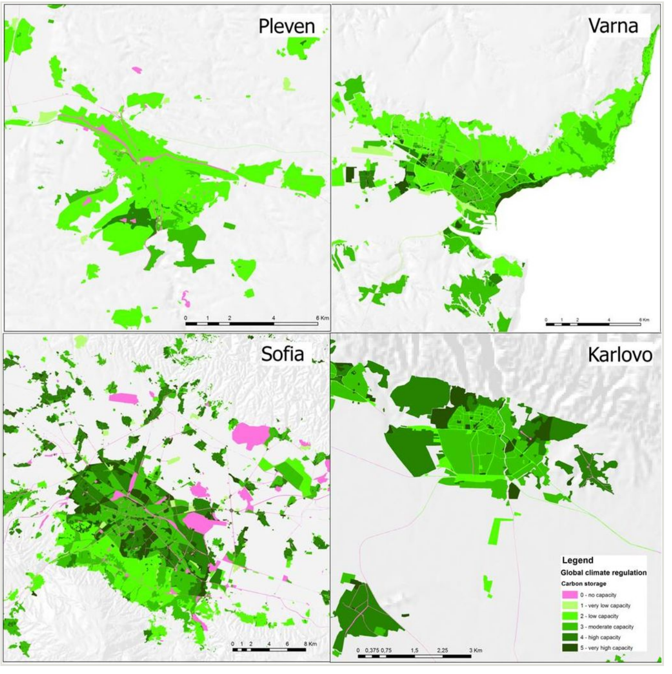

Figure 6.

Maps of carbon storage capacity in selected cities.

The overall analysis of the results indicated that the Bulgarian urban ecosystems had a moderate to good capacity for local and regional climate regulation. The spatial distribution of this ecosystem service showed that the most widespread urban ecosystem subtype in Bulgaria - J3 (Residential and public low density areas), was characterised by a high capacity (60% of cases). J1 was rated with moderate capacity (over 70%) and, only in district centres, the number of polygons with score "low" increased. Subtypes J2 and J4 were rated with high capacity (over 80%). As expected, the greatest effect was obtained within the range of polygons of Urban green areas (J5 – "very good"). These results were due to natural factors (geographic conditions - heterogeneous landscapes, favourable climate balances and significant presence of deciduous vegetation) as well as anthropogenic factors - historical traditions in the establishment and enlargement of settlements and the character of building process with significant participation of yards, gardens and other green areas in the landscape pattern. The results for J6 (industrial sites, including commercial sites) indicated that under 20% of the polygons were of low capacity and over 50% were of moderate capacity. These outcomes can be explained by the depopulation trend which leads to reduction of economic activity and occurrence of self-restoration processes in the landscapes. The distribution of local climate regulation capacity in the selected cities is given in Fig. 7.

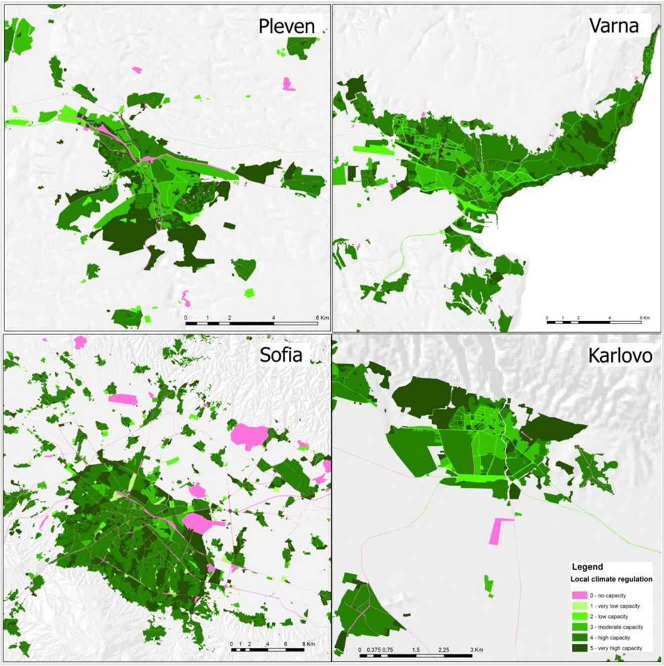

Figure 7.

Maps of local climate regulation in selected cities.

Discussion

The proposed approach gives an opportunity to reveal some important aspects of the spatial structure of urban ecosystems at national level. In this study, data sources were used that are specific for Bulgaria such as restored property plans or the city cadastre which are not available for other European cities. However, it is possible to use alternative sources in other countries and furthermore the delineation of ecosystem subtypes is possible also by using only satellite or orthophoto images. They can be used as a source for visual interpretation and identification of built and land cover types within predefined urban ecosystems in a vector polygon format. The approach is useful for a national ecosystem assessment which necessitates identification and evaluation of great numbers of spatial units in large areas. The visual interpretation is a time- and labour-consuming method but enables identification of site specific features which are very important for correct definition of the built and land cover types. Thus, it can be used as an effective tool in meeting the requirements of the EU Biodiversity Strategy to 2020 and the implementation of MAES urban ecosystem assessment framework (Maes et al. 2016).

As urban condition is dependent on many factors, the combination of built types and land cover types in urban territories is an informative complex indicator for assessing the condition of specific subtypes of urban ecosystems. The integrated index of spatial structure can be used as an indicator for the ecosystem condition as well as to support the quantification of other important indicators such as vegetation cover, soil sealing and fragmentation of green infrastructure. It can also be used effectively in ecosystem services' assessment. The results obtained for local climate regulation has the potential to meet the important issues in relation to landscape and urban planning and management by providing answers to the following questions: (i) where are the hotspots of the analysed ES in the current configuration and the composition of the Green Infrastructure (GI); (ii) what is the potential of GI to influence local climate in particular locations of importance to the development of the town – e.g. trade centres, transport hubs, social institutions, densely populated residential areas etc. and (iii) where should further improvement of GI be targeted to strengthen the supply of analysed ES? The resulting maps will increase public understanding and enables greater participation in public hearings and discussions.

In the process of implementation of the proposed index in the national assessment and mapping, some limitations were observed. The identification of the index was performed on the basis of preliminary delineated polygons representing urban ecosystems. This predefined dominance of mixed land cover types as the polygons delineation did not take into account the character of the vegetation. The identification of built types, based on the principle of dominance, ignored the existence of some built types which led to another source of uncertainty. For large scale urban ecosystems mapping, it is better to perform ecosystems delineation and index identification in parallel, thus providing more precise results. A comparison of these results, with much more detailed mapping, will provide sufficient data for uncertainty analysis and further improvement of the approach.

The scores of ecosystem services were relevant only for urban ecosystems in Bulgaria. For instance, very high capacity of carbon storage supply was assigned to ecosystems which have from 123 to 266tC/ha. Although the latter figure was the highest amount calculated for the urban ecosystems in Bulgaria, in forest ecosystems, this figure could be higher and the scoring scheme would be different. The same problem could arise at sub-national, continental or global scale.

For territorial and urban planning purposes (especially from national to regional scale of analysis), it is highly recommended to combine the spatial index with the indicator for population density. Such an approach would significantly optimise the results from the assessment of urban ecosystem condition and the assessment of the potential for particular ESs (mainly of regulation services). Integration of the demographic information in integrated assessment would support the analysis of the balances “potential-flows", "demand-consumption” and "supply-demand”. The results of such an expanded version of the assessment approach are expected to be a highly informative for ES economic valuation.

Conclusions

The integrated index of spatial structure revealed the spatial arrangements of land cover and built types in combination with functional characteristics of the urban ecosystems. It provided an appropriate basis for characterisation and assessment of the urban ecosystems' condition and ecosystem services following the requirements of the European Biodiversity Strategy and the MAES process. The proposed approach enabled the definition of the internal heterogeneity of the urban ecosystems at national level which is one of the main challenges in studying urban ecological systems (Grimm et al. 2000). Furthermore, it can be used to calculate vegetation cover in urban ecosystems of extensive areas with no appropriate data for automatic land cover classification. The results for the urban ecosystem condition in Bulgaria presented in this work should be regarded as preliminary results and hypotheses that need to be further tested and verified in different case studies in greater detail.

The index can be used in assessment and mapping of several ecosystem services especially when there is a lack of appropriate spatial data. It contains valuable information on the green infrastructure which enabled calculation of important indicators such as above-ground biomass and carbon storage. The assessment and mapping of ecosystem services based on integrated approaches, including the presented spatial indicator, provided significant spatial information in support of decision-making and planning activities for sustaining the actual flows of local and regional climate regulation service.

Acknowledgements

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Supplementary materials

Suppl. material 1: Examples of catalogues for identification of built types and land cover types doi

Authors: Stoyan Nedkov, Petar Nikolov
Data type: Figure and text
Brief description: Figure representing examples of catalogues used during the identification built and land cover types.
Filename: Catalogue_example.pdf - Download file (2.20 MB)

Suppl. material 2: Combinations of index of spatial structure in urban ecosystems in Bulgaria doi

Authors: Stoyan Nedkov, Ivo Ihtimanski, Rositsa Yaneva
Data type: Table
Brief description: Table representing all combinations of the integrated index of spatial structute in urban ecosystems in Bulgaria
Filename: Sp_Index_Table.pdf - Download file (235.77 kb)

Suppl. material 3: Map of urban ecosystem condition based on the integrated index of spatial structure (example map sheet) doi

Authors: Rositsa Yaneva
Data type: Map
Brief description: Map of urban ecosystem condition representing an example of map sheets that cover the whole country
Filename: E550N220_PLOVDIV_ES State.pdf - Download file (5.57 MB)

Suppl. material 4: Descriptions of Urban ecosystem subtypes doi

Authors: Stoyan Nedkov
Data type: Table
Brief description: Contains descriptions of urban ecosystem subtypes and their relation to EUNIS habitat classess
Filename: Urban_ecosystem_subtypes.pdf - Download file (446.59 kb)