GIS Modeling of Green Infrastructure of Mediterranean Cities for the Management of Urbanized Ecosystems

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Abstract—The article discusses methodological approaches to the assessment of the spatial configuration and structure of green spaces and fragments of the natural landscape (for Malaga, Spain). Modern modeling techniques using geographic information systems (GIS) are used to assess Malaga's green infrastructure in terms of the configuration, fragmentation, and spatial structure of green spaces (with GuidosToolBox software). Morphological spatial pattern analysis (MSPA) focuses on the geometry and connectivity of components based on a raster image of the study area, can automatically identify ecological corridors of different sizes, and can further rank them within the network, thereby making it possible to assess the connectivity of the natural framework of the city. With MSPA, it is possible to identify the configuration and structure of green spaces, the main basic reserves (cores) and islands of green infrastructure, and the ecological corridors and to assess the connectivity and fragmentation of green spaces, which is critical for the determination of the unity of the ecological framework of the parameters. The scientific novelty of the research consists of the developed methodological approaches for the determination of high-priority areas of the green infrastructure network, which are simultaneously important for both the conservation of biodiversity and for the development of the recreational and aesthetic qualities of green spaces.

Keywords: urban green infrastructure, GIS modeling, connectivity, fragmentation of green areas, morphological spatial pattern analysis (MSPA)

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INTRODUCTION

Greening is one of the main ecological methods used for the recovery and improvement of an urban environment (Golubchikov, 2001). Maintaining a green infrastructure as a source of ecosystem services is a key area of sustainable urban development (Wei et al., 2018). However, the cohesion of the ecological framework is often limited by the reduced connectivity of green infrastructure and the high degree of fragmentation of green spaces (McNicoll, 2005). Therefore, it is important task not only to plan the introduction of new green spaces and their management but also to conduct a subsequent analysis of their functional properties.

Urbanized territories, as such, are complex and diverse systems, and the analysis of their evolution often suffers from a lack of spatial data and insufficient understanding of the impact of socioeconomic and physical–geographical factors. Given these constraints, the European Mediterranean, which is constantly evolving due to the active involvement of tourism resources, is one of the most favorable regions for this type of research.

The Mediterranean climate, dry and hot, strongly influences the need to provide cities with a developed green infrastructure. The shade from green spaces helps to soften high temperatures, while the use of elements such as green roofs helps to reduce energy consumption for the cooling of rooms and enhances the aesthetic appearance of cities.

In the scientific literature, the principle of connectivity is mainly used to assess the ability of green infrastructure to preserve animal habitats and provide species with the opportunity to migrate (Liquete et al., 2015). Thus, many of the connectivity research papers are not directly related to urban systems. Rather, they focus on the analysis of the green infrastructure of the suburbs of large metropolitan areas or rural areas. Nevertheless, in the context of green infrastructure, the idea of connectivity is just as important as the principle of its multifunctionality, i.e., its ability to perform many different functions in any territory (Hansen et al., 2014).

This study proposes a set of spatial indicators to help assess the connectivity of the urban green infrastructure elements of the City of Malaga. Landscape connectivity can be calculated with the integral index
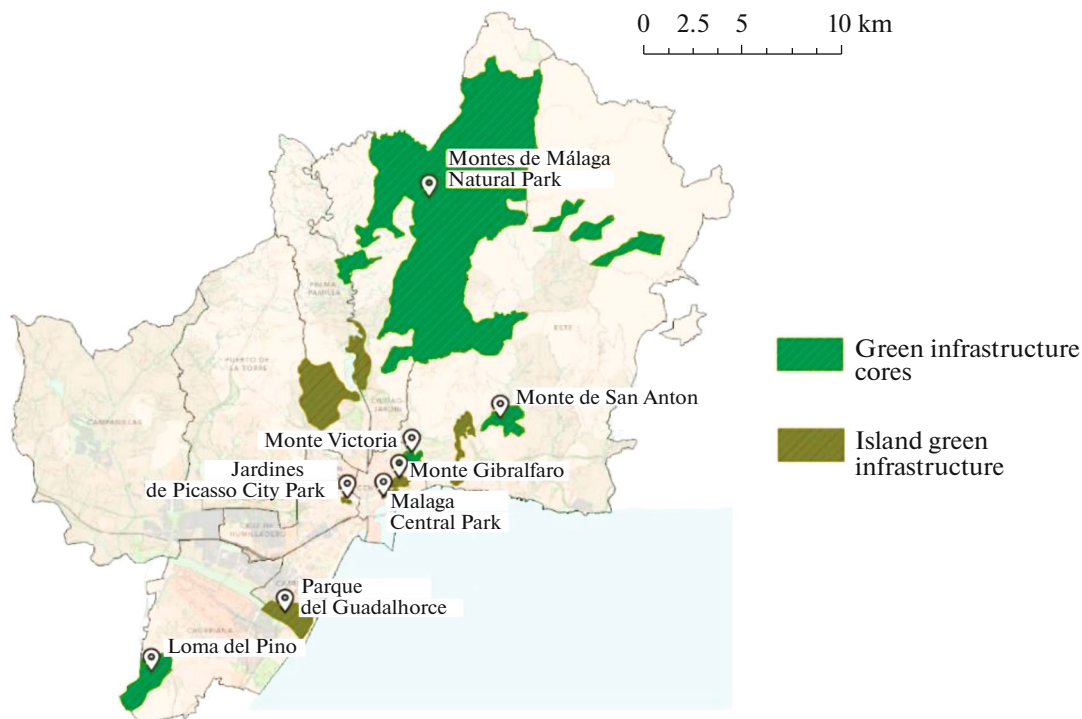
Fig. 1. Major elements of the green infrastructure of Malaga.

of connectivity (IIC) and the probability of connectivity (PC), indicators based on graph theory (Flynn and Traver, 2013). An alternative is morphological spatial pattern analysis (MSPA), which provides a more flexible approach to accounting for green infrastructure connectivity. It focuses on the geometry and connectivity of components based on a raster image of the study area and can automatically identify existing ecological corridors (Batty and Rana, 2002).

The city of Malaga was chosen as the object of research (Fig. 1). Its rapid population growth since the 1960s has raised a number of questions regarding the effectiveness of urban planning, including the field of landscaping.

The main objective of this study is to assess the connectivity of the elements of Malaga's green infrastructure as one of the most important geo-ecological components of the urban system. The tasks of the work were to apply a new methodological approach to the analysis of the structure of green spaces and fragments of the natural landscape in the city (morphological spatial analysis) and, based on the constructed model, to assess the critically important parameters of connectivity and fragmentation of green spaces.

EXPERIMENTAL

A unique feature of morphological spatial pattern analysis (MSPA) is the automatic detection of ecological corridors of different scales between the main functional cores of the image, as well as the subsequent ranking of these detected paths, with allowance for the relative importance of each component (a node or a corridor) in a given network (Vogt and Riitters, 2017). In addition, MSPA only requires raster data on the land use of the region and the associated software, i.e., the method is extremely easy to apply.

The nonprofit software GuidosToolBox (GTB) was used to extract elements of Malaga's green infrastructure. All GTB tools are based on geometric principles and therefore can be applied at any scale and for any kind of raster data. GTB is used to represent land use objects in a binary image, in which the spatial position of each pixel is determined by the code "1" or "0" (where "1" is the foreground, i.e., precisely the studied elements of the landscape, and "0" is the background). In this case, "1" represents the actual green infrastructure (foreground), and "0" represents urban development (background).

The analysis result is highly dependent on the Edge Width parameter. An increase in Edge Width increases the background area at the expense of the main foreground area and may change the MSPA class accordingly. In this work, the Edge Width is four pixels.

The foreground area of a binary image is divided into seven general MSPA classes: Core, Islet, Perforation, Edge, Loop, Bridge, and Branch; Table 1). This segmentation results in mutually exclusive classes that, when merged, match the original foreground area exactly. The background area of an image is divided

Table 1. Foreground and background classes and their spatial significance

Class	Spatial value
Core	Green infrastructure pixels surrounded on all sides by foreground pixels at a distance greater than the specified distance
Islet	Green infrastructure pixels not surrounding the core. This is the only unrelated class
Perforation	Green infrastructure pixels that form a transition zone between foreground and background for interior areas
Edge	Green infrastructure pixels that form a transition zone between the foreground and background for the outer areas
Bridge	Green infrastructure pixels that connect two or more disjoint cores
Loop	Green infrastructure pixels that connect the core region to itself
Branch	Green infrastructure pixels that extend from the core region but do not connect to another core region
Core Opening	Background pixels that form the inner area of the hole
Border Opening	Background pixels that form a transition zone between the edge and the background
Background	Background pixels surrounded on all sides by background pixels and are more than the specified distance

into three classes: Background, Core Opening, and Border Opening.

MSPA is focused on the identification of the most important indicators of the ecological state of the environment (in this case, urban), and it can be used to solve a whole range of different problems related to the management and conservation of ecosystems. The method is applicable in various areas related to the optimization of the urban environment and the general planning of cities, and its use makes it possible to assess changes in the state of ecosystems and to obtain a clearer idea of existing geo-ecological problems and methods to solve them; spatial analysis provides the information needed to prioritize future research.

Contagion and Entropy, part of the Fragmentation toolset, help determine the degree of fragmentation in a city's green infrastructure. The tools have an important difference: while the entropy fragmentation estimate is based on the simultaneous estimation of the foreground and background (as a whole), Contagion is based only on the consideration of the foreground objects (Vogt, 2015). Accordingly, the Contagion tool was used to analyze green infrastructure in isolation from the analysis of the entire urban system, with an exclusive focus on foreground objects.

Fragmentation is expressed as a percentage scale, where indicators tending to 0% indicate the minimum degree of area fragmentation and those tending to 100% are characteristic of areas with maximum fragmentation.

An equally useful approach to the study of the fragmentation of green infrastructure is the Foreground Area Density (FAD) tool. FAD analysis is carried out via measurement of the foreground pixel density index on five observation scales (with moving-window analysis) with square adjacent areas of 7, 13, 27, 81, and 243 pixels long (Riitters et al., 2012). The result of the analysis is a set of maps with different results for each selected observation scale. The FAD values are color-coded according to the following infrastructure integrity classes: Rare, Patchy, Transitional, Dominant, Interior, and Intact.

RESULTS AND DISCUSSION

Based on the results of morphological spatial analysis, the city's territory was divided into areas belonging to each of the ten spatial classes (Fig. 2).

The cores are the largest basic reserves and the most interconnected. In Malaga, the cores of the green infrastructure system are, primarily, the Natural Park of Montes de Málaga, which occupies most of the northeastern region of Ciudad Jardin, the Loma del Pino (Pine Hill) park in southwestern Churriana, the park Monte de San Anton in the Este area, and the forest park Monte Victoria in the city center. In total, the cores of green infrastructure occupy about 9% of the city's territory and account for 34.1 km^2 (Fig. 3).

The islet green infrastructure is smaller (27.5 km^2) but has a much greater spatial fragmentation. Large islets
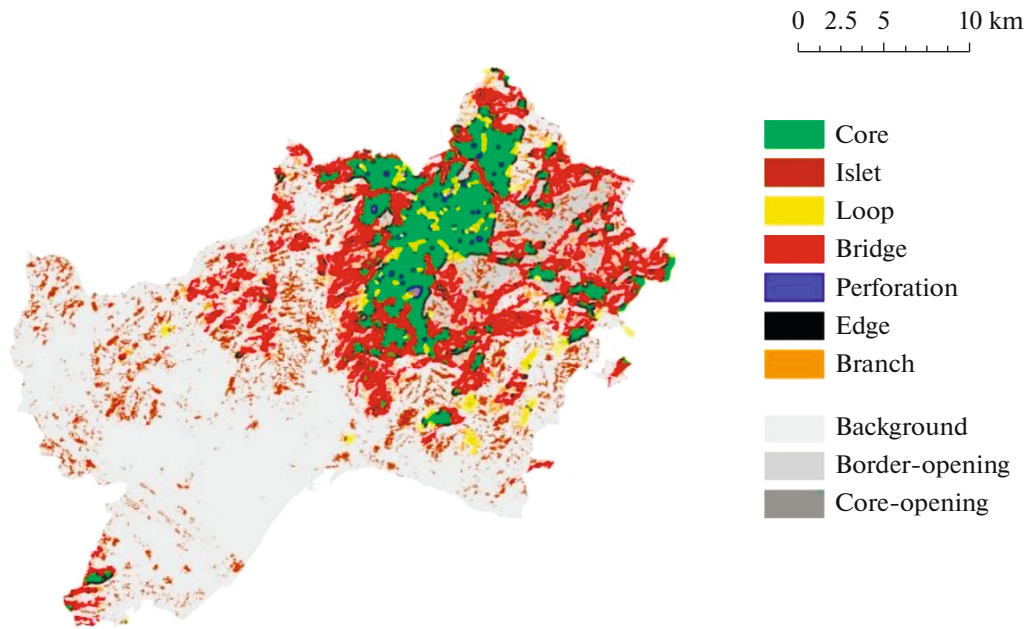
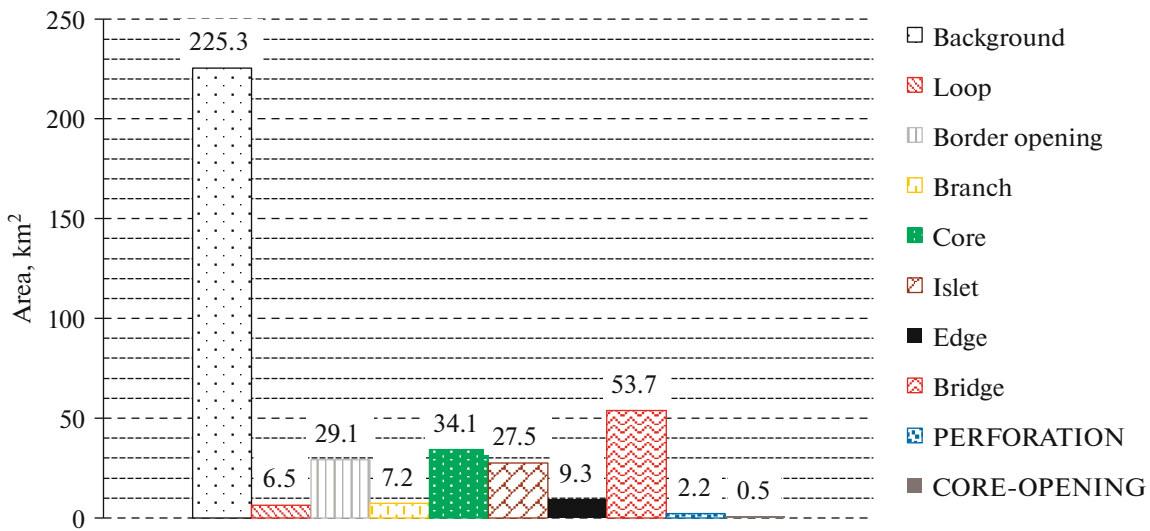**Fig. 2.** MSPA results for the city of Malaga.

Fig. 3. Total area of each class based on MSPA analysis.

of green infrastructure include the park of the mouth of Guadalhorce River, natural vegetation along Campanillas River, the Monte Gibralfaro park, and much of the Puerto de la Torre, Este, and Campanillas areas. In the city center, the islet green infrastructure includes the Jardines de Picasso Street Park and Malaga Central Park, one of the city's main attractions. However, despite the close proximity of these green spaces to each other, the strong fragmentation of green infrastructure in the central part of the city makes it impossible to speak of connectivity. Almost all major elements of green infrastructure within the urban core are islets: these are city parks and squares, gardens, and areas for recreation and recreation.

Much of the city is covered by Bridges patches of vegetation that connect the non-intersecting cores of green infrastructure to each other. The total area of such bridges is almost 53.7 km^2 and exceeds the area of the cores themselves. The largest area of the bridges is in the Este region. Also, large areas of this class of vegetation grow in the areas of Palma Pamilla and Puerto de la Torre.

In general, cores and bridges should be given the most attention in urban green infrastructure connec-
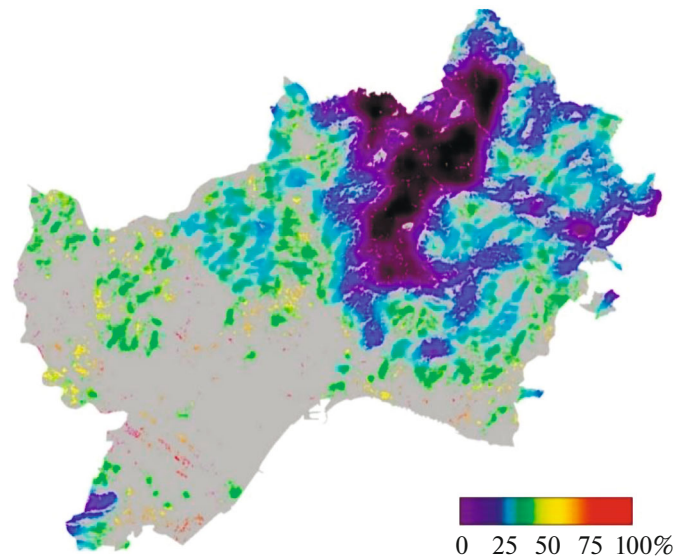
Fig. 4. Fragmentation of Malaga's green infrastructure (Contagion tool).

tivity research; the other elements for the most part do not contribute to an increase or decrease in the structural connectivity of the system.

In the case of Malaga, the minimum fragmentation (Contagion tool) is characterized primarily by cores for which the degree of fragmentation does not exceed 15% (Fig. 4). A significant part of the area is characterized by an average degree of fragmentation of 30–60%; this is the green infrastructure of the Puerto de la Torre, Campanillas, and Palma Pamilla districts. It is interesting that, despite the small area and scattered territory, the green infrastructure in the central area of the city is also characterized by an average degree of fragmentation, less than 50%. The most "torn apart" green infrastructure is in the Churriana area, where most of the green space is insular and, therefore, 80% or more fragmented.

The green infrastructure in Malaga (including pine and oak tracts, agricultural land, wetlands of the Guadalhorce estuary, etc.) has been highly fragmented, primarily by the active expansion of dense residential development along the northwest beam over the past several decades. This expansion is putting tremendous pressure on the region's biodiversity, with less connectivity between increasingly isolated areas of green infrastructure.

FAD analysis on different observation scales is of interest, since often very different results, if not diametrically opposite, can be obtained.

Analysis of Malaga's territory on a least detailed observation scale (seven pixels) showed that 29% of the green infrastructure is complete and intact, while 18.2 and 28.8% belong to the classes of interior and dominant infrastructure unity (Fig. 5). Fragmented vegetation makes up about 23.8% of the foreground

areas (where the transitional class occupies 13.7%, the patchy class is 9.4%, and the rare class is 0.7%).

The main difference between the results on the most detailed observation scale (243 pixels) is the complete absence of a class of intact vegetation.

Moreover, the interior class occupies less than 1% of the territory, and the least fragmented areas (Montes de Málaga and the area near the small settlement of Esparteros on the eastern outskirts of the city) belong to the dominant integrity class and occupy 43.2% of the foreground. About 1.3% is in the most fragmented green infrastructure in Churriana, Puerto de la Torre, and Centro. The second largest, patchy class occupies 31.7% of the territory; It is worth noting that, of the large islands of green infrastructure popular with tourists, the parks of Monte Victoria, Monte Gibralfaro, and Monte de San Anton belong to this class. The rest of the foreground (about 23%) is in the transitional class.

CONCLUSIONS

The method of morphological spatial pattern analysis applied to the assessment of the connectivity of the elements of the green infrastructure of the city of Malaga gave unambiguous results. About five to six large green infrastructure cores have been allocated within the green space network. Only these few cores are interconnected by corridors and have loops that favor animal migration. Despite the relatively high rates of the provision of the population with green infrastructure and the vast areas of greenery (according to the regulatory documents of the urban planning project Agenda Urbana Málaga), most of the green spaces are of an insular (fragmented) nature and have a low parameter of connectivity of the elements of
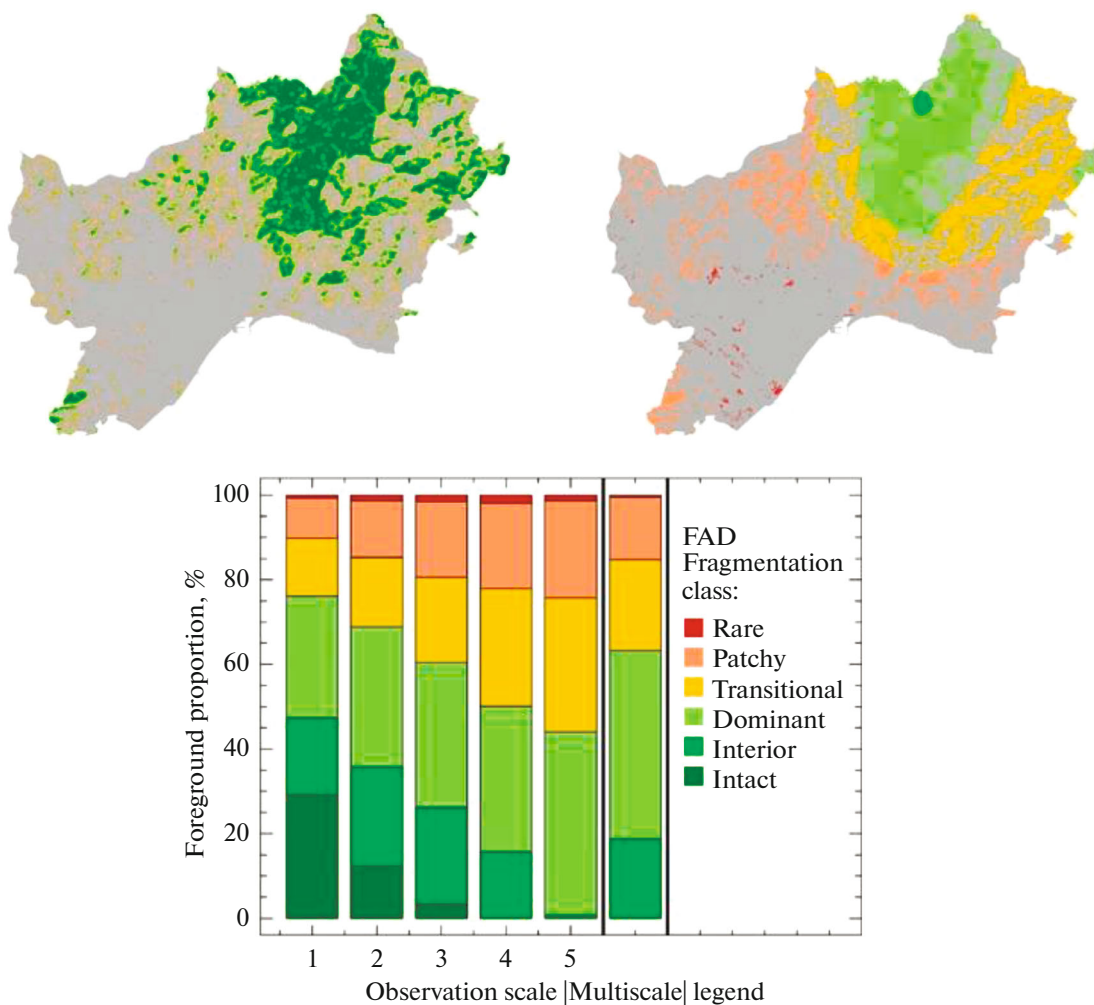
Fig. 5. FAD analysis of Malaga's green infrastructure with the least (1, left) and most (5, right) detailed observation scales.

green infrastructure, which does not contribute to the creation of a single network or ecological framework as such.

A GIS is a key tool that makes it possible both to direct attention to individual features of the landscape and to explore them together. The method of morphological spatial analysis has certain limitations, which are primarily related to the determination of the scale of the input data, since different landscape-ecological projects require different study details. The user is required to understand the appropriate scale for a particular MSPA application. The results of the assessment of the spatially dependent parameters of entanglement and fragmentation can also depend not only on the level of analysis but also on the ecological processes analyzed within the framework of the landscape matrix. Also, a noticeable limitation is that the green infrastructure cannot be differentiated by morphometric parameters (parameters of elevation and terrain slope) belonging to the grid of elementary catchments

and other spatial characteristics in a three-dimensional coordinate system of real space.

COMPLIANCE WITH ETHICAL STANDARDS

Conflict of interests. The author declares that they have no conflicts of interest.

Statement on the welfare of humans or animals. This article does not contain any studies involving animals performed by any of the authors.

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