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GIS MODELING OF GREEN INFRASTRUCTURE OF MEDITERRANEAN CITIES FOR MANAGEMENT OF URBANIZED ECOSYSTEMS

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Green infrastructure is one of the most important components of the urban environment which severely affects the quality of human life. Green spaces can be a tool for maintaining the integrity and resilience of urban ecosystems. Both continuous research of the structure and functions of urban green infrastructure and monitoring of its quality are necessary in terms of optimization of the urban environment.

Using the example of the Mediterranean city of Malaga (Spain), as one of the leading "smart" cities in Europe, three methodological approaches to assessing the spatial configuration and structure of green spaces and fragments of the natural landscape of the city are considered. Modern methods of GIS modeling are applied to assess the green infrastructure of Malaga in terms of land cover characteristics (using CORINE Land Cover), the potential quantity of ecosystem services (using Urban Atlas), and configuration, fragmentation, and spatial structure of green spaces (using GuidosToolBox). Based on the method of Morphological Spatial Pattern Analysis (MSPA), the main cores, islets, and bridges of green infrastructure are identified, and the connectivity and fragmentation of green spaces are assessed, them being critically important for determining the unity of the ecological framework. The quantitative characteristics of green infrastructure are given, which are potentially comparable at different levels of land cover studies. The study results are given based on a combination of several methods that allowed to analyze the territory at different levels of spatial analysis and to determine the "backbone" areas of the green infrastructure network.

Keywords: urban green infrastructure, GIS modeling, CORINE Land Cover, Urban Atlas, connectivity, fragmentation, MSPA.
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Greening is undoubtedly one of the main ecological methods of improving the urban environment (Golubchikov, 2001). Part of a comprehensive program of measures for the planning of any urban ecosystem is the introduction of an extensive and developed network of green infrastructure (Porshakova, 2016). The resilience of the cities of the future will largely depend on the extent to which humankind can maintain the quality of urban green spaces and their ecological functions (Breuste et al., 2015). The existence and development of cities within the framework of the concept of sustainable development is often limited not only by the spatial underdevelopment of the ecological framework but also by the reduced connectivity of green infrastructure and a high degree of fragmentation of green spaces (McNicoll, 2005). Therefore, an extremely important task is not only the introduction of new green spaces and their management but also the subsequent analysis of their quality.

Urban areas are complex and diverse systems, the analysis of the evolution of which often suffers from a lack of spatial data and insufficient understanding of the influence of socio-economic and physical factors on the growth of these systems. The most interesting systems are those that, on the one hand, experience strong anthropogenic pressure, but, on the other hand, retain a significant part of the natural framework. The European Mediterranean which is constantly evolving through the active involvement of tourism resources is one of the most favorable regions for this kind of research.

This paper suggests the city of Malaga as the region for the case study, considering the number of popular tourist resorts and the rapid population growth since the 1960s that raised several questions about the effectiveness of urban planning. This research is an attempt to integrate geographic information systems used to model the growth of cities and predict the development of territories into the geoecological assessment of urbanized territories. The study is also aimed at applying the main methodological approaches to monitoring and analyzing the growth process of urbanized areas to further predict the impact of urbanization on the environment and suggest tactics for effective urban planning.

The research aims at identifying the role of green infrastructure as one of the most important geoecological elements of the urbanized areas of Malaga, as well as applying modern methods of assessing the state of green infrastructure. To achieve this it is necessary to a) identify the physical-geographical and socio-economic prerequisites for the spatial growth and development of the city; b) consider modern methodological approaches to assessing the spatial configuration and structure of green spaces and fragments of the natural landscape in the city; c) select the approach that most fully solves the tasks. The selected methods will allow solving the problem of assessing the critical parameters of connectivity and fragmentation of green spaces based on spatial morphological analysis.

Materials and Methods

The subject of the study. Green infrastructure as a term does not have a single universally accepted definition. The modern understanding of the concept of “green infrastructure” (GI) in the context of this study is most often consistent with the definition given by the European Commission in 2013 (Green Infrastructure ..., 2013): green infrastructure includes a wide range of natural and semi-natural assets strategically planned as a single network of interconnected components. The spectrum of assets that fall under the definition ranges from outdoor green spaces and small squares to large parks, cemeteries, green walls, and roofs (i.e. vertical green elements).

Urban greening is one of the most important pathways for improving urban environments. Green spaces soften the perception of hot and dry weather conditions, increase air ionization, have an anti-noise effect, protect against chemical pollution, and absorb many harmful impurities. It is believed that 1 hectare of healthy forest absorbs about 0.25 tons of carbon dioxide per day while releasing 0.2 tons of oxygen (Golubchikov et al., 2001).

In recent decades, the enormous potential of urban green infrastructure has been highlighted in addressing current urban planning challenges, especially in the context of sustainable development. Developing green infrastructure does not mean creating a completely new framework; rather, it symbolizes improving the connectivity of an already existing network of green spaces to enhance ecosystem functioning.

Region of the study. The region of study, the city of Malaga (Autonomous Community of Andalusia, Spain), is located on the Mediterranean coast at the foot of the Montes de Málaga (Malaga Mountains), which are part of the Andalusian system. The southwestern part of the region is occupied by vast alluvial plains between the rivers Guadalhorce, Campanillas, and Guadalmedina.

The Malaga region is characterized by a dry and hot Mediterranean climate, which undoubtedly affects the need to provide the city with a developed green infrastructure. Mediterranean cities with their hot and dry summers are in need of shady areas that can moderate the high temperatures, thus improving the quality of life for the citizens. The rapidly advancing green roof technology also contributes to energy savings through efficient indoor cooling.

Malaga is located in the zone of xerophytic light forests and shrubs, which have the local name of tomillar (Romanova et al., 2014). Tomillar is the result of prolonged overgrazing characterized by sparse tree cover but extensive shrubland consisting of thyme (*Thymus* spp.), rosemary (*Rosmarinus* spp.), cistus (*Cistus salviifolius*[1], *C. albidus*), and other low-growing shrubs. Zonal Mediterranean vegetation creates quite specific conditions for the formation of a green infrastructure framework. The shrubby nature of the vegetation is poorly conducive to the formation of urban parks with a large-mass tree cover. In this regard, the overwhelming part of the green infrastructure is formed either by introduced species, such as magnolia (*Magnolia grandiflora*), tipuana (*Tipuana tipu*), jacaranda (*Jacaranda mimosaefolia*), or by hybrids and cultivars, for example, colored linden (*Tilia* × *euchlora*) and bitter orange (*Citrus* × *aurantium*; Table 1).

Table 1. The most common species in urban parks and green boulevards in Malaga (Plan General ..., 2011).

	Introduced species	**Indigenous species**
Trees	Tipuana (*Tipuana tipu*), Bottletree (*Brachychiton* sp.), Bitter orange (*Citrus* × *aurantium*), Jacaranda (*Jacaranda mimosaefolia*), Chinaberry (*Melia azedarach*), Black locust (*Robinia pseudoacacia*), Silk oak (*Grevillea robusta*), Carob (*Ceratonia silique*)	Judas tree (*Cercis siliquastrum*), Olive (*Olea europaea*), Ash (*Fraxinus excelsior*), Stone pine (*Pinus pinea*)
Shrubs	Evergreen spindle (*Euonymus japonicus*), Common lantana (*Lantana camara*), Chinese privet (*Ligustrum lucidum*)	Jasmine (*Jasminum* sp.), Oleander (*Nerium oleander*), Tamarisk (*Tamarix* sp.), Phillyrea (*Phillyrea angustifolia*), Lentisk (*Pistacia lentiscus*), Bridal broom (*Retama monosperma*), Rosemary (*Rosmarinus officinalis*), Common hawthorn (*Crataegus monogyna*)

The origin of most of the woody vegetation in the city dates back to the 1930s in the Montes de Málaga region, where at that time significant areas were set aside for green space in order to protect the city from severe flooding associated with the Guadalmedina River. Species used were stone pine (*Pinus cembra*) and Aleppo pine (*Pinus halepensis*), both being ideal for poor and highly eroded soils. On the basis of artificial plantations, over time, typical Mediterranean vegetation began to develop, consisting of holly oak (*Quercus ilex*), cork oak (*Q. suber*), carob (*Ceratonia siliqua*), common myrtle (*Myrthus communis*), ash (*Fraxinus* spp.), strawberry tree (*Arbutus unedo*), etc.

Urban planning plays an important role in understanding the configuration of a city's green infrastructure. Within the modern borders of Malaga, two large zones can be distinguished, the first being the nucleus of urbanization, the “city” itself, and the second, being the periphery, which is a large but sparsely populated area. Peripheral areas, inherently rural, were incorporated into the city borders after Malaga experienced a new kind of demographic pressure in the form of a migratory influx of villagers affected by the introduction of the grape phylloxera (*Dactylosphaera vitifoliae*) in Europe. The last decades of the 19th century and the beginning of the 20th century were marked by a deep economic depression, which was caused by the simultaneous collapse of the metallurgical

[1] Latin names are given according to “Plan General de Ordenación Urbana (PGOU) de Málaga” (2011).

industry and the decline of viticulture. In this context, Malaga began to promote housing policies of "cheap houses" for the new population, and new neighborhoods in Trinidad and Ciudad Jardin were designed for political purposes (Reinoso-Bellido et al., 2010). The "cheap development" project eventually attracted so many interested residents that it was no longer able to cover the demand for housing. Overcrowding in the neighborhoods of La Trinidad, Capuchinos, and many others has increased so much that it has caused spontaneous settlement nuclei on the outskirts of the city, for example, El Palo in the modern district of Este, Arroyo del Cuarto in the district of Cruz de Humilladero, Mangas Verdes in Ciudad Jardin and many others (Del Carmen Díaz Roldán, 1996).

Starting in the 1990s, the municipality government began preparing a plan to renovate the city center which was slowly losing its attractiveness. With the tourism boom of the 1960s the main activity of managing new areas in the periphery falls into the hands of private initiative. Then the city begins to grow chaotically and irrationally, without control from the administration. Gentrification, though, has allowed the city center to become a key symbolic space in the city. However, it did not help make the central area much more suitable for everyday life; now, due to overuse of tourism, places in the city such as Malagueta Beach, Plaza de la Marina, Paseo del Parque, and Alameda Principal avenue suffer from an oversupply of visitors (Barrera-Fernández at al., 2019).

The process of renovating the city and improving the comfort of the urban environment continued throughout the last decade of the 20th century. In 1997, Malaga received the 2nd European Prize, awarded by the Council of European Municipalities and Regions, for the concept of sustainable urban planning. In 1998, the city also received the Dubai Best Practice Award for Leading Sustainable Development Agenda, including Excellence in Green Infrastructure Development. In 2000, the government agency, the Observatory of the Urban Environment of Malaga (OMAU), was established.

In 2013, the Urban Empathy 2013 project was launched; a partnership of 11 Mediterranean cities under the auspices of the European Union aimed at collaborating in achieving sustainable urban development models. Besides, Agenda21 was approved in 2015, which is the Agenda Urbana Málaga for the Comprehensive Sustainability of Urban Environment 2020-2050 (Agenda Urbana Málaga, 2016). The program report contains a theoretical explanation of urban planning and the current state of the green infrastructure in Malaga.

Today, the Malaga government is trying to change the situation for the better by promoting plans to implement more greenery in the city. Many environmental projects such as Agenda Urbana Málaga, Urban Empathy, and Smart Cities receive financial support. The analysis of the evolution of green areas for the period from 2005 to 2013 showed that during the period studied, the green space per capita ratio showed a continuous upward trend, in 2008 amounting to 6.33 m^2 per inhabitant, and in 2015 already reaching the level of 7.60 m^2 per inhabitant (Fig. 1; Trigo, 2015; Agenda Urbana Málaga, 2016).

In 2020, the city became the winner among all nominees for the European Capitals of Smart Tourism prize, including for its success in organizing a healthy and comfortable urban environment to attract tourists (European Commission ..., 2020). The developing city programs have a significant drawback, since they are largely not supported by a sufficient number of geoecological studies, and the effectiveness of already existing projects has not been scientifically assessed.

It should be noted that the transformation is far from uniform throughout Malaga. Thus, in the regions of Bahía de Málaga and Guadalhorce there was a decrease in the area of green space per capita, the increase indicators being -0.42 m^2 per inhabitant and -0.09 m^2 per inhabitant, respectively (Agenda Urbana Málaga, 2016; Fig. 2).

Methods. There are three main GIS modeling methods applied in the study: a) the models used to characterize the land cover (CORINE Land Cover); b) the models used to assess green infrastructure in relation to the potential quantity of ecosystem services (Urban Atlas); and c) the models used to assess the configuration, fragmentation and spatial structure of green infrastructure

(Morphological Spatial Pattern Analysis using the GuidosToolbox software package). Each of these methods has its advantages and disadvantages, as well as the limits of application at various levels of territorial differentiation. Below is an overview of the methods used and their comparison to identify the most suitable for solving the tasks.

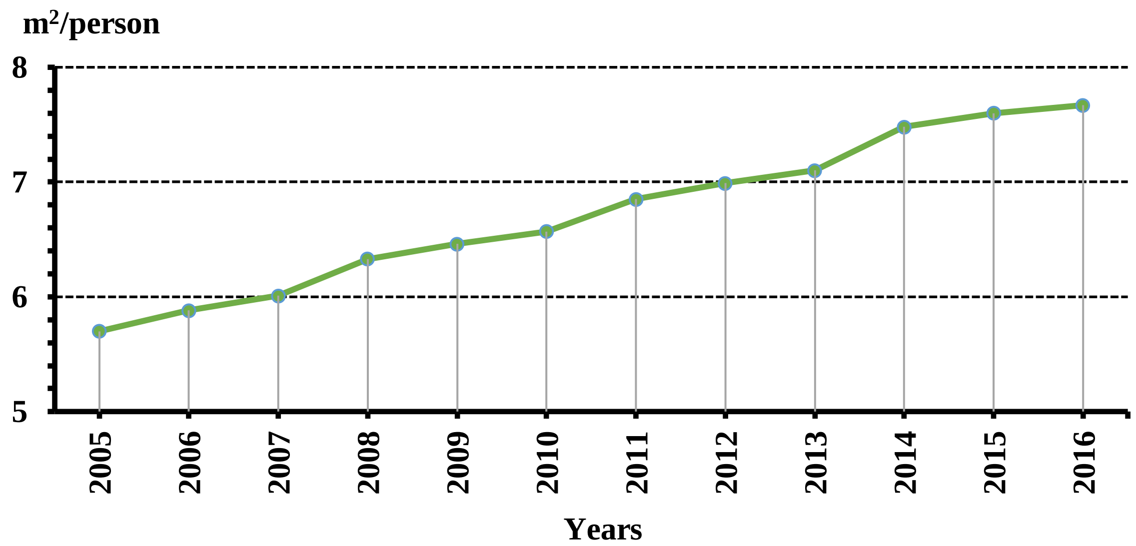

Fig. 1. Dynamics of the indicator of green area per capita (m^2/person) for the period from 2005 to 2016.

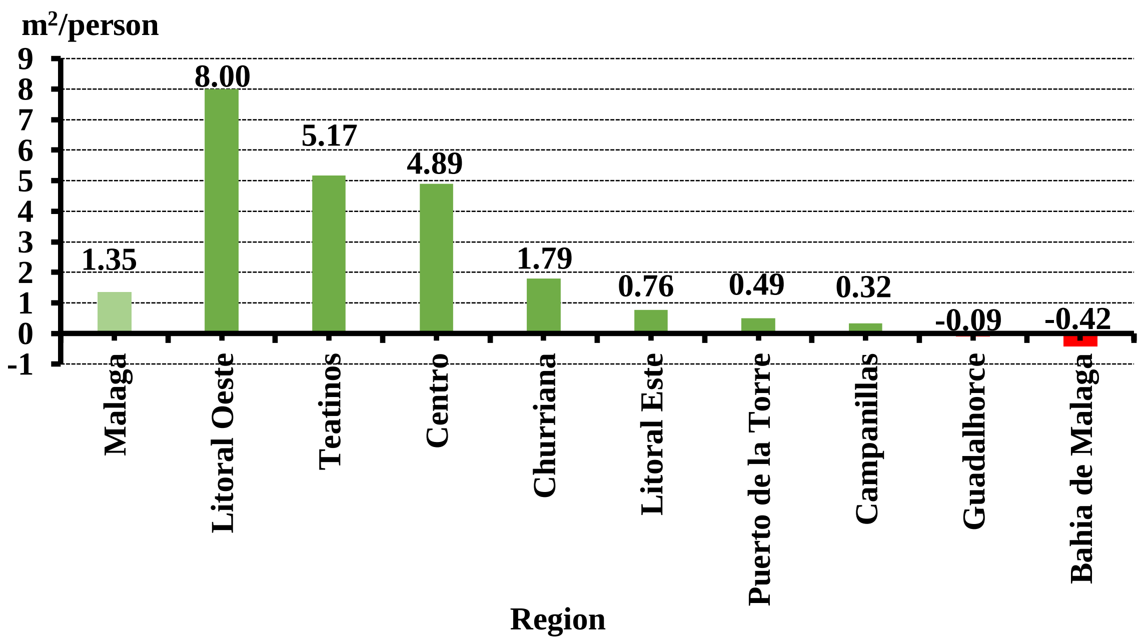

Fig. 2. Increase in the indicator of green area per capita (m^2/person) for the period from 2005 to 2012 by districts.

CORINE Land Cover. In the context of studying green infrastructure, CORINE Land Cover, a subsidiary of the Copernicus system (Copernicus Land Monitoring ..., 2020), can serve as a basic source of spatial data on land-use and land cover. The CORINE database, which includes various land-use categories with a unique three-digit code assigned to them, is updated regularly every 6-

10 years, providing publicly available data in vector and raster formats available for free use. The quality of CORINE Land Cover data can be assessed as high, and the number of misidentified land-use categories is usually small (Dige et al., 2011). However, these data are more suitable for assessing at the national level than at the regional level. CORINE rasters are not detailed enough to conduct urban green infrastructure assessments. Mixed classes with complex use patterns in the CORINE classification, such as, for example, “land principally occupied by agriculture with significant areas of natural vegetation” (class 243), “annual crops associated with permanent crops” (class 241), are fairly subjectively delineated classes. In the context of green infrastructure, integrated agricultural use classes are vital to biodiversity and therefore need to be considered as separate elements; however, identifying the structure of such integrated sites is difficult.

The same problem arises when modeling a green infrastructure framework within settlements, in an urban area. Given the lack of detail and possible erroneous classification of some objects, CORINE is not always suitable for local analysis of technogenic complexes. For example, according to the CORINE team land can be classified in class 112 (“discontinuous urban fabric”), when buildings, roads, and other artificial surfaces cover between 50% and 80% of the total area (Updated CLC ..., 2019). Thus, the level of generalization when using this method is very high, and the local green infrastructure located within the boundaries of the development zone will most likely not be taken into account. Consequently, the detailed classification of CORINE Land Cover does little to deepen the study of green infrastructure problems, and the lower spatial resolution complicates the task (Dige et al., 2011).

Urban Atlas. The European Urban Atlas, analogous to CORINE Land Cover, is part of the Copernicus Land Monitoring Service (Copernicus Land Monitoring ..., 2020). Urban Atlas has a resolution of 50 meters, which is double that of the CORINE Land Cover geodatabase. The Urban Atlas is the highest resolution urban land-use database, and its main difference from CORINE Land Cover is that CORINE contains three-tier classifications for cropland (by crop type) and forest (by vegetation type) categories, which allows for better differentiation of land cover types, whereas Urban Atlas does not use this classification. Land cover is subdivided into 20 different land-use classes, with 17 of them being different technogenic categories.

Urban Atlas is the result of thousands of images from European satellites; the classification is based on a combination of photointerpretation and object-oriented classification with a three-step validation including internal quality control of the interpretation, peer review, and technical verification by the European Topic Center Land Use and Spatial Information (Prastacos, Chrysoulakis, 2011). Therefore, Urban Atlas can be considered a more convenient and rational tool for obtaining data on green infrastructure than CORINE.

It is possible to group the Urban Atlas land cover categories according to the ecosystem services provided by each class. Categories such as forests, herbaceous vegetation, and open spaces are responsible for biodiversity conservation, climate change mitigation, water management, recreation, and human wellbeing and health. Also, agricultural land (categories of arable land, pastures) is conducive to climate change mitigation; also, they have important functions such as food security and water management. Urban green infrastructure, along with climate change mitigation and recreational opportunities, also ensures the cultural identity of the population and provides an important land capitalization service. Also, the location of water bodies and zones for sports and recreation affects land capitalization.

Morphological Spatial Pattern Analysis (MSPA). The method of Morphological Spatial Pattern Analysis is based on the principle of connectivity of elements of green infrastructure. Basically, in the scientific literature the analysis of the principle of connectivity is to assess the ability of green infrastructure to preserve fauna habitats and provide species with the opportunity to migrate (Liquete et al., 2015). Because of this, many of the connectivity studies are not directly related to urban systems. Rather, they focus on analyzing the green infrastructure of the suburbs of large metropolitan areas, or rural areas. However, in the context of green infrastructure, the idea of connectivity is just as important as the principle of its multifunctionality (Hansen et al., 2014).

Landscape connectivity can be calculated using the integral connectivity index (IIC) and connectivity probability (PC), indicators that are based on graph theory (Flynn, Traver, 2013). IIC and PC not only take into account the barrier effect of the landscape matrix but also assess the bearing capacity of each of its sections. However, these indicators are not enough to extract spatial morphological information when modeling a green infrastructure network, since already existing structural nodes and corridors are ignored (Wickham et al., 2010).

As an alternative to the above indicators, the Morphological Spatial Pattern Analysis (MSPA) can be used, which provides a more flexible approach to account for the connectivity of green infrastructure. MSPA, using a raster image of the study area as input, focuses on the geometry and connectivity of the components and can automatically determine existing corridors (Batty, Rana, 2002). The uniqueness of the method is added by the system of automatic detection of ecological corridors of different scales between the functional cores of the image, as well as further ranking of the identified paths based on the determination of the relative importance of each component in a given network (Vogt, Riitters, 2017). Because the method is applicable to any territory for which raster data on the land-use of the region are available and the process is fully automated, it is extremely convenient to use.

To analyze the elements of Malaga's green infrastructure, the non-commercial software GuidosToolBox (The Graphical User Interface for the Description of Objects and their Shapes Toolbox) (Vogt, Riitters, 2017) was used. All GuidosToolbox tools are based on geometric principles and therefore can be applied at any scale and for any kind of raster data. The program uses a binary image as input, in which the spatial position of each pixel is determined by the code “1” or “0”. At that rate, the value “1” corresponds to the foreground of the image, namely the studied elements of the landscape, in this case, the green infrastructure; the value “0” corresponds to the background, i.e. elements other than green infrastructure. Such elements can serve as urban fabric, industrial facilities, water bodies, etc.

The analysis result is highly dependent on the Edge Width parameter. Increasing the Edge Width (literally the width of the foreground edges) increases the background area at the expense of the main foreground area, and, accordingly, can change the MSPA class. In this work, the Edge Width value that builds the most visual picture is 4 pixels.

The foreground area of a binary image is divided into seven general MSPA classes: Core, Islet, Perforation, Edge, Loop, Bridge, and Branch (Table 2, Fig. 3). This segmentation results in mutually exclusive classes that, when merged into one object, exactly match the original foreground region. The background area of the image is divided into three classes: Background, Core Opening, and Border Opening.

Results and Discussion

Quantitative characteristics of land cover according to CORINE Land Cover

Land-use systems in Malaga can be divided into 3 units: urbanized areas, agricultural regions, and areas of least anthropogenic interference, where natural vegetation predominates (Fig. 4).

According to CORINE Land Cover, within the coastal urban core of Malaga, a significant part of the territory is occupied by continuous (23.7 km^2) and discontinuous (18.9 km^2) urban fabric. About 21 km^2 of the territory is occupied by industrial zones.

The main agricultural areas are located on the periphery, in the northeast and northwest of Malaga. Most of the territory is occupied by orchards (43.8 km^2), also a significant part is made up of olive plantations, occupying 28.7 km^2. Areas of complex, but mainly agricultural use make up a total of 34.2 km^2. The cultivated land occupies only 9.5 km^2, of which 2.3 km^{2}are areas of nonirrigated agriculture and 7.2 km^{2}of irrigated agriculture. Pastures occupy 17.7 km^2.

Among the natural vegetation, shrubs predominate covering lands with a total area of 93.6 km^2. Coniferous forests occupy 45.7 km^2, broadleaf forests – 2.9 km^2 and mixed forests – 3.12 km^2. Sparse forest vegetation grows on a territory with a total area of 14.2 km^2. Natural vegetation is most preserved in the northeastern sector of the city in less populated regions.

Table 2. Foreground and background classes and their spatial significance.

Class	Spatial significance
Core	Foreground pixels surrounded by also foreground pixels, at a distance greater than the specified distance
Islet	Foreground pixels not surrounding the core. This is the only isolated class.
Perforation	Foreground pixels forming a transition zone between the foreground and the background for interior areas
Edge	Foreground pixels forming a transition zone between the foreground and the background for outer areas
Bridge	Foreground pixels connecting two or more disjoint cores
Loop	Foreground pixels connecting the core region to itself
Branch	Foreground pixels extending from the core region but not connecting to another core region
Core Opening	Background pixels forming an interior area of a perforation
Border Opening	Background pixels forming a transition zone between the edge and the background
Background	Background pixels surrounded by also background pixels, at a distance greater than the specified distance

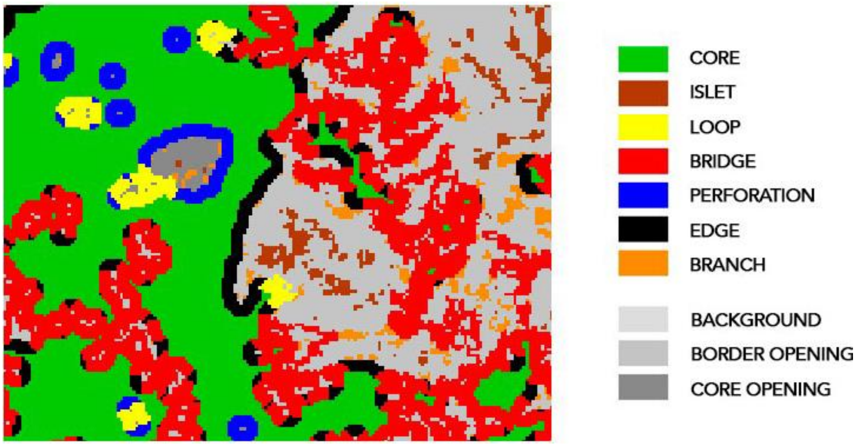

Fig. 3. Fragment of MSPA raster.

Thus, the land-use structure of Malaga is as follows: 82.8 km^2 (21%) is occupied by urbanized territories, 163.2 km^2 (41%) by natural vegetation, and 149.7 km^2 (38%) by agricultural land.

Within the urban core of Malaga, according to CORINE Land Cover, the total area covered by vegetation is only 1.45 km^2 and is confined to areas of urban green infrastructure.

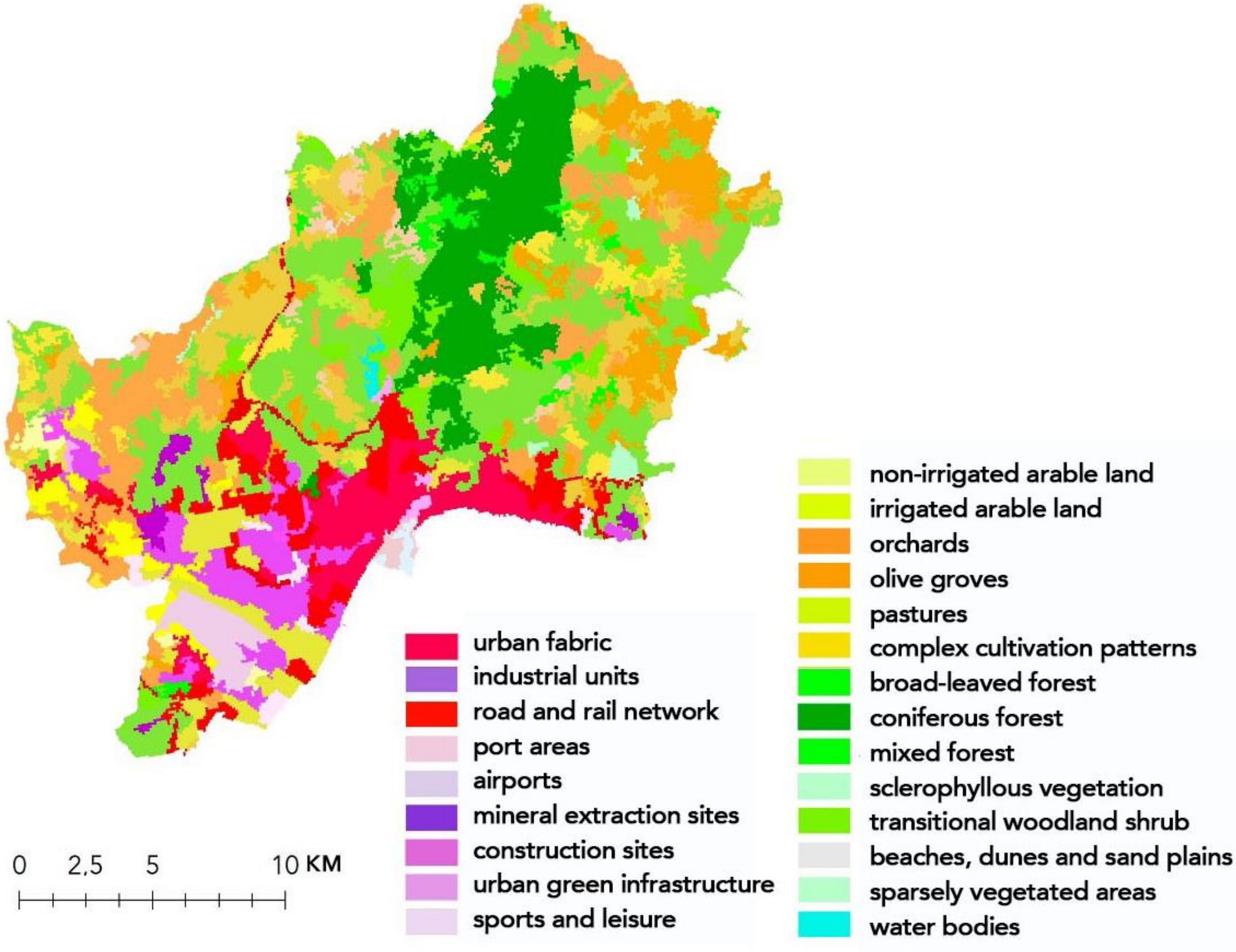

Fig. 4. Land cover of the city of Malaga (according to CORINE Land Cover 2018).

CORINE Land Cover allows you to get a general idea of the land cover of the city, however, it is not possible to study the configuration of green infrastructure in the zone of residential urban development due to the excessive degree of generalization. In this case, the Urban Atlas which is characterized by a more detailed classification of the urban fabric is a more suitable method for quantifying green infrastructure.

Assessment of the potential quantity of ecosystem services offered by GI according to Urban Atlas

In total, according to Urban Atlas, green infrastructure in its various forms in Malaga occupies about 313.9 km^2, or 80% of the territory (Fig. 5, Table 3).

Green spaces are known to actively trap and neutralize physicochemical elements and compounds potentially hazardous to health; GI also performs several important functions in the city, including environmental, sanitary and hygienic, and recreational functions (Golubchikov et al., 2001). Of course, the decorative function of green spaces is no less important. The analysis of the generalized groups of green infrastructure services and the categories included in each group (Table 4) made it possible to draw some conclusions.

Table 3. Potential of generalized green infrastructure service groups and correlation with Urban Atlas categories responsible for services in Malaga.

Service group	Urban Atlas categories	Area, km^2	Area, %
Biodiversity conservation	forests; shrubs and herbaceous vegetation; open spaces with little or no vegetation; water bodies	261.37	66.69
Adaptation to climate change	arable land; vineyards, olive groves, and orchards; pastures; forests; shrubs and herbaceous vegetation; open spaces with little or no vegetation	305.56	77.96
Climate change mitigation	green urban areas; sports and leisure; arable land; vineyards, olive groves, and orchards; pastures; forests; shrubs and herbaceous vegetation; open spaces with little or no vegetation	312.06	79.62
Water management	arable land; vineyards, olive groves, and orchards; pastures; forests; shrubs and herbaceous vegetation; open spaces with little or no vegetation; water bodies	305.56	77.96
Food security	arable land; vineyards, olive groves, and orchards; pastures	46.05	11.75
Recreation and wellbeing	green urban areas; sports and leisure; forests; shrubs and herbaceous vegetation; open spaces with little or no vegetation; water bodies	267.87	68.34
Land capitalization	green urban areas; sports and leisure; forests; water bodies	54.40	13.88
Cultural identity	green urban areas; sports and leisure	6.50	1.66

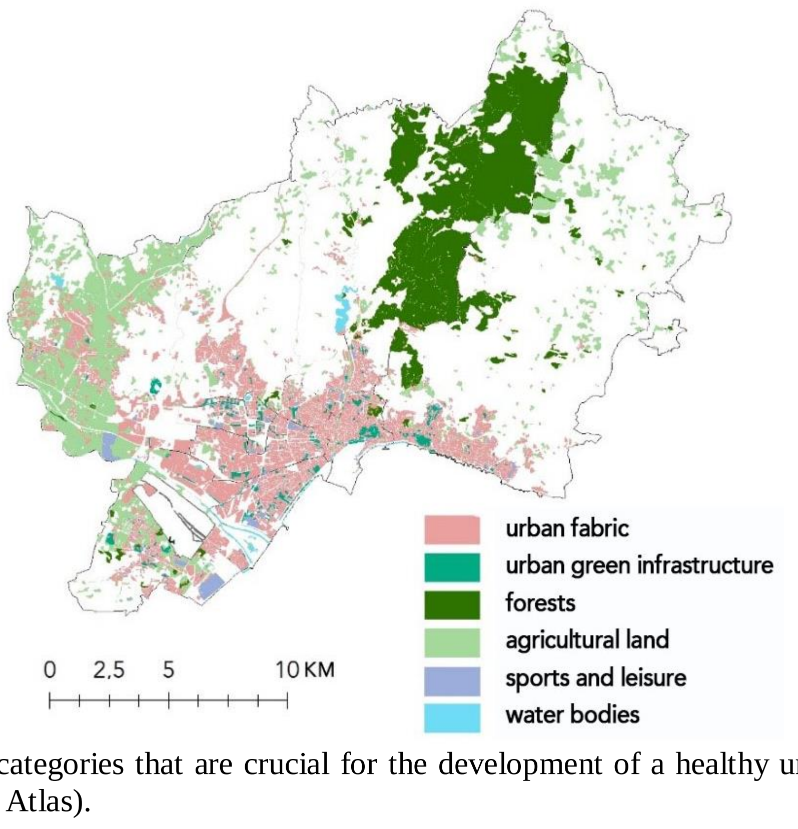

Fig. 5. Land cover categories that are crucial for the development of a healthy urban environment (according to Urban Atlas).

Urban green infrastructure, responsible for the conservation of biodiversity and protection of species, makes up about 67% of the territory of the urban area of Malaga. This is a very high indicator of the greening of the city. However, the fragmentation of ranges suggests that this figure may in fact not adequately illustrate the real situation since it does not take into account the insufficient fulfillment of some ecosystem functions due to the fragmentation of greenery.

About 80% of the city's territory is occupied by green infrastructure that contributes to the climate change mitigation, and about 78% of the territory is favorable to the adaptation to climate change.

Table 4. Land cover categories in Malaga (according to Urban Atlas).

UA code	Category	Area, km^2	Area, %
11100	Continuous urban fabric (with density >80%)	12.31	3.14
11210	Discontinuous dense urban fabric (with density 50-80%)	5.17	1.32
11220	Discontinuous medium and low density urban fabric (density 10-50%)	8.05	2.05
11240	Discontinuous very low density urban fabric (density <10%) and isolated structures	4.55	1.16
12100	Industrial, commercial, public, military, and private units	20.12	5.13
12220	Fast transit and other roads and associated land	17.78	4.54
12300	Port areas	0.48	0.12
12400	Airports	5.55	1.42
13300	Construction sites	1.36	0.35
13400	Land without current use	2.65	0.68
14100	Urban green areas	3.33	0.85
14200	Sports and leisure facilities	3.17	0.81
21000	Arable land	30.60	7.81
22000	Vineyards, orchards, and olive groves	9.64	2.46
23000	Pastures	5.81	1.48
31000	Forests	46.03	11.74
32000	Shrublands and grasslands	211.44	53.95
33000	Open spaces	2.03	0.52
50000	Water bodies	1.86	0.48
	Total	391.94	

Agricultural production, in turn, is very limited being just under 12%. There are few agricultural zones on the territory of the urban area, since, for the most part, agricultural production is moved to the suburbs.

The results of land capitalization evaluation indicate that in Malaga most land is a relatively cheap resource; the most valuable are the lands along the banks of the city’s large watercourses (the Guadalmedina and Guadalhorce rivers), as well as on the Mediterranean coast.

Assessment of connectivity and fragmentation of GI based on MSPA

The result of the Morphological Spatial Pattern Analysis was the division of the city into areas belonging to each of the 10 spatial classes (Fig. 6). In the context of green infrastructure connectivity, cores, islets, and bridges are of greatest interest. The rest of the elements for the most part do not contribute to an increase or decrease in the structural connectivity of the system. The cores correspond to large reserves, which are most interconnected. In Malaga, such cores are, first of all, the Natural Park of Montes de Málaga, which occupies most of the northeastern district of Ciudad Jardin, the Loma del Pino ("Pine Hill") park in the south-west of the Churriana district, the Monte de San Anton park in the Este district, and the forest park of Monte Victoria in the city center (Fig. 7). In total, the cores of green infrastructure occupy about 9% of the city's territory, making up 34.1 km^2 (Fig. 8).

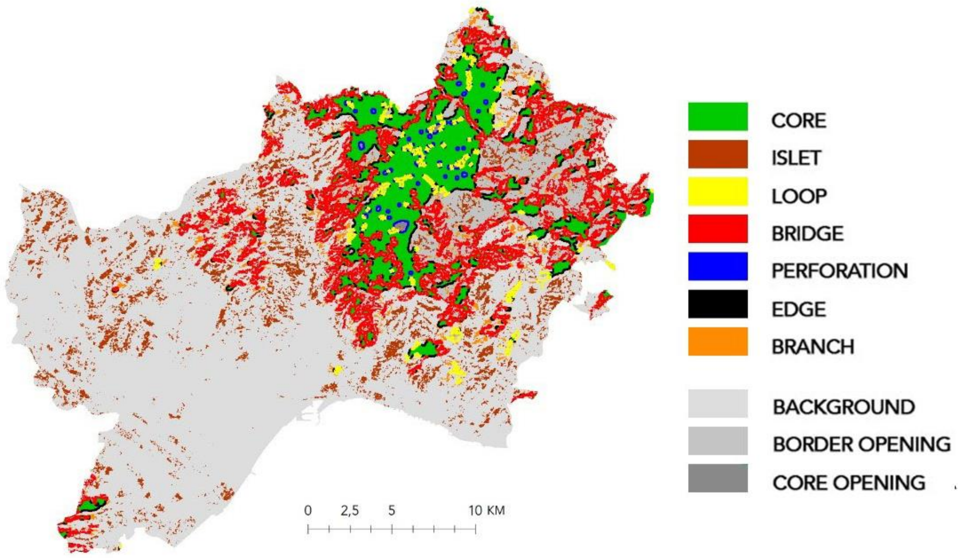

Fig. 6. Results of MSPA analysis.

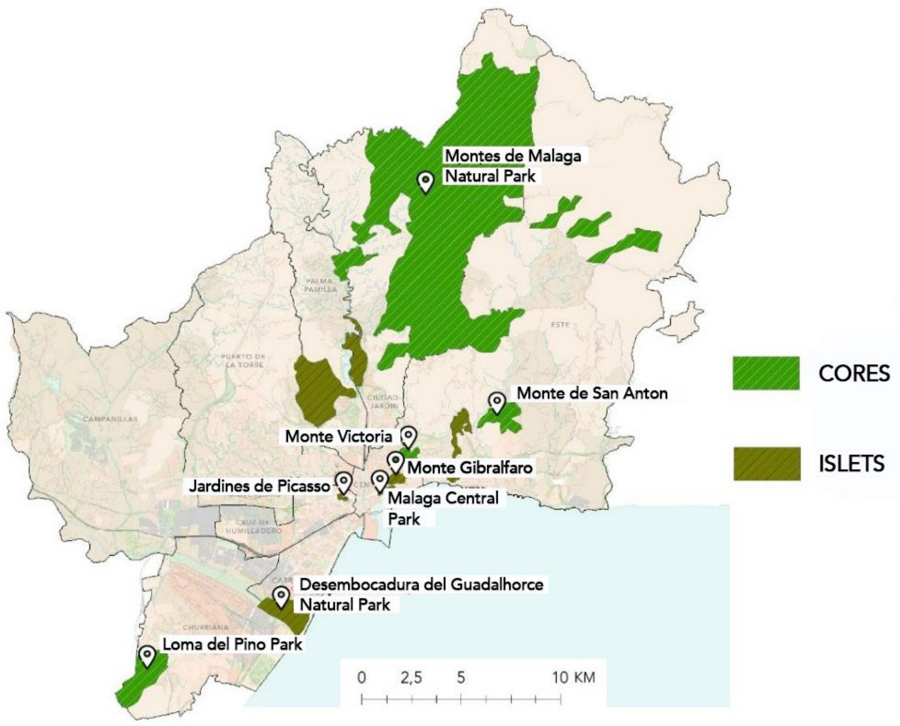

Fig. 7. The largest structural elements of the green infrastructure of Malaga (cores and islets).

Islets are characterized by a greater degree of spatial fragmentation and occupy 27.5 km^2. Large islets of green infrastructure include the Desembocadura del Guadalhorce Natural Park, natural vegetation along the Campanillas River, the park of Monte de Gibralfaro, and most of the Puerto de la Torre, Este, and Campanillas districts. In the city center, the islets include the Jardines de Picasso street park and Malaga Central Park, one of the city's main attractions (Fig. 7). However, despite the proximity of these green spaces to each other, the strong fragmentation of green infrastructure in the central part of the city does not allow us to consider these areas connected.

Bridges are patches of green space that connect non-overlapping cores, totaling nearly 53.7 km^2, which exceeds the area of the cores themselves. In the Este area, the bridges cover the largest area; followed by the districts of Palma-Palmilla and Puerto de la Torre.

The total area of green infrastructure branches that can be interpreted as fragmented green bridges is 7.2 km^2. On the territory of 6.5 km^2, there are zones of the so-called loops that are areas of green infrastructure that provide migration opportunities for species within one core of the system.

For Malaga's urban nucleus, it is advisable to analyze a more detailed level, for which the previously mentioned Edge Width parameter is responsible. When the parameter value is equal to 1 pixel, it is possible to distinguish local classes at another level of the urban system (Fig. 9).

Several distinct cores of green infrastructure have been identified within the core urban development area. First of all, these are the parks of Monte Gibralfaro and Monte Victoria, which are also massive cores at the level of the entire city. There are also smaller cores, such as El Morlaco Forest Park, El Jardín de la Heredad de Nuestra Señora de los Dolores Park, and San Anton Pine Park. Only these parks have a clear structure, consisting of bridges and branches.

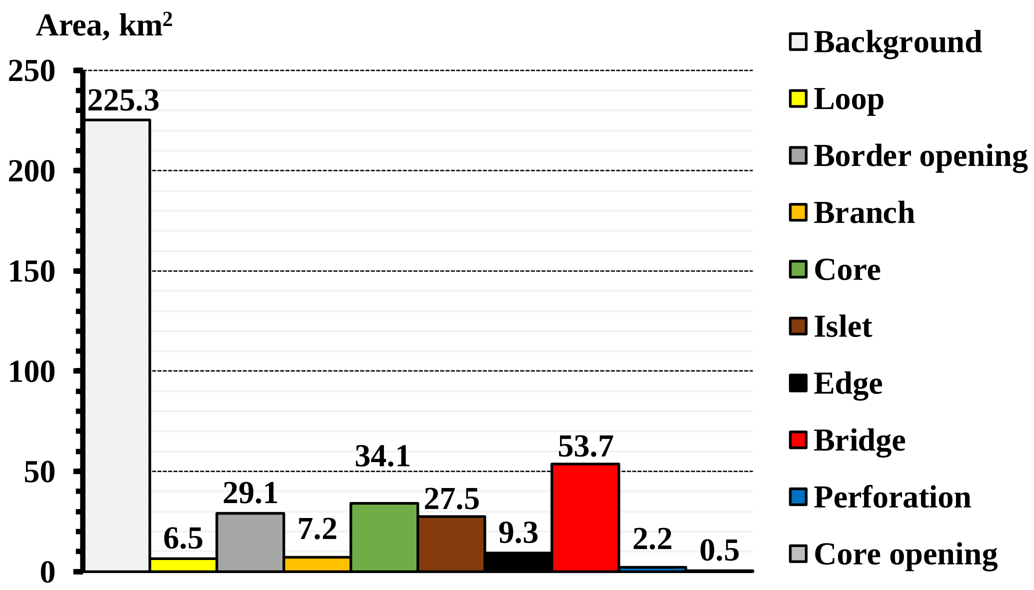

Fig. 8. The total area of each MSPA class.

Almost all major elements of green infrastructure within the urban nucleus are islets. These are city parks and squares, gardens, and recreation areas. Despite the great detail, the main sights of the city, Jardines de Picasso and Malaga Central Park, are also islets that do not have bridges, and have a rather small territory of influence.

The GuidosToolBox software has a range of tools (in addition to the MSPA group), with the help of which it is possible to establish some quantitative indicators of the spatial configuration of the green infrastructure of the city. The Contagion and Entropy tools (from the Fragmentation toolset) help determine the degree of fragmentation in green spaces. The tools have an important difference: while the Entropy fragmentation is based on the simultaneous estimation of the foreground and background (as a whole), the Contagion parameter is based on only the foreground objects (Vogt, 2015). For example, an image with a dominant background coverage and few isolated foreground objects will give high fragmentation values in terms of Contagion. For Entropy, this image, on the contrary, will have low fragmentation values, because the dominant coverage of the area (the background) is only slightly fragmented by the foreground (for example, by islets of a forest against a background of farmland). Thus, the Contagion tool which focuses exclusively on foreground objects is more suitable for analyzing green infrastructure which is carried out separately from the analysis of the entire city system.

Fragmentation is expressed as a percentage scale, where indicators tending to 0% indicate the minimum degree of area fragmentation, while those tending to 100% are characteristic of areas with maximum fragmentation. In the case of Malaga, the cores (Montes de Málaga, as well as a large part of the Este area) are characterized by minimal fragmentation. The degree of fragmentation here does not exceed 15% (Fig. 10). Also, the core in the south-west of the city (the Loma del Pino park) has significant integrity. A remarkable part of the area is characterized by an average degree of fragmentation (within 30-60%); it is the green infrastructure of Puerto de la Torre, Campanillas, and Palma-Palmilla districts. The green infrastructure of the central region of Malaga is also characterized by a moderate degree of fragmentation (less than 50%). The most “torn apart” greenery is located in the Churriana area, where most of the green infrastructure is insular and, therefore, fragmented at 80% or more.

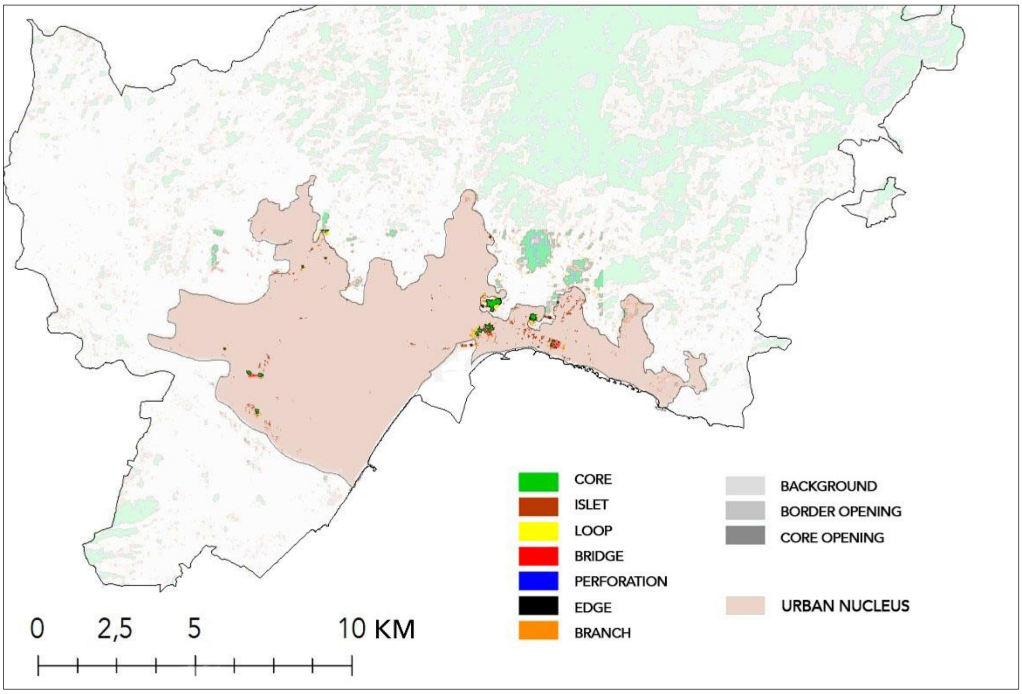

Fig. 9. Results of MSPA analysis at the level of the urban nucleus of Malaga.

The main reason for the high degree of fragmentation of the green infrastructure of the city was relatively recent (over the past two decades) active expansion of residential development along the northwest beam. The accompanying reduction in connectivity between increasingly isolated sections of green infrastructure has become one of the main triggers for growing pressure on the biodiversity of the region.

An equally interesting approach to studying the fragmentation of green infrastructure is the FAD (Foreground Area Density) analysis. FAD analysis is carried out by measuring the foreground pixel density index on five observation scales (using the moving window analysis method) with square adjacent areas of 7, 13, 27, 81, and 243 pixels (Riitters et al., 2012). The result of the analysis is a set of maps with different results for each selected observation scale (Fig. 11). FAD values are color-coded according to the following infrastructure integrity classes: Rare, Patchy, Transitional, Dominant, Interior, Intact.

FAD analysis on different scales of observation is of interest, since often, if not diametrically opposite, then very different results can be obtained. Analysis of the territory of Malaga on a scale of minimal detailing (7 pixels) showed that 29% of green infrastructure is complete and Intact, while 18.2% and 28.8% belong to the classes of Interior and Dominant infrastructure unity, respectively. Fragmented vegetation makes up about 23.8% of the foreground areas (where the Transitional class occupies 13.7%, the Patchy one − 9.4%, and the Rare one − 0.7%).

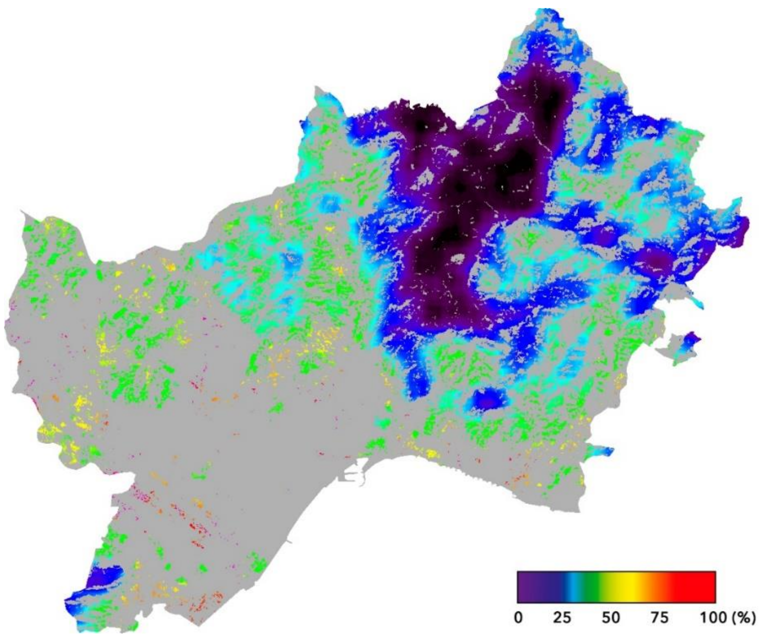

Fig. 10. Fragmentation of green infrastructure (“Contagion” tool).

When studying the territory of Malaga within the most detailed observation scale (243 pixels), there is a complete absence of the Intact class of 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) correspond to the Dominant class and occupy 43.2% of the foreground. The second in terms of coverage area was the Transitional class which occupies 31.7% of the foreground. It is worth noting that among the large islets of green infrastructure, the parks of Monte Victoria, Monte de Gibraltar, and Monte de San Anton belong to this class. The most fragmented areas are found in the districts of Centro, Puerto de la Torre, and Churriana (1.3%); the remaining 23% of the foreground belongs to the transitional class.

Thus, according to the results of the FAD-analysis of the studied region, in the areas with the highest population density and the highest activity, green infrastructure is the most fragmented and chaotic; the core of the Montes de Málaga Natural Park is characterized by the least degree of fragmentation.

The Influence Zones of green infrastructure can be calculated using the eponymous tool of the Distance toolset (Fig. 12). Influence Zones are outer areas that separate foreground objects (in this case, elements of green infrastructure). The boundary of the Influence Zone is determined by applying the morphological operator of determining watersheds to the map of Euclidean distances of the background image (Soille, Vogt, 2008).

Understanding the pattern of Influence Zones helps to identify areas with the highest or lowest degree of access to potentially provided recreational, health, and aesthetic services. For example, residents of these zones have a higher availability of ecosystem services provided by parks and squares located within the city limits. These services include clean air, aesthetic value, the availability of recreation and recreational facilities, and the supporting and regulating functions of the green frame.

As expected, the largest Influence Zone at 151.2 km^2 is possessed by the Montes de Málaga Natural Park which is the main source of ecosystem services in the Este and Ciudad Jardin districts (Fig. 13). The other main elements of Malaga's green infrastructure have much smaller zones of influence. Among the main cores of green infrastructure, in addition to Montes de Málaga, the leader is the Monte de San Anton Park with its Influence Zone exceeding 2.4 km^2; also, a large Influence Zone corresponds to the Loma del Pino park (2.1 km^2).

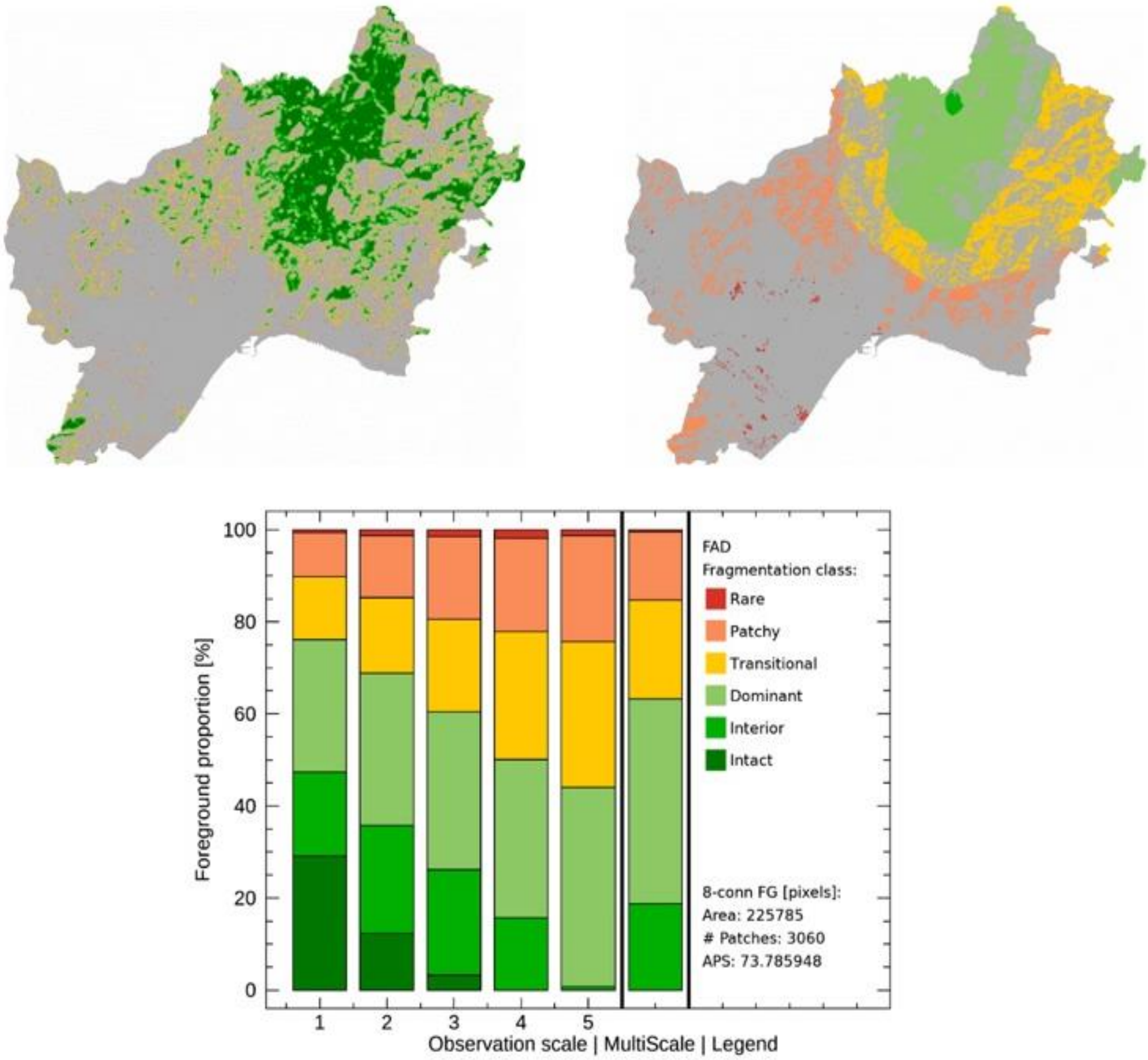

Fig. 11. Results of FAD analysis of green infrastructure using the least (1, left) and most (5, right) detailed observation scales ("Foreground Area Density" tool).

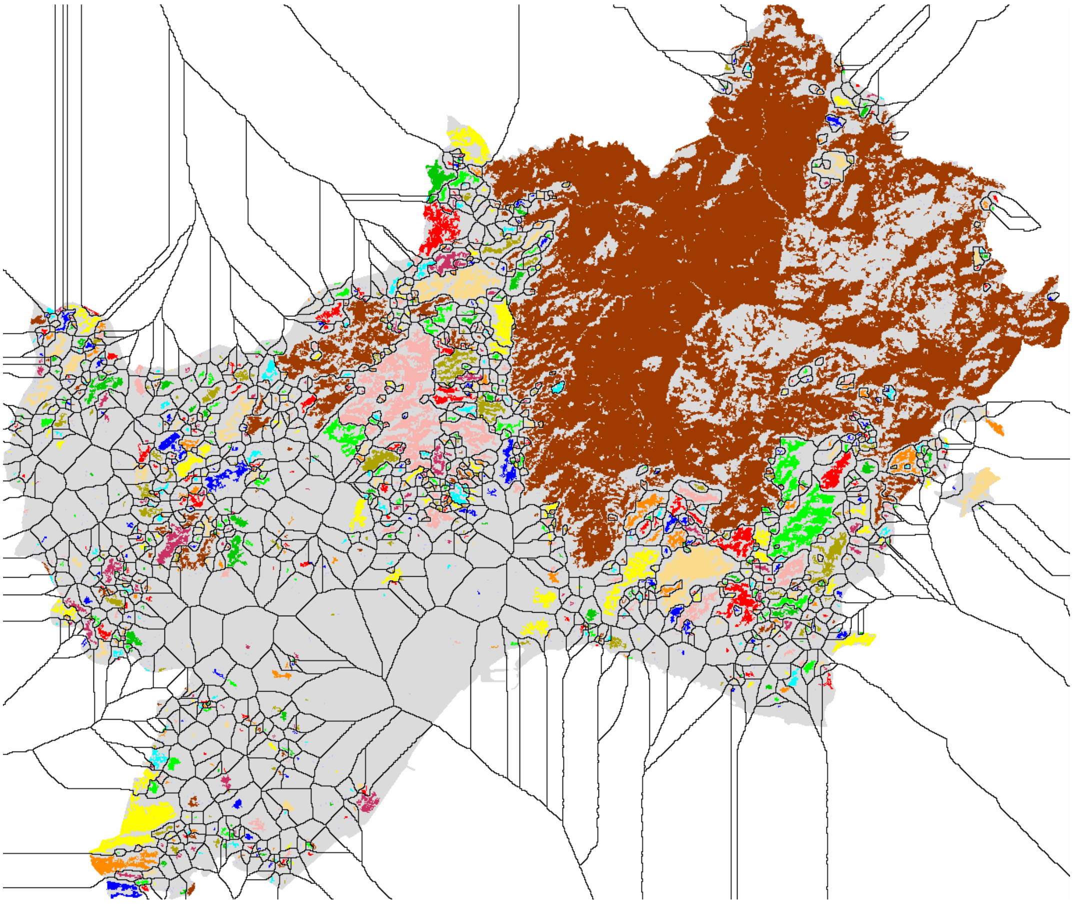

Fig. 12. Influence Zones of green infrastructure (“Influence Zones” tool).

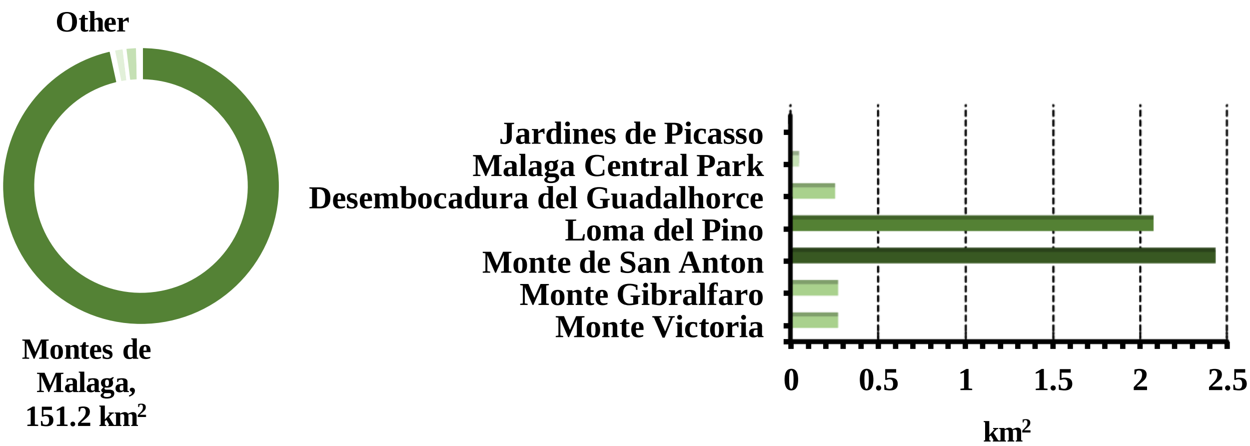

Fig. 13. The total area of the Influence Zones of the main cores and islets of the green infrastructure, km^2.

Among the islets of green infrastructure, the largest Influence Zones correspond to the parks of Monte Victoria and Monte Gibralfaro (0.27 km^2 each) and the Desembocadura del Guadalhorce Natural Park (0.25 km^2). The main attractions of the city center, the Jardines de Picasso and the Central Park of Malaga have zones of influence of 0.01 and 0.05 km^2 respectively.

Thus, the method of Morphological Spatial Pattern Analysis makes it possible to identify the most important indicators of the quality of the urban environment, and the possibilities of using this method are very wide. MSPA analysis can solve a wide range of problems related to the management of urban systems and optimization of the urban environment, as well as provides the opportunity to get a clearer idea of existing environmental problems and ways to solve them.

Like any other method, MSPA has certain limitations, primarily related to the determination of the scale of the input data and the impossibility of differentiating green infrastructure by morphometric indicators. Taking into account the three-dimensionality of real space, the impossibility of comparing the pattern of green spaces and the grid of elementary watersheds, the parameters of the height and slope of the terrain, and other spatial characteristics indicates the need for further research at the local level. The results of assessing the contagion and fragmentation parameters may also depend not only on the level at which the analysis is carried out but also on the ecological processes analyzed within the landscape matrix.

In the case of Malaga, the main catalyst for urbanization was the increase in tourist flows in the 1960s, which in turn was justified by the favorable physical and geographical conditions of the Costa del Sol region. Unfortunately, Malaga is still struggling with the consequences of the era of irrational administration which led to the desolation and marginalization of the historical center at the end of the 20th century and its excessive commercialization in the 21st century at a new stage of its functioning in a renewed form.

Conclusion

For a correct comprehensive assessment of the urban environment it is necessary to use a number of different parameters. The Agenda Urbana Málaga project, whose regulatory and methodological documents highlight the concept of green infrastructure development for the period from 2020 to 2050, takes into account such indicators as the area of green space per capita, the number of green spaces per capita, and the availability of green infrastructure for the population. Although all these indicators are high and close to optimal on the average for the city, a more detailed analysis at the regional level indicates many gaps in the ecological framework. Often, due to certain historical and typological characteristics of city districts, in some areas there is an insufficient number of green zones to ensure the maximum comfort of the urban environment. Also, the project whose development is largely based on the documentation of the General Plan of Malaga (Plan General de ..., 2011) does not take into account the importance of the functional cohesion of the green infrastructure network. It is necessary not only to have centers (cores) of green infrastructure but also connecting elements of the frame which would ensure the continuity of the natural space and would perform transit functions.

The method of Spatial Morphological Pattern Analysis, innovative for domestic environmental studies, applied to the entire city and the urban nucleus separately, gave unambiguous results. Around 5 to 6 large green infrastructure cores have been identified within the Malaga Protected Areas network. Only these few cores are interconnected by bridges and have loops that favor migrations of species. Despite the relatively high coefficients of the provision of the population with green infrastructure and vast areas of greenery, most of the green spaces have an islet (or fragmented) nature to them and a low parameter of connectivity of the elements of green infrastructure, which does not contribute to the creation of a unified network and ecological framework as such.

This work is an example of a study proposing new methods for identifying priority areas of the green infrastructure network, both important for the conservation of biodiversity and the development of recreational and aesthetic qualities of green spaces. The application of the MSPA analysis method can be helpful when it is necessary to use the available data more effectively and make informed decisions regarding the trajectories of sustainable development.

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