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RESEARCH ARTICLE

Landscape spatial patterns in Mexico City and New York City: contrasting territories for biodiversity planning

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Abstract
Context Large cities contain different sizes and distributions of green spaces in a sea of buildings and roads. This urban landscape establishes habitats for different species that migrant through or persist in cities.
Objectives To describe and analyze how green spaces patterns differ in large cities by using new mapping methods. This tool helps urban planning for land use decisions.
Methods Using Patch Analyst Metrics, we propose a new method to analyze the current spatial arrangement of green spaces in Mexico City and New York City, long-established urban areas, as case studies.
Results The two cities differ in the number, size, and spatial distribution of green spaces. Mexico City has high numbers of large green spaces for native species habitat, but most of them are in a cluster in the south. In New York City, large spaces are distributed scattered throughout the whole territory, but New York City has much small areas than Mexico City. This spatial analysis shows areas for connectivity among existing green spaces that can improve the dispersal of many taxa of plants and animals. However, ecological planning must vary between the cities; no single generalization is appropriate.
Conclusions Much data are available on the potential dispersal of species through cities, but a easily applied framework for understanding the existing habitat distribution is needed for future decisions. The results suggest mapping mechanisms can help to increase plant and animal movement patterns. However, these older cities have idiosyncratic starting points that must be the basis of future improvements.

Keywords Landscape pattern · Ecological planning · Urban biodiversity · Spatial patterns

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Introduction

The presence of green spaces in large cities provides many ecosystem services that improve the quality of

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urban life and the health of the human population (TEEB 2010; Secretariat of the Convention on Biological Diversity 2012; Elmqvist et al. 2015). Urban biodiversity can be high, with many species present, even in large, historical cities (Aronson et al. 2017; Spotswood et al. 2021).

The distribution of green spaces directly impacts the ecological community of organisms (Gilpin and Hanski 1991). Species move at different rates and have different generation times. Urban population dynamics differ from more rural areas (e.g., Piana et al. 2019). For example, detailed urban genetic studies (e.g., Johnson and Munshi-South 2017) show population isolation among even closely placed urban parks. Consequently, biodiversity in a new urban green space may not immediately replicate communities in other areas but will develop as surrounding species immigrate. This may happen slowly or not at all, as species have different dispersal rates and distances (Chesson 2000; Cadotte 2006).

A simple mapping method is needed that can reasonably address many taxonomic groups, all of which play roles in urban ecological function. Consequently, we address general habitat arrangement questions that can be of use to urban planners, not focus on the niche requirements of any one group. Disturbance rates and the presence of barriers in the landscape matrix modify the movement pattern, a classic metapopulation process (Gilpin and Hanski 1991). Consequently, cities with more green patches may have closer patches that can increase dispersal, yielding more favorable habitat types stochastically, which then can harbor more species. The movement patterns are broad for some taxa, and the green spaces are functionally close, not distant habitat islands.

In urban areas, species dispersal must occur through a built landscape which is dense, tall and contains stresses not experienced in natural environments. The concentration of urban infrastructure acts as barriers that challenge species' ability to move to new favorable areas, though there is much deviation in the capacity of species to move through urban centers (Angold et al. 2006; Nielsen et al. 2014). Additionally, there must be a favorable time sequence for movement to occur; plant habitat must be established before many animals can successfully colonize.

Connectivity among green spaces affects the persistence of urban biodiversity (Bennett 2003). Connectivity usually has a positive (increase dispersal potential) impact on biodiversity, although adverse effects (movement of pests and enemies) can depress this advantage (Collinge 2009). Together, these spatial factors make the ability of species to navigate and colonize in cities quite different from in natural and rural areas.

Urban habitat spaces are often small and separated by this hardscape/infrastructure, which impedes the movement of many species and their propagules. The small area of many urban green spaces results in small population sizes, leading to local extirpation by biotic or stochastic pressures (Collinge 2009). For example, these smaller areas have a relatively large edge/center ratio, affecting their quality, favoring species that can persist in those changed edge spatial conditions.

These related problems influencing biodiversity in urban green spaces have led to an interest in generating corridors or additional "stepping stone" green parcels to increase conditions that favor higher biodiversity (Bennett 2003; Collinge 2009). These types of connections may be more easily designed in new cities, where urban planning that emphasizes biodiversity can be included from the start of the process. In contrast, old cities are constrained to support biodiversity by the pattern of urban infrastructure around existing, often isolated, green spaces.

These already built cities have cultural, economic, and historical drivers of spatial patterns that are often blind to biodiversity drivers (Müller et al. 2010). These determinants of urban structure constrain biodiversity (Clifton et al. 2008; Forman 2014). Ecological improvements, however, can occur if urban planning is better married to ecological principles and an understanding of existing conditions (Harris 1984; Hobbs and Saunders 1993; Zipperer et al. 2000; Parris et al. 2018).

Many different landscape metrics have been used to categorize landscape structures that can influence biodiversity (Haines-Young and Chopping 1996; Hargis et al. 1998; Walz 2011; Reis et al. 2016). It is well understood that different landscape patterns influence the movement and persistence of different taxa in idiosyncratic ways (Uuemaa et al. 2009) (Table 1). For example, plant community structure varies with habitat patch shape, size, and distance from other patches (Moser et al. 2002; Kumar et al. 2006). Other species can have different movement patterns and niche requirements (Uuemaa et al. 2009).

Table 1 Number of and area occupied by urban green spaces in each city

Size	UGS number	%	Hectares	%
MXC				
0.5–5 ha	2132	89	2900	4
5.1–25 ha	210	9	2026	3
25.1–100 ha	32	1	1566	2
Larger than 100 ha	17	1	65,685	91
Total	2391	100	72,177	100
NYC				
0.5–5 ha	472	76	641	7
5.1–25 ha	88	14	1044	11
25.1–100 ha	36	6	1914	20
Larger than 100 ha	22	4	5909	62
Total	618	100	9508	100

UGS Urban green space

Many older cities have numerous green spaces, but this varies enormously among cities with different developmental histories (Fuller and Gaston 2009). Similarly, many new urban greening projects have been designed over the past decades, but often without attention to the spatial interplay among new and old green spaces (Kemp 2006). The mapping of biotic communities in cities can be based on at least four spatial characteristics:

A. Number of green spaces (Fig. 1a). Species diversity usually increases as the number and heterogeneity of areas increase, creating a mosaic of potential urban biota spaces (Walz 2011). More areas buffer against stochastic extirpation in any one area.

B. Area of green spaces (Fig. 1b). Larger areas may increase survivorship as each population usually can be more numerous, also avoiding stochastic local extinctions. Larger sizes also increase the probability of the parcels containing diverse soil, nutrient, water, and refuge conditions that can safely harbor species during unfavorable and changing climatic conditions (e.g., La Sorte et al. 2020; Turrani and Knop 2015).

C. Distribution of green spaces (Fig. 1c). Movement capacities vary widely among taxa, and increased distance can filter biodiversity. Urban parcels, even if geographically close, can be unavailable to species that have limited ability to migrate. For example, a framework for animal movement modes by the landscape architects Studio-MLA (2017) suggests a typology where different species can persist if there are contiguous surface paths (corridors), bypasses that avoid unfavorable surface zones (bridges), or are separated but close enough for regular aerial dispersal to succeed (patches). Flying species (and the seeds they carry) may move among patches even if inappropriate surface conditions separate them (e.g., La Sorte et al. 2020). Other species walk, crawl, or are carried by surface-bound transporters (fur, clothing, vehicles), but must remain earth-bound. Another way to categorize these movement styles is as wide travelers, pedestrians, homebodies (do not move from natal areas), and jumpers (saltators). Built conditions between green spaces may be so inhospitable that even common species may not move to nearby areas. This has been demonstrated by the significant genetic differences among mouse populations in New York City green spaces (Munshi-South and Kharchenko 2010; Munshi-South and Nagy 2014). Precise mapping of green space locations within old cities can improve our understanding of possible biotic improvements with new landscape plans.

D. Quality of green spaces (Fig. 1d). The ability to support species' niches must be present. "Quality" is a metric that varies with each space's ability to provide the unique niche axes of each species. Urban areas so often have past land uses, which modify conditions (Forman 2014); even adjacent areas may have quite different soil profiles, for example (Craul 1999; Scharenbroch et al. 2005). The space now may be inadequate, even for regionally common species. Restoration science may not be able to remediate the area adequately to return to the original conditions (Handel 2013). Understanding quality requires fine-scaled site work of each parcel and is beyond the scope of this study.

The mapping of urban green space for any biota must accompany landscape metrical analyses. Here, we explore methods to map and analyze the spatial conditions of urban green spaces using data from two very large cities, Mexico City and New York City, whose current forms and infrastructure began 400–500 years ago. This type of map is necessary before urban planners can decide on new green space initiatives. This research aims to contrast the distribution of urban green spaces in the two old cities, by using a mapping method that applies landscape metrics. There are many established landscape metrics of use to urban ecologists (e.g., Haines-Young and

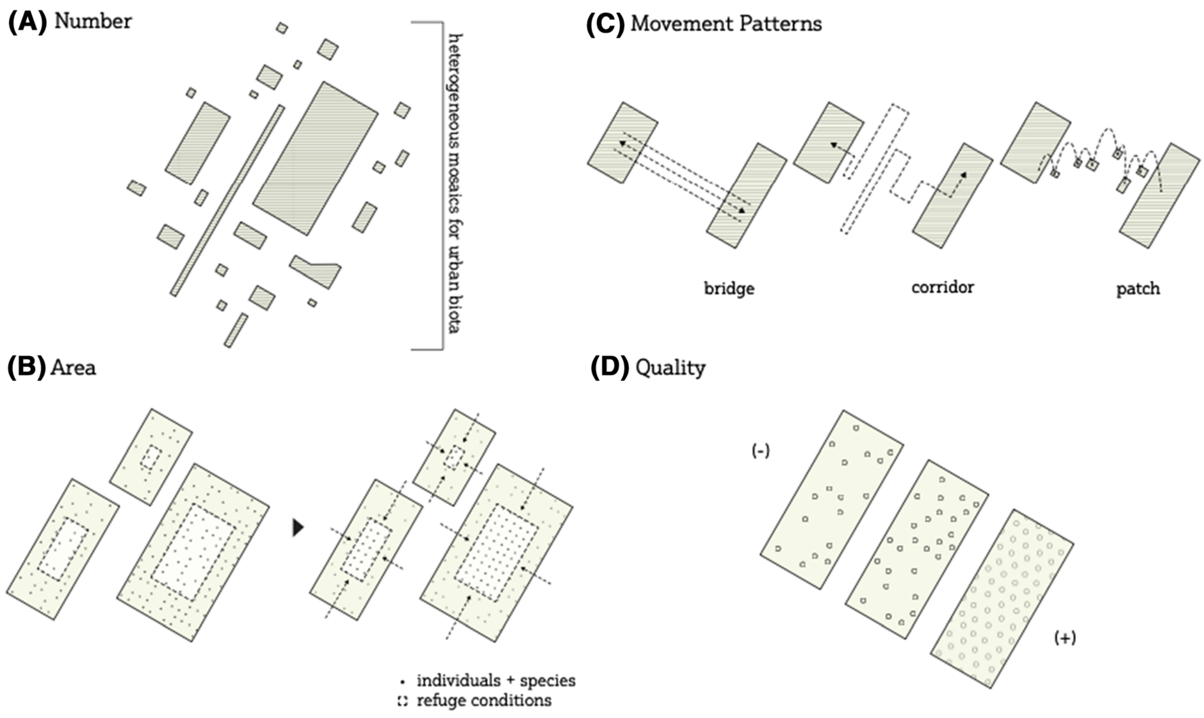

Fig. 1 Spatial characteristics of green areas that affect biotic communities in cities. **a** Number of green spaces within an urban area. **b** Area occupied by green spaces, which may increase the habitat for species. **c** Distribution of green spaces within the landscape, which can modify the movement patterns, the possibility of dispersal of species by green bridges, corridors or patches. **d** Quality within a green space, which can increase the number of habitats for species

Chopping 1996; Walz 2011). We develop here a method that could allow planners and park regulators to more simply understand green space availability and relationships, based on existing municipal maps. This may improve the bridging of information between planners and ecologists. The aim is to link the traditional graphics used by urban designers and planners to the concerns of urban ecologists, before detailed statistical metrics can be focused into improving the function in any one sector of a city. Also, we wish to quantify how different two similarly scaled cities can be, based on historical differences in their development patterns.

This approach will help understand the pattern of existing green spaces and what actions can be made to secure existing biodiversity and improve biodiversity in both cities. This is important when the climate is rapidly changing, and current species diversity and abundance are expected to change significantly (Grimm et al. 2008). New land management actions (addition of green spaces, or new management of existing green spaces to increase the area and quality characteristics in Fig. 1, for example) may be needed to maintain or improve ecological functions.

Methods

To generate this method, we first need to frame the work in the two cities with mapping protocols which were different because the data sources were created at different times and with different information source method:

Mexico City (MXC)

The distribution of the green spaces for Mexico City (Fig. 2) was based on Landsat 8 satellite images of May 18, 2018, in which green spaces (not including street trees) were identified from the Normalized Vegetation Index analysis (NDVI). Through this index, an area's photosynthetic activity is reported, the "greenness" of the plants. In general, this method assumes that photosynthetically active vegetation

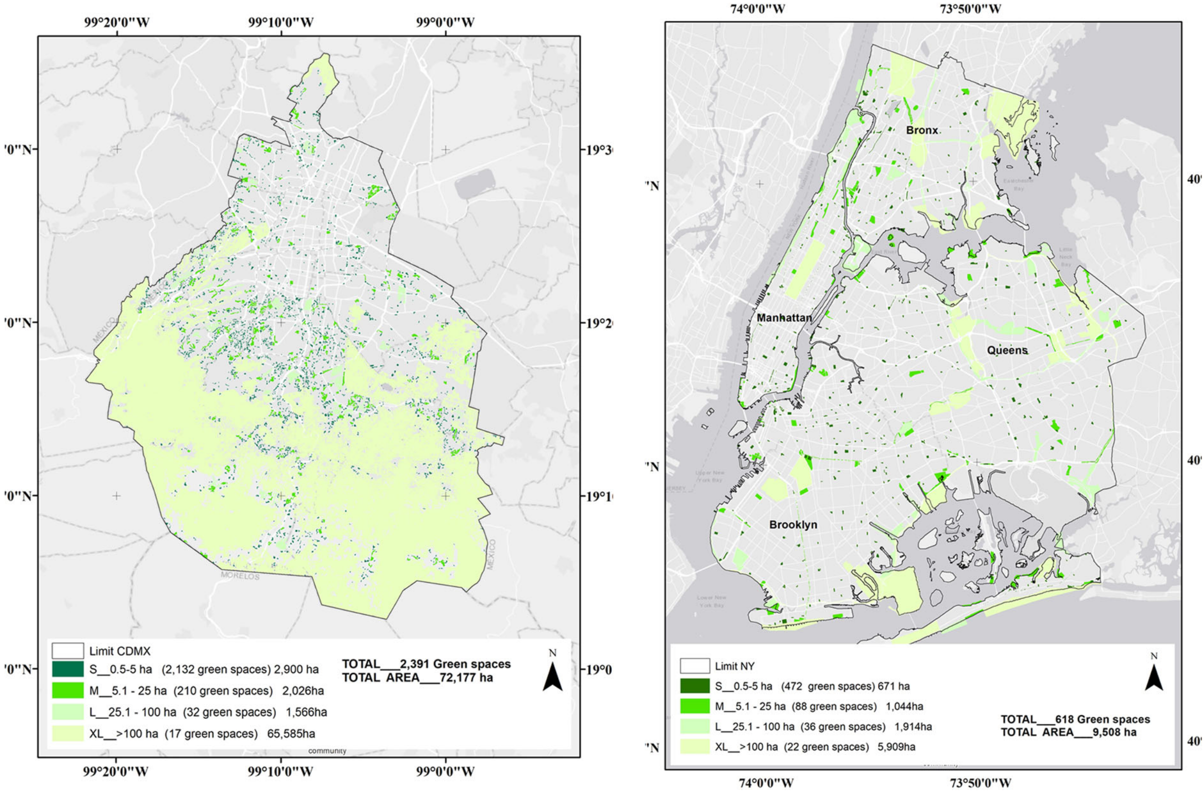

Fig. 2 Mexico City and New York City green spaces maps

absorbs most of the red light and reflects much of the near-infrared light (Bannari et al. 1995). Surfaces without vegetation have a much more uniform reflectance across the entire spectrum of light. The NDVI is obtained by dividing the difference between the red and near-infrared spectra (Jones and Vaughan 2010). This study used the administrative borders of the city that provide the official name of Mexico City.

City of New York (NYC)

The green spaces' base data were found on ArcGIS Online under NYC_Parks_Properties_2016 and Green Space Paton, Green spaces in NYC [Feature Service by cp2983_columbia, 6-17-2017] (Paton 2017) (Fig. 2).

New York City is 63,188 hectares large (without Staten Island), and Mexico City is 149,340 hectares. Green areas are 48% of Mexico City and 15% of New York City's area. Mexico City has an extensive green area in the southern sector of the city. This is politically part of MXC and is governed and managed by a natural protected areas agency; this area must be included in this mapping exploration.

To evaluate this new method, spatial statistics are used in urban planning and were generated for different purposes such as urban characterization and planning, mainly in growing cities such as those presented in this analysis (Reis et al. 2016). There are various spatial metrics for urban analysts. Those used in this study have shown a good fit in the analysis of urban growth and landscape ecology, the spatial analysis of landscape parcels (in this study, the green areas within each hexagon), and the modeling of attributes associated with these.

The method presented requires of the Patch Analyst Extension in ArcGIS version 10.2 for landscape analysis. We are using hexagons of 500 ha as the "patches" of the ArcGis Program. Mexico City has 352 hexagons and NY 187. In this study, we defined "patches" as the individual green spaces within hexagons. We tested different sizes of hexagons and concluded that the 500 ha could provide the most useful information at this city scale. When we tested larger hexagons, a large proportion of them fell partially outside the cities' boundaries, which does not help for proper analysis. The size included many variables that together did not give useful information. On the contrary, smaller patches were primarily empty of green patches, without information to underlie our analyses.

Patch Analyst was developed under the Spatial Ecology Program (Centre for Northern Forest Ecosystem Research) (Rempel et al. 2012). Variables generated in the patch were related to the spatial characteristics listed in the introduction (here we use the official names of the Patch Analyst Method): (1) Number of Patches (NP) are the total number of patches per hexagon; (2) Mean Patch Size (MPS) is the average patch size inside where high MPS patches are clustered to form large patches, and low MPS is fragmented; (3) Mean Nearest Neighbor (MNN) is the shortest distance to the fragment of the same nearest class in meters, higher values of MNN = larger dispersion; (4) Total Green Area (TGA) is a measure of the amount of green area in each hexagon (Subirós et al. 2006). These hexagon maps give spatial guidance on designing corridors for biodiversity based on ecological landscape principles. Descriptive statistics were applied to evaluate the abundance patterns of green spaces based on indexes per hexagon.

In both cities, spaces smaller than 0.5 hectares were identified and eliminated for this level of mapping. This scale of small spaces is poorly represented on city maps as they are often not owned by public agencies, are ephemeral as land-use conditions may quickly change, and often fall "under the radar" of city planners as their areal cover and development potential can be modest. Including such very small areas potentially introduces a large source of imprecision to this type of analysis. We caution that urban ecologists have shown that small areas can harbor populations of various taxa from invertebrates and urban birds to ruderal plants, for example. (Even in New York City, a localized sample of fifty small sidewalk plots yielded 121 plant species (Stalter and Rachlin 2018). However, a 0.5 ha area is below a minimum size for many other species' survival capacities and home range (Rudd et al. 2002). Biodiversity drops sharply with small area for well-studied taxa (Turrini and Knop 2015; La Sorte et al. 2020). With the data available, areas less than 0.5 ha could increase sampling error for some of the variables, since the borders are not clear. Finally, the known < 0.5 ha locations are not a large proportion in number and area of the total green spaces. For example, small areas are 16% of the total number of NYC green spaces and much less of the total area. Smaller spaces have ecological value but usually are a lower priority for land-use decisions by city planners (Handel 2012).

This study explores mapping approaches that can be most useful for many taxa, particularly those of interest to the general public, necessary to secure public support for biodiversity management. For that reason, the study includes green spaces consisting of the Brooklyn Green-wood Cemetery, Floyd Bennett Field, and between Hendrix and Betts Creeks to the analysis by tracing and editing. Although these are not city-managed parks, they have extensive vegetation, including woodlands consistent with the mapped parks. The natural protected area in the south of Mexico City also was included as a large bulk of green space. Then by exporting the Attribute Table of each shapefile, the universe of green spaces and their respective areas used for this study were obtained.

Each variable was divided into five categories, which helped analyze current frequency patterns of green space size and the city's overall distribution. The categories helped to visualize the characteristics of the green spaces within each city. We emphasized differentiating small values of the variables by splitting more categories than in bigger values. The only variable classified equally among patch values was the Number of Patches (NP. The Mean Patch Size (MPS) variables were sorted into five categories: None (N). Small (S) = 0.5–5 ha; Medium (M) = 5.1–25 ha; Large (L) = 25.1–100 ha; Extra Large (XL) = larger than 100 ha. These categories fit with dispersion models presented in Rudd et al. (2002).

For the Mean Nearest Neighbor (MNN), variable classification provides more categories in smaller distances than in larger distances, because smaller distances between green spaces may change more in different species' dispersal capacities than larger distances. The first category was 0–50 m, the second 51–100 m, the third, 101–200 m, fourth 201–400 m, and the fifth > 400 m.

Finally, for the Total Green Area (TGA) variable, we used a percentage of green space covering an individual hexagon area. The first three categories embrace up to 20% of the hexagon covered by green space, and the largest category covers more than 50% of a hexagon.

Results

By using this mapping method, an alternative method to contrast urban green space patterns in both cities has been developed. The two cities have contrasting patterns of green space that have evolved over the centuries. In both cities, the existing green spaces are surrounded by the urban matrix, roads, residential districts, and other infrastructure and are constrained from growing by urban needs and history.

In MXC (Fig. 2), substantial green spaces are in the southern section of the city. This is an area of mountainous topography that had small settlements during the pre-Colombian era. During the colonial period, settlement continued to be focused on the northern half, the lowlands. Consequently, much of the land in the south is a continuous forest and grassland mosaic occupying more than 90% of the green space areas. However, in the past 70 years, new settlements have arisen throughout this southern sector (Graizbord and González Granillo 2019). Most of the 2132 small-scale (0.5–5 ha) green areas are present in the northern half, surrounded by the urban matrix. Even though there are thousands of small areas, these represent only 4% of the city's green space area (Table 1).

In NYC (Fig. 2), there are 22 extra-large (> 100 ha) green spaces scattered over the landscape, not concentrated in one area; these represent 62% of the total green area. The majority (472) of individual green spaces are small in NYC, but they represent 7% of the total area (Table 1). The NYC extra-large green areas represent planning decisions based on geology (the land on the terminal moraine and the glacial outwash plain was low quality for agriculture and was consequently used for parks such as Prospect, Greenwood, Forest, and Marine) and by political and social actions (e.g., Central and Van Cortland Parks) (Schuberth 1968; Kieran 1982). Political planning decisions reserved the smaller parks for local neighborhoods as the city grew from its original location in the southern tip of Manhattan.

This mapping method not only helps visually to analyze the distribution but also is able to provide new numerical information. The analyses based on our 500 ha hexagon data sets catalog each city's green space spatial characteristics help evaluate each city's capacities to hold habitat for native species. Figures of each variable helped to compare green spaces presence, number, and distance across both cities' areas (Fig. 3). The number (NP) of green spaces appears to have a log-normal distribution. The number of smaller green spaces per hexagon is more common than large ones in both cities. On the contrary, the mean patch size (MPS) distribution contrast in the cities. NYC has many hexagons with small areas and fewer hexagons with larger areas, but in MXC, the number of hexagons with different-sized green spaces is almost constant.

Consequently, these findings affect the distance between green space neighbors. In NYC, the number of hexagons with different distances remains almost constant (MNN), and in MXC, most are concentrated at distances lower than 50 m. This is expected since large areas covered by green space usually have a small distance between them. The total green area (TGA) present within hexagons also shows a difference between cities. Few hexagons are covered predominantly by green areas in NYC, but in MXC, the number of hexagons covered predominantly by green areas is large (Fig. 3). In NYC, there are almost no hexagons with green space larger than 100 ha, but in MXC, there are several hexagons with green space of this size. In NYC, most hexagons have less than 5% covered by green space and very few with greater green space coverage.

These spatial patterns suggest that NYC has an urban area distribution with a low area for green spaces. At the same time, MXC is a green city in which biodiversity has many habitat parcels throughout most of the city's area. However, the spatial distribution of the green spaces in each of the cities reveals another story. In MXC, most of the green spaces are concentrated in the south part of the city within protected areas (Fig. 4). However, the number of patches per hexagon in MXC shows the predominance of small spaces in the southern part of the dense urban area, in the middle of the city map. In the northeast section, very few places were reserved for green spaces during urban planning decisions. The frequently encountered green spaces arrayed over short distances are within the mountainous and protected district at the bottom of the figure. The bottom of Fig. 4 shows the impact of recent urbanization, where non-green areas have pierced the once continuous green space hexagons.

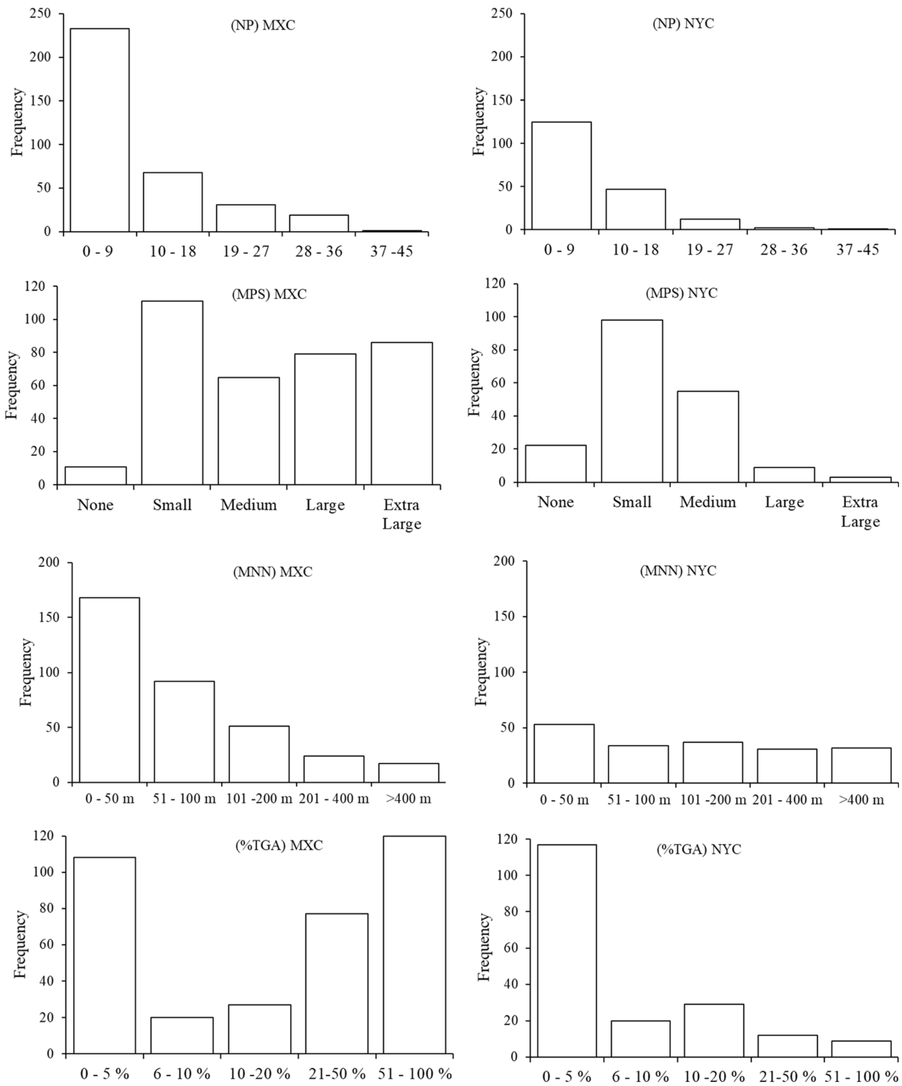

Fig. 3 Frequency analysis considering categories of each variable. *NP* Number of green spaces within each hexagon; *MPS* Mean patch (green space) size of each hexagon; *MNN* mean nearest neighbor between green spaces; and *%TGA* Percentage of total green area of each hexagon; *MXC* Mexico City and *NYC* New York City

In contrast, many parts of the NYC landscape have few green spaces per hexagon (Fig. 4). This results from large parks dominating some hexagons (such as Van Cortlandt in the Bronx and Marine and Prospect Parks in Brooklyn) and other areas being devoid of green space planning during the urbanization of the early twentieth century. As illustrated in Fig. 2, the southern belt of Brooklyn and Queens are park-poor. Many small green spaces are concentrated in upper Manhattan and small sections of the Bronx and central Brooklyn.

Analysis of the mean patch size per hexagon (Fig. 5) confirms that for MXC, the southern district has predominantly green space within most of the hexagonal units. However, the northern urbanized section almost completely lacks hexagons with large green spaces. The many green units here are relatively small, constraining their potential ecological community structure and ecosystem services. In NYC, hexagonal units with large mean green space sizes (Fig. 5) are more regularly distributed across the landscape. Additionally, the pattern of larger spaces

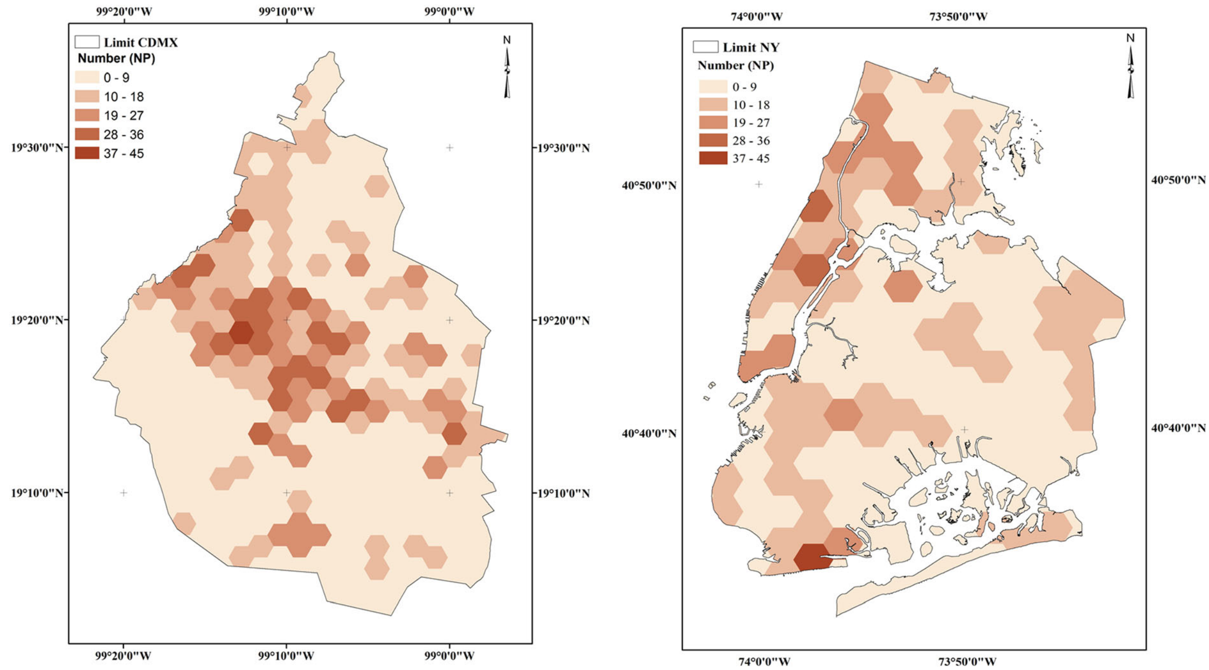

Fig. 4 Number of green spaces per hexagon (NP) in Mexico City and New York City

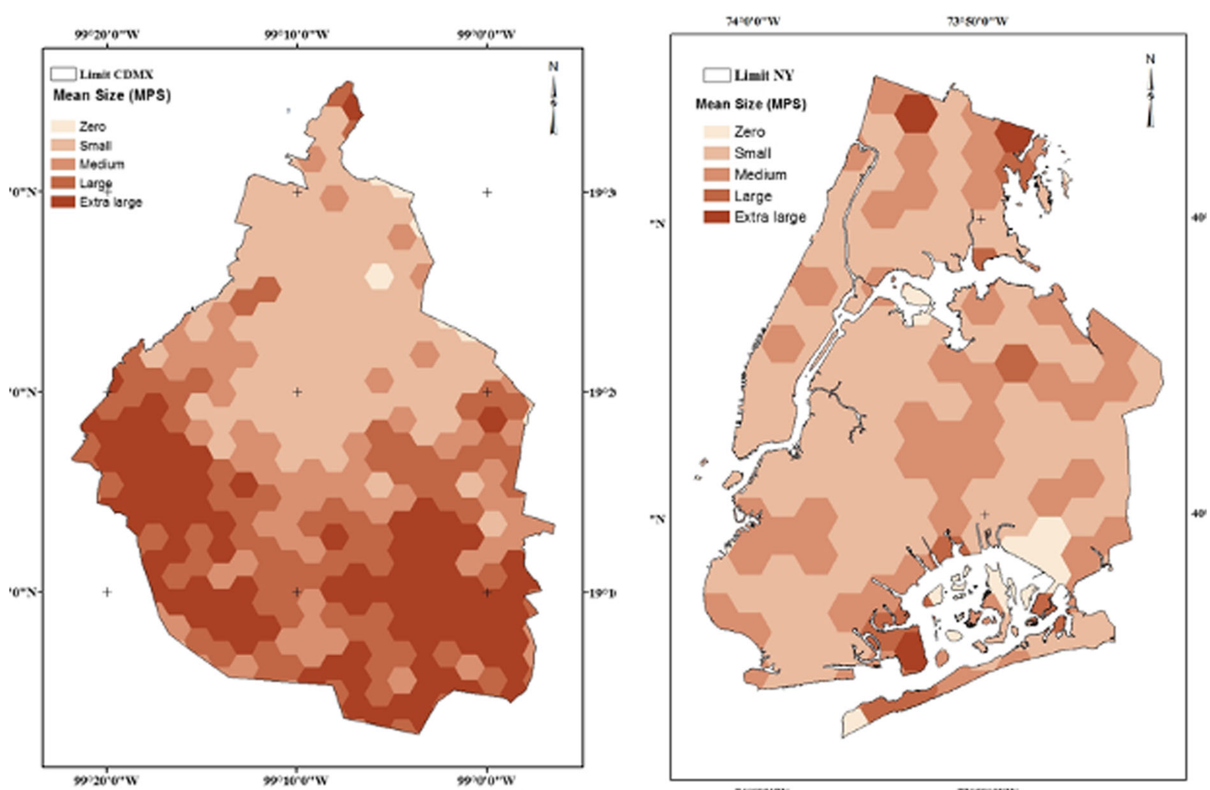

Fig. 5 Mean green space size on each hexagon (MPS) in Mexico City and New York City

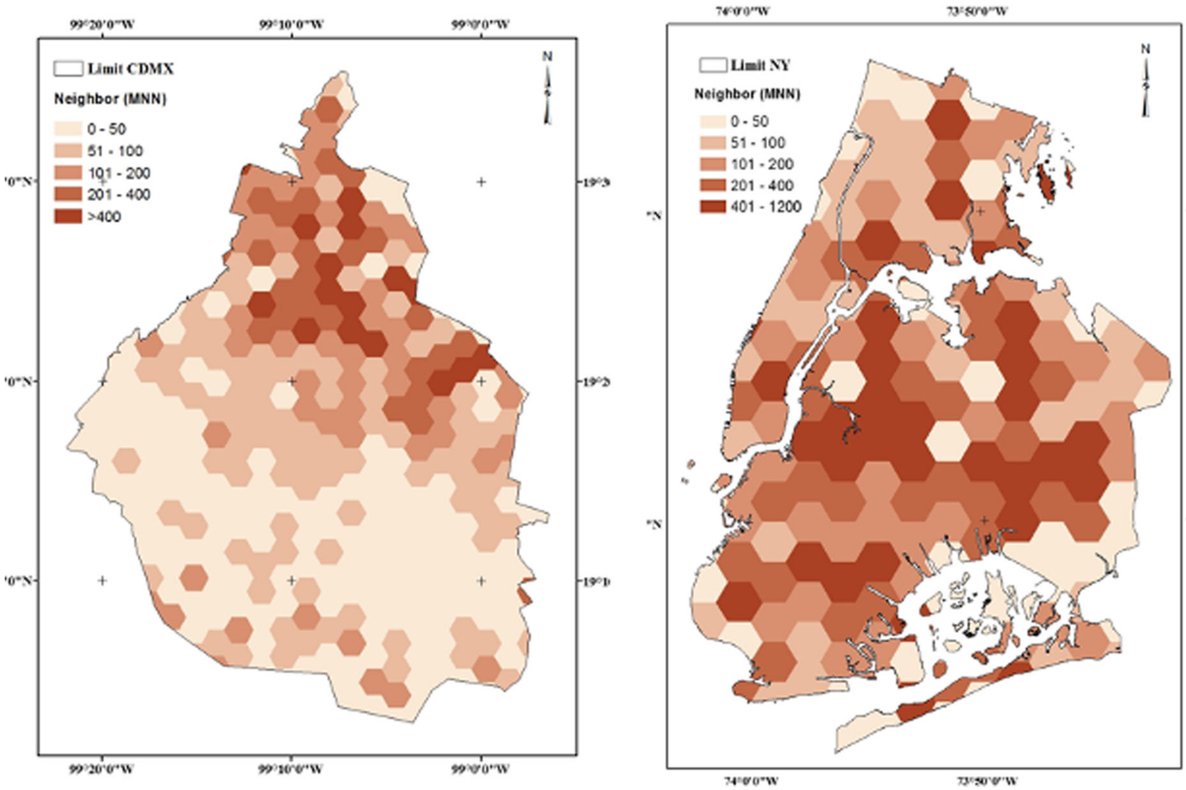

Fig. 6 Mean nearest green space neighbor (MNN) on each hexagon in Mexico City and New York City

forms almost continuous bands across large sections of each borough.

The nearest neighbor between any two green spaces helps to understand the potential for organisms' movement between areas in a city's layout. In MXC (Fig. 6), most green spaces are close, < 200 m, from the next one across the entire landscape. This results from many small green spaces in the northern section and the vast contiguous green space that predominates in the city's southern part. In contrast, in NYC (Fig. 6), the lack of green spaces across Brooklyn and Queens in particular (Fig. 2) yields a pattern of relatively large distances between adjacent green spaces. This would correlate with a more complicated movement of many organisms between adjacent green spaces. Also, there is a band of more widely spaced green areas across the east–west center of the Brooklyn-Queens geography (Fig. 6).

The total area covered by green spaces per hexagon also shows a contrasting pattern between the cities (Fig. 7). In Mexico City, there is a distinct green area reduction from the south to the northeast. However, in New York City, numerous green areas are in The Bronx, Queens, and Brooklyn, Central Park, and northern sections of Manhattan.

Discussion

This mapping method provides a analyses different from existing metrics and representations to understand the interaction of urban green spaces distribution with socio-ecosystemic process. We have used this mapping method to contrast possible biodiversity process in two cities that have similar number of years of modern urban process but different ecosystems and cultural influences over the centuries. However, the urban space distribution can be related with many other socio-ecosystem process such as hydrology, temperature, and human life quality. In consequence, this mapping method can be used for the understanding of different urban phenomena. The plasticity of the scale of different variables used in this mapping method should be seen as an advantage. The size of the

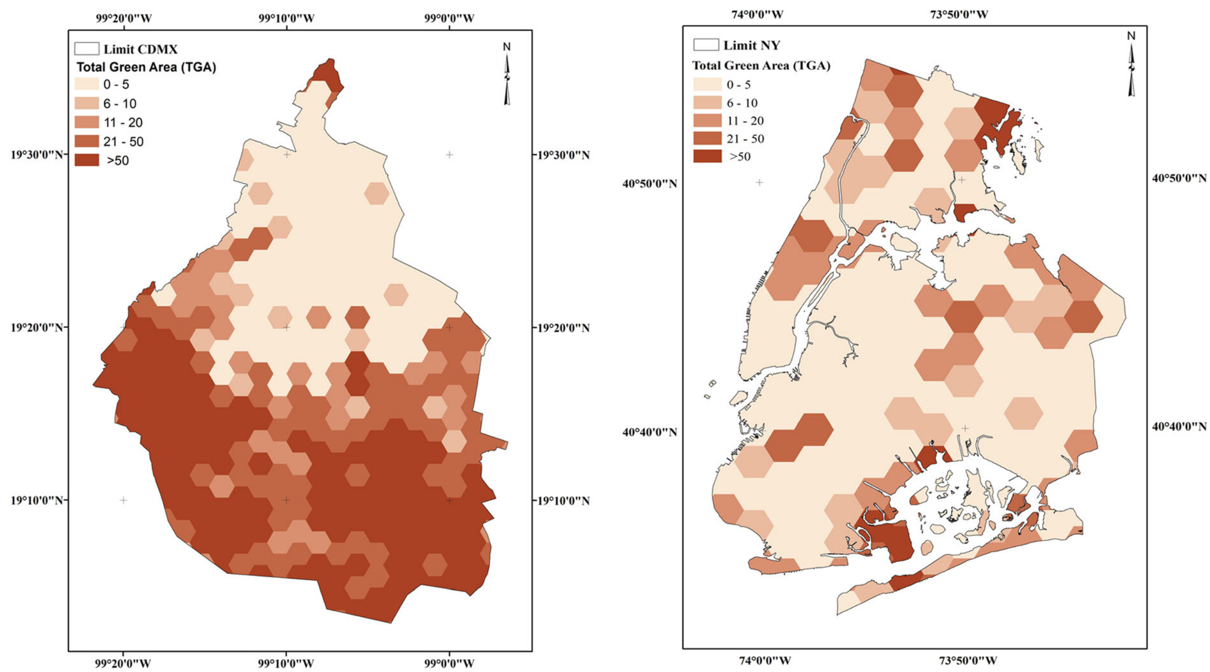

Fig. 7 Percentage of Total area covered area by green spaces (%TGA) on each hexagon in Mexico City and New York City

hexagons, as well as the categorization of all the variables such as the distance of the neighbors or the minimum size of the green spaces considered, can be adapted to other cities and the goals of the practitioners' research. The many differences in urban green space patterns that have been revealed by this analysis cautions, once again, that "urban ecology" is not a singular condition but is a rich diversity of patterns. These must be understand and then enhanced with attention to past cultural and landscape histories.

Ecological processes and the distribution of green spaces

These analyses of the two cities show the enormous variation that lies under the heading "urban ecology." These urban greenspaces being part "archipelagos" of patches in a continuous ocean of infrastructure, susceptible to be colonized from relatively nearby parcels that are a reservoir of local biodiversity. The data sets make apparent the differences between cities. MXC functions as an archipelago of medium islands fed by a large green space in the south (= mainland), and a vast sea of buildings without any green space. NYC functions more like a small group of "mainland" centers with medium-size islands in an archipelago spread in the vast city territory. Island biogeography theory suggests these differences must have consequences in the distribution and survival capacities of species of both cities. The green "mainland" can harbor many species in both cities, including those whose niches require more contiguous areas. The figures suggest that the mainland at the south part of MXC is still capable to harbor most of the 83 native species of mammals (Guevara-López et al. 2016), particularly large ones, such as the puma (*Puma concolor*), grey fox *(Urocyon cinereoargenteus*), deer (*Odocoileus virginianus*), teporingo rabbit (*Romerolagus diazi*), cacomixtle (*Bassariscus sumichrasti*), and opossum (*Didelphis virginiana*) (García et al. 2014).

The data from NYC present several medium-sized "mainlands" capable of hosting many species (Kieran 1982; Gargiullo 2007). In NYC, green spaces are closely positioned to waterways such as Hudson and East Rivers, Newark, New York, and Jamaica Bays. These have high biodiversity; Jamaica Bay is a vast wildlife preserve (Stalter and Lamont 2002; Handel et al. 2016), and New York Harbor is the site of large-scale bird and fish migrations (US Fish and Wildlife Service 1997). These fringing habitats facilitate many plant and animal species dispersing and having access to the green spaces inland. In these ways, many community ecology processes vary between the two urban centers.

The distribution and size of green spaces modify their colonization capability, including barriers, such as highways, that must be navigated by species like big cats (Vickers et al. 2015). The number of green spaces in each hexagon of both cities is highly heterogeneous. Most green spaces have another green neighbor within 200 m, but many areas are 400 m distant, beyond the regular dispersal pattern of many species. However, in MXC, there are vast areas in the northeast without any green space and consequently a reduced possibility of colonization. In NYC, there are two extensive infrastructure belts between Queens and Brooklyn that may reduce dispersal from the south to the north there.

Both cities need planning for more hexagons with larger and closer green areas, notably where they are lacking. This would be possible by increasing the number of areas that would increase habitat heterogeneity (Gaston et al. 2013; Chang and Lee 2016). This is important in NYC, where there is no large mainland analog, making smaller areas responsible for sustaining the city's diversity. High quality within an urban park, especially larger ones, is critical for biodiversity support.

The dispersal of plant species depends on the movement patterns of seeds in open or forested areas (Howe and Smallwood 1982). Dispersal patterns of species common in urban areas also are known. For example, oak (*Quercus)* species are common in New York and Mexico City. Oak seeds can be carried up to 2 km by jays (Darley-Hill and Johnson 1981). These broader movements help link tree populations widely separated across urban matrices (Lundberg and Moberg 2003; Lundberg et al. 2008). However, the seed shadow is short, 15–20 m, for most bird-dispersed species (Howe and Smallwood 1982; Hoppes 1988). A 2 km distance would move a diaspore among many urban parcels in this study, but 20 m movement would typically land on the pavement, not a recruitment site. There is a wide variation for wind-dispersal plants, but most seeds fall close to the mother plant of less than 100 m (e.g., Vittoz and Engler 2007). The less-common broadly dispersing seeds are critical for starting new populations and genetic mixing, but we have few studies of how tall and dense urban structures block movement. Human actions (fragmentation, logging) interfere with dispersal dynamics in non-urban areas, but the interplay maybe even more intense in the built hurdles of cities (Markl et al. 2012). In these ways, the spatial patterns described in this study point to plant population dynamics that vary in many ways between MXC and NYC; there is not a generalization that is useful for guiding planning decisions in both urban centers.

Differences in urban dispersal capacities also occur for animals. Within NYC, movement and genetic relatedness studies of coyotes (*Canis latrans*) have shown rapid spread in very dense areas and that animals across many city parks are closely related (Nagy et al. 2016; Henger et al. 2020). In MXC, mammals such as cacomixtles and opossums are common in urban areas. The mammals use house roofs and trees to reach even small gardens, which become habitats. For these taxa, wide dispersal in both urban areas would be possible.

Birds have greater dispersal capability than terrestrial organisms. In a broad review of birds and other taxa in urban parks (Nielsen et al. 2014), the micro-habitat heterogeneity and quality of habitat within the parks were most decisive in improving biodiversity. It is possible to watch herons, ducks, and coots flying to small 10m^2 ponds in the south part of MXC, but rarely in the north (pers. obs.). The distribution and number of bird species in NYC are positively correlated with the green space area. However, the shape and isolation of patches were not significant to the number of bird species (La Sorte et al. 2020). In MXC, the 355 recognized species of birds (Melendez-Herrera et al. 2006) can share green spaces habitats regardless of their native, exotic, or migratory condition (Ramírez-Cruz et al. 2019), but the diversity increases in areas where there is canopy (Ortega-Álvarez and MacGregor-Fors 2009). This supports the conclusion that larger urban green spaces are essential for maintaining high bird biodiversity and may underlie different biodiversity patterns determined by the spatial differences of the two study areas.

The invertebrate biodiversity is essential for urban food web structure, and the different spatial contexts of the two cities themselves may influence the potential of dispersal for invertebrates. In NYC, bee species diversity in small urban gardens is significant, 54 species, although this is smaller than surveys in the larger NYC urban parks (Matteson et al. 2008). In MXC, at least 269 species of bees have been identified (Cano-Santana and Romero-Mata 2016). Bee diversity was also positively correlated with the area of the plots and presence of wild, “unmanaged” plant species (Matteson and Langellotto 2010), but floral resources and bee diversity varied across space and time in NYC and MXC vegetated urban areas (Domínguez-Alvarez and Cano-Santana 2008; Matteson et al. 2013). These studies are mirrored by other, more exhaustive insect studies in urban areas (Winfree et al. 2011; Harrison and Winfree 2015). Small urban fragments have high insect β-diversity (Tscharntke et al. 2002) with arthropods that respond positively to the vegetated area. Still, patch isolation was less important (Turrini and Knop 2015). Together, these several insect-focused studies show that insect diversity can be high in urban centers, patch quality is essential, and insect diversity would follow different trajectories in the two cities. Consequently, design improvements within parks by planners and landscape architects may have significant value compared to purchasing new green spaces (Nielsen et al. 2014).

Advancing ecological structure in urban planning

These two cities are old, and urbanization patterns reflect historical and cultural processes as well as geologic and topographic patterns of the landscape. In both NYC and MXC, there are areas with a substantial number of parks and other areas where fast urbanization, not always planned, did not consider or leave urban green areas. These hardscape areas are difficult for many species to cross. On the contrary, in both cities, some medium-size urban green spaces are related to their historical processes for Central Park and the Brooklyn Botanical Garden in NYC and Chapultepec Park and Xochimilco in MXC. This shows the serendipitous way that cultural needs can support biodiversity concerns. Cultural initiatives can advance ecological progress in this way. To restore functional networks of green spaces in our historical cities’ design using these two goals, we need to understand which information, data sets, and institutional changes are required.

The base maps this study constructed are templates upon which biodiversity improvements can be molded. The quality of existing patches must be studied to determine what ecological improvements are feasible. Additional research on current biodiversity, movement, and pragmatic ecological targets is needed for a large city to prioritize urban landscape architects and planners (e.g., Alvey 2006; Saura and Rubio 2010; Palazzo and Steiner 2014). What are the dispersal distances of various taxa within the urban theater? More data must be developed, particularly for smaller animals and seed movement in urban areas (Nielsen et al. 2014). Which species can persist in existing spatial arrangements of green spaces and will need some type of corridor, management change, or additional patches to maintain their population structure (e.g., Angold et al. 2006; Threlfall et al. 2016)?

Our mapping of these old cities is a possible way to assist planners in locating new parcels to advance urban biodiversity. Ecological improvements within historical cities can then be expanded to regional metropolitan areas (Forman 2008), as has been done for the NYC region (Flores et al. 1998; Lewis et al. 2019).

The life span of an urban patch and the addition of new habitats varies with local regulations and development pressures (Le Roux et al. 2014). The economic factors important in urban design can be incorporated into decisions on ecological corridor construction and improvement (Peng et al. 2017). Because the change in an urban green patch’s presence or surroundings occurs regularly, species equilibrium may not always occur, a metapopulation effect. In both cities, “stepping-stone” areas are of value (Ignatieva et al. 2011; Andersson and Colding 2014) and may be easier to create than continuous corridors. Ecological connections have been used in other cities (LaPoint et al. 2015), and those case studies can be a foundation for plans elsewhere. The study’s hexagons also help to prioritize paths for ecological restoration, for example, in the grey belts between Queens and Brooklyn in NYC and the North East area in MXC (Zambrano et al. 2019). The findings help support the conclusion that these areas must be a priority for biotic corridors.

“Green streets” can increase biodiversity movement (Mason et al. 2007), as well as increase engineering value (stormwater absorption, mitigation of heat).

Historical cities’ place-specific constraints challenge the improvement of urban biodiversity. It is better to have an ecological presence in decision-making early in planning and design (Dunnett and Hitchmough 2004; Beatley 2017). Patterns that will allow sustainability of urban biodiversity have been explored theoretically and by site analyses (e.g., Ikin et al. 2012; Markl et al. 2012; Beninde et al. 2015;

Hauck and Weisser 2017). New conceptual areas for improving urban efforts are continually being posed (Angold et al. 2006; Müller et al. 2010; Lepczyk et al. 2017). The value of the urban biotic connections takes time to be expressed. Damschen et al. (2019) showed that biodiversity among reconnected habitat fragments increased after 18 years and still had not reached an asymptote. In both NYC and MXC, the hexagon-based analysis can support decisions and policies for adding green areas that can slowly increase ecological structure into the future. This method offers an alternative, intuitive tool for planners interested in this urgent goal.

Conclusion

To better include ecologically functioning urban green spaces into city land management protocols, we must start with an easily understandable mapping of existing spaces. There is scattered available information on the potential dispersal of species through cities, but a better framework for understanding the existing habitat distribution is needed to underlie future landscape improvement decisions. Positioning of new urban green spaces can increase plant and animal movement patterns, but these two large, older cities have idiosyncratic starting points and many land-use constraints. The green space patterns vary significantly between the two cities, showing the importance of local conditions in developing an overall framework for urban ecology. This study is an alternative landscape approach to cataloging urban green space distribution that can be meshed with existing numerical models. Deeper understanding of the dispersal patterns of organisms as well as the capacities of very small green spaces to host species and advance ecosystem dynamics are necessary to improve existing ecosystem resources. In these ways, future urban planning can have a more accurate ecosystem foundation.

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