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Topological analysis of the spatial distribution of plant species richness across the city of Rome (Italy) with the echelon approach

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Abstract

It is generally agreed that urban vegetation significantly contributes to the well-being of individuals and society. Therefore, plant species richness in urban environments is a variable of considerable interest to landscape planners and conservation biologists. While all monitoring activities have a spatial context to a varying degree, monitoring of urban plant species richness distribution requires an objective method for defining the boundaries of areas that are species rich or poor compared to their surroundings. By aggregating the cells of tessellated numerical surface variables into hierarchically related topological entities, the echelon approach provides a new way to objectively characterize the structure of spatial data bases and is thus appropriate for monitoring environmental indices such as urban plant species richness. In this paper, we apply the echelon approach to the characterization of the broad-scale spatial distribution of plant species richness across the city of Rome (Italy).

Keywords: Echelon approach; Rome; Species richness; Topological analysis; Urban flora

1. Introduction

Urban vegetation significantly affects many aspects of individuals and society. The presence of vegetation substantially improves urban climate reducing heat island effects, and the air quality filtering out dust and pollutants (Stülpnagel et al., 1990; Mc Pherson et al., 1995). In addition, large green areas in the city center act as refuge for numerous plant and animal species increasing urban biodiversity (Sukopp and Werner, 1983). Such areas are particularly important in several historical cities in Italy where archaeological sites and large parks cause an unusual pattern of species richness distribution with high biodiversity values in the city center (Celesti Grapow and Blasi, 1998). An objective approach to biodiversity monitoring in urban environments is thus the first step towards an effective preservation of urban vegetation.

While all monitoring activities have a spatial context in varying degrees, monitoring of species richness requires an objective, criterion-based method for characterizing the spatial distribution of areas that are relatively species rich or poor. Imagine the distribution of a numerical variable over a geographic area that is either systematically tessellated into regular cells or partitioned into irregular polygons (e.g. counties or watersheds) so that each cell/polygon is associated to a measured value of the variable. Often, a primary

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interest is to identify "hot spots" in the variable distribution, which are regions of interest due to either high or low response values relative to their surroundings (Johnson et al., 1998). The echelon approach introduced by Myers et al. (1997) and Johnson et al. (1998) aggregates the cells of the analyzed distribution into hierarchically related structural entities providing a framework to objectively characterize the spatial structure of environmental indices, and is thus appropriate for monitoring plant species richness in urban environments. In this paper, we apply the echelon approach to the characterization of broad-scale spatial distribution of spontaneous plant species richness across the city of Rome (Central Italy).

2. Study area

The municipality of Rome extends over 1500 km^2 on the lower plain of the Tiber River. The city proper, which hosts 2,900,000 inhabitants, covers an area of about 300 km^2 delimited by the course of the Grande Raccordo Anulare (GRA), a 68.2 km-long periurban circular highway, which acts as an external physical and psychological barrier against urban expansion (Sanfilippo, 1993). The urban landscape is extremely complex and stratified as in any area of long-standing settlement. The superimposition of different historical periods spanning more than 2000 years, from the ancient Roman remains in the city center to the modern buildings of the suburbs, severely affects the urban distribution of vegetated areas and plant species richness.

From a bioclimatic viewpoint, Rome belongs to the Mesomediterranean region, with mild winters and a severe summer drought (Blasi, 1994). The average annual temperature measured at the meteorological station of Rome Monte Mario is 15.1°C. The average annual rainfall is 839 mm with a principal maximum in autumn and a secondary maximum in winter.

The potential natural vegetation of Rome is mainly composed of a mixed deciduous oak forest dominated by *Quercus cerris* and *Quercus frainetto*. In the most exposed areas, thermophilous woods with *Quercus pubescens, Pistacia terebinthus, Cercis siliquastrum* and Mediterranean evergreen woods with *Quercus ilex, Arbutus unedo, Viburnum tinus* and *Pistacia lentiscus* prevail (Blasi et al., 1995).

The natural vegetation of Rome (Fig. 1) is dominated by a mosaic of pastures and fallow lands (Celesti Grapow and Fanelli, 1993). Cultivated areas are most common in the suburbs and along the bank of the Tiber and Aniene Rivers and include fields, small orchards, vineyards and vegetable gardens. Numerous residual forest patches are scattered in the western part of the city and represent the remains of a swathe of woody vegetation that colonized the western suburbs of the city (Montelucci, 1953–1954). These forests host important flora that include several rare species, such as *Ilex aquifolium* and *Galanthus nivalis*. Among the trees, oaks are dominant, including *Quercus suber, Q. cerris, Q. frainetto, Q. pubescens, Q. robur, Q. ilex* and, more rarely, *Q. crenata*. Other common woody species are: *Acer campestre, Fraxinus ornus, Corylus avellana, Crataegus monogyna* and *Viburnum tinus*.

Despite the intense degradation of the riparian habitats, there are still patches of urban riparian woods along the banks of the Tiber and Aniene Rivers principally composed of *Salix alba, Salix purpurea, Populus alba, Populus nigra* and *Alnus glutinosa* (Anzalone, 1986). Significant nuclei of natural vegetation are also present in the main urban parks and archaeological sites. Spontaneous vegetation is found even in the most densely populated areas, usually on walls and roadsides (Anzalone, 1951), in courtyards and in sidewalks cracks (Blasi and Pignatti, 1984).

Due to its richness, the flora of Rome has been studied since the 17th century (Panaroli, 1643; Sebastiani, 1815; Sanguinetti, 1867). More recently, a series of new studies focused on single biotopes threatened by increasing urbanization (Anzalone, 1952, 1953; Montelucci, 1953–1954). Finally, since the modern view of urban ecology considers the urban environment as a global system of interconnected biotopes (Giacomini, 1981), the latest study on the natural vegetation of Rome was extended to the entire area within the GRA (Celesti Grapow, 1995). Following the protocol introduced by Menichetti et al. (1987), the area within the GRA was spatially organized in a grid composed of 190 rectangular cells of roughly 1.2 km × 1.4 km. Within each cell, the species of spontaneous vascular plants were sampled (Fig. 2). According to this census, the flora of Rome includes 1285 spontaneous species distributed in 591 genera and 131 families (Celesti Grapow, 1995). While this may appear inconsistent with the intense degradation of urban

Fig. 1. Land cover map of the city of Rome. (1) Insugherata, (2) Monte Mario, (3) Pineto, (4) Infernaccio, (5) Villa Ada, (6) Villa Borghese, (7) Villa Doria Pamphili, (8) Vejo Archaeological Park, (9) Roman Forum Archaeological Site, (10) Appia Archaeological Park; GRA: Grande Raccordo Anulare.

environments, cities generally offer a great variety of habitats to natural flora and fauna and constitute important nuclei for the immigration and naturalization of non-native species (Henke and Sukopp, 1986).

3. Methods and results

The species richness distribution in Fig. 2 was analyzed following the echelon approach (Myers et al., 1997; Johnson et al., 1998). The census of the natural vegetation of Rome consists of a gridded layer made up of 190 cells in which the response variable represents the plant species richness per unit cell. This gridded layer can be considered as a virtual topographical surface in which rows and columns are the cell coordinates, while the values of the response variable embody the imaginary cell elevation. The echelon approach aggregates the cells of the analyzed database into hierarchically related structural entities, which are essentially topological subsets of the original virtual surface (Myers et al., 1997).

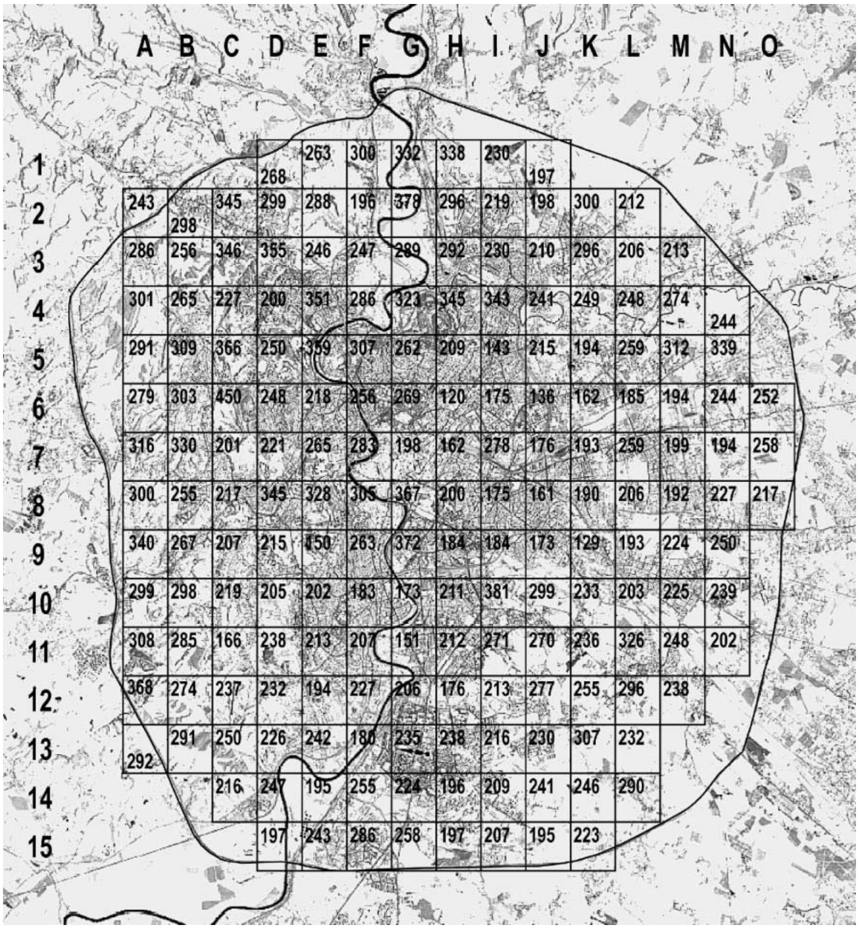

Fig. 2. Spontaneous plant species richness distribution in the city of Rome. Labels are number of species per unit cell. The background represents a Landsat TM5 image acquired on 26 July 1995.

The subsetting procedure can be best understood from the perspective of the one-dimensional hypothetical profile in Fig. 3. The first step consists in identifying local peaks within the analyzed profile. Second, first-order echelons are obtained by moving downward from local peaks until saddles are reached in the virtual topography. Saddle levels determine the structural divisions between first-order echelons and their foundation. Following a recursive procedure, this process is repeated to identify higher-order topological subsets (echelons) of the virtual surface until the structure of the analyzed profile has been fully determined. This method was called an echelon approach to quantitative spatial variables because it subsets a virtual surface into hierarchically related structural components in a similar manner as troops are organized in step like echelons (Myers et al., 1997). Notice that for two-dimensional spatial distributions contacts at corners between adjacent cells are considered as well as contacts along sides.

Due to its hierarchical nature, the echelon approach can be considered as a higher-dimensional elaboration of the organization of streams in a drainage basin following Strahler (1964). This system classes all unbranched streams as first-order streams. When two first-order streams meet the resulting channel is a second-order stream, when two second-order streams meet a third-order stream results, and so on. Any lower-order tributary than the main channel is ignored.

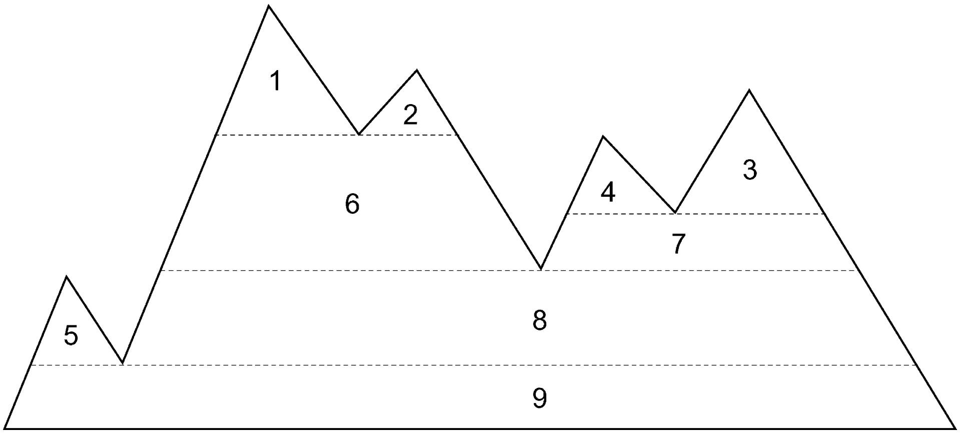

Fig. 3. Hypothetical one-dimensional profile for illustrating the echelon generation procedure. The symbols 1, 2, 3, 4, and 5: first-order echelons; 6 and 7: second-order echelons; 8 and 9: third-order echelons. Echelon objects within each echelon order are numbered in decreasing order of the surface top level.

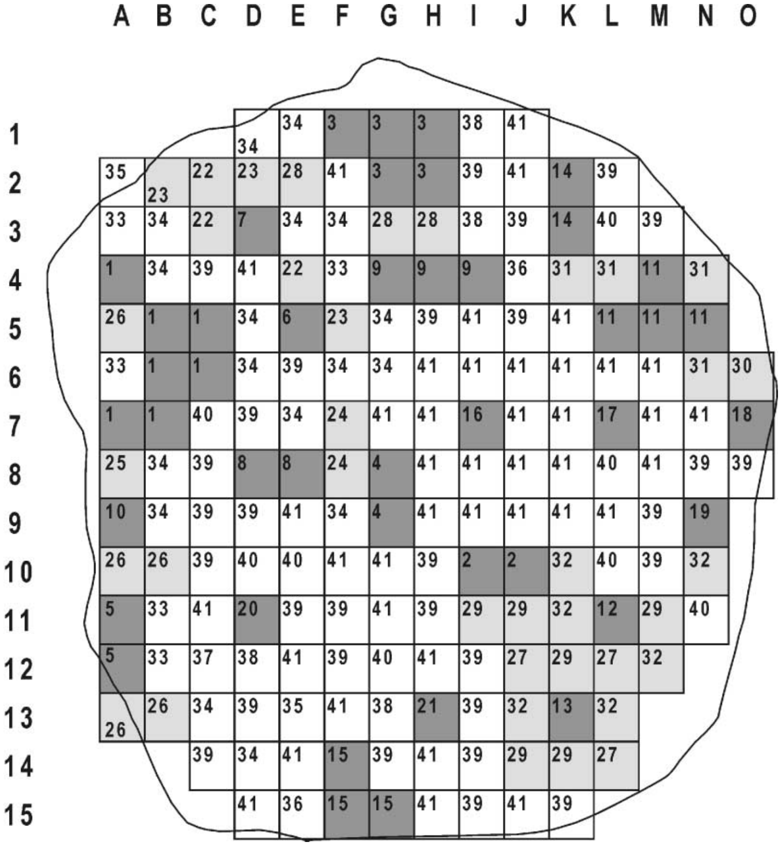

Fig. 4. Echelon top view of spontaneous plant species richness in the city of Rome. Echelon orders are displayed in gray scale showing high orders in bright shade and low orders in dark, respectively. Echelon objects within each order are numbered in decreasing order of the surface top level.

Following generation of echelon objects, a top-view perspective of the analyzed species richness distribution can be mapped where each original cell is part of an echelon object. Fig. 4 shows an echelon top view map of the spontaneous plant species richness distribution across the city of Rome. On such maps, different echelons and echelon orders can be distinguished in a variety of ways depending on the cell size and extent of the analyzed dataset. In Fig. 4, echelon orders are displayed in gray scale showing high orders in bright shade and low orders in dark, respectively, while echelon objects within each order are numbered in decreasing order of the surface top level. Notice that, due to the nature of the echelon generation process, in a top view map the lower-order echelons might appear as disjointed sectors.

4. Discussion

In good agreement with the mosaic-like structure of most urban spaces (Henke and Sukopp, 1986), the echelon top view in Fig. 4 shows a relatively fragmentary picture. Third order is the highest degree of hierarchical organization in the analyzed data set. Twenty-one different first-order echelon objects were delineated out of a total of 190 cells, whereas 11 of those first-order echelon objects, mainly in the southeastern part of the city, are composed of one single cell. The greatest number of plant species is found in the western forested areas, in particular at Pineto where a local peak of 450 species per unit cell is reached (C6). First-order echelons with local peaks of over 300 species per cell have also been measured along the upper course of the Tiber River (G2), at Insugherata (D3), Monte Mario (E5) and Infernaccio (A9, A12). In the east and southeast, urban vegetation is more dispersed and mostly composed of pasture and fallow species. Within this context, notice that due both to historical and ecological factors, the course of the Tiber draws a major barrier that separates the forest vegetation of the western part of the city from the pastures and fallow areas in the east and southeast (Celesti Grapow, 1995).

A diversity hot spot in the city center is uncommon in urban environments. However, the archaeological site of the Roman Forum (G9) offers refuge to a very high number of spontaneous plants. From the city center towards the southeast, plant species richness is still high within the first-order echelons of the Appia Archeological Park (I10, K13, L11). Outside these areas, first-order echelons are dispersed along the upper course of the Aniene River (N5), in the urban parks of Villa Doria Pamphili (D8) and Villa Ada (H4), in the fallow areas of the eastern suburbs (L7) and at the rural/urban interface along the GRA (F15, K2, N9, O7). In the rest of the city about 150–250 species per unit cell are found. The minimum number of species per unit cell was found in the eastern-central part of the city where the only large green area is the monumental cemetery of Verano (I7).

In order to preserve urban species richness, it is necessary to keep biodiversity hot spots in contact with one another and with the vegetation at the rural–urban interface (Simberloff and Cox, 1987; Starfinger and Sukopp, 1994). For this reason, connections that reduce isolation between first-order echelons are important. Taking into account, the combined distribution of first and second-order echelons, these connections become more evident.

In the western sector of the city, the forest patches of the upper course of the Tiber River, Insugherata, Monte Mario, Pineto, and Infernaccio form connective networks that act as an "ecological whole" (Duvernoy, 1995) preserving the floristic richness of these forests (Figs. 1 and 4). In the eastern sector, the picture is more fragmentary. For this reason, the green areas nearby or along the course of the Aniene River are very important for preserving high biodiversity levels in the northeast. In addition, the green corridor that connects the fallow areas of the southeastern suburbs with the Roman Forum through the Appia Archaeological Park is of particular relevance acting as principal connection between the rural–urban interface in the southeast and the city center. From this perspective, in order to maintain the plant species richness of Rome, it is necessary to preserve the integrity of the network of natural and semi-natural urban biotopes along with its connections to the rural–urban interface rather than individual species.

5. Conclusions

The analysis of the natural plant species richness distribution across the city of Rome shows two dominant patterns. In the west and northwest, a system of highly interconnected fragments of urban and suburban forests with high biodiversity levels is dominant. In contrast, in the east and southeast, urban vegetation is more dispersed and composed mostly of pasture and fallow species. These species penetrate into the city center through a green corridor that supports an unusually rich flora.

In this view, structuring the spontaneous plant species richness distribution of the city of Rome into echelon objects proved to be useful in assessing broad-scale plant biodiversity hot spots and the related connections to the rural fringe. However, this way of structuring quantitative spatial variables into topological subsets should not be uncritically accepted. For instance, one might argue that when we compare Figs. 2 and 4, it is clear that there is a strong correlation between the results of each one. Therefore, Fig. 2, which presents plant species richness within each cell, seems adequate for understanding the spatial distribution of species richness across the city of Rome without any statistical treatment. Nevertheless, unlike the conventional cartographic approach based on regularly stepped contour lines, the echelon approach takes into account the spatial distribution of plant species richness during the subsetting procedure. For example, due to their high richness values relative to their surroundings, cells L7 (259 species) and D11 (238 species) represent two first-order hot spots (i.e. peaks in the virtual topography of the response variable), whereas cell F5 that hosts 307 species is part of a second-order saddle between the first-order echelons D3 and E5. Similarly, from a topological viewpoint, cells B11 (285 species) and B12 (274 species) are part of a third-order echelon despite their higher species richness values with respect to the first-order echelon H13 that hosts only 238 species. In addition, due to the topological subsetting procedure, the number of cells that constitutes an echelon object is also related to the two-dimensional structure of the response variable. Thus, the large first-order echelon in the northwestern part of the city that represents a connected network of urban and suburban forests with high to very high species richness levels extends over seven grid cells (A4, A7, B5, B6, B7, C5, C6). Conversely, in the eastern-central part of the city where natural vegetation is more fragmented, first-order echelon objects I7 and L7 are composed of one single cell. In this sense, due to these major differences, the echelon approach constitutes a novel approach, which is complementary rather than competitive relative to more conventional subsetting procedures.

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