COENOSES 13(2): 57-64, 1998

LANDSCAPE CHANGES IN ROME, ITALY

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Keywords: Landscape indices, GIS, land use changes.

Abstract. Various landscape pattern indices were used to quantify landscape spatial structure and historical modifications in the north-west sector of Rome, Italy. Historical land-use data were obtained from interpreted aerial photos dating from 1944, 1974 and 1991. The maps were digitized and a series of structural, shape, change and pattern indices were calculated to quantify changes of the landscape matrix over the past fifty years. One feature of note is a progressive increase in forest cover over time, from 4.3% in 1944 to 8.3% by 1991. This increase is attributed to natural successional processes that occurred with changing socio-economic and geomorphological factors. Our analyses also revealed some redundancy in landscape measures, such as the dominance and contagion indices. The analyses also demonstrated the need to examine many landscape indices simultaneously in order to obtain sufficient information regarding the development of a particular land use type as well as the landscape as a whole. We conclude that further research is needed to more fully examine the relationship between measured landscape indices and underlying ecological functions and processes at the landscape scale.

1. Introduction

Landscape changes result from the interaction of physical, biological and socio-economic factors, which in turn determine a mosaic of habitats (Forman and Godron 1986; Forman 1995; Turner and Gardner 1991). Landscape pattern and the size, shape and connectivity of landscape elements influence many critical ecological processes, such as the dispersal of plant and animal species and habitat species richness (Merriam and Lanoue 1990; Brown and Gibson 1983; Jarvinen 1982; Thebaud and Debussche 1991). The relationship between species richness and the size and isolation of habitat as explained by the theory of island biogeography has also been applied to strongly disturbed environments (MacArthur and Wilson 1967; McCoy 1983; Balser et al. 1981; Nyland et al. 1986; Knaapen et al. 1992). Although some researchers have report deficiencies in island biogeographical theory as applied to urban environments (e.g. Hobbs 1988), the quantification of landscape elements is nonetheless useful in verifying ecological principles linked to spatio-temporal patterns of the landscape. Geographic information systems (GIS) that can effectively handle and analyse digital spatial data (Burrough 1986; Tomlin 1990), used in conjunction with landscape pattern indices (O'Neill et al. 1988; Turner and Gardner 1991), represents the technological and scientific background for such studies.

The objective of this study is to evaluate the efficiency and utility of various landscape indices for analysing spatio-temporal patterns of urban landscape use in Rome, Italy. The overall aim is to provide a methodological model for researchers and practitioners interested in the planning and management of natural resources in an urban environment.

2. Study area and historical land use modification

The study region encompasses an area of approximately 55 km^2 in northwest Rome inside the *Raccordo Anulare* highway (Fig. 1). The landscape consists mainly of low hills of volcanic and alluvial origin. The highest elevation is the hill of Monte Mario at 139 m. During the Pleistocene the area was occupied by a gulf, the sediments of which are today represented by the richly fossiliferous clay of the Monte Mario and Gianicolo hills. During the lower Pleistocene, tectonic movements caused the gulf to be filled with gravel, sand and clay carried out by the Tiber River and forming an alluvial plain. About 700,000 years ago, volcanic activity in the Sabatini and Albani complexes covered the area with a thick layer of pyroclastic tuffs. This material was later eroded by the many tributaries of the Tiber River, resulting in a geomorphology that is today characterised by a hilly landscape that is abruptly interrupted by deep ravines in a southwest to northwest orientation.

The city of Rome occurs in a transitional region between the Mediterranean climatic zone of the coast and the more temperate climatic zone of the Apennine chain. The aridity of the Mediterranean climate, characterized by three months of summer drought, is somewhat mitigated by precipitation in Rome (the annual mean ranging between 81 and 94 cm). Under these climatic conditions, the natural potential vegetation is represented by a mixed deciduous woods dominated by oaks (mostly *Quercus cerris* and *Quercus frainetto*), with evergreen sclerophyllous woods occurring on drier substrates.

The landscape of region has been strongly modified for agriculture and grazing activities since the ninth century B.C., beginning with early Etruscan and Latin settlement.

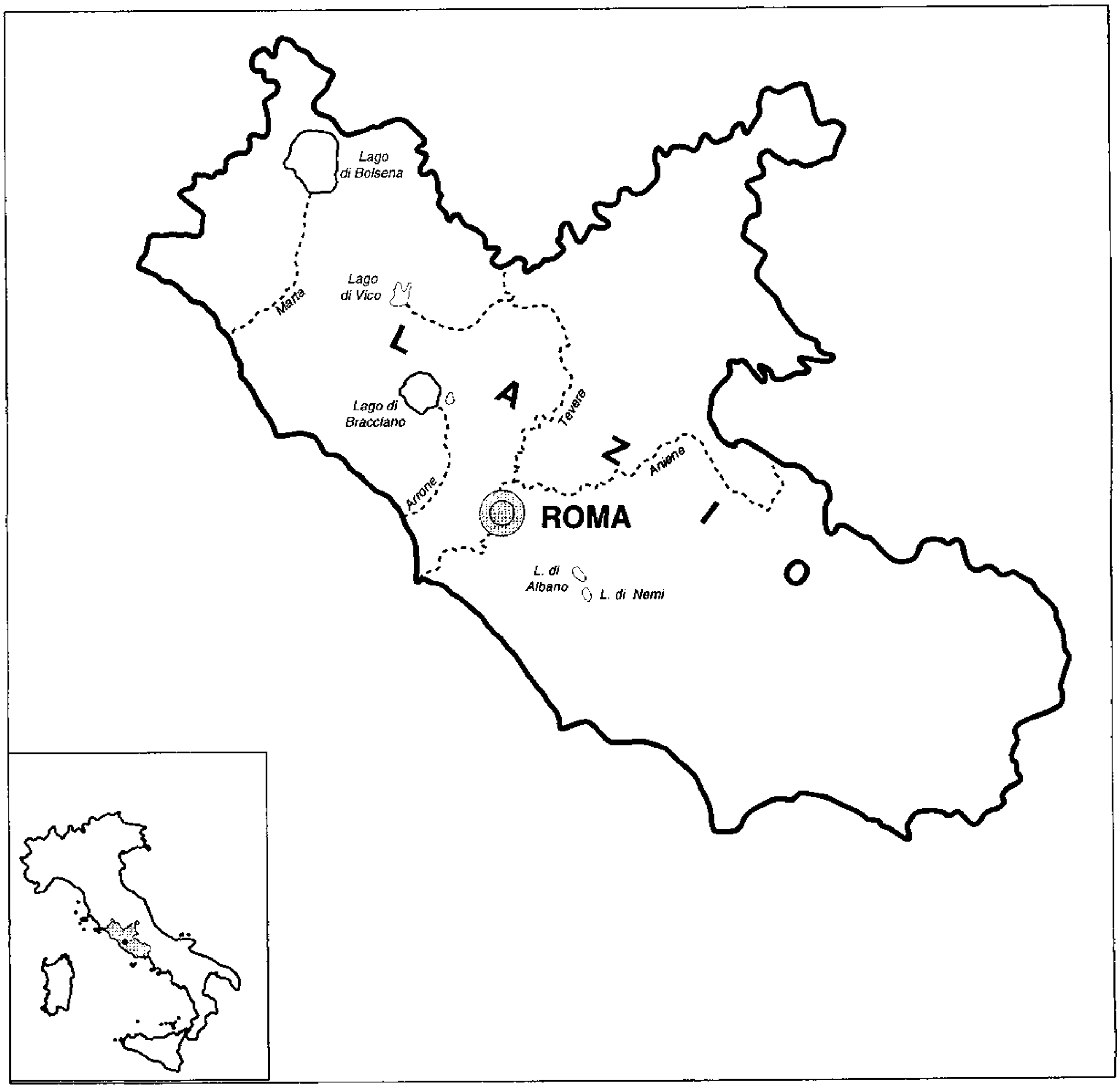

Figure 1. Study area.

However, it was during the Roman empire (third century B.C., when the city's population exceeded one million) that the region developed landscape features that have been maintained until the last century. Broad patrician estates (the *villae rusticae*) were established, and most of the territory was used for agriculture or grazing; only the deepest ravines were maintained as woodlands. This structure, which was later inherited by the Church and the feudal nobility, was maintained unchanged until the last century. In 1870, Rome became the capital of Italy and was subjected to intensive and often uncontrolled expansion, especially during the second half of this century. Today, Rome has a population of four million but still maintains various 'natural areas' within its urban fringes.

3. Methods

Land use data for the study area were obtained from historical black and white aerial photos dating from 1944, 1974 and 1991 (Fig. 2). The boundaries of each class were reported on 1:10,000 scale topographical maps. These maps were then digitized using the program ILWIS. Five land use categories were recognized:

1. Forest (no distinction was made between deciduous and evergreen woods).
2. Shrublands and wastelands (degraded habitat or succession to woody vegetation).
3. Pastures and meadows.
4. Agricultural land.
5. Urban areas.

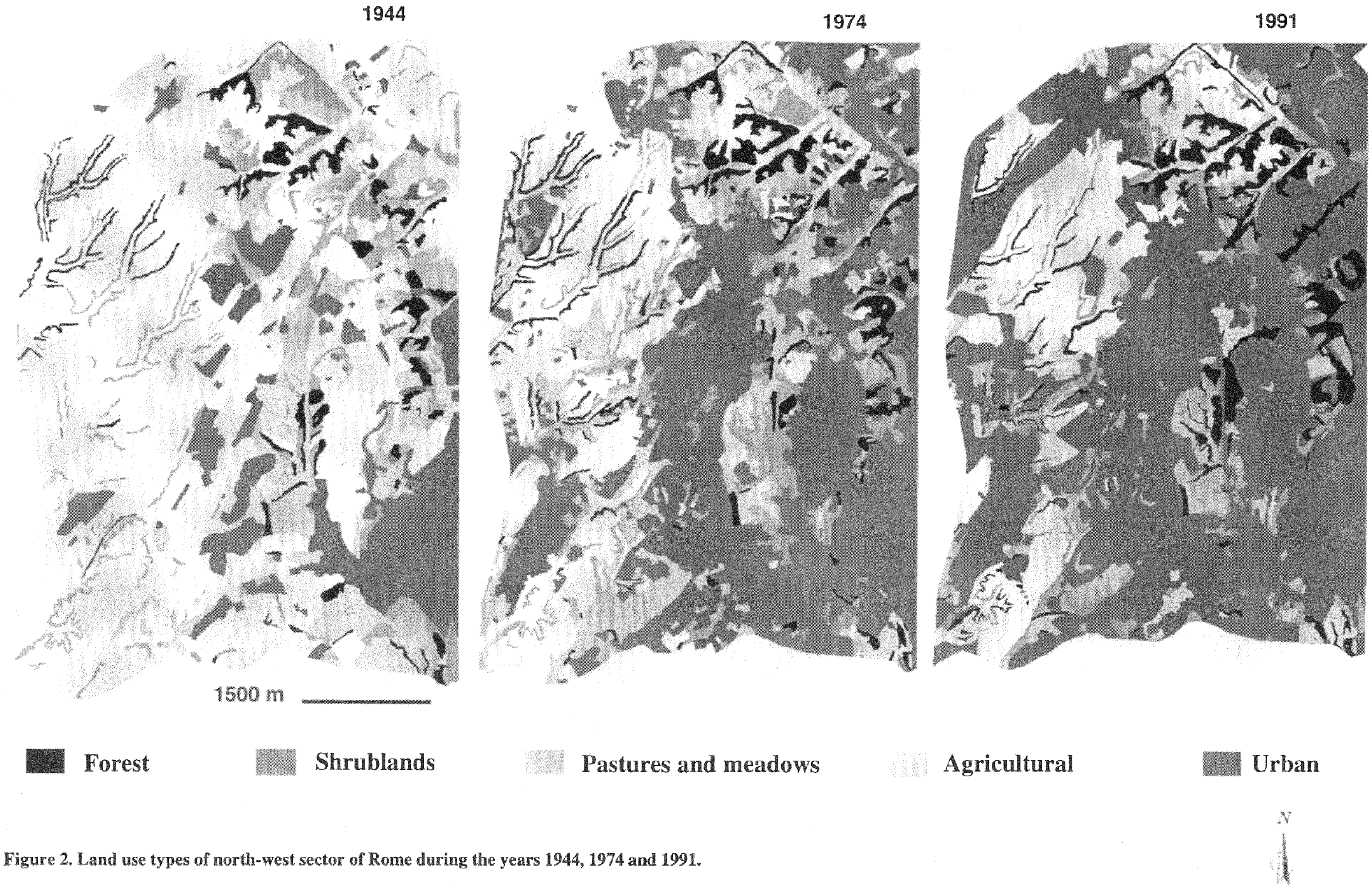

Figure 2. Land use types of north-west sector of Rome during the years 1944, 1974 and 1991.

Only maps produced through photo interpretation were used in this study; other available historical maps were not considered. Since cartography is an interpretive art, changing aims or methods could introduce an *a priori* source of misinterpretation.

The various landscape indices used were grouped into four classes:

3.1 Structural indices

P = proportion of each land use type.

N = number of patches of each land use type.

S and *s.d.* = mean size and standard deviation of patches.

3.2 Shape indices

S1 = shape index 1. This is calculated as the mean of the perimeter-area ratio of patches of one land use type:

$$S1 = \frac{1}{n_i} \sum_{j=1}^{n} p_{ij}/a_{ij} \qquad (1)$$

where n_i = number of patches of type i, p_{ij} = perimeter (m) of patch j in category i, and a_{ij} = area (m^2) of patch j in category i. High values of this index indicate that a land use type is characterised by patches of small internal area (Iverson 1988).

S2 = shape index 2. This measures the deviation of a patch from an isodiametric one of the same area:

$$S2 = \frac{1}{n_i} \sum_{j=1}^{n} \frac{p_{ij}}{2\sqrt{\pi\, a_{ij}}} \qquad (2)$$

The further $S2$ deviates from 1, the more the patches deviate from an isodiametric shape (Forman 1995). The Spearman rank correlation was calculated for these two shape indices.

DF = fractal dimension, which is an alternative method for measuring patch shape. This index is obtained from the slope of the regression line between log area (m^2) and log perimeter (m) of patches of one type. DF = 1 for simple shapes such as a perfect square or circle, and approaches 2 for highly complex and convoluted forms (O'Neill et al. 1988; Kienast 1993). This index alleviates problems related to interior patches, which are typical of landscapes strongly disturbed by man (Rex and Malanson 1990).

3.3 Changes indices and edge analysis

T = transitions between different land use types.

CG = change index (Sharpe et al. 1982), which calculates the rate of change of each class (in ha/years/km^2) using the formula:

$$CG = \left(\frac{P_{i2} - P_{i1}}{t_2 - t_1}\right)\frac{1}{s} \qquad (3)$$

where P_{i2} - P_{i1} = difference in ha of category i in the period time 2 - time 1; t_2 - t_1 = difference in years between time 2 and time 1; and s = total surface area in square km. This index measures the rate of changes of one land use type irrespective of changes in its geographical position. Here CG is reported separately as rates of change for the periods 1994-1974 and 1974-1991.

L = percentage of different kinds of edges. This index was calculated since edges play an important ecological role as transition zones between different habitats (Forman 1995). Following Kienast (1993), edges between different

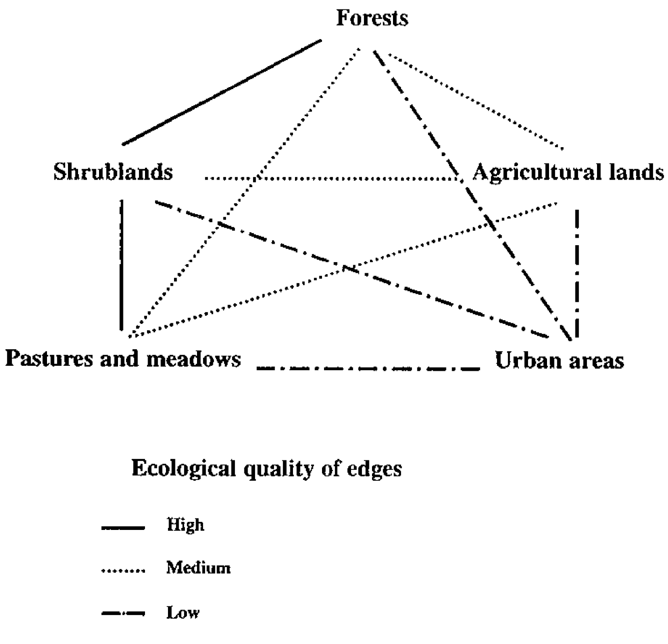

Figure 3. Edges types and grouping (following Kienast, 1993, modified).

land use types were grouped according to ecological quality, from high to medium to low (Fig. 3).

3.4 Pattern indices

D = dominance index, calculated as:

$$D = \ln c + \sum_{i=1}^{c} P_i \ln P_i \qquad (4)$$

where c = total number of categories; and P_i = proportion of the landscape in category i. Large values of D indicate that the landscape is dominated by one or a few land use type, while a value close to 0 indicates that land use types are equally frequent.

C = contagion index (Li and Reynolds 1993). In order to calculate this index, the maps were converted into raster format using a cell dimension of 10 m x 10 m. This index consists of the sum (over patch types) of the product of two possibilities: the probability that a randomly chosen cell belongs to patch type 1 (estimated by the proportional abundance of patch type i), and the conditional probability that, given a cell of patch type i, one of its neighbouring cells belongs to patch type j (estimated by the proportional abundance of patch i adjacencies involving patch type j). The product of these probabilities equals the probability that two randomly chosen adjacent cells belong to patch type i and j. This index therefore measures the spatial distribution of a patch type. All else being equal, a landscape in which patch types are well interspersed will have lower contagion than a landscape in which patch types are poorly interspersed. Thus high values (maximum 100) indicate landscape with few, broad and contiguous patches, while values close to 0 characterise landscape with numerous, small and interspersed patches. This index is calculated as:

$$C = \left[1 \sum_{i=1}^{m} \sum_{k=1}^{m} \left[P_i \frac{g_{ik}}{\sum_{k=1}^{m} g_{ik}} \right] \left[\ln P_i \frac{g_{ik}}{\sum_{k=1}^{m} g_{ik}} \right] / 2 \ln m \right] \times 100 \qquad (5)$$

where P_i = proportion of the landscape in category i; g_{ik} = number of adjacencies (joins) between pixels of patch types i and k; and m = number of landscape patches.

The final pattern index computed was the fractal dimension. This was calculated for the whole landscape in order to measure overall landscape complexity.

4. Results and Discussion

4.1 Structural indices

The structural indices (Table 1) indicate changes in the landscape matrix between 1944 and 1991 ('matrix' is the land use type covering 60% of the total area, or the most connected landscape element). In 1944 the landscape was typically agricultural, with agricultural and pastures together accounting for 73% of the study area. By 1991, the matrix is defined by urban areas (58% of the study area). Urbanisation occurred mainly on former agricultural lands and pastures (Table 3), reflecting the fact that these are flat areas that are most useful for building.

Forest cover increased progressively over time, from only 4.9% of the study area in 1944 to 8.3% by 1991. This increase is attributable to successional processes that began following a decrease in silvicultural activities following urbanisation. This natural reforestation is also linked to socio-economic and geomorphological factors. Complex land-inheritance events resulted in the conservation of many large estates containing forests. In addition, the sandy substrates of wooded hillsides are susceptible to intense erosion, preventing urban development by property speculators. These wooded hillsides are undergoing succession and reforestation from nuclei of natural old-growth forest stands (Attorre et al. 1997). Natural successional processes prevent the establishment of exotic species such as *Robinia pseudoacacia* and *Ailanthus altissima*, species that are strong competitors in environments highly disturbed by human activities.

4.2 Shape indices

Spearman rank correlation analysis between the shape indices *S1* and *S2* confirmed results reported by Hulshoff

Table 1. Proportion of landscape occupied by each cover type (P), number of patches (n), mean size and standard deviation of patches (S, s.d.).

Total study area = 5563 ha

	1944				1974				1991			
Land use	P	n	S	s.d.	P	n	S	s.d.	P	n	S	s.d.
Forest	4.9	83	3.3	3.6	7.1	119	3.3	4.8	8.3	99	4.6	8.9
Shrubland	7.2	134	3.0	5.7	8.8	162	3.0	5.5	6.7	133	2.8	3.0
Meadow	12.4	64	10.8	23.7	13.4	92	8.1	16.0	7.3	77	5.3	6.6
Agricultural	61.6	12	286.5	835.6	27.3	73	20.8	85.1	19.3	23	45.6	95.9
Urban	13.8	73	10.6	42.1	43.4	64	37.7	252.7	58.3	17	190.6	670.7

Table 2. Shape indices: S1, S2 and fractal dimension FD.

Land use	S1 mean (s.d.)			S2 mean (s.d.)			FD		
	1944	1974	1991	1944	1974	1991	1944	1974	1991
Forest	522.5	500.0	583.3	2.12	2.07	2.31	1.55	1.55	1.44
	(249.3)	(187.4)	(250.7)	(0.80)	(0.58)	(0.63)			
Shrubland	560.7	525.5	512.9	3.00	1.93	1.95	1.44	1.48	1.47
	(228.8)	(224.3)	(240.6)	(0.51)	(0.61)	(0.59)			
Meadow	376.0	351.9	396.1	1.96	2.00	1.83	1.34	1.43	1.36
	(205.5)	(148.2)	(199.6)	(0.57)	(0.67)	(0.44)			
Agricultural	185.8	372.3	268.0	2.94	1.93	2.61	1.49	1.40	1.42
	(101.6)	(243.2)	(195.7)	(2.79)	(1.10)	(1.12)			
Urban	633.1	457.5	274.2	1.54	1.66	2.11	1.17	1.36	1.28
	(1331.7)	(277.7)	(237.2)	(0.27)	(0.93)	(2.09)			

Table 3. Land use transitions (T) during the period 1944-1991. The average rate of landscape change (GC) of two periods is respectively 0.46 and 0.38 (ha/year/Km^2).

	Transition (%)	
	1944-1974	1974-1991
F-F	50.1	61.1
F-A	14.5	9.9
F-U	14.0	18.9
F-S	13.6	6.5
F-M	7.7	3.6
A-F	3.7	2.5
A-A	37.5	55.3
A-U	38.2	29.3
A-S	6.4	5.2
A-M	14.2	7.6
U-F	0.0	0.5
U-A	2.0	0.6
U-U	96.6	97.0
U-S	1.5	1.3
U-M	0.0	0.6
S-F	16.8	23.8
S-A	18.8	14.6
S-U	22.8	32.0
S-S	27.9	20.2
S-M	13.6	9.3
M-F	8.3	5.5
M-A	12.4	14.9
M-U	39.4	34.6
M-S	14.7	17.3
M-M	25.2	27.7

(1995): these two indices are poorly correlated, but both are useful in quantifying the shape of landscape elements. *S1* is influenced by the internal area of patches (high values indicating a broader internal area), while *S2* is more sensitive to the complexity of the perimeter (higher values indicating deviation from an isodiametric shape). The urbanized areas are a good example. Increased urbanisation from 1994 to 1991 resulted in a decline in *S1* from 633.1 to 274.2 (Table 2). This resulted from an increase of the internal area of urban patches over time, which together with a reduction of their number (see Table 1) demonstrates how the city was sprawling outwards. Conversely, *S2* increased over time since socio-economic and geomorphological factors allowed some natural woody patches to be preserved in the urban matrix.

Both the forest and shrubland types have a fractal dimension close to 1.5. This confirms the 'naturalness' of their edges, which is linked to the geomorphology of the area. Mandelbrot (1983) hypothesized that land-use features determined by topographic and hydrologic factors (as opposed to human influences) should have fractal dimensions 1.5.

4.3 Change index and edge analysis

The change index and transition values (Table 3) are more meaningful when analysed together with *P*. In this way, it is possible to obtain useful information regarding the rate of change of one type and how land-use types replace one another. In the present study, the combination of these three indices gives the following information about the forest class: (a) its increase is attributable mainly to a natural transition from shrublands and meadows; (b) the rate of reforestation was constant, increasing by approximately 0.7% during both the 1944-1974 and 1974-1991 periods.

Edge analysis (Table 4) revealed that the total edge length reached its highest value (411.4 km) in 1974, which represents the transition period between two very different and more homogeneous landscapes in 1944 and 1991. The percentage of ecological quality of edge increased in both the low and high quality classes. Low quality urban edges in-

Table 4. Percentage of three categories of quality edge to the total edge length.

	Percentage of total edge lenght		
Ecological quality of edge	1944	1974	1991
Low	46.8	62.2	67.3
Medium	48.7	31.6	20.9
High	4.5	5.2	11.8
Total edge lenght (km)	321.8	411.4	351.3

Table 5. Landscape pattern indices, dominance (D), contagion (C) and fractal dimension.

Index	1944	1974	1991
Dominance	0.44	0.22	0.40
Contagion %	57.38	49.01	56.03
Fractal dimension	1.36	1.43	1.39

creased, as did 'high ecological quality' classes (from 4.5 to 11.8%) reflecting natural reforestation.

4.4 Pattern indices

These indices, which describe the entire landscape, have some limitations in that the degree of information is sometimes incomplete (Hulshoff 1995). Pattern indices should therefore be analysed together with structural indices. The dominance index, for example, does not indicate which is the predominant land use type. Furthermore, some indices are redundant, for example the dominance and contagion indices (O'Neill et al. 1988). Despite these problems, pattern indices capture important features of the landscape. It is worth noting that while the dominance and contagion indices have the same trend, the fractal dimension has an opposite one (Table 5). The results confirm that 1974 was a transition period characterised by higher landscape heterogeneity (lower dominance value), higher fragmentation and dispersion (lower contagion value), and greater complexity (higher fractal dimension). Landscape pattern values in 1944 and 1991 were similar, despite a change in the landscape matrix from agricultural to urban.

5. Conclusions

This study evaluated the effectiveness of various indices and methods for examining spatio-temporal changes in the urban landscape pattern of Rome. The combination of GIS and landscape indices was used to quantify the complexity and temporal development of the whole landscape, as well as individual land-use types. The multitemporal analysis elucidated the relationship between landscape heterogeneity and both natural and human factors. However, limitations in both methodology and landscape indices were also revealed. Sources of error may arise during the digitalisation, data analysis and overlapping processes (Johnson 1990). Furthermore, some indices are highly redundant (e.g. the dominance and contagion indices), while others are only meaningful in the context of other indices (e.g. the proportion of land use types, rates of change, and transitions should be examined together to provide adequate information regarding changes in land-use type). To conclude, our approach is useful in quantifying the relationship between spatio-temporal landscape pattern and biological, physical and socio-economic factors, even if an ecological meaning has to be given to index values during landscape development.

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