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Relationship between vegetation units and terrain parameters in vegetation maps using GIS tools: a case study in the eastern Pyrenees

Utilisation d'un S.I.G. pour étudier les relations entre unités de végétation et paramètres du terrain dans les cartes de végétation : étude d'un cas dans les Pyrénées orientales

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ABSTRACT

A 1:50,000 vegetation map covering 486 km^2 with 78 cartographic units was digitised and "rasterised" to 150 x 150 m grid-cell. Vegetation units were based on floristic criteria. Four other raster layers were also produced to the same format: slopes, aspect, altitude and bedrock type. The relationship of vegetation units (total of 58 units) and physiognomic communities (forests, shrublands, grasslands, agricultural land and rocky areas) with terrain parameters was studied by overlaying these raster layers. Spatial structure (autocorrelation, fragmentation and shape) of the forest communities was also studied. The results show that the area is covered mainly by a large number of forest communities and grasslands, however most of these vegetation types cover a small area or are highly fragmented. Vegetation units and physiognomic communities are highly related to terrain parameters, among which altitude and bedrock type are the most important. Nearly half of the potential forest area is deforested, specially at high altitude. The application of accurate vegetation maps linked with GIS to environmental conservation and management is discussed.

Key-words: vegetation mapping, landscape structure, potential vegetation, actual vegetation, land-use, Geographical Information System, vegetation-environment

RESUME

Nous avons numérisé et "rasterisé" une carte de végétation à 1:50 000° couvrant 486 km^2 et comprenant 78 unités cartographiques. Les unités de végétation ont été définies selon un critère floristique. De la même façon, nous avons produit également quatre couches raster additionnelles : pente, exposition, altitude et lithologie. Les relations entre les unités de végétation (58 unités) et les unités physionomiques (forêts, formations arbustives, pâturages, cultures et aires rocheuses) et les paramètres du terrain ont été étudiées par superposition de ces couches raster. Nous avons aussi étudié la structure spatiale (autocorrelation, fragmentation et forme) des communautés forestières. Les résultats montrent que le territoire est surtout couvert par un grand nombre de forêts et de pâturages et que la plupart de ces types de végétation occupent de petites surfaces ou sont nettement fragmentés. Aussi bien les communautés végétales que les unités physionomiques présentent une corrélation très étroite avec les paramètres du terrain, parmi lesquels l'altitude et la nature de la roche mère sont les plus importants. A peu près la moitié de l'aire potentiellement forestière est déboisée, notamment en altitude. Dans ce cadre, on discute l'intérêt des cartes de végétation intégrées au sein d'un S.I.G. pour la conservation et la gestion de l'environnement.

Mots-clés : cartographie de la végétation, structure du paysage, végétation potentielle, végétation actuelle, usage du sol, Système d'Information Géographique, végétation-environnement

INTRODUCTION

Current world-wide concerns about the management and conservation of native vegetation has led to a renewed interest in land-cover mapping. Vegetation maps provide basic information for any environmental decision-making process and when linked to a Geographical Information System (GIS), they can be powerful tools for environmental management. Before any assessment on the vegetation of a given area can be made, it is necessary to know the potential vegetation type, which species are predominant, how they are distributed, and their relative abundance. Vegetation maps, when accurate, provide this information. Cartographic units of vegetation maps also reflect climatic conditions and previous management patterns, and integrate other parameters such as habitat suitability for the fauna (e.g. Mead *et al.*, 1981; Haslett, 1990). Size, shape, distribution and composition of patches across a landscape determine the availability of wildlife habitat (Forman & Godron, 1981; Burges & Shape, 1981). Entire ecosystems, rather than individual species, are increasingly seen as the units which conservation should address, especially when the threatened status and ecological requirements of each individual species is unknown. All these characteristics make vegetation maps a powerful source of information for conservation and management, and GIS tools are an excellent way to extract it (Marguire *et al.*, 1991). GIS can greatly assist us in assessing relationships between vegetation types and terrain parameters (landscape attributes). Landscape pattern is the result of both natural processes and human-induced disturbances, and these two groups of factors should be studied to understand landscape structure (e.g. Krummel *et al.*, 1987). A quantitative basis for measuring spatial structure is a prerequisite for implementing forest landscape management (Baskent & Jordan, 1995).

The present study aims to extract and quantify the information of a vegetation map in a topographically complex area in the eastern Pyrenees (NE Iberian Peninsula, Spain) using GIS tools, and to show the implications of the results for the land management of the study area. Emphasis is given to the forest communities, for which landscape structure (e.g. autocorrelation and shape indices) is also studied. The questions addressed are: Is there any relationship between vegetation (as defined by cartographic units) and terrain parameters (altitude, slope, aspect and bedrock type)? If so, is this relation similar for the different physiognomic vegetation types (forests, shrublands and grasslands)? What is the relationship between actual and potential vegetation at the landscape level? How can we explain the difference between actual and potential vegetation? What is the spatial structure of the forest communities in the study area? Most of the studies addressing this kind of questions use simple and broad vegetation types obtained from aerial photographs or satellite data. We have used field-based high resolution vegetation units because of the complexity of the landscape studied. The increased understanding of the landscape will enhance our ability to manage our resources wisely.

METHODS

The map

We select a vegetation map recently produced by our research team. This map corresponds to the sheet of La Pobla de Lillet (sheet number 255; scale 1:50,000; Carreras *et al.*, 1994; Carreras & Vigo, 1994) from the map of vegetation of Catalonia. It covers an area of 486 km^2 (18 x 27 km) and is delimited by the UTM co-ordinates 402269, 7669171, 429269, 7687171 (31T DG). This map was created by combining photo-interpretation and an intensive field survey and include both potential and actual vegetation. The vegetation units were defined using floristic criteria and phytosociological studies in the area (Soriano, 1990; Font, 1993; Carreras *et al.*, 1995; Vigo 1996). These units do not always correspond to simple plant communities (e.g. associations), but may correspond to a group of communities (Carreras & Vigo, 1994; Vigo, 1998). For this reason, three types of units were used (see Appendix 1): i) simple units (corresponding to the dominance of a single plant community), ii) complexides (corresponding to a dominant plant community with other close successional stages), and iii) mosaics (group of small communities that are not possible to separate at the scale of the map, often together due to a complex topographic or geological pattern). The map has three interpretation levels: i) physiognomic, with 14 units (10 units of forests, plus shrublands, grasslands, agricultural land, and others; indicated on the map by different symbols and patterns); ii) potential natural vegetation, with 19 units (displayed on the map with different colours); and

iii) actual vegetation, with 78 units (indicated with numbers).

Study area

The map of La Pobla de Lillet covers a montane area located in the southern Pre-Pyrenees (NE Iberian Peninsula), with altitudes ranging from 625 m at the lowest point to 2536 m at the highest peak (Tosa d'Alp). It includes the upper part of the Llobregat basin and a small part of the Ter and Segre basins. The main ranges (Moixeró-Tosa d'Alp and Serra de Mogrony) run from E to W, and have contrasting vegetation on N and S slopes. The bioclimate type (following Banyouls & Gaussen, 1957) is axeric cold in the higher parts and axeromeric in the lower parts. A detailed description of the study area is given by Carreras & Vigo (1994).

Analysis

The vegetation map was digitised and incorporated into ARC/INFO software. This vector coverage with two items, one for potential natural vegetation units and the other for actual (present day) vegetation units, was transformed into two grids of 150 m-square cells, giving 21,600 cells (i.e. 120 cells north-south by 180 cells east-west). This cell size was found to match the resolution of the topographical feature mapping. From the 78 actual vegetation units, only 73 were used in subsequent analyses because the remaining 5 were unvegetated land-use types (urban zones, badlands, etc.). A total of 58 of these units (forests, shrublands and grasslands) are reported at unit level. The remaining units are agricultural land, rocks and aquatic vegetation.

A digital elevation model (DEM) was produced from a topographic map (scale 1:50,000) with altitude contour lines (equidistance of 20 m), the river system, and the main slope bréaking lines, using the TIN system available with ARC/INFO. From this vectorial model (TIN), three grids (150x150 m cell size) were produced: slopes, aspect and altitude. For each one of the 21,600 cells obtained, a value for altitude and slope was assigned. Aspect was transformed to a very simple Moisture Index with values from 1 (SSW), the driest, to 9 (NNE), the wettest following Pausas & Carreras (1995). This index is, in fact, a quantified form of the aspect, which is the main factor affecting moisture in the study area. A simplified lithological map was also digitised and transformed to the same raster format. Lithology was classified in two groups: calcareous bedrock (rich in calcium carbonate) and siliceous bedrock (without calcium carbonate). Previous studies have shown the importance of calcium carbonate in determining vegetation patterns in the study area (Pausas, 1994, 1996a,b; Pausas & Carreras, 1995, 1996). Each cell is considered as a homogeneous unit for any given factor, and so each cell contains one value for each of the above-listed variables.

Level	Measurement
Patch	Size Shape Distance between patches
Unit	Number of patches Mean size, Sd size Total area Mean shape Mean distance between patches Fragmentation Autocorrelation
Physiognomic groups	Number of units Total area Shannon diversity of units
Landscape (whole map)	Total area Shannon diversity of units

Table 1. Summary of the spatial structure measurements computed in the present study organised by hierarchical level

The four raster layers were used to relate terrain parameters (slope, altitude, moisture and bedrock type) with the cartographic units of the actual vegetation. Actual vegetation was also compared with the potential vegetation by superimposing the two corresponding raster layers. Spatial structure measurements were also computed at different hierarchical levels (Table 1). An index of forest fragmentation was computed as the number of patches of a given unit over the total area (patch density of the unit). Spatial autocorrelation (i.e. the degree of clustering, uniformity or randomness of the vegetation patches in the space) was computed by the Geary Index and the Moran Index (Ebdon, 1977; Feoli & Ganis, 1986; Goodchild, 1986; Pausas, 1996c). Shape index was computed as perimeter/2π area (Forman & Godron, 1986). The lowest possible value for this shape index is 1, when the patch is circular. Values increase without limit as the patch shape becomes more irregular.

The size of the different vegetation units (area) was computed using both raster and vectorial methods, to test the validity of the cell size used in the study area. However, vectorial results are used for any value of areas, while the raster format is used for overlaying layers and for testing the relationship between vegetation units and terrain parameters. This relationship was tested by computing mean and deviation values of quantitative independent parameters (altitude, slope and moisture index) and computing the percentage of area covered by each class of the qualitative independent parameters (i.e. bedrock type) for each vegetation type.

The units of the actual vegetation were grouped in 6 vegetation groups based on physiognomic characteristics: forests (including closed forests and open woodlands), shrublands, grasslands, agricultural lands, rocks and scree communities, and others (urban area, badlands, aquatic communities). The cover of each of these groups and the Shannon diversity index (diversity of units) were computed using the cover values from the vectorial data. Forest units were subdivided into three groups on the basis of the leaf physiognomy of the dominant tree: sclerophilous, deciduous and needle leafed. Differences in environmental variables between vegetation groups were tested by analysis of variance and multiple pairwise comparison.

RESULTS

The general analysis of the grid with 21,600 pixels shows that the study area is located in the montane belt (Figure 1), with most of the area (ca. 60%) between 1000 and 1400 m altitude a.s.l. (mean altitude = 1309 and SD= 350). The mean slope value is high (mean slope = 19.4 and SD= 10.4), and the variation in slope and altitude is also high, indicative of mountainous terrain; only 8.2% of the area has slopes lower than 5°. Most of the area (82.9%) is on a calcareous bedrock type (Table 2).

The relationship between areas of vegetation units computed by raster and by vectorial methods is close to 1:1 (Figure 2) suggesting that the size of the cell and the method of rasterisation are appropriate and that computations made using the raster format are accurate.

Vegetation

In total, 60.8% of the area is covered by forest and 22.7% by grasslands (Table 2). Shrublands and other vegetation groups are much less abundant.

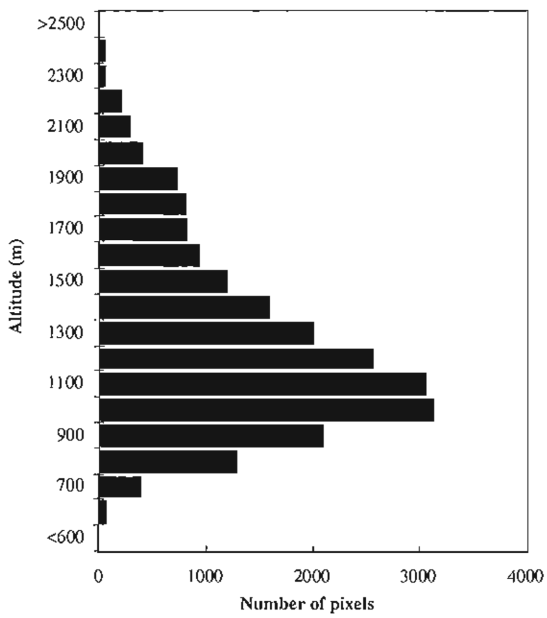

Figure 1. Frequency distribution of altitude for the study area

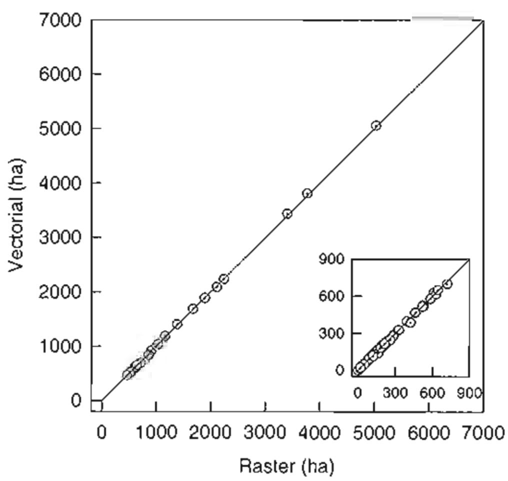

Figure 2. Relationship between size of vegetation patches computed from vectorial and from gridded data (cell size of 150 m). The line refers to 1:1.

The number of units and the diversity of units for each vegetation group is given in Table 2. There is a strong relationship between vegetation groups and altitude: rocky communities are located at the highest altitude, followed by grasslands, shrublands, forests, and cultural lands (Table 2).

These groups also show a strong relationship with moisture: forests and agricultural lands are found on the moistest areas (the former on steeper slopes and at a higher altitude than the agricultural lands), followed by grasslands, rocky vegetation, and shrublands. Rocky vegetation is located on the steepest slopes, shrublands are on steeper slopes than forests, and these are on steeper slopes than grasslands. Most of these vegetation groups are located mainly (>70% by area) on a calcareous bedrock type, and only shrublands are well represented on siliceous bedrock types (Table 2). This may be due to the strong deforestation process on south slopes of the Ribes valley where siliceous bedrock is dominant.

1. Forests

Twenty-nine cartographic units of forest vegetation were distinguished (Tables 2 and 3, Appendix 1) by Carreras *et al.* (1994): one sclerophilous forest (U1), 14 deciduous forests (U2-U15), four montane needle-leafed forests (U16-U19), 6 subalpine needle-leafed forests (U20-U25), and 4 secondary woodlands dominated by needle-leafed trees with a grassy understorey (U26-U29). Only 2.3% of the forested area is sclerophilous forest (*Quercus rotundifolia* forest), located at a lower altitude under drier conditions and on steeper slopes than the other forests (Table 4). 63.4% of the forests are dominated by needle-leafed trees, mainly *Pinus sylvestris* and *Pinus uncinata*. Forests dominated by broad-leaved deciduous trees (mainly *Quercus humilis*, *Fagus sylvatica*) represent 34.3% of the total forested area. There is no altitudinal segregation between deciduous and needle-leafed communities.

There is a strong relationship between forest vegetation units and altitude (Figure 3). The forest unit at the highest altitude is U23 (mean altitude = 1916 m), that is, *Pinus uncinata* forests growing on dry slopes (MI= 2.67) and mainly on calcareous bedrock types. At the lower end of the altitudinal range, three main units occur: secondary *Pinus sylvestris* woodlands (U26 and U27) and *Quercus rotundifolia* forests (U1), the latter occurring on drier and steeper sites. The maximum diversity of forest communities is located between 1100 and 1500 m altitude, and the minimum at above 1700 m. Mean moisture index ranges from 2.3 (U23) to 8.2 (U13, *Corylus avellana* communities).

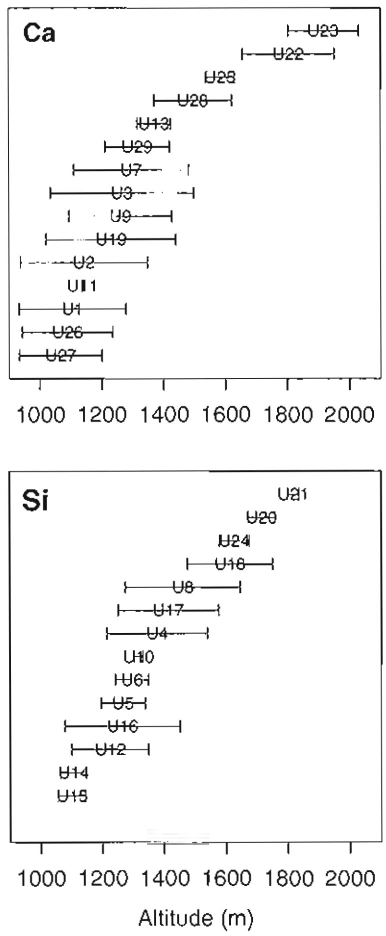

Figure 3. Relationship between forest units (U1-U29) and altitude. The code of the units (U1, U2...) represents the mean value of altitude for the unit, and the horizontal line the standard deviation. Ca (upper graph): units with more than 50% of the area on calcareous bedrock; Si (lower graph): units with more than 50% of the area on siliceous bedrock

Most of the units show a clear preference for one of the bedrock types. The most abundant units (U26, with 22.5% and U27 with 18.8%) are secondary pine woodlands with a grassy understorey, and these covered the lowest altitudinal range of the study area. These pine woodlands are highly managed secondary communities (wood production and grazing) which have developed after the harvesting of original deciduous forest (mainly oaks, *Quercus humilis*). The third and fourth most abundant units are U9 (mix forest dominated by *Pinus sylvestris* and *Fagus sylvatica*) and U2 (mosaic of oak *Q. humilis* forests).

Land-cover	Area Km^2	%	Num. units	Altitude (m) mean	sd	Slope (°) mean	sd	Moisture Index mean	sd	Bedrock (%) Ca	Si	H' bits
Forest	295.86	60.88	29	1222.4	250.2 d	20.1	10.4 c	5.26	2.47 a	86.8	13.3	1.04
Shrubland	23.07	4.75	9	1478.4	214.2 c	24.7	8.7 b	3.21	1.96 d	46.0	54.0	0.83
Grassland	110.18	22.67	20	1549.8	441.8 b	17.4	9.0 d	4.44	2.50 b	81.6	18.4	1.02
Cultural land	26.01	5.35	4	1115.9	204.3 e	12.1	6.9 e	5.23	2.44 a	73.3	26.8	0.28
Roeky & Scree	15.73	3.24	9	1663.9	431.6 a	30.7	12.3 a	4.15	2.23 c	88.1	11.9	0.69
Others	15.16	3.12	7	973.5	216.8 f	12.9	9.0 e	5.42	2.40 a	84.1	15.9	0.65
Total	486.00	100	78	1309.1	349.8	19.38	10.42	4.95	2.5	82.9	17.1	1.46
ANOVA				****		****		****				

Table 2. Area covered (and percentage of the total), number of cartographic units, mean and sd of altitude, slope and moisture index, pereentage of area covered in calcareous (Ca) and siliceous (Si) bedrock types and diversity of units (H', Shannon index). for the main physiognomic groups of land-cover. ANOVA (**** p< 0.0001) and multiple mean comparison are also included (rows with different letters refer to means significantly different at p<0.05).

Forest units	Area %	Altitude (m) mean	sd	Slope (°) mean	sd	Moisture Index mean	sd	Bedrock (%) Ca	Si
U1	2.35	1105.3	172.9	28.2	11.5	3.00	1.97	100.0	0.0
U2	11.54	1142.3	205.1	23.4	11.0	3.89	2.29	99.2	0.8
U3	2.12	1265.4	232.1	23.5	10.3	4.24	2.34	81.4	18.6
U4	3.09	1377.0	162.7	23.1	9.0	3.05	1.77	27.9	72.1
U5	0.33	1266.6	71.1	23.0	8.1	3.00	1.57	4.6	95.5
U6	0.03	1295.5	54.2	14.3	13.4	4.25	2.63	0.0	100.0
U7	2.82	1295.6	184.9	24.8	9.9	6.20	1.93	99.7	0.3
U8	0.45	1459.9	185.7	27.1	11.0	3.92	1.87	23.3	76.7
U9	12.80	1260.5	166.3	22.1	10.7	6.43	1.91	99.0	1.0
U10	0.03	1316.3	14.1	11.0	14.9	4.75	2.75	0.0	100.0
U11	0.02	1137.5	0.7	29.5	12.0	5.50	4.95	100.0	0.0
U12	0.86	1224.8	125.0	21.4	8.0	5.58	2.36	30.1	69.9
U13	0.04	1368.8	53.5	26.8	5.1	8.20	0.84	80.0	20.0
U14	0.09	1105.4	42.4	19.0	10.5	5.00	2.92	0.0	100.0
U15	0.05	1101.0	44.6	10.2	7.9	5.67	1.51	0.0	100.0
U16	0.67	1264.7	185.8	18.0	7.7	6.35	1.80	39.3	60.7
U17	5.72	1412.9	162.3	21.6	8.4	6.74	1.76	18.4	81.6
U18	2.08	1612.6	137.5	20.5	7.9	3.67	2.16	8.7	91.3
U19	5.41	1230.2	209.7	23.8	9.5	6.18	2.28	94.3	5.7
U20	0.03	1714.5	43.8	20.8	15.2	6.25	2.06	0.0	100.0
U21	0.03	1816.5	18.6	19.8	3.6	2.25	0.50	0.0	100.0
U22	4.72	1803.2	148.1	26.2	8.7	6.59	1.94	81.3	18.7
U23	0.35	1916.2	114.5	26.0	10.7	2.67	1.43	60.9	39.1
U24	0.14	1626.4	48.2	25.9	9.5	6.68	1.60	0.0	100.0
U25	0.18	1583.2	46.9	22.5	10.0	7.83	1.17	100.0	0.0
U26	22.55	1089.1	146.8	15.1	9.2	4.03	2.26	99.7	0.3
U27	18.78	1067.1	132.9	17.1	9.4	6.68	1.79	99.7	0.3
U28	2.10	1494.6	125.2	15.7	8.4	4.68	2.53	97.1	2.9
U29	0.62	1314.9	104.5	21.1	9.0	4.16	2.58	61.0	39.0
	100								

Table 3. Percentage of area, mean and sd of altitude, slope and moisture index and percentage of area covered in calcareous (Ca) and siliceous (Si) bedrock for the cartographic units of woodland vegetation. The total area covered by woodlands is 295.86 km^2.

Woodland types	Area %	Altitude (m) mean	sd	Slope (°) mean	sd	Moisture Index mean	sd	Bedrock (%) Ca	Si
Sclerophilous	2.3	1105.3	172.9 b	28.2	11.5 a	3.00	1.97 c	100.0	0.0
Deciduous	34.3	1235.8	200.0 a	22.9	10.5 b	5.02	2.46 b	87.4	12.6
Needle-leafed	63.4	1219.5	274.7 a	18.3	9.8 c	5.48	2.43 a	85.9	14.1
Total	100.0								
ANOVA		****		****		****			

Table 4. Percentage of area, mean and sd of altitude, slope and moisture index and percentage of area covered in calcareous (Ca) and siliceous (Si) bedrock for the main physiognomic groups of forest types. The total area covered by forest is 295.86 km^2.

Shrubland units	Area %	Altitude (m) mean	sd	Slope (°) mean	sd	Moisture Index mean	sd	Bedrock (%) Ca	Si
U30	3.3	1556.3	88.1	26.9	7.6	2.74	1.4	91.2	8.8
U31	3.5	980.3	155.3	27.3	7.4	5.44	1.7	100.0	0.0
U32	15.6	1354.9	225.0	26.2	9.1	2.56	1.7	99.4	0.6
U33	13.9	1578.9	131.7	25.8	9.9	2.69	1.7	32.6	67.4
U34	19.6	1666.3	84.4	23.9	9.4	2.75	1.6	69.0	31.0
U35	1.5	1593.5	56.2	28.5	12.7	6.80	1.9	100.0	0.0
U36	25.0	1369.1	166.2	23.8	7.1	3.46	2.1	12.6	87.5
U37	14.4	1491.1	96.2	23.8	8.7	3.74	1.9	5.4	94.6
U38	3.0	1719.5	78.1	22.3	7.2	3.42	1.7	12.9	87.1
	100								

Table 5. Percentage of area, mean and sd of altitude, slope and moisture index and percentage of area covered in calcareous (Ca) and siliceous (Si) bedrock for the cartographic units of shrublands. The total area covered by shrublands is 23.07 km^2.

Grassland units	Area %	Altitude (m) mean	sd	Slope (°) mean	sd	Moisture Index mean	sd	Bedrock (%) Ca	Si
U39	21.1	1097.5	181.1	18.6	10.2	3.16	2.00	100.0	0.0
U40	5.3	1065.2	159.6	17.5	9.1	4.21	2.26	100.0	0.0
U41	1.8	1622.5	117.0	22.7	9.6	3.19	2.18	87.8	12.2
U42	20.5	1231.3	254.1	14.8	7.9	4.28	2.39	78.0	22.0
U43	1.1	1469.8	140.1	16.0	8.7	4.00	2.30	15.4	84.6
U44	0.1	1481.8	77.1	27.2	4.4	2.67	1.37	0.0	100.0
U45	2.1	1381.8	120.4	17.6	8.0	5.33	2.66	16.8	83.2
U46	1.2	1886.6	175.1	21.0	9.2	3.80	2.10	100.0	0.0
U47	0.5	1220.4	80.9	7.5	5.5	6.68	2.03	100.0	0.0
U48	4.8	1924.3	170.8	22.6	9.3	6.53	2.30	82.8	17.2
U49	10.7	1862.6	98.9	18.3	8.2	3.54	2.12	74.6	25.4
U50	4.8	1842.6	145.7	13.6	8.0	4.58	2.63	97.0	3.0
U51	13.0	1896.6	135.0	16.1	7.3	6.17	2.17	78.8	21.2
U52	1.3	2020.2	95.0	17.6	6.2	6.91	1.92	84.6	15.4
U53	2.3	1781.6	99.9	17.0	8.7	3.77	2.07	57.7	42.3
U54	0.6	1994.5	126.2	14.0	7.0	5.61	1.83	60.7	39.3
U55	0.7	2095.8	137.9	18.6	4.6	3.82	1.99	44.1	55.9
U56	0.2	1950.9	46.5	30.0	11.9	2.00	0.87	88.9	11.1
U57	6.2	2273.7	106.3	21.1	9.8	5.10	2.44	68.2	31.8
U58	1.8	2262.4	95.5	12.8	6.7	6.25	2.06	61.8	38.2
	100								

Table 6. Percentage of area, mean and sd of altitude, slope and moisture index and percentage of area covered in calcareous (Ca) and siliceous (Si) bedrock for the cartographic units of grasslands. The total area covered by grasslands is 110.18 km^2.

The former is located at a higher altitude and in wetter sites. These four units cover 65.6% of the forested area (39.8% of the total area studied).

2. Shrublands

Shrubland covers 4.7% of the study area. From the 9 shrubland units (U30-U38), 5 occur mainly on calcareous bedrock and 4 on siliceous bedrock (Table 5). Unit U36 is the most abundant shrubland in the study area (25% of the shrubland area, and 1.18% of the total area). Shrublands dominated by *Buxus sempervirens* (U32-U35) account for 50.6% of the total shrubland area and the shrublands dominated by *Sarothamnus scoparius* and *Genista balansae* subsp. *europaea* (U36 and U37) represent 42%. Shrubland communities show a clear altitudinal distribution (Figure 4) and the maximum diversity of shrubland communities is at around 1500-1700 m altitude. The shrubland located at the lowest altitude is dominated by the Mediterranean *Quercus coccifera* shrub (U31, mean altitude = 980 m), which occur on steep calcareous slopes (Table 5). Shrublands also show a clear bedrock type preference: most of the units occur mainly on one of the bedrock types (Table 5). Most of the shrub communities show low moisture index values, suggesting that they dominate mainly in dry, south facing slopes. An exception is unit U35, which occurs preferentially on north facing slopes.

3. Grasslands

Grasslands cover 22.6% of the studied area, corresponding to 20 cartographic units (U39-U58), 16 occurring mainly on calcareous bedrock types and 4 on siliceous bedrock types (Table 6). The most abundant unit is U39 (pastures dominated by *Aphyllantes monspeliensis*; 21.1% of the grassland area) followed by U42 (pastures of *Euphrasio-Plantaginetum mediae*; 20.5%), the former at a lower altitude and on drier sites than the latter.

Grassland units are segregated by altitude (Figure 5), and the maximum diversity of units was at around 1700-2000 m altitude.

The mean altitude for grasslands ranges from ca. 1100 m (U39 and U40, mainly pastures dominated by *Aphyllantes monspeliensis*) up to ca. 2300 m (U57 and U58, alpine pastures dominated by *Festuca gautieri* and *F. airoides*, respectively). Most of the units occur mainly on one of the bedrock types suggesting that soil parameters are also important in determining the grassland unit. The mean moisture index ranges from 2 to 6.9.

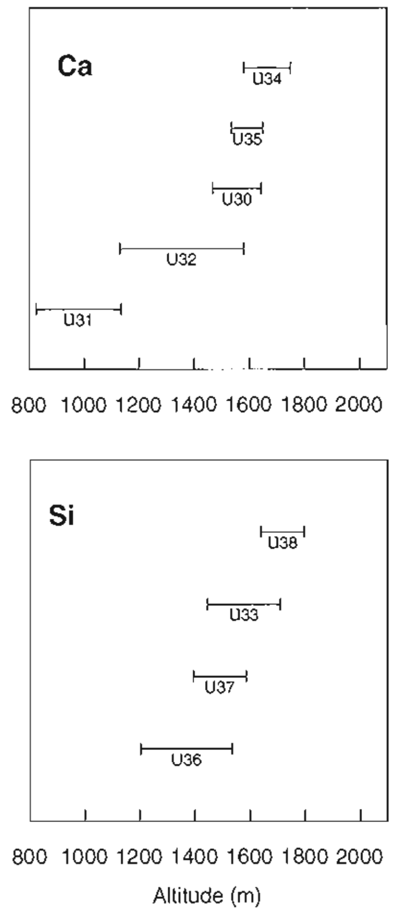

Figure 4. Relationship between shrubland units (U30-U38) and altitude. See Figure 3 for more details.

Relationship between actual and potential vegetation

The potential vegetation of the study area is divided into 19 domains (Appendix 2). Most of the area (95%) is considered to have potentially forested vegetation. Currently, only 61% of the area is dominated by tree species (closed forest or open woodlands) and 55.9% is dominated by closed forests (Table 7). The proportion of deforested area (area with potential forests but currently without forests) shows two peaks, at low and at high altitude, the largest deforested area being at high altitude (Figure 6). Some of the potential vegetation units (PV1, PV4, PV5, PV6, PV8, PV10, PV11) have more than 65% of the area covered by the forest while others (PV13 and

PV14) have less than 10% of the area covered by forests. The most abundant unit of potential vegetation (PV2, *Quercus humilis* forests) have only 23.1% of the area covered by closed forests, 45.7 % covered by secondary open woodlands of *Pinus sylvestris*, and 3.9 covered by shrublands. Some low abundance forest types (e.g., PV3, PV7, PV12) have a large proportion of their area occupied by agricultural land or managed grasslands. A large proportion of the area with potential vegetation assigned to PV3 and PV9 is covered by shrublands. Grasslands cover a large proportion of the area assigned to *Pinus uncinata* forests (P13 and P14), plus the area where grasslands is supposed to be the potential vegetation (alpine pastures P15 and P16).

Landscape structure

About 60% of the area studied is covered by forests or woodland communities, distributed in 73 patches (Table 8). The size of these patches is highly variable (mean= 4 km^2, sd= 25 km^2). For the different forest vegetation units, 497 patches were mapped with sizes ranging from 9343 m^2 (the smallest patch of U12, without considering the fraction of patches at the edge of the map) up to ca. 16 km^2 (the largest patch of U26). There is a positive relationship between the number of patches and the total area covered (Figure 7) and so, no large continuous forest units occur: the units are either small, or large and fragmented. Different forest units show different spatial patterns (autocorrelation) and degrees of fragmentation (Table 8). The lowest clustered distribution (low values of the Moran index) is found for riverine communities (e.g., U14 and U15). Indices of autocorrelation and fragmentation are highly related (Figure 8; Correlation Geary-Moran: -0.96). Units with a large number of patches (i.e., more than 40) show low autocorrelation and high fragmentation (U2, U9, U26, U27); however, the degree of autocorrelation and fragmentation of the units with a lower number of patches depends on the size and the spatial distribution of the patches (Figure 9). The shape index of these patches ranges from 1.02 to 5.84 (mean= 1.68, sd= 0.575); however, at unit level the variation is much smaller (1.19-1.87, Table 8).

On the basis of the landscape structure (Table 8), cartographic units may be classified as follows:

a) units with very low representativeness (one or two small patches), occupying a small area of the map (<0.5km^2). These are mainly *Corylus avellana* communities (U13), *Quercus petreae* forests (U6), deciduous mixed forests (U10, U11), acidophilous *Pinus uncinata* forests (U20, U21), *Salix purpurea* communities (U15), and *Abies alba* forests (U24, U25);

Potential Vegetation		Actual Vegetation				
		Closed forests	Secondary woodlands	Shrublands	Grasslands	Cultural lands
Unit	Area					
PV1	2.02	72.7	3.5	15.2	8.4	0
PV2	55.40	23.1	45.7	3.9	20	7
PV3	1.55	12.7	18.5	30.7	2.6	35.3
PV4	0.04	100	0	0	0	0
PV5	11.40	86.3	11.4	0	1.9	0.3
PV6	0.29	100	0	0	0	0
PV7	0.97	58.5	0	0	2.9	38.5
PV8	4.12	84.2	1.7	0.7	7.1	5.9
PV9	3.36	37.8	0.2	45.4	13.9	2.4
PV10	1.62	65.8	0	10.6	15.5	8
PV11	0.14	100	0	0	0	0
PV12	7.83	36.8	0	0.05	62.2	0.8
PV13	0.46	3.9	0	1.9	94.0	0
PV14	4.22	5	0	0.3	94.6	0
PV15	0.18	-	-	-	100	0
PV16	0.58	-	-	-	100	0
PV17	1.40	100	0	0	0	0

Table 7. Percentage of area covered by each potential vegetation unit (PV1-PV17; Appendix 2), and percentage of each potential vegetation unit covered by different actual vegetation types (closed forests, secondary open woodlands, shrublands, grasslands and agricultural land). Rocky areas and urban zones are not included. - *: not applicable (above the timber-line)*

Forest units	Num. of patches	Mean Distance km	Mean Shape	Total Area km^2	Mean Size km^2	Sd Size km^2	Num./ T. area	Autocorrelation Moran Index
U1	25	6.17	1.64	7.20	0.29	0.29	3.47	0.58
U2	77	9.80	1.79	34.03	0.44	0.58	2.26	0.62
U3	14	8.49	1.70	6.12	0.44	0.31	2.29	0.64
U4	11	5.00	1.79	9.09	0.83	1.07	1.21	0.73
U5	12	2.68	1.20	0.96	0.08	0.04	12.49	0.39
U6	2		1.19	0.08	0.04	0.01	23.77	0.25
U7	33	11.47	1.45	8.61	0.26	0.25	3.83	0.58
U8	7	5.88	1.43	1.40	0.20	0.21	5.00	0.57
U9	42	10.01	1.74	37.68	0.90	1.91	1.11	0.73
U10	2		1.17	0.09	0.05	0.03	21.48	0.25
U11	1	-	1.15	0.03	0.03	-	31.11	0.25
U12	27	5.47	1.46	2.65	0.09	0.15	10.19	0.42
U13	2		1.34	0.14	0.07	0.00	14.75	0.20
U14	8	1.86	1.29	0.33	0.04	0.02	24.57	0.08
U15	2		1.80	0.16	0.08	0.07	12.19	0.00
U16	10	9.61	1.61	2.13	0.21	0.23	4.69	0.56
U17	13	10.08	1.86	16.91	0.99	1.57	0.77	0.78
U18	16	9.91	1.49	6.29	0.37	0.49	2.54	0.68
U19	22	9.55	1.87	16.10	0.56	0.61	1.37	0.69
U20	2		1.40	0.09	0.04	0.02	22.57	0.25
U21	1	-	1.76	0.13	0.13	-	8.00	0.38
U22	15	9.36	1.78	13.84	0.92	1.92	1.08	0.76
U23	5	3.75	1.63	1.05	0.21	0.15	4.77	0.50
U24	1	-	1.68	0.46	0.46	-	2.16	0.64
U25	2		1.16	0.52	0.26	0.01	3.85	0.67
U26	59	9.97	1.78	66.13	1.02	2.60	0.89	0.74
U27	69	10.46	1.81	55.52	0.76	1.35	1.24	0.69
U28	9	4.60	1.77	6.31	0.63	0.59	1.43	0.68
U29	8	9.01	1.48	1.79	0.22	0.20	4.46	0.58

Table 8. Number of patches, mean distance between the centre of the patches, mean shape index, total area of the unit, size patch mean and sd, number of patches: total unit area, and Moran autocorrelation index for the different forest units

b) units with low representativeness (<1 km^2) but better represented than the previous units, and with a high fragmentation value and low spatial autocorrelation: *Alnus glutinosa* forests (U14), Ash forests (U12), and *Quercus humilis* forests with *Pteridium aquilinum* (U5);

c) units covering a large area (>25 km^2), with a high number of patches (>40): calcicolous and thermophilous *Quercus humilis* forests (U2), mosaic of mixed *Fagus sylvatica* and *Pinus sylvestris* forests (U9), and sub-montane woodlands of *Pinus sylvestris* (U26, U27);

d) the rest of the units that have fewer patches and occupy a smaller area than c) but higher than b): *Fagus sylvatica* forests (U7, U8), montane coniferous forests (U16-U19), montane *P. sylvestris* woodlands (U28, U29), calcicolous *P. uncinata* forests (U22, U23), and calcicolous and siliceous mesoxerophilous *Quercus humilis* forests (U3 U4). This heterogeneous group includes some units (U8, U23, U29) with lower representativity and higher fragmentation than the others.

DISCUSSION

The area studied is an abrupt montane area covered mainly by forest communities and by grasslands. About 60% of the forest area is occupied by four of the 29 forest units (U2, U9, U26, U27). 16 units cover less than 1% of the forest area. This implies that although the area contains a rich variety of forest types, most of them are badly represented. Furthermore, the two largest units (U26 and U27, ca. 40% of the forests) are highly managed secondary pine woodlands (for wood production and grazing) which have developed after the harvesting of the original deciduous forest (mainly oaks, *Quercus humilis*). These pine woodlands have a low conservation value for both flora and fauna. Most of the forests are also fragmented, and no large fragments occur.

Scots pine (*Pinus sylvestris*) is the most abundant tree in the area. Units dominated by Scots pine cover about 60% of the forest area (ca. 35.2 % of the total map). The vegetation patterns and ecology of these forests has been studied within the study area (Pausas, 1994, 1996a,b,c, 1997; Pausas & Carreras, 1995, 1996). *Buxus sempervirens* is the most abundant shrub. It is the dominant species in more than 50% of the area covered by shrublands, and is the main understorey species in some of the forest communities (e.g. U2, U3, U4, U7, U8; Carreras *et al.*, 1995). The ecology of this species is still poorly understood. Vegetation units are related to terrain parameters at different hierarchical levels.

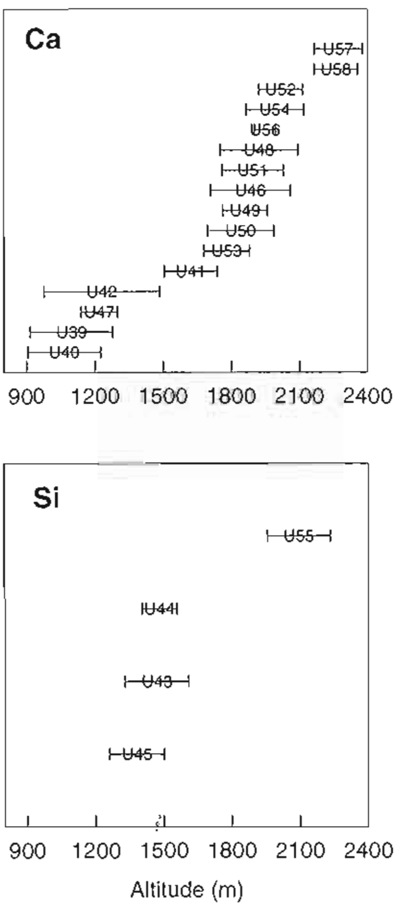

Figure 5. Relationship between grassland units (U39-U58) and altitude. See Figure 3 for more details.

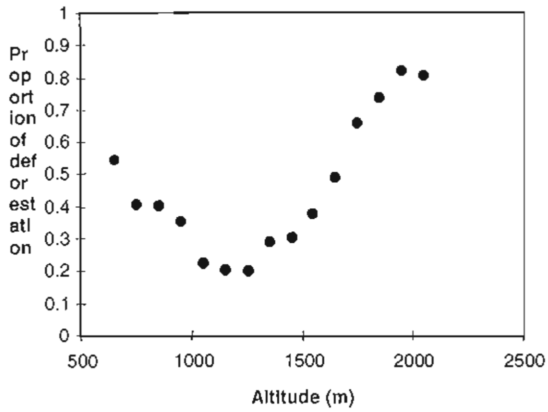

Figure 6. Proportion of deforested area in relation to altitude. Each dot represents the proportion of potentially forested cells but currently without forest in 100 m altitude steps.

Physiognomic communities (forests, shrublands, grasslands, agricultural land, and rocky and scree communities) are clearly segregated by the terrain parameters studied (altitude, slope, moisture and bedrock type). The fact that agricultural land is on the moistest sites (like forests but on less steep slopes at a lower altitude than forests) may be due to the higher productivity of these conditions (flat sites or low slopes sites facing north) and to the abandonment of south-facing agricultural land in the last few decades (García-Ruiz *et al.*, 1996). North-facing forests are also more productive than south facing ones (Pausas & Fons, 1992). Segregation with terrain parameters is also found for several forests dominated by different tree types (sclerophilous, deciduous and needle-leafed trees). However, no altitudinal segregation is found between deciduous forests and needle-leafed forests, probably due to the large areas of secondary pine woodlands resulting from the harvesting of deciduous trees. Communities dominated by needle-leafed trees (U16-U29) may be closed forests (U16-U25) or secondary open woodlands with a grassy understorey (U26-U29). At the level of the smallest cartographic unit, the relationship with terrain parameters is also demonstrated (Tables 3, 5 and 6), especially for altitude (Figures 3, 4 and 5).

Climate is a complex parameter related to altitude (especially the temperature). Most of the vegetation groups show some pattern with altitude, suggesting the importance of climatic parameters in explaining the vegetation distribution. Note also that the minimum diversity of grassland units (1200-1500) is at the altitudinal range where the maximum diversity of forest units is found (compare Figure 3 and 5). However, a better estimation of climate, other than altitude, would be more meaningful (e.g. mean annual temperature, etc.).

Bedrock type is another parameter that is clearly related to a large number of units. For example, from the 29 forest units, 24 have more than 75% covering one of the bedrock types. A similar pattern is observed for the shrublands and grasslands. Some understorey species have been found to be strongly related to the calcium carbonate (Pausas, 1996a), and the diversity of these forest has also been related to the concentration of calcium in the soil or the presence of carbonate in the bedrock (Pausas, 1994; Pausas & Carreras, 1995).

Although the area is dominated by calcareous bedrock types (ca. 83% of the total area; Table 2), a large number of vegetation units occur mainly on siliceous bedrock types. Eleven forests units, seven shrublands units and three grasslands units (from a total of 29, 9 and 20 units respectively) have more than 75% of their area on siliceous bedrock types. This suggests that plant diversity may not be related to the size of the area, but to the diversity of terrain factors (i.e. landscape heterogeneity), as has been shown in other landscapes (Harner & Harper, 1976; Burnett *et al.*, 1998).

There is a strong relationship between vegetation units defined by floristic criteria and terrain parameters. This relationship helps us to understand the ecology of the different plant communities, and may be used to develop maps for predicting vegetation communities in adjacent areas where vegetation maps are not yet available. The predictive value of the vegetation may also be used in revegetation and afforestation planning (Coulson *et al.*, 1991).

Nearly half of the potential forest sites are deforested, and the deforestation is more acute at high altitude with a second peak at low altitude (Figure 6). This pattern may be explained by different land-uses (García-Ruiz *et al.*, 1996): high altitudes areas have been deforested and converted to pastures for summer grazing, while intermediate altitudes have been used for production forests. The high altitudinal grazing has led to the lowering of the timber-line (Braun-Blanquet, 1948; Carreras *et al.*, 1996). The largest deforested areas of the upper forest (forests dominated by *Pinus uncinata*, PV11 - PV14) are on south-facing slopes (PV13, PV14, Table 7). This fact may be because of north slopes are often preferred for wood production (because of the better growth) while south slopes may be dedicated to summer grazing. South slopes have more contrasted climatic conditions (very dry in summer, cool in winter) that make tree growth and regeneration more difficult than in north slopes.

The spatial structure of the forest units suggests that most of the forest communities were either poorly represented or highly fragmented. No units were found to have few patches occupying large and continuous areas and half of the forest units each covered less than 1% of the forested area.

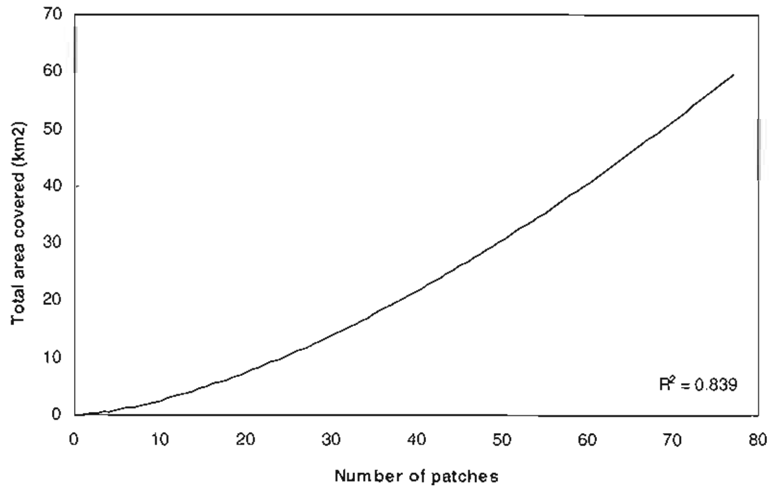

Figure 7. Relationship between number of patches of each forest unit and the area covered (km^2)

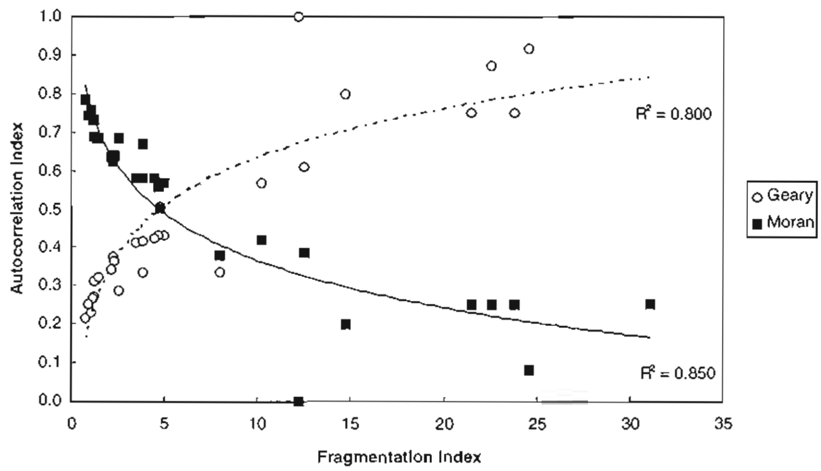

Figure 8. Relationship between autocorrelation indices and fragmentation index. Lines are logarithm fit.

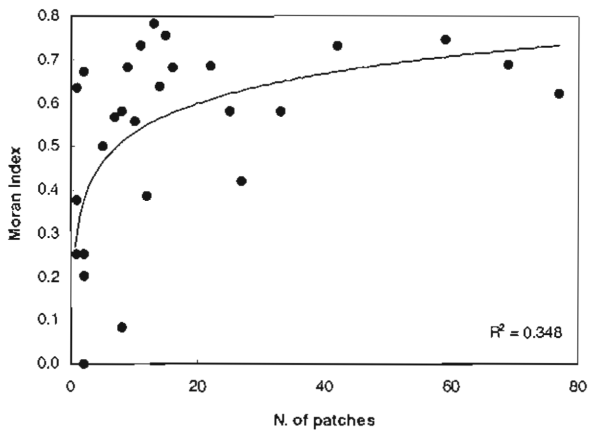

Figure 9. Relationship between autoeorrelation (Moran Index) and number of patches for the different forest units. Line is the logarithm fit.

CONCLUDING REMARKS

A prerequisite to sustaining ecosystems is the inventory and classification of landscape composition and structure. We have shown that accurate vegetation maps linked to GIS allow us to quantify the different land-cover and vegetation units as well as their spatial structure. The long-term maintenance of biological diversity may require a management strategy with an emphasis on the regional and landscape level (Noss, 1983). Vegetation maps for the adjacent areas are currently being developed and GIS tools will allow us to study the vegetation patterns at a larger regional level (large ranges or basins). This would exemplify a regional land-use analysis and management in a south European range where human impact is very high.

We have detected some communities with very low representativeness in the study area that have few and small patches or are highly fragmented. Knowledge of the landscape structure (e.g. area, shape) and the geographical location of these poorly represented communities are basic information for the conservation of biodiversity objectives. The approach used may also allow us to test the threatened status of plant communities in a study area and may help in selection of the most important or urgent communities to be preserved. It may also allow us to assess habitat quality for fauna populations by linking vegetation units to habitat suitability values of a target species (or guild);

or ecosystem productivity by linking vegetation units to site quality classes.

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APPENDIX 1

List of actual (present day) vegetation units for the map "La Pobla de Lillet" (simplified and modified from Carreras *et al.*, 1994). This list typifies the 58 units quoted in the figures and tables of the present study. Additional units not detailed here (U59 -U77) are agricultural land, rocky and scree vegetation, and unvegetated land (e.g., urban areas and badlands). Although the description of the units here show some ecological parameters (mesophilous, thermophilous, acidophilous, etc.), they were defined using floristic criteria only, on the basis of phytocoenogical studies in the area. A colour map (scale 1:50,000) with a full description of all units may be purchased at the *Institut Cartogràfic de Catalunya* (Barcelona); a copy of the legend of the map with a phytocoenological description of all units may be provided by the authors upon request.

A. FORESTS AND WOODLANDS

A.a. Sclerophilous forests

U1. Complexide of *Quercus rotundifolia* forests

A.b. Deciduous forests (occasionally with pines)

U2. Complexide of calcicolous and thermophilous *Quercus humilis* forests
U3. Complexide of calcicolous and mesoxerophilous *Quercus humilis* forest
U4. Complexide of *Quercus humilis* -or *Pinus sylvestris*- forests on south facing, siliceous slopes
U5. Acidophilous *Quercus humilis* forests with *Pteridium aquilinum*, on south facing slopes
U6. Acidophilous and mesophilous *Quercus petraeae* forests
U7. Mosaic of calcicolous *Fagus sylvatica* forests
U8. Complexide of acidophilous *Fagus sylvatica* forests
U9 Mosaic of mixed *Fagus sylvatica* and *Pinus sylvestris* forests on north facing, calcareous slopes
U10. Acidophilous and mesophilous mixed forests with predominance of oaks and *Betula pendula*
U11. Thermophilous mixed forests (with lime, ash, oaks, etc) of Sub-montane belt
U12. Ash forests (occasionally hazel thickets or oak woods)
U13. *Corylus avellana* thickets (or mixed, mesophilous forests) of the higher montane belt
U14. *Alnus glutinosa* forests
U15. *Salix purpurea* communities

A.c. montane coniferous forests

U16. Acidophilous, secondary *Pinus sylvestris* forest on north facing slopes
U17. Acidophilous primary *Pinus sylvestris* forest on north facing slopes
U18. Complexide of acidophilous *P. sylvestris* forests of the higher montane belt, on south facing slopes
U19. Mosaic of calcicolous scots pinewoods with blue sesleria

A.d. Coniferous forests of the sub-alpine (and higher montane) belt

U20. Acidophilous forests of *Pinus uncinata* on north facing slopes
U21. Complexide of acidophilous forests of *Pinus uncinata* on south facing slopes
U22. Calcicolous forests of *Pinus uncinata* on north facing slopes
U23. Complexide of open pinewoods of *Pinus uncinata* on calcareous south facing slopes
U24. Acidophilous forests of *Abies alba*
U25. Calcicolous forests of *Abies alba*

A.e. Submontane and montane pine woodlands with non forest understorey

U26. Sub-montane woodlands of *Pinus sylvestris* (or *P. nigra*) with grassy mesoxerophylous understorey, on south facing slopes
U27. Sub-montane woodlands of *Pinus sylvestris* (or *Pinus nigra*) with grassy mesoxerophilous understorey on north facing slopes

U28. montane woodlands of *Pinus sylvestris* over calcicolous pastures
U29. Woodlands of *Pinus sylvestris* over heaths of *Calluna vulgaris*

B. SHRUBLAND VEGETATION
U30. Mesoxerophilous *Corylus avellana* comunities
U31. Complexide of *Quercus coccifera* scrubs
U32. Complexide of xerothermophilous scrubs of *Buxus sempervirens* on south facing, calcareous slopes
U33. Complexide of xerothermophilous scrubs of *Buxus sempervirens* on south facing siliceous slopes
U34. Complexide of mesoxerophilous scrubs of *Buxus sempervirens* on south facing calcareous slopes
U35. Complexide of high montane scrubs of *Buxus sempervirens* on north facing, calcareous slopes
U36. Complexide of montane heaths of *Sarothamnus scoparius* on south facing, siliceous slopes
U37. Complexide of higher montane heaths of *Genista balansae* subsp. *europaea* and *Sarothamnus scoparius* on south facing, siliceous slopes
U38. Complexide of sub-Alpine heaths of *Genista balansae* subsp. *europaea* on south facing slopes

C. GRASSLAND VEGETATION
C.a. Pastures of sub-montane and montane belt
U39. Pastures of *Aphyllanthion* on calcareous, south facing slopes
U40. Initial pastures on abandoned cultures
U41. Xerophilous and mesophilous pastures on limestone soils
U42. Mesophilous pastures on limestone soils
U43. Acidophilous pastures, rocky areas and *Genista balansae* subsp. *europaea* heaths
U44. Complexide of dry, acidophilous pastures
U45. Complexide of acidophilous, mesophilous pastures of *Genistella sagittalis*

C.b. Sub-alpine (and higher montane) pastures
U46. Thermophilous pastures of higher mountainous belt on limestone soils
U47. Calcicolous, dry pastures on rocky soils
U48. Complexide of *Festuca gautieri* pastures
U49. Complexide of xerophilous and mesophilous pastures on limestone, on south facing slopes
U50. Complexide of masophilous and xerophilous pastures on limestone, on north facing slopes
U51. Complexide of calcicolous, mesophilous pastures
U52. Complexide of more or less acidophilous pastures on limestone soils
U53. Complexide of acidophilous pastures of higher montane belt, with *Nardus*, *Genistella sagittalis*
U54. Complexide of acidophilous pastures with *Festuca airoides* of sub-Alpine belt
U55. Acidophilous pastures of *Nardus stricta*
U56. Acidophilous, thermophilous pastures of *Festuca paniculata*

C.c. Alpine pastures
U57. Mosaic of calcicolous pastures
U58. Mosaic of acidophilous pastures

APPENDIX 2

List of the cartographic units of potential vegetation for the map "La Pobla de Lillet" (simplified and modified from Carreras *et al.*, 1994). See Appendix 1 for comments on the availability of the full description.

PV01 - *Quercus rotundifolia* forests
PV02 - Submediterranean basiphilous (or neutrophilous) *Quercus humilis* -or *Pinus sylvestris*- forests
PV03 - Submediterranean calcifugous *Quercus humilis* -or *Pinus sylvestris* - forests
PV04 - Acidophilous *Quercus petraea* forests
PV05 - Calcicolous beech (or *Abies alba*) forests
PV06 - Acidophilous *Fagus sylvatica* forests
PV07 - *Fraxinus excelsior* forests and related hygromesophilous mixed forests
PV08 - Montane acidophilous and mesophilous forests of *Pinus sylvestris* (or *Abies alba*)
PV09 - Montane acidophilous and xerophilous *Pinus sylvestris* forests
PV10 -Montane calcicolous forests of *Pinus sylvestris*
PV11 - Acidophilous and mesophilous *Pinus uncinata* forests
PV12 - Calcicolous and mesophilous *Pinus uncinata* forests
PV13 - Acidophilous and xerophilous *Pinus uncinata* forests
PV14 - Calcicolous and xerophilous *Pinus uncinata* forests
PV15 - Acidophilous alpine pastures, mainly *Festuca airoides*
PV16 - *Festuca gautieri* pastures and other calcicolous Alpine pastures
PV17 - *Alnus glutinosa* and *Salix purpurea* communities
PV18 - Calcicolous vegetation on rocky areas and scree
PV19 - Acidophilous vegetation on rocky areas and scree