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Integrating Landscape Ecology and Geoinformatics to Decipher Landscape Dynamics for Regional Planning

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Abstract We used remote sensing and GIS in conjunction with multivariate statistical methods to: (i) quantify landscape composition (land cover types) and configuration (patch density, diversity, fractal dimension, contagion) for five coastal watersheds of Kalloni gulf, Lesvos Island, Greece, in 1945, 1960, 1971, 1990 and 2002/2003, (ii) evaluate the relative importance of physical (slope, geologic substrate, stream order) and human (road network, population density) variables on landscape composition and configuration, and (iii) characterize processes that led to land cover changes through land cover transitions between these five successive periods in time. Distributions of land cover types did not differ among the five time periods at the five watersheds studied because the largest cumulative changes between 1945 and 2002/2003 did not take place at dominant land cover types. Landscape composition related primarily to the physical attributes of the landscape. Nevertheless, increase in population density and the road network were found to increase heterogeneity of the landscape mosaic (patchiness), complexity of patch shape (fractal dimension), and patch disaggregation (contagion). Increase in road network was also found to increase landscape diversity due to the creation of new patches. The main processes involved in land cover changes were plough-land abandonment and ecological succession. Landscape dynamics during the last 50 years corroborate the ecotouristic-agrotouristic model for regional development to reverse trends in agricultural land abandonment and human population decline and when combined with hypothetical regulatory approaches could predict how this landscape could develop in the future, thus, providing a valuable tool to regional planning.

Keywords Coastal watershed · Land use/cover change · Landscape metrics · Physical attributes · Human attributes · North East Aegean · Regional planning

Introduction

Contemporary landscapes exhibit dramatic changes worldwide under the influence of a suite of social (economic, technological, demographic, institutional, cultural, historic) and biophysical (e.g., geology, water bodies presence and extent, climate, soil) factors (Lambin and Geist 2006). The application of remote sensing (RS) and geographic information system (GIS) technologies allowed the development of landscape metrics to trace, explain and manage changes in composition and configuration at the landscape level based on studied relationships among structure, process, and function in a landscape (Turner 2005).

Metrics of landscape structure, land use/cover change in particular, provide indicators for the (socio-economic) Driving, (environmental) Pressure, State, Impact, and (policy) Response (DPSIR) auditing framework (Smeets and Weterings 1999; Cave and others 2003; Yu and Ng 2006; Valenzuela Montes and others 2008) and for the assessment of cumulative impacts of human activities on the environment (Jones and others 2001; Lin and others 2006). Also, monitoring of landscape metrics aims to establish a time series against which changes in landscape

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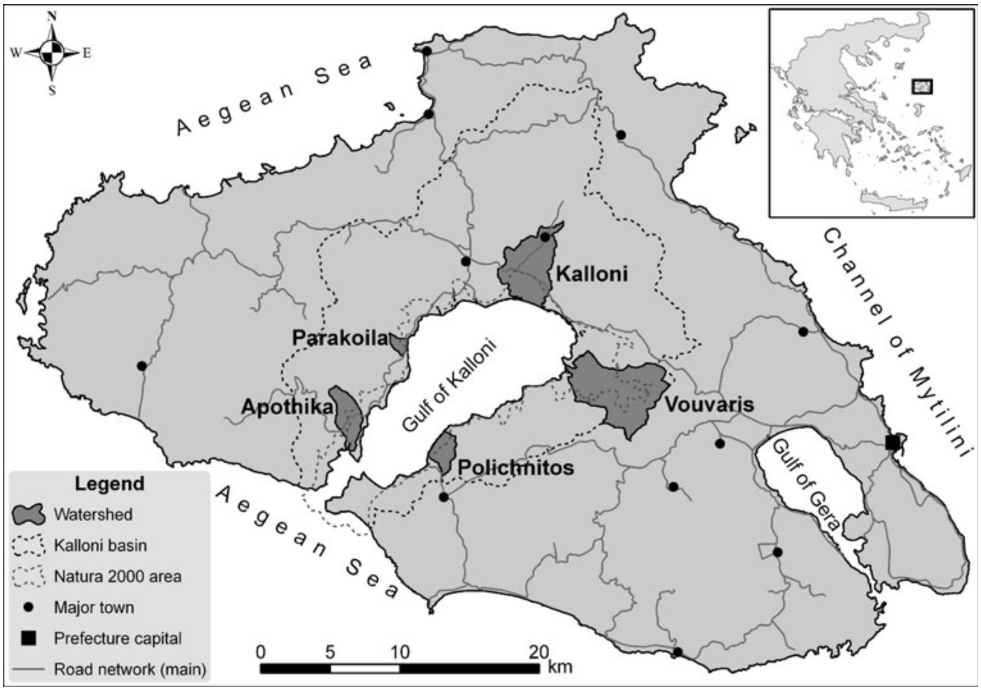
structure can be detected (e.g., Duncan and others 1999; Nelson and others 2002; Alphan and Yilmaz 2005; Yu and Ng 2006; Papastergiadou and others 2008), their direction, magnitude and significance determined (Remmel and Csillag 2003), and empirical relationships with socio-economic (human) and physical variables evaluated for their explanatory and constraining power, respectively (Pan and others 1999; Geist and Lambin 2001; Fucamachi and others 2001; Bürgi and Turner 2002; Black and others 2003; McKonnell and Keys 2005). Furthermore, understanding of landscape dynamics facilitates better management of natural resources at the landscape scale through policy evaluation, modelling and scenario development (Wear and others 1996; Zomeni and others 2008; Walz 2008).

Albeit the selection of landscape metrics depends on the specificity of research/management objectives (Yang 2005), the gamut of metrics describing landscape pattern expands rapidly driven by developments in pertinent methodologies integrating RS and GIS technologies (Klemas 2001; Wu and others 2002; Yang and Lo 2002; Yang 2005). Much empirical work is still necessary, however, before landscape ecology develops adequate understanding of the relationship between landscape pattern and ecological process at different spatial and temporal scales and best indicators for this purpose (Li and Wu 2004; Turner 2005 review). As a consequence, the interpretation of many landscape indicators to elucidate change and driving forces at and across different scales remains as yet an area amenable to research (Gustafson 1998; but see Black and others 2003). Furthermore, landscape indicators present considerable redundancy because they derive from a limited set of functions and, thus, the application of redundancy techniques has been advocated for the selection of core indicators (Riitters and others 1995; Yang and Liu 2005). Landscape indicators are also sensitive to scale (grain and extent; Cain and others 1997; Gustafson 1998) and, thus, comparison of their values is useful only temporally for the same sites. Furthermore, we are still lacking a robust methodology to test for statistical significance in landscape metrics but for binary landscapes (Remmel and Csillag 2003). Therefore, only subjective comparisons among landscape indicators at different times can be made. Nevertheless, the watershed has been widely employed by both scientists and managers as a convenient and meaningful spatial unit to assess, monitor, and interpret change in landscape pattern (Johnston and others 1990; Duncan and others 1999; Jones and others 2001; Alphan and Yilmaz 2005; Frost and others 2006; Valenzuela Montes and others 2008).

Our study presents a methodology that integrates RS and GIS to develop core landscape metrics with multivariate statistics to determine and interpret landscape dynamics so as to provide historic baseline trends and support decision-making in regional planning for sustainable development. We applied our methodology on the coast of Kalloni gulf, Lesvos Island, Greece (Fig. 1), which has been incorporated into the European Network of protected areas Natura 2000 (GR4110004; Mandylas and Kardakari 1998), the list of CORINE biotopes, the list of important areas of avian fauna of Greece (SPPE), and the 20 national Ecological Hot Regions (Hotspots) for avian fauna (Troumbis and Dimitrakopoulos 1998) because it supports an ecological

Fig. 1 Location of the five coastal watersheds studied at Kalloni gulf, Lesvos Island, Greece



network of wetlands. In particular, five wetlands-bearing coastal watersheds (Kardamas River basin, 6.2 km^2; Lagadas River basin, 1.2 km^2; Kalloni saltpans basin, 15.8 km^2; Vouvaris River basin, 25.3 km^2; and Polichnitos saltpans basin, 3.7 km^2) of Kalloni gulf (110 km^2 watershed; Fig. 1) are utilised to: (i) quantify and compare landscape composition and configuration in 1945,1960, 1971, 1990 and 2002/2003 using landscape indicators, (ii) evaluate the relative importance of physical and human factors on landscape composition and configuration at the landscape and at the patch level spatial scales and (iii) characterize the major processes that led to land cover changes through land cover transitions between these five successive periods in time. The natural and developmental potential of the Natura 2000 protected area of Kalloni gulf indicated the ecotouristic-agrotouristic model of development in the future (Mandylas and Kardakari 1998). The success of the application of such a model relies on the health and protection of coastal wetlands, the marine ecosystem, important biotopes, and coastal settlements, which will constitute the nucleus of the proposed developmental model (Mandylas and Kardakari 1998). Maintenance of ecological integrity, however, requires understanding of critical changes and interactions at different scales to scale management activities effectively.

Methods

In our study we used RS and GIS technologies to extract core landscape metrics of composition and configuration from a time series of aerial and satellite images. Then, we performed multivariate analysis to interpret trends in these metrics, to evaluate the relative importance of natural *vs* human factors and the relative importance of processes of conversion from one land cover type to another.

Landscape- and Patch-Level Indices

We used:

(i) five popular metrics of landscape pattern (dependent variables), which are robust to scale (Wu and others 2002) and redundancy (Riitters and others 1995) issues, to describe composition, heterogeneity, boundary, diversity and configuration attributes of the landscape. These variables were: (1) percentage of landscape (PLAND), which is a measure of landscape composition that quantifies the proportional abundance of each land cover type in the landscape; (2) patch density (PD, number of patches per km^2), which is a measure of heterogeneity of the landscape mosaic; (3) fractal dimension (FRAC), which measures how much of the geographical space is filled by boundaries; the more complex the shape of the patch, the greater the fractal dimension; it approaches a value of one for shapes with very simple perimeters, such as circles or squares, and approaches a value of two for shapes with highly complex, plane-filling perimeters ($1 < \mathrm{FRAC} < 2$); (4) Shannon's diversity index (SHDI), which is a measure of diversity at the landscape scale; it equals 0 when the landscape contains only one land cover type (i.e., no diversity) and increases as the number of different land cover types increases and/or the proportional distribution of area among land cover types becomes more equitable; (5) contagion (CONTAG), which is a measure of configuration that measures the extent to which land cover types are interspersed; it approaches 0 when the patch types are maximally disaggregated (i.e., every unit is a different land cover type) and interspersed (equal proportions of all pair-wise adjacencies) while it approaches 100 when all land cover types are maximally aggregated (i.e., when the landscape consists of a single patch); it is undefined and reported as "Not Applicable" ("N/A") when the number of patch types is less than two or all classes consist of one land cover type adjacent to background only;

(ii) three metrics pertaining to hydrology, geology and geomorphology of the landscape as constraining, physical (independent) variables (e.g., Pan and others 1999; Geist and Lambin 2001; Black and others 2003; McKonnell and Keys 2005). These variables were: (1) average watershed slope (SLOP; in degrees); (2) percent of geological substrate classes (GEOL); (3) percent distribution of length of hydrographic network into different stream orders (HYDRO); and

(iii) two popular (e.g., Forman and Alexander 1998; McGarigal and others 2001; Geist and Lambin 2001; Black and others 2003; McKonnell and Keys 2005; Hawbaker and others 2006) metrics pertaining to human presence/activity as explanatory (independent) variables of landscape pattern. These variables were: human population density per km^2 (POPDEN) and degree of fragmentation (FRAG), which is a measure of human intervention caused by linear elements on the landscape and is expressed as km of road per km^2 of watershed.

Each type of land cover conversion (patch) between successive pairs of the five periods in time was categorized a posteriori into a major process (dependent variable) (Appendix A) (e.g., Bürgi and Turner 2002), namely negative (backward) ecological succession (NEGSUC) or degeneration; positive (forward) ecological succession

Table 1 Range and average (numbers in brackets) of RMS errors of scanned topographic map sheets georeferencing and photo/image orthorectification procedures

		Map sheets georeferencing	Orthorectification	
			Aerial-photos	Satellite images
Control points		6–12 (9)	7–17 (12)	9–16 (12)
Control point RMS (meters)	X		2.58–6.22 (3.96)	0.89–2.90 (1.71)
	Y		1.91–6.12 (4.03)	1.09–2.47 (1.70)
	Z		0.92–5.58 (2.91)	
	Total	0.32–1.64 (0.92)		1.84–2.91 (2.37)
Check points			3–12 (8)	6–11 (9)
Check point RMS (meters)	X		1.84–6.11 (3.19)	1.12–4.38 (2.39)
	Y		2.10–5.58 (3.63)	1.82–4.18 (2.62)
	Z		1.25–7.13 (3.07)	
	Total			2.31–5.05 (3.50)

(POSSUC) or regeneration; abandonment (ABAND); agricultural intensification (CULT); decrease in wetland (DECWET); increase in wetland (INCWET); urbanization (URBAN); regeneration (REGEN); and aquatic expansion (AQEXP). Patch conversion was then explained on the basis of nine (physical and human) indices pertaining to the patch itself and its neighborhood (independent variables) (e.g., Pan and others 1999). These indices were: (1) area in m^2; (2) type of most proximal road (PROXR), i.e., dirt road 6–8 m; dirt road 4–6 m; asphalt road; dirt road >8 m; fire road; (3) distance from the most proximal road (DPROXR) in m; (4) order of the most proximal stream (HYDRO), i.e., 1st to 5th order according to Strahler classification; (5) distance from the most proximal stream (DHYDRO) in m; (6) mean slope (SLOP) in degrees; (7) geologic substrate (GEOL), i.e., volcanic (basalt, ignimbrites); Holocene quaternary deposits; schist, phyllite, kaolin; peridotites; (8) location of a changed patch (POS): edge; interior; (9) number of times a patch converted from one land cover type to another (CHANGE), i.e., first; second; third.

Processing of Remote Sensing Images

Primary Sources of Data

To identify and record accurate land cover changes within the five watersheds, a set of 51 aerial stereophotographs, scanned at a resolution of 1600 dpi were acquired in digital format from HAGS[1] for the years 1945, 1960, 1971, 1990. Also, a set of 6 high resolution Quickbird satellite images were provided by NDL[2] for the years 2002 and 2003. The aerial photographs were at various scales: 1:42,000 (1945), 1:30,000 (1960 & 1990) and 1:40,000 (1971), all taken during late summer time giving moisture free and comparable temporal 'snapshots' of the areas under study, suitable for photo interpretation. The coastline was blacked-out in all photographs by HAGS prior to delivery for national security purposes. The satellite images were recorded at various dates during the years 2002 and 2003 (but most of them during summer time): Apothika, Parakoila and Polichnitos on August 26 2002, Kalloni on October 19 2002 and Vouvaris on July 1 2003. During photo/image pre-processing all required ground truth was obtained from 21 topographic map sheets of scale 1:5,000 scanned at a resolution of 200 and 300 dpi. All map sheets were compiled by HAGS in mid '70 s and as of to date are considered the only detailed source of topographic information for many non-urban parts in the country. These base maps were also used to aid the actual photo interpretation process as well as to provide the means for accurately digitising other utility data, e.g., terrain elevations, stream network, coastline. It was assumed that no changes occurred to terrain elevations in between years.

Data Pre-Processing

All data pre- and post-processing was performed using commercial GIS and RS software. In some occasions though, in-house software had to be written in order to simplify and automate the various processing tasks or to perform special processing not provided by the software available.

First, the corresponding map sheets of each study site were georeferenced to EGSA87 (Greek Geodetic Reference System) using affine transformations and a suitable number of control points (9 points were used in most cases). In all but two cases, the georeferencing resulted in RMS errors (Table 1) well below the maps' nominal horizontal accuracy (1.5 m). The high RMS errors obtained in the two occasions mentioned were mainly due to poor

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[1] Hellenic Army Geographic Service

[2] Natural Disasters Laboratory of the Department of Geography of the University of the Aegean

quality of the original map sheets. Therefore in these cases, an increased number of control points were used in order to evenly distribute the error through-out the map's extent.

Elevation data in the form of contour lines (4 m contour interval) and elevation points were digitized from the georeferenced maps. Additional utility data, such as borderline of the wetland of interest, streams, ponds and coastline, were also manually digitized. A hydro-logically corrected Digital Elevation Model (DEM) of each study site was produced at a spatial resolution of 5 m by combining elevation and utility data and applying drainage enforcement (Harlow and others 2004). The watershed of each study wetland was automatically produced from the corresponding DEM using standard flow direction calculation procedures (Harlow and others 2004). This effectively delineated the extent of each study site.

The final pre-processing step was the production of orthophotos and orthoimages out of the scanned aerial stereo-pairs and the available satellite images, respectively. The orthophotos were produced by applying standard aerial-photograph block triangulation (Leica Geosystems 2003a, b). The resulted orthophotos were generated at various spatial resolutions (0.53–0.90 m) using bilinear resampling depending on the original scale of the aerial photographs. The larger RMS errors of the orthorectification process (Table 1) were obtained for the years 1945 and 1960 where no camera calibration report was available. Smaller errors were obtained for the aerial photographs of 1971 and even smaller for 1990, where camera calibration details were available and used. Even though such errors are normally considered very large for the corresponding scale of the aerial-photographs, they were readily accepted since (a) they meet the required accuracy levels of photo-interpretation and (b) no better accuracy could be obtained considering the ill-geometry of the original scanning process that was applied by the supplier using an off-the-shelf desktop A3 scanner instead of an accurate photogrammetric scanner, lack of camera calibration reports and age of the photographs. The ortho-images were produced in a similar manner using the standard image ortho-rectification procedures for Quickbird satellite images (Leica Geosystems 2003a), i.e. RPC modelling with refined third order polynomial. Again, the total horizontal RMS errors that obtained from the process (Table 1) were readily accepted since they are falling within the spatial resolution of satellite images (2.4–2.8 m) and fulfil the accuracy requirements of photo-interpretation.

Data Extraction by Photo-Interpretation

The photo interpretation process was initiated by examining the 1990 data since suitable ground validation was available from a prior study (Mandylas and Kardakari 1998) to guide the accurate identification of the individual land cover types of each studied watershed. The cover types that were identified for the year 1990 were then used to drive the interpretation process for the prior years. The identification was mainly based on the corresponding ortho-photos and all cover types were manually digitized as vector polygons (Pfaff and others 2004). The process was further aided by stereo viewing the corresponding aerial stereo-pairs (Leica Geosystems 2003c). This was the case for all years except for 2002/2003 where the satellite ortho-images were used. In this case the interpretation process was aided by the multi-spectral nature of the images themselves. It must be noted that the photo interpretation of the years 1960 and 1945 was a very difficult and awkward task because of the low sun angle causing great shadowing effect. Image quality was also very poor due to small cartographic scale and low contrast of the photographs caused mainly by the recording means available at that time (camera and film technology between 1945 and 1960) and the deterioration of the original film recording due to aging. Furthermore, validation of the identification of plough land and abandoned plough for the years 1960 and 1945 was based on detectable, yet subtle, changes between successive periods and knowledge of local activities during the periods of study.

There was no systematic accuracy assessment applied during photo-interpretation, e.g., building an error matrix. The high spatial resolution of the stereo aerial photographs and satellite images proved to be more than adequate in clearly identifying most classes during the process apart from the 1960 and 1940 cases already mentioned. Nevertheless, when the class identification of an area was questionable, it was resolved by taking under consideration the opinion of a second analyst, conducting field surveys when appropriate or performing limited interviews with locals that happen to know the course of events in the sites under study.

Apart from the detailed land cover digitization, each watershed's road network was manually digitized as linear (polyline) features and classified in six major categories: dirt road 4–6 m wide; dirt road 6–8 m wide; dirt road >8 m wide; asphalt road; and fire lanes. The fire lanes (fire control lines 25–45 m wide within the forested area) at Vouvaris site were also manually digitized since, together with the road network, they represent probable ecosystem barriers.

Area, perimeter and length values were calculated having all historic land cover types and road network in vector format. During this process the elevation data (DEM produced in pre-processing) was also used to get real world values of the required quantities. It must be noted that a difference between 0.006% and 0.035% in area measurements were found when using standard 2D methods compared to 3D methods, i.e., taking into account terrain elevation, even though no real differences were found when comparing relative area percentages. Similar observations were made for the perimeter values but in a much smaller magnitude. Since only relative comparisons of landscape metrics were required, it was safe to use the popular landscape metric calculation software FragStats (McGarical and others 2002), which uses 2D area calculations.

Production of Landscape Metrics

Five landscape metrics were calculated using FragStats spatial pattern analysis program after converting the land cover data to raster format at a spatial resolution of 5 m, i.e., percentage of landscape, patch density, fractal dimension, Shannon's diversity index, and contagion. During metric calculations using FragStats, there was no special care to minimize any boundary effects, i.e., patches falling on either side of the watershed boundary. The rest of the metrics used in this study were calculated using standard overlay and feature characteristics calculations on appropriate digitized data.

Strahler stream ordering was assigned to the digitized stream network of each watershed. The metric, distribution of length of hydrographic network into different stream orders, was then derived by calculating the total length of sub-streams for each different order.

A slope raster with a spatial resolution of 5 m was calculated from the available DEM, clipped by the corresponding watershed extent. The required value was then obtained by the resulting raster statistics (mean slope value).

Available digital geological data of scale 1:50,000 provided by NDL were extracted in the form of vector polygons for each watershed under study via clipping. Then, the total area of each geological class within each watershed was calculated and the required percentage was obtained. The difference in scale between landcover and geological data is justified by the fact that (a) only relative comparisons of the metric are required, and (b) geological data was not available in any finer scale since most geological survey maps for non-urban areas in Greece are provided at a scale of 1:50,000, which gives a horizontal accuracy of 15 m.

Past population data per municipality was obtained by the General Secretariat of National Statistical Service of Greece for the years 1940, 1951, 1961, 1971, 1981, 1991 and 2001. Municipality population from adjacent surveying periods were interpolated for the years of interest (1945, 1960, 1971, 1990 and 2002; for the year 2002, the 2001 data was used without any interpolation). The total area of each municipality was calculated using available digital data of municipality borderlines (scale 1:50,000) provided by NDL. The population density of each municipality for the years of interest was calculated based on the interpolated municipality's population and its total area. The percentage of each municipality's cover to each watershed under study was calculated. Finally, the total population density of each watershed was extracted.

Using the available digitized road network, the total length of each road type was calculated (including fire control lanes for the Vouvaris watershed). The required metric, degree of fragmentation, was derived by dividing its value by the corresponding watershed area value.

Statistical Analysis

To compare frequencies of land cover type distributions among the five successive points in time for each coastal watershed we used the Friedman chi-square test (Fχ^2). To evaluate relationships between landscape indices of configuration and explanatory variables we used non-parametric Spearman rank correlations. The relative importance of natural versus human variables in shaping landscape composition was determined with redundancy analysis (RDA) using CANOCO (Lepš and Šmilauer 2003). RDA was also used to determine significant correlates of patch transitions indicating relevant processes of change from one land cover type to another. RDA is an extension of multiple linear regression; it assumes a linear model of relationship between multiple dependent and multiple independent (explanatory) variables.

Results

Patterns of Landscape Composition and Configuration and Their Change

Twelve types of land cover were identified at the five coastal watersheds studied: phrygana, maquis, pine forests, *Quercus macrolepis* forest, wetland vegetation, interchangeable land use (agriculture-pasture), olive groves, plough-land, plough-land abandoned (including agricultural land and olive groves), water (sea surface), salt pan, and urban (Fig. 2). Kalloni and Polichnitos were dominated by plough-land and olive groves (severe human interference); Apothika and Parakoila were dominated by phrygana and olive groves (moderate human interference); Vouvaris was dominated by pine forests (modest human interference). The largest cumulative changes did not take place at dominant land cover types. Thus, distributions of land cover types did not differ among the four time periods at the five watersheds studied (F$\chi^2_{\mathrm{APO}} = 1.176$, $P = 0.882$; F$\chi^2_{\mathrm{PAR}} = 1.132$, $P = 0.889$; F$\chi^2_{\mathrm{KAL}} = 1.138$, $P = 0.998$; F$\chi^2_{\mathrm{VOU}} = 1.153$, $P = 0.886$; F$\chi^2_{\mathrm{POL}} = 5.143$, $P = 0.273$).

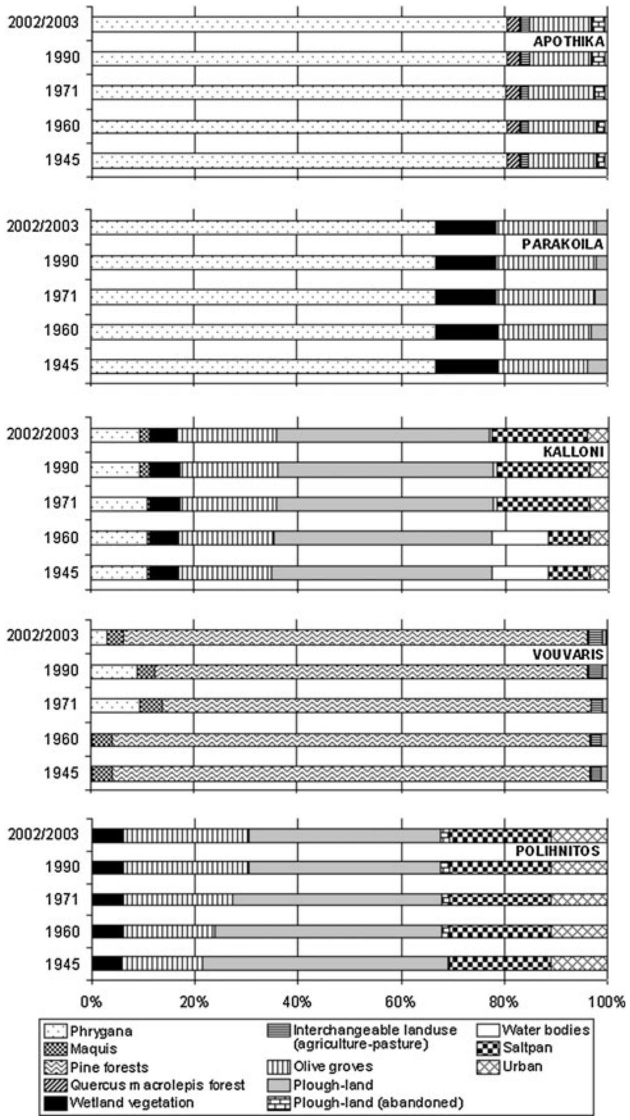

Fig. 2 Temporal variation in percent cover of land cover types for five watersheds (Apothika, 6.2 km^2; Parakoila, 1.2 km^2; Kalloni, 15.8 km^2; Vouvaris, 25.3 km^2; Polichnitos, 3.7 km^2) of Kalloni gulf, Lesvos Island

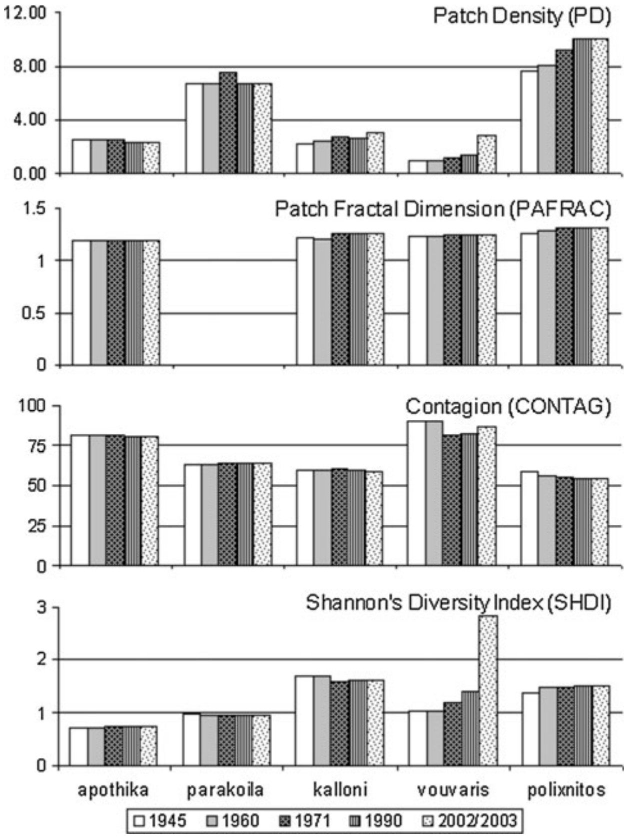

Fig. 3 Temporal variation in landscape indices of configuration for five watersheds (Apothika, Parakoila, Kalloni, Vouvaris, Polichnitos) of Kalloni gulf, Lesvos Island

During the last 50 years, abandoned plough land has increased by 63.5% (0.06 km^2) while olive groves have decreased by 9.1% (0.07 km^2) at Apothika; plough land has decreased by 37.4% (0.02 km^2) while olive groves have increased by 10.5% (0.02 km^2) at Parakoila; maquis and salt pan have increased by 264.9 (0.22 km^2) and 128.1% (1.61 km^2), respectively, while water has decreased by 93.9% (1.63 km^2) at Kalloni; phrygana, water and interchangeable land-use have increased by 920.0 (0.73 km^2), 84.7 (0.01 km^2) and 26.8% (0.13 km^2), respectively, while maquis have decreased by 20.5% (0.20 km^2) at Vouvaris; abandoned plough land and olive groves have increased by 636.6 (0.05 km^2) and 56.3% (0.33 km^2), respectively, while plough-land has decreased by 22.0% (0.39 km^2) at Polichnitos.

The behavior of landscape metrics of configuration varied among the five watersheds studied (Fig. 3). Patch density values ranged between 1.02 and 10.00. Highest values of patch density appeared at Polichnitos watershed while lowest values of patch density appeared at Vouvaris and Apothika watersheds. Percent change in patch density between successive points in time ranged between –11.1% (Parakoila 1971–1990) and 102.9% (Vouvaris 1991–2002/2003). Heterogeneity of the landscape mosaic increased substantially between 1945 and 2002/2003 at Vouvaris (176.0%), Kalloni (37.1%) and Polichnitos (32.1%) but decreased slightly at Apothika (−6.7%). Values of the fractal dimension index were low (min-max: 1.2–1.3), i.e., perimeters of patches were quite simple, at all five watersheds. Also, percent change of the fractal dimension index was low (min-max: −0.8%–4.3%) between successive periods in time and cumulatively between 1945 and 2002/2003. It was not possible to obtain a fractal dimension index for Parakoila because FragStats computes this index only if the number of patches is equal or larger than ten patches.

Maximum values of the five successive estimates of Shannon's diversity index values were lower at Apothika (0.74) and Parakoila (0.95) compared to Kalloni (1.68), Polichnitos (1.51) and Vouvaris (2.82) watersheds (Fig. 3). The largest percent changes in Shannon's diversity index appeared at Vouvaris watershed during 1960–1971 (79.4%) and 1991–2002/2003 (−27.0%) and cumulatively during 1945–2002/2003 (29.0%).

Based on the range of five successive estimates, high contagion index values at Vouvaris (81.87–89.88) and Apothika (81.23–81.68) watersheds indicated that land cover types tend to aggregate compared to Polichnitos (54.19–58.72), where land cover types were more interspersed. Percent changes in contagion ranged between −7.7 to 1.9% for the period 1945–2002/2003 (Fig. 3). The largest percent changes in contagion index were measured at Vouvaris watershed between 1960 and 1971 (−8.9%) and at Polichnitos watershed between 1945 and 2002/2003 (−7.7%).

Patterns of Natural and Human Variables

Average watershed slope and standard deviation were 10.9 ± 6.0, 11.8 ± 8.8, 5.9 ± 6.2, 12.5 ± 8.0 and 4.1 ± 4.7 degrees for Apothika, Parakoila, Kalloni, Vouvaris and Polichnitos, respectively. Volcanic substrate dominated at Apothika (86.1%), Parakoila (69.5%) and Kalloni (56.3%) while peridotites and Holocene quaternary deposits dominated at Vouvaris (85.1%) and Polichnitos (76.4%), respectively. Strahler stream ordering indicated that first order streams dominated all studied watersheds but Polichnitos, where the majority of streams are of second order.

There has been a gradual decline in human population density during 1945–2002/2003 at all five watersheds (Fig. 4a). Kalloni (−67.22%) and Apothika (−31.09%) exhibited the largest and the smallest cumulative decline in human population density, respectively, between 1945 and 2002/2003. Polichnitos exhibited the highest degree of fragmentation (range between successive estimates: 8.38–8.62) due to roads network (Fig. 4b). However, it was the least fragmented Apothika (range between successive estimates: 0.43–1.46) and Vouvaris (range between successive estimates: 1.23–3.90), which showed the largest percent increases in fragmentation due to roads network between 1945 and 2002/2003, i.e., 248.11 and 191.55% for Apothika and Vouvaris, respectively (Fig. 4b).

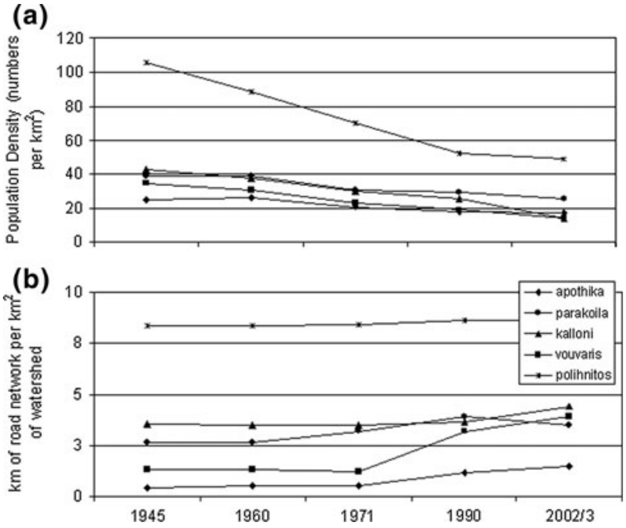

Fig. 4 Temporal variation in **a** human population density (numbers per km^2) and **b** km of road network per km^2 of watershed (Apothika, Parakoila, Kalloni, Vouvaris, Polichnitos) for five coastal watersheds of Kalloni gulf, Lesvos Island

Relation of landscape composition and configuration with natural and human variables

Physical variables are dominantly responsible for land cover composition at the five watersheds studied. Variation partitioning using redundancy analysis showed that of the 99.4% total explained variability in land cover type composition, 71.9% could be explained by physical variables, namely stream order, geological substrate and slope (Table 2).

Direction, magnitude and significance of Spearman correlations between landscape indices of configuration

Table 2 Results of redundancy analysis (RDA) with all environmental variables (P: population density; F: road fragmentation; S: stream order distribution; G: geologic substrate distribution; L: mean slope of watershed) as explanatory variables of landscape composition and partial analysis with the group of physical (S, G, S) variables as the explanatory variables and the group of human variables (P, F) as covariables (in parenthesis) and vice versa

	Cumulative percentage variance of landcover types				Sum of all canonical eigenvalues	*F*-value	*P*-level
	Axes						
	1	2	3	4			
P,F,S,G,L	57.9	98.2	98.9	99.4	0.994	539.39	0.002
P,F(S,G,L)	27.5	28.3	69.0	97.5	0.002	3.55	0.002
S,G,L(P,F)	74.8	98.2	99.0	99.2	0.719	584.66	0.002

Table 3 Spearman rank correlations between landscape metrics of composition and configuration (PD: patch density; FRAC: fractal dimension; CONTAG: contagion; SHDI: Shannon diversity) and natural (SLOP: slope; GEOL10: volcanic, GEOL15: Holocene quaternary deposits, GEOL20: schist, phyllite, kaolin; GEOL30: peridotites; HYDRO: stream order 1,2,3,4, and 5) and human variables (POPDENS: population density; FRAG: road fragmentation)

	PD ($n = 25$)	FRAC ($n = 20$)	CONTAG ($n = 25$)	SHDI ($n = 25$)
SLOP	−0.57**	−0.62**	0.88**	−0.34
GEOL10	0.05	−0.54*	0.00	−0.65**
GEOL15	0.76**	0.62**	−0.98**	0.44*
GEOL20	−0.31	−0.75**	0.35	−0.69**
GEOL30	−0.57**	−0.05	0.69**	0.15
HYDRO1	−0.30	−0.27	0.10	0.30
HYDRO2	0.31	0.62**	−0.69**	0.48*
HYDRO3	−0.18	−0.62**	0.59**	−0.92**
HYDRO4	−0.73**	−0.51*	0.88**	−0.29
HYDRO5	−0.57**	−0.05	0.70**	0.15
POPDENS	0.53**	0.55**	−0.62**	0.22
FRAG	0.70**	0.85**	−0.77**	0.69**

* Significant at $P < 0.05$, ** Significant at $P < 0.01$

and explanatory variables are presented in Table 3. Patch density increases as Holocene quaternary deposits, population density and road fragmentation increase and as slope, peridotites, 4th and 5th stream orders decrease. Fractal dimension increases as Holocene quaternary deposits, 2nd stream order, population density, and road fragmentation increase and as slope, volcanic substrate, schist, phyllite and kaolin substrate, 3rd and 4th stream order decrease. Contagion increases as slope, peridotites, 3rd, 4th and 5th stream orders increase and as Holocene quaternary deposits, 2nd stream order, population density and road fragmentation decrease. The Shannon diversity index increases as 2nd stream order and road fragmentation increase and as volcanic substrate, schist, phyllite and kaolin substrate, and 3rd stream order decrease.

Major Types of Land Cover Change

The main processes involved in land cover transitions were plough-land abandonment, change in cultivation, increase in wetland and positive ecological succession (regeneration), ecological succession (either negative (degeneration) or positive), and plough-land abandonment and change in cultivation for Apothika, Parakoila, Kalloni, Vouvaris and Polichnitos, respectively (Table 4). Land cover changes occurred mainly at walking distance from dirt road 4–6 m or dirt road 6–8 m, close to 1st order streams, a few meters above sea level, at relatively flat areas, and on either volcanic rocks or quaternary Holocene deposits (Table 4). 82.4% of patches changed only once during the study period and 93.8% of changed patches were located at the edge of a land cover type (Table 4). Significant explanatory (natural and human) variables accounted for 25.9% of the variance in land type conversion data (Table 5). Among those variables, quaternary Holocene deposits, first change of patch, and 5th order proximal stream showed largest significant conditional effects and correlations with the first three ordination axes (Table 5).

Discussion

At the rural Kalloni gulf, landscape composition related primarily to the physical attributes of the landscape examined, namely slope, stream order and geological substrate. On the other hand, the combined effect of the human attributes examined, namely human population density and road network, appeared negligible. The greatest changes in the geographical distribution and the total area occupied by the various types of land use on Lesvos Island have already occurred during the first half of the last century (Marathianou and others 2000). Olive groves significantly expanded and were redistributed covering more fertile and productive land on hilly areas by clearing mainly pine forests. Oak forests increased on previous pasture areas. Today, pasture is the main type of land use in hilly areas. In naturally derived landscapes, land use patterns are expected to be closely related to the physical attributes of the landscape (Pan and others 1999; Walsh and others 2003). The relative importance of physical versus human attributes in shaping landscape composition has been found to reduce, however, even in rural settings due to human interference (Paquette and Domon 1997; Bürgi and Turner 2002; Jobin and others 2003) or be poor in human manipulated landscapes such as urban settings (Iverson 1988). Fucamachi and others (2001) found that drastic social, economic, and technological developments occurring after the 1970s were responsible for changes in patterns of land use in a Japanese traditional rural landscape, comprised of an integral social and ecological network of a village and its surroundings, such as agricultural lands, open forestlands and forests. Black and others (2003) found that broad-scale social systems encompassing land ownership systems, economic market structures, and cultural value systems to be significant correlates of change in forested landscapes of the interior Columbia basin, USA while biophysical parameters describing growing site conditions moderated or exacerbated changes.

In our study, increase in population density and road network were found to increase heterogeneity of the landscape mosaic (patchiness), complexity of patch shape (fractal dimension), and patch disaggregation (contagion).

Table 4 Description of major processes corresponding to land cover changes during four successive time periods (A:1945–1960, B:1960–1971, C:1971–1991; D:1991–2002/3) for five (a–e) coastal watersheds (APO: Apothika, PAR: Parakoila, KAL: Kalloni; POL: Polichnitos; VOU: Vouvaris) at Kalloni gulf, Lesvos Island. NEGSUC: negative (backward) or degeneration, POSSUC: positive (forward) succession or regeneration; ABAND: plough-land and olive groves abandonment; CHCULT: change in cultivation; CULT: cultural intensification; DECWET: decrease in wetland area; INCWET: increase in wetland; URBAN: urbanization; REGEN: regeneration; AQEXP: aquatic expansion. Most proximal road types 6–8: dirt road 6–8 m; 4–6: dirt road 4–6 m; a: asphalt road; >8: dirt road >8 m; f: fire road. Geologic substrate types 10: volcanic (basalt, ignimbrites); 15: Holocene quaternary deposits; 20: schist, phyllite, kaolin; 30: peridotites

Watershed	Time period	Process	Mean patch area (m^2)	Most proximal road type					Mean distance from most proximal road (m)	Most proximal stream order (# of patches)					Mean distance from most proximal stream (m)	Mean elevation (m from sea level)	Mean slope (degrees)	Geologic substrate (# of patches)			
				6–8	4–6	a	>8	f		1	2	3	4	5				10	15	20	30
(a)																					
APO	B	NEGSUC	1236.8	1					1296.9	1					65.2	33.9	13.6			1	
APO	B	POSSUC	6087.6	1					1387.8	1					0.6	35.2	13.8			1	
APO	B	ABAND	17912.6	2					173.2		2				52.0	44.8	8.0			2	
APO	C	ABAND	11997.1		2		1		25.0	2	1				18.1	53.8	7.9			3	
(b)																					
PAR	A	CHCULT	3369.6		2				137.6	1		1			7.3	2.3	1.2				2
PAR	B	CHCULT	4289.0		1		1		133.4	2					108.6	1.9	0.5				2
PAR	B	CULT	4281.1	1					33.7	1					0.3	4.6	3.4				1
PAR	C	CHCULT	2637.4	1					170.5						176.9	2.1	0.6				1
(c)																					
KAL	A	CHCULT	7129.0		11				36.2	5	1	5			299.2	6.0	1.5			5	6
KAL	B	CHCULT	5538.5		9				45.7	4	2	3			265.1	18.8	2.1			5	4
KAL	B	CULT	6657.9		1		7		93.4	7	1				514.2	1.6	10.6				8
KAL	B	DECWET	26651.4		2		1		101.2	2	1				954.3	0.03	4.4				3
KAL	B	INCWET	514782.9		2		1		198.5	1	2				623.0	0.8	7.0				3
KAL	B	DECWET	11102.3		1		1		125.0	1	1				1093.5	1.6	6.7				2
KAL	C	CHCULT	3616.7		6	2			27.3	3	4	1			490.2	3.3	0.5				8
KAL	C	POSSUC	220409.8		1				0.8	1					101.8	165.8	7.4			1	
KAL	D	CHCULT	4638.0				1		73.8	1					191.2	60.7	8.9			1	
KAL	D	INCWET	54052.6	1					0.00	1					1610.0	1.4	0.5				1
KAL	D	URBAN	14244.4	1	1	4			1.4	4	1	1			350.3	32.5	4.6			3	3
(d)																					
VOU	A	CULT	3325.8		1				325.2				1		3.5	5.6	1.1				1
VOU	B	NEGSUC	165248.0		14				88.2	10	3	1	1		61.4	68.5	11.1		3	12	1
VOU	B	POSSUC	15411.5		2		1		32.9	1	1		1		79.1	50.2	3.9			2	1
VOU	B	CULT	4951.0		2				9.7			2			0.9	20.1	2.9			1	1
VOU	C	NEGSUC	35801.8	5	15		1	1	71.4	19	2		1		69.0	69.5	15.1			19	3

Table 4 continued

Watershed	Time period	Process	Mean patch area (m^2)	Most proximal road type					Mean distance from most proximal road (m)	Most proximal stream order (# of patches)					Mean distance from most proximal stream (m)	Mean elevation (m from sea level)	Mean slope (degrees)	Geologic substrate (# of patches)		
VOU	C	POSSUC	35769.3	6	22			1	79.4	21	2	2	4		78.1	40.3	8.6	9	18	2
VOU	C	REGEN	1259.4	12	13			1	81.3	17	5	3	1		83.1	36.1	8.1	3	20	3
VOU	C	DECWET	461.8					7	70.9					7	6.0	0.9	0.8			7
VOU	C	CULT	15669.4	9	2				17.2	4	4	3			13.3	33.0	7.8	3	6	2
VOU	D	POSSUC	107546.2	8	5				17.6	9	2		2		48.2	62.1	11.7	5	8	
VOU	D	REGEN	33752.7	2	3				15.2	3	1	1			46.1	32.2	11.3	1	4	
VOU	D	AQEXP	851.5	5	4		3		2.0		7	5			10.3	33.2	9.2	4		8
(e)																				
POL	A	CHCULT	7245.4	5	7		1		11.0	2	10	1			126.1	22.7	4.3		1	12
POL	A	CULT	400.0		1				1.4		1				352.7	1.3	1.1			1
POL	A	ABAND	16647.1	2	1				2.3		2	1			145.9	34.8	10.2		1	2
POL	A	URBAN	396.5		1				1.8		1				341.3	1.5	0.7			1
POL	A	INCWET	4954.4	1	1				0.9		2				372.3	1.5	0.5			2
POL	B	CHCULT	5248.7	10	10		2		12.2	10	8	4			77.1	31.2	5.6		9	13
POL	B	CULT	5542.1		1				0.8			1			317.6	36.1	11.6			1
POL	C	CHCULT	3934.9	9	12	2		7	21.0	17	9	4			72.7	31.4	5.1		11	19
POL	C	ABAND	4849.7	1	2				14.3	1		2			256.5	26.8	9.1			3

Table 5 Summary of RDA performed on land type conversions. Conditional effects were obtained from the summary of forward selection in order to select significant explanatory variables. GEOL30: peridotites; CHANG1: first time change of a patch; PROXHYDRO5: distance from 5th order stream; DPROXHYDRO: distance from most proximal stream; SLOP: slope; PROXHYDRO4: distance from 4th order stream; PROXHYDRO3: distance from 3rd order stream; PROXR4: distance from asphalt road; ELEV: elevation; PROXR1: distance from dirt road 6–8 m diameter; CHANG3: third time change of patch; DPROXR: distance from most proximal road; PROXHYDRO1: distance from 1st order stream; PROXR5: distance from dirt road >8 m diameter; AREA: area of a changed patch; POS1: location of changed patch at the edge of a land cover type; GEOL15: Holocene quaternary deposits; PROXR2: distance from dirt road dirt road 4–6 m diameter; PROXR6: distance from fire road; CHANG2: second time change of a patch

Explanatory variables	Conditional effects			Correlations of environmental factors with ordination axes				
	Lambda A	*P*	*F*	Axis 1	Axis 2	Axis 3	Axis 4	
GEOL30	0.07	0.002	21.49	−0.49	0.18	0.21	−0.02	
CHANG1	0.06	0.002	19.88	−0.33	−0.50	0.20	0.01	
PROXHYDRO5	0.03	0.002	11.38	0.05	0.08	0.50	−0.19	
DPROXHYDRO	0.03	0.002	7.70	−0.06	0.04	0.32	0.10	
SLOP	0.02	0.002	7.54	0.40	−0.19	−0.17	−0.08	
PROXHYDRO4	0.01	0.002	5.59	0.17	0.21	−0.10	0.03	
PROXHYDRO3	0.02	0.002	4.84	−0.10	0.07	0.09	0.21	
PROXR4	0.01	0.004	3.88	−0.12	0.02	−0.03	−0.09	
ELEV	0.01	0.008	3.63	0.30	−0.07	−0.29	−0.10	
PROXR1	0.00	0.012	3.25	−0.02	0.18	−0.13	−0.00	
CHANG3	0.01	0.008	3.39	0.07	0.21	−0.05	−0.06	
DPROXR	0.01	0.008	2.91	0.16	−0.09	0.10	−0.01	
PROXHYDRO1	0.01	0.026	2.77	0.19	−0.24	−0.13	−0.03	
PROXR5	0.00	0.018	2.60	−0.10	0.11	0.27	−0.05	
AREA	0.01	0.032	2.48	0.11	0.08	0.04	0.09	
POS1	0.00	0.268	1.20					
GEOL15	0.01	0.384	1.00					
PROXR2	0.00	0.896	0.22					
PROXR6	0.00	0.886	0.36					
CHANG2	0.00	0.826	0.41					
Summary statistics for ordination axes								
Eigenvalues				0.122	0.070	0.042	0.025	
Land type conversions-explanatory variables correlations				0.70	0.69	0.68	0.38	
Sum of unconstrained eigenvalues								1.000
Sum of canonical eigenvalues								0.309
Cumulative percentage variance of land type conversions data								25.9
Probability associated with Monte Carlo tests								0.002

An increase in road network was also found to increase landscape diversity probably due to the creation of new patches. Consequently, Vouvaris exhibited the largest increase in patchiness and diversity (probably due to summer fires and the new anti-fire road network) while Polichnitos showed the greatest decrease in contagion. Increase in human population density was positively associated with urbanization and deforestation in developing nations (Dewan and Yamaguchi 2009; Ruiz-Luna and Berlanga-Robles 2003) albeit with forest increase in Southern Appalachian Mountains, USA (Turner and others 2003) reflecting differences in natural resource use. In the Mediterranean region, agricultural abandonment was positively associated with human population decline, fragmentation of agricultural land and homogenization of the landscape (Bielsa and others 2005; Zomeni and others 2008). Roads have been recognized as primary causes of human-induced changes in land use (Wear and Bollstad 1998; McGarigal and others 2001), landscape structure (Forman and Alexander 1998; McGarigal and others 2001; Hawbaker and others 2005, 2006), and ecosystem function (Miller and others 1996; Hawbaker and Radeloff 2004;

Hawbaker and others 2006) through habitat fragmentation, destruction of natural vegetation, soil erosion and invasion of exotic species.

Distributions of land cover types have not changed significantly during the last 50 years at the five watersheds of Kalloni gulf studied because the largest cumulative changes did not take place at dominant land cover types of the five coastal watersheds studied. Thus, cumulative land cover change during 1945–2002/2003 corresponded to 0.15, 0.30, 1.27, 0.14, and 0.15% of the watershed of Apothika, Parakoila, Kalloni, Vouvaris and Polichnitos, respectively. Land cover change was mainly attributed to increase in abandoned plough-land, decrease in plough land, increase in salt pan, increase in phrygana and increase in abandoned plough-land at Apothika, Parakoila, Kalloni, Vouvaris and Polichnitos, respectively. Agricultural abandonment and a general decline in farming intensity were also the most important processes of land cover change among the processes considered between 1938 and 1992 in the cultural landscape along the Wisconsin River, USA (Bürgi and Turner 2002).

The group of explanatory variables employed at the patch level explained only a quarter of the variance in land cover type conversions indicating that there are other physical and human factors responsible for the types of patch conversions at the studied watersheds. These factors may operate at the same or higher spatial scales (Turner and others 2003).

The current study quantified change in landscape composition and configuration of five coastal watersheds within a Natura 2000 site in 1945, 1960, 1971, 1990 and 2002/2003, evaluated the relative importance of physical and human variables on landscape composition and configuration, and characterized the major processes that led to land cover changes through land cover transitions between these five successive periods in time. Our methodology provided better knowledge of land cover change processes and dynamics. Landscape dynamics during the last 50 years corroborate the ecotouristic-agrotouristic model for regional development in order to reverse trends in agricultural land abandonment and human population decline. Historical land cover dynamics combined with hypothetical regulatory approaches to the proposed agrotouristic development model could better predict how this landscape could develop in the future, thus, providing a valuable tool to regional planning. For example, Wear and others (1996) simulated the development of landscape for a study site in the southern Appalachian highlands, USA, under a number of different scenarios designed to reflect historical land cover dynamics as well as hypothetical regulatory approaches to forest management and concluded that public land management may have only limited influence on overall landscape pattern and that spatially targeted approaches on public and private lands may be more efficient than blanket regulation for achieving landscape-level goals. Also, Zomeni and others (2008) when analysed the impacts of agricultural change on landscape structure at Ipiros, Greece, between 1945 and 1995 found that the directionality of the observed landscape changes did not comply with the anticipated transformations that the Common Agricultural Policy instruments of the European Union should have caused; the post-productivist rationale of current policy change was not followed by a transition towards post-productivist agricultural regimes. Finally, Walz (2008) evaluated the impact of structural changes of land use on recreational value of the rural area within the national park region Saxon-Bohemian, Switzerland based on attributes such as degree of naturalness of land use, proportion of open space, edge effect, shape of land use elements, relief diversity, and panorama and pointed to overlays of maps from different time periods giving exact spatial information regarding the persistence of biotopes and ecosystems over long time periods of time, which, in turn, could be useful for nature conservation and in the allocation of limited financial resources for landscape conservation and development.

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Appendix A

See Table 6.

Table 6 Grouping of land cover type transitions into processes involved. NEGSUC: negative (backward) succession or degeneration, POSSUC: positive (forward) succession or regeneration; ABAND: plough-land and olive groves abandonment; CHCULT: change in cultivation; CULT: cultural intensification; DECWET: decrease in wetland area; INCWET: increase in wetland; URBAN: urbanization; REGEN: regeneration; AQEXP: aquatic expansion

Land cover type conversions		
From	To	Process
Quercus macrolepis forest	Phrygana	NEGSUC
Phrygana	*Quercus macrolepis* forest	POSSUC
Olive groves	Plough land (abandoned)	ABAND
Olive groves	Phrygana	ABAND
Plough land	Olive groves	CHCULT
Wetland vegetation	Olive groves	CULT
Water	Plough land	CULT
Wetland	Plough land	CULT
Wetland	water	DECWET
Wetland vegetation	water	DECWET
Water	Salt pan	INCWET
Wetland	Salt pan	INCWET
Water	Wetland vegetation	DECWET
Wetland	Wetland vegetation	DECWET
Phrygana	Maquis	POSSUC
Wetland vegetation	Salt pan	INCWET
Plough land	Urban	URBAN
Pine forest	Plough land	CULT
Plough land	Phrygana	POSSUC
Maquis	Phrygana	NEGSUC
Phrygana	Pine forest	POSSUC
Pine forest	Interchangeable land use (agriculture-pasture)	CULT
Pine forest	Maquis	NEGSUC
Interchangeable land use (agriculture-pasture)	Maquis	POSSUC
Pine forest	Phrygana	NEGSUC
Interchangeable land use (agriculture-pasture)	Phrygana	POSSUC
Plough land	Pine forest	REGEN
Interchangeable land use (agriculture-pasture)	Pine forest	REGEN
Maquis	Pine forest	REGEN
Phrygana	Interchangeable land use (agriculture-pasture)	CULT
Maquis	Interchangeable land use (agriculture-pasture)	CULT
Phrygana	Water	AQEXP
Pine forest	Water	AQEXP
Interchangeable land use (agriculture-pasture)	Water	AQEXP
Olive groves	Plough land	CHCULT
Wetland vegetation	Plough land	CULT
Plough land	Plough land (abandonded)	ABAND
Wetland vegetation	Urban	URBAN
Plough land	Wetland vegetation	INCWET
Plough land abandoned	Olive groves	CULT
Plough land	Plough land (abandoned)	ABAND

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