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Monitoring land use/land cover transformations from 1945 to 2007 in two peri-urban mountainous areas of Athens metropolitan area, Greece

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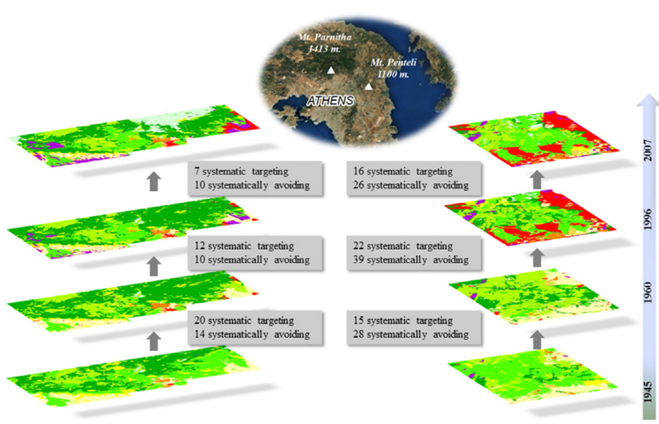
HIGHLIGHTS

- We investigated LULC transformations in two adjacent mountains in Southern Europe.
- We used Intensity Analysis for identifying systematic and stationary processes.
- Common trends are related to socioeconomic changes and European policies.
- Differences are linked with recurrent forest fires and special protection regimes.

GRAPHICAL ABSTRACT



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ABSTRACT

The aims of this study were to map and analyze land use/land cover transitions and landscape changes in the Parnitha and Penteli mountains, which surround the Athens metropolitan area of Attica, Greece over a period of 62 years.

In order to quantify the changes between land categories through time, we computed the transition matrices for three distinct periods (1945–1960, 1960–1996, and 1996–2007), on the basis of available aerial photographs used to create multi-temporal maps. We identified systematic and stationary transitions with multi-level intensity analysis.

Forest areas in Parnitha remained the dominant class of land cover throughout the 62 years studied, while transitional woodlands and shrublands were the main classes involved in LULC transitions. Conversely, in Penteli, transitional woodlands, along with shrublands, dominated the study site. The annual rate of change was faster in the first and third time intervals, compared to the second (1960–1996) time interval, in both study areas. The category level analysis results indicated that in both sites annual crops avoided to gain while discontinuous urban fabric avoided to lose areas. At the transition level of analysis, similarities as well as distinct differences existed between the two areas. In both sites the gaining pattern of permanent crops with respect to annual crops and the gain of forest with respect to transitional woodland/shrublands were stationary across the three time intervals. Overall, we identified more systematic transitions and stationary processes in Penteli.

We discussed these LULC changes and associated them with human interference (activity) and other major socio-economic developments that were simultaneously occurring in the area. The different patterns of change

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of the areas, despite their geographical proximity, throughout the period of analysis imply that site-specific studies are needed in order to comprehensively assess the driving forces and develop models of landscape transformation in Mediterranean areas.

1. Introduction

Significant impacts on human and physical environments arise from the transformations observed in the land use and land cover (LULC) of the earth's surface (Alvarez Martinez et al., 2011; Evrendilek et al., 2011). LULC changes (LUCC), which occur over a range of spatial and temporal scales, have profound effects on climate, biochemistry, biodiversity, hydrology, biodiversity, and ecosystem services (Teferi et al., 2013; Teixeira et al., 2014). Gaining an understanding of the processes, as well as the consequences of LUCC, is an important task for landscape ecologists, regional land-use planners, and biodiversity conservation managers (Pelorosso et al., 2009). From a local to a global scale, characterizing and linking the detected LUCC patterns with the processes that cause the transitions, are helpful in understanding environmental change, and developing effective land management strategies (Huang et al., 2012). This is especially important in the fragile landscapes of Mediterranean-climate ecosystems. These areas account for under 5% of the Earth's surface, yet they host 20% of the world's plant species (Cowling et al., 1996; Serra et al., 2008). They indicate a high level of population density, and so are at risk of habitat deterioration (Cincotta et al., 2000).

In recent decades, European Mediterranean landscapes have experienced major LUCC as a result of relocation of people to coastal areas, forest fires, rural depopulation and associated demographic shifts from rural to urban areas, open mining, logging, rapid expansion of activities related to tourism, and intensification of agriculture (Feranec et al., 2007; Mallinis et al., 2011; Serra et al., 2008; Viedma et al., 2006). The variability observed in the Mediterranean region, with regard to the socio-economic factors beyond landscape changes, and the environmental parameters that determine the type of change, makes it difficult to develop general models of the changes in land cover (Mallinis et al., 2011). In order to develop and apply conservation practices as well as socio-economic initiatives and policies, site-specific studies and monitoring are required to quantify and interpret historical changes and eventually project them into the future (Serra et al., 2008).

Understanding the fundamental processes of land transitions requires estimation and analysis of various components of change as well as detection of systematic, dominant and stationary land cover transitions (Aldwaik and Pontius, 2012, 2013; Alo and Pontius, 2008; Braimoh, 2006; Huang et al., 2012; Pontius et al., 2004). Through detection of systematic transitions, the focus can be placed on the most dominant signals of land change, establishing policies to prevent or minimize the undesirable impacts (Braimoh, 2006). Superficial assessment of changes, focusing on transitions that are neither systematic nor stable over time, may lead to biased hypotheses and findings (Aldwaik and Pontius, 2012). For example, without accounting for the sizes of the categories, dominant processes and systematic changes might be obscured, since it is expected that large changes occur between the largest land-cover categories under a random process of change (Romero-Ruiz et al., 2012).

Fig. 1. Location of the two mountain study areas surrounding the Athens metropolitan area.

Despite the need for detailed insights with regard to the change trajectories, as described above, relatively few studies have examined different change components and rates of systematic transitions during multi-temporal LUCC studies (Alo and Pontius, 2008; Antrop, 2005; Braimoh, 2006; Manandhar et al., 2010; Romero-Ruiz et al., 2012). However, in a move in this direction, Aldwaik and Pontius (2012) developed and presented intensity analysis as a paradigm for a unified, multi-scale, analysis of LUCC over several time intervals in a straightforward, holistic manner (Aldwaik and Pontius, 2013; Huang et al., 2012).

The overall research goal of this study was to analyze LUCC in two mountainous areas in the northeast and northwest limit of the Athens metropolitan area of Greece, between 1945 and 2007, using historical and recent maps. In the general Mediterranean and European context, an increasing number of studies are aiming to detect and quantify landscape changes in mountain systems, since they are highly valuable in providing multiple services (Morán-Ordóñez et al., 2011). The two mountainous ecosystems we focused on in this study are adjacent to the Athens metropolitan area, which is among the most densely populated areas in the world, harboring 3,074,160 inhabitants in 2011 (Bekker and Taylor, 2010), and this exposes them to constant human pressure expressed through activities such as legal and illegal urban sprawl, infrastructure development, overgrazing, illegal waste disposal, recreational activities, and reoccurring fires.

Table 1
Equations and mathematical notation used in intensity change analysis.
After Aldwaik and Pontius (2012).

Interval level

S_t

$$\frac{\text{area of change during interval}\,[Y_t, Y_{t+1}]}{(\text{duration of interval}\,[Y_t, Y_{t+1}]) * (\text{area of study region})}100\% = \frac{\sum_{j=1}^{J} * \left[\left(\sum_{i=1}^{J} C_{tij}\right) - C_{tjj}\right]}{(Y_{t+1} - Y_t) * \left(\sum_{j=1}^{J}\sum_{i=1}^{J} C_{tij}\right)}100\% \quad (1)$$

U

$$\frac{\text{area of change during all intervals}}{\text{duration of all intervals} * (\text{area of study region})}100\% = \frac{\sum_{t=1}^{T-1}\sum_{j=1}^{J} * \left[\left(\sum_{i=1}^{J} C_{tij}\right) - C_{tjj}\right]}{(Y_T - Y_1) * \left(\sum_{j=1}^{J}\sum_{i=1}^{J} C_{tij}\right)}100\% \quad (2)$$

Category level

G_{tj}

$$\frac{\text{area of annual gain of category } j \text{ during interval}\,[Y_t, Y_{t+1}]}{\text{area of category } j \text{ at } Y_{t+1}}100\% = \frac{\left[\left(\sum_{i=1}^{J} C_{tij}\right) - C_{tjj}\right]/(Y_{t+1} - Y_t)}{\left(\sum_{i=1}^{J} C_{tij}\right)}100\% \quad (3)$$

L_{ti}

$$\frac{\text{area of annual loss of category } i \text{ during interval}\,[Y_t, Y_{t+1}]}{\text{area of category } i \text{ at } Y_t}100\% = \frac{\left[\left(\sum_{j=1}^{J} C_{tij}\right) - C_{tii}\right]/(Y_{t+1} - Y_t)}{\left(\sum_{j=1}^{J} C_{tij}\right)}100\% \quad (4)$$

Transition level

R_{tin}

$$\frac{\text{area of annual transition from } i \text{ to } n \text{ during interval}\,[Y_t, Y_{t+1}]}{\text{area of } i \text{ at } Y_t}100\% = \frac{C_{tin}/(Y_{t+1} - Y_t)}{\left(\sum_{i=1}^{J} C_{tij}\right)}100\% \quad (5)$$

W_{tn}

$$\frac{\text{area of annual gain of category } n \text{ during interval}\,[Y_t, Y_{t+1}]}{\text{area of not category } n \text{ at } Y_t}100\% = \frac{\left[\left(\sum_{i=1}^{J} C_{tin}\right) - C_{tnn}\right]/(Y_{t+1} - Y_t)}{\sum_{j=1}^{J}\left[\left(\sum_{i=1}^{J} C_{tij}\right) - C_{tnj}\right]}100\% \quad (6)$$

Q_{tmj}

$$\frac{\text{area of annual transition from } m \text{ to } j \text{ during interval}\,[Y_t, Y_{t+1}]}{\text{area of } j \text{ at } Y_{t+1}}100\% = \frac{C_{tmj}/(Y_{t+1} - Y_t)}{\sum_{i=1}^{J}\left[C_{tij}\right]}100\% \quad (7)$$

V_{tm}

$$\frac{\text{area of annual loss from category } m \text{ during interval}\,[Y_t, Y_{t+1}]}{\text{area of not category } m \text{ at } Y_{t+1}}100\% = \frac{\left[\left(\sum_{j=1}^{J} C_{tmj}\right) - C_{tmm}\right]/(Y_{t+1} - Y_t)}{\sum_{i=1}^{J}\left[\left(\sum_{j=1}^{J} C_{tij}\right) - C_{tim}\right]}100\% \quad (8)$$

J is the number of categories, i is the index for a category at the initial time point for a particular time interval; j is the index for a category at the final time point for a particular time interval; T is the number of time points; t is the index for the initial time point of an interval $[Y_t, Y_{t+1}]$, where t ranges from 1 to $T-1$; Y_t year at time point t; C_{tij} is the number of pixels that transition from category i at time Y_t to category j at time Y_{t+1}.

Table 2
Equations used in error analysis.
After Aldwaik and Pontius (2013).

Interval level

$$\text{commission of change intensity during } [Y_t, Y_{t+1}] = \frac{(S_t - U)}{S_t}100\% \quad (9)$$

$$\text{omission of change intensity during}\,[Y_t, Y_{t+1}] = \frac{(U - S_t)}{S_t + (U - S_t)}100\% \quad (10)$$

Category level

Gain of category

$$\text{commission of } j \text{ intensity at } t+1 = \frac{\left(\sum_{i=1}^{J} C_{tij}\right)\left(G_{tj} - S_t\right)}{(100\% - S_t)\left(\left(\sum_{j=1}^{J} C_{tij}\right) - C_{tjj}\right)}100\% \quad (11)$$

$$\text{omission of } j \text{ intensity at } t+1 = \frac{\left(\sum_{i=1}^{J} C_{tij}\right)\left(S_t - G_{tj}\right)}{\left(\left(\left(\sum_{i=1}^{J} C_{tij}\right) - C_{tjj}\right)(100\% - S_t)\right) + \left(\sum_{i=1}^{J} C_{tij}\right)\left(S_t - G_{tj}\right)}100\% \quad (12)$$

Loss of category

$$\text{commission of } i \text{ intensity at } t = \frac{\left(\sum_{j=1}^{J} C_{tij}\right)(L_{ti} - S_t)}{(100\% - S_t)\left(\left(\sum_{j=1}^{J} C_{tij}\right) - C_{tii}\right)}100\% \quad (13)$$

$$\text{omission of } i \text{ intensity at } t = \frac{\left(\sum_{i=1}^{J} C_{tij}\right)(S_t - L_{ti})}{\left(\left(\left(\sum_{j=1}^{J} C_{tij}\right) - C_{tii}\right)(100\% - S_t)\right) + \left(\sum_{j=1}^{J} C_{tij}\right)(S_t - L_{ti})}100\% \quad (14)$$

Transition level

Transition from i

$$\text{commission of } i \text{ intensity at } t = \frac{\left(\sum_{j=1}^{J} C_{tij}\right)(Y_{t+1} - Y_t)(R_{tin} - W_{tn})}{(100\% - (Y_{t+1} - Y_t)W_{tn})(C_{tin})}100\% \quad (15)$$

$$\text{omission of } i \text{ intensity at } t = \frac{\left(\sum j = 1JC_{tij}\right)(Y_{t+1} - Y_t)(W_{tn} - R_{tin})}{(100\% - (Y_{t+1} - Y_t)W_{tn})(C_{tin}) + \left(\sum j = 1JC_{tij}\right)(Y_{t+1} - Y_t)(W_{tn} - R_{tin})}100\% \quad (16)$$

Transition to j

$$\text{commission of } j \text{ intensity at } t+1 = \frac{\left(\sum_{i=1}^{J} C_{tij}\right)(Y_{t+1} - Y_t)\left(Q_{tmj} - V_{tm}\right)}{(100\% - (Y_{t+1} - Y_t)V_{tm})\left(C_{tmj}\right)}100\% \quad (17)$$

$$\text{omission of } j \text{ intensity at } t+1 = \frac{\left(\sum_{i=1}^{J} C_{tij}\right)(Y_{t+1} - Y_t)\left(V_{tm} - Q_{tmj}\right)}{(100\% - (Y_{t+1} - Y_t)V_{tm})\left(C_{tmj}\right) + \left(\sum_{i=1}^{J} C_{tij}\right)(Y_{t+1} - Y_t)\left(V_{tm} - Q_{tmj}\right)}100\% \quad (18)$$

In this study, we specifically aimed to: (i) quantify changes in LULC in three sequential periods over the past 62 years in both areas, (ii) identify the largest systematic transitions, and (iii) assess the differences observed in the context of major socioeconomic and environmental factors occurring in the two areas during recent decades.

2. Study areas

The two mountainous areas, namely Mt Parnitha and Mt. Penteli lie within the limits of Attica region. Although the overall forest cover in the Attica region was approximately 65% at the beginning of the 20th century, forest areas were gradually further reduced to 30% before the 1940s and dropped sharply to 12% at the end of the Second World War; the total loss of forest areas in the Attica region during the war was approximately 45,000 ha. These losses were due to illegal logging to cover the heating demands of the people, as well as to the timber trade. Furthermore, near the end of the occupation, arson within the Penteli mountain region resulted in a 7-day catastrophic fire, meaning that only minor forest areas remained intact at the starting point of our study (Stefanou, 1968).

Mt Parnitha with an altitude of 1410 m is the highest of the four mountains surrounding the Attica basin, lying 30 km north west of central Athens (Fig. 1). The main substrates are limestone and marble, followed by schists (which appear in the valleys), and some flysch. The average annual rainfall is 822 mm. The flora of the area is exceptionally rich, including 1093 plant species, 93 of which are Greek endemics (Andriopoulos et al., 2007). With regard to vegetation, the thermomediterranean pine, *Pinus halepensis* Mill. dominates up to a height of 800 m, replaced by forests of the endemic fir, *Abies cephalonica* Loudon. In 1961, the mountain was declared a National Park and most human activities were prohibited (Aplada et al., 2007).

Mt Penteli is situated north east of Athens and south west of Marathon. It reaches an altitude of 1200 m. The climate, similar to Mt Parnitha, is characterized as Mediterranean type (Csa), according to Köeppen classification. The average annual rainfall is 413 mm. The main bedrock of the mountain is schists, while parts of the north-facing slopes consist of limestone. The southern and western plains

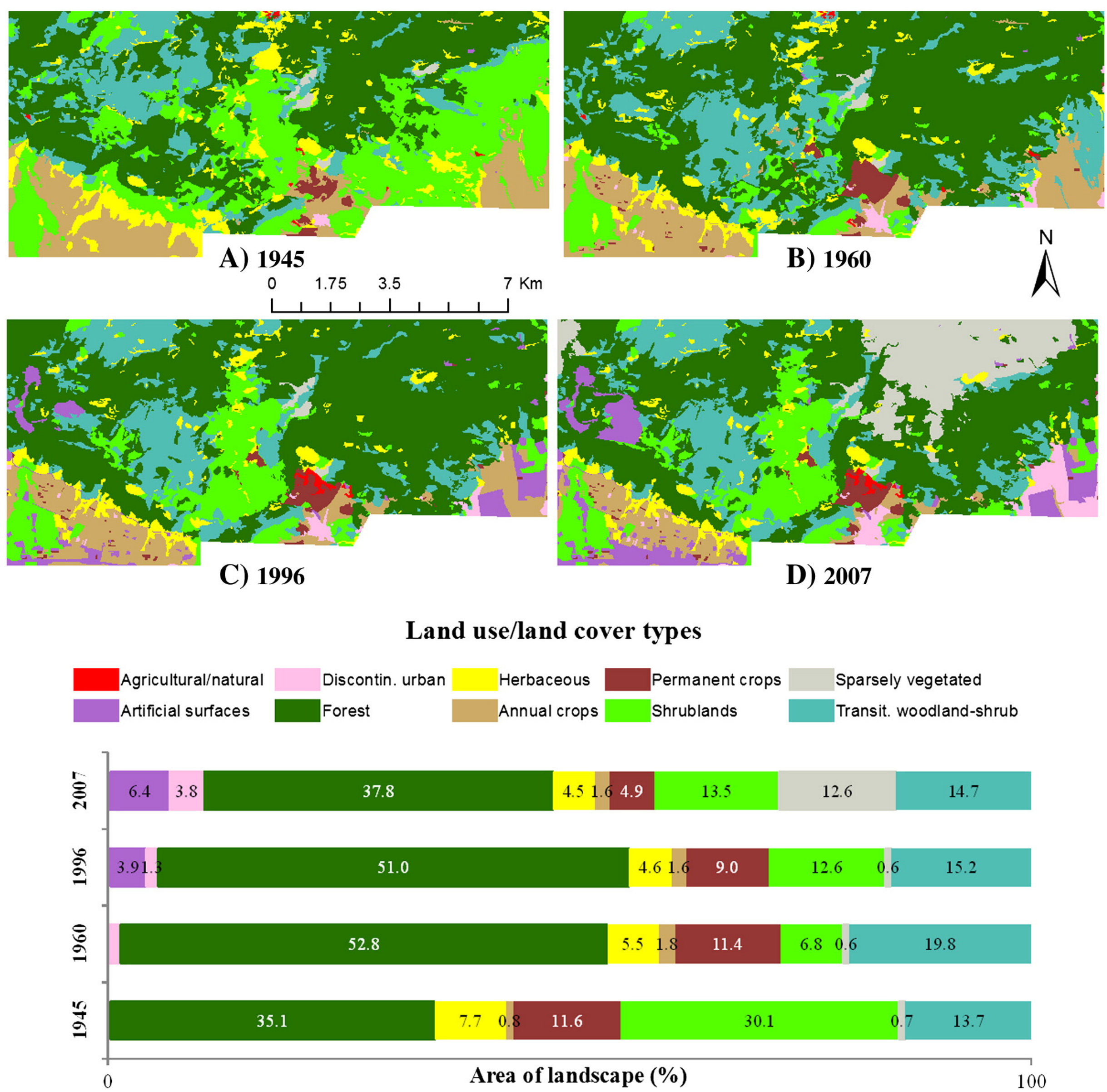

Fig. 2. Land cover/land use maps produced for the Parnitha study site by image segmentation and photo-interpretation of remote sensing data.

comprise tertiary deposits. The vegetation of the area is typically thermomediterranean (Goudelis et al., 2007). During the middle of the 20th century, the majority of the mountain was covered by *P. halepensis* Mill. forests (Arianoutsou et al., 2002). A significant part of the area corresponds to discontinuous urban fabric, so a significant presence of wildland–urban interface (the area where structures and other human developments meet with wildland) is observed.

3. Data

The earliest known sources of LULC data relating to the study area are black and white aerial photographs taken in 1945 by the Hellenic Military Geographical Service. More specifically, to reconstruct the LULC in 1945, we acquired 12 contact prints of aerial photos for the Parnitha site and 14 for the Penteli site, on a scale of 1:42,000. For 1960, we acquired 15 and 21 contact prints for the two sites, respectively, on a scale of 1:30,000. We scanned aerial photography in A3 format with a 600 dpi resolution, in order to obtain a ground resolution of 1.8 and 1.3 m for the 1945 and 1960 photos, respectively. In addition, we acquired large-scale black and white orthophotographs on a scale of 1:5000, in order to reconstruct landscape composition in 1996, while for 2007 we used natural color orthoimages of 0.5 pixel m provided by Ktimatologio S.A.

Orthorectification and mosaicking of the aerial photographs by the application of photogrammetric methods with high accuracy ensured data quality and allowed us to further process the earth observational data. The aerial photos were orthorectified using a Digital Terrain

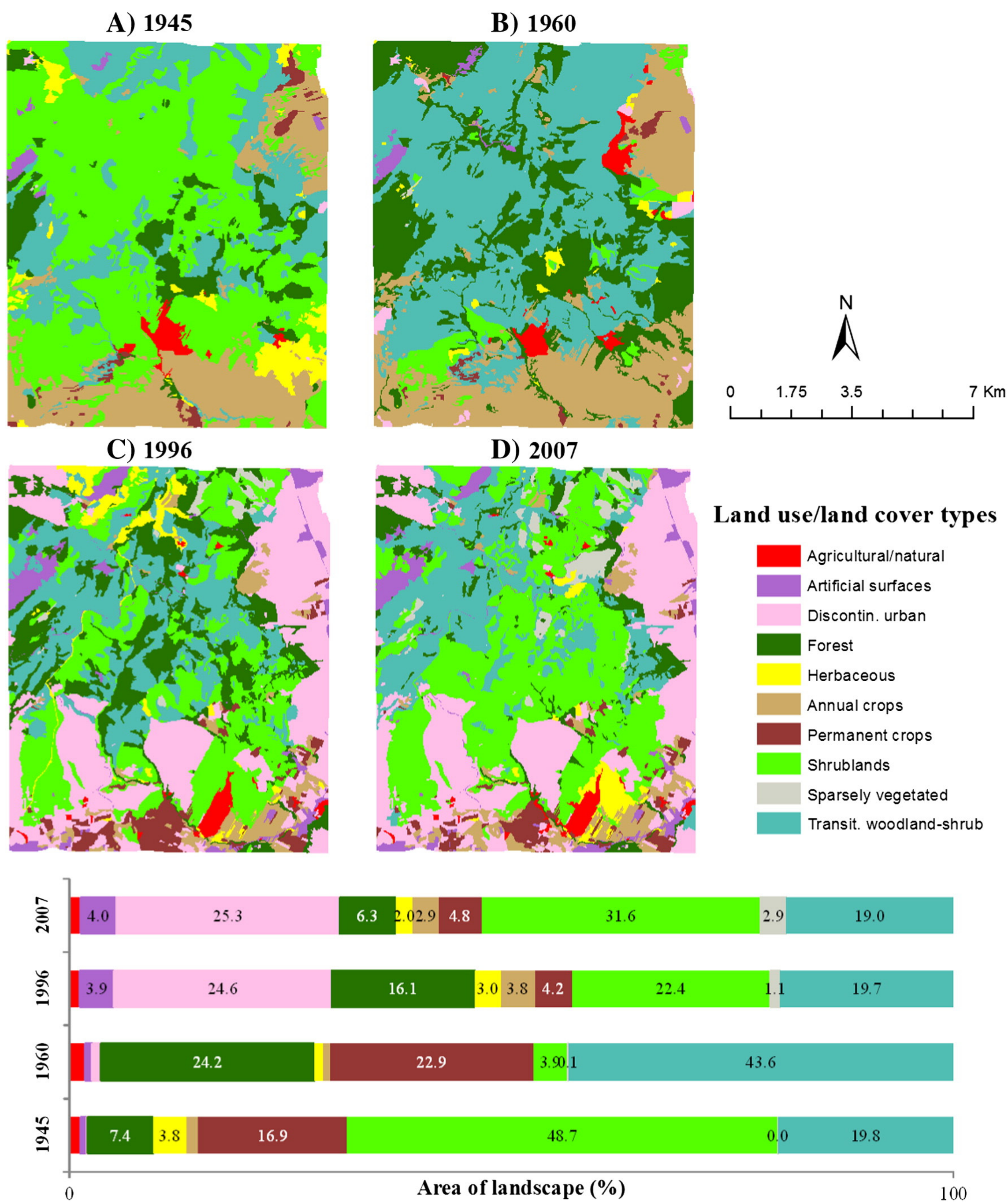

Fig. 3. Land cover/land use maps produced for the Penteli study site by image segmentation and photo-interpretation of remote sensing data.

Elevation Data of 5 m spacing, fiducial marks (mm), the camera's focal length (mm) and ground control points extracted from the available orthophotographs. Since lack of camera calibration reports is a common issue in the processing of historical photos, we measured the fiducial coordinates from the aerial photographs, such that the origin of the coordinate system is the principal point of the aerial photograph (Teferi et al., 2013).

In an attempt to gain some insights regarding the observed changes and relative differences between the sites, we also acquired, digitized, and spatially georeferenced demographic and socioeconomic variables from ten-year interval census records available from the Hellenic Statistical Authority, namely population (1941–2011), agrarian active population and livestock heads (1961–2001) for the municipalities within the extent of the study areas. In addition road infrastructure (1945–2007) was delineated following digitization of the orthophotographs and density estimation of road network using a kernel density interpolation approach. Finally, we acquired analog topographic maps from the National Forest Service, depicting the extent and location of fires for the two local-scale study sites between 1960 and 1996. We digitized and integrated fire perimeters, along with the fire scars extracted on an annual basis, from Landsat TM data (path: 183, row: 33) acquired on late autumn designating the end of fire-season, to compile the geo-database of recent fire history at the two sites (Koutsias et al., 2013).

4. Methods

4.1. Land use/land cover mapping

We applied an image segmentation algorithm to the 2007 natural color orthophotographs, delineating homogeneous land cover polygons for both the Parnitha (109 km^2) and Penteli (103 km^2) study sites, according to the approach described by Mallinis et al. (2011). We classified the time series observational data backwards in time, with a minimum mapping unit of 0.1 ha; we interpreted recent images first, to become familiar with the study area (Narumalani et al., 2004). We followed a backdating approach to minimize errors that may occur during the independent generation of spatial maps (Feranec et al., 2007). We used available stereo-pairs of air photos as a supplement to monoscopic on-screen interpretation to identify indistinct features for 1945, 1960, and 1996, as the poor spectral resolution and radiometric quality of gray-scaled aerial photos restricts the use of automated classification techniques (Geri et al., 2011; Mallinis et al., 2011).

The classification scheme followed consisted of ten classes: Land principally occupied by agriculture, with significant areas of natural vegetation; artificial surfaces; discontinuous urban fabric; forest; herbaceous vegetation; permanent crops; annual crops; shrublands; sparsely vegetated areas; and transitional woodland-shrub (Table A.1). We did not discriminate individual classes for coniferous, broadleaves, and

Table 3
The transition matrix of the Parnitha study site from 1945 to 1960 (a), from 1960 to 1996 (b), and from 1996 to 2007 (c). Values represent percent of landscape.

1945–1960	1960										
1945	ag/na	artif	d.ur	for	herb	perm	ann	shr	spar	w/sh	Total
ag/na	0.12			0.02	0.01						0.15
artif		0.01		0.01			0.00				0.02
d.ur			0.15	0.00							0.15
for		0.02		30.89	0.20	0.01	0.02	0.07		3.85	35.06
herb			0.22	1.13	4.00	0.18	1.07	0.46		0.67	7.73
perm			0.01			0.71	0.09				0.81
ann	0.01		0.44	0.07	0.56	0.7	9.51	0.28		0.04	11.61
shr	0.01	0.02	0.38	14.09	0.26	0.17	0.67	6.01		8.51	30.12
spar					0.12				0.57		0.69
w/sh				6.56	0.37	0.00	0.00	0.01	0.04	6.69	13.67
1960–1996	1996										
1960	ag/na	artif	d.ur	for	herb	perm	ann	shr	spar	w/sh	Total
ag/na		0.03								0.10	0.13
artif		0.03						0.02			0.05
d.ur			1.19								1.19
for		0.15	0.02	49.10				3.00		0.51	52.77
herb		0.16	0.00	0.29	4.45	0.01		0.11		0.51	5.52
perm	0.24					1.53					1.77
ann	0.04	2.00	0.04	0.06	0.13	0.02	8.87	0.14		0.09	11.37
shr	0.01	0.30	0.03	0.04				6.13		0.31	6.81
spar									0.62		0.62
w/sh		1.24		1.51	0.04		0.10	3.21		13.67	19.77
1996–2007	2007										
1996	ag/na	artif	d.ur	for	herb	perm	ann	shr	spar	w/sh	Total
ag/na	0.27							0.01			0.28
artif		3.88							0.02		3.90
d.ur			1.28								1.28
for		0.61	0.05	37.76	0.09			0.41	11.64	0.44	50.99
herb				0.02	4.21		0.03	0.32	0.03		4.61
perm		0.01				1.55					1.56
ann		1.46	2.42		0.02	0.00	4.87	0.20			8.97
shr		0.11						12.48		0.02	12.61
spar					0.15				0.47		0.62
w/sh		0.36		0.02	0.02			0.09	0.46	14.25	15.19
Total	0.27	6.42	3.75	37.80	4.49	1.55	4.90	13.51	12.62	14.70	

ag/na: Agricultural–natural; artif: Artificial surfaces; d.ur: Discontinuous urban fabric; for: Forest; herb: Herbaceous vegetation; perm: Permanent crops; ann: Annual crops; shr: Shrublands; spar: Sparsely vegetated areas; w/sh: Transitional woodland-shrub.

mixed forest, to minimize misclassification errors arising from the limited spectral resolution of the photographs.

4.2. Post classification comparison and transition matrices

We adopted a post-classification comparison change detection technique to determine changes in LULC between two different dates. Although this technique has some limitations, it is the most common approach used to compare maps of different sources over time. We quantified spatio-temporal LUCC by using transition matrices obtained by cross-tabulating the maps of 1945, 1960, 1996, and 2007. A transition matrix is actually a two-dimensional table, in which the rows display the map categories of an initial time and the columns correspond to categories at a subsequent time. The row totals show the size of LULC category at the start date and the column totals show the corresponding sizes at the finish date. The difference between the two is the "net change", usually reported in studies of LULC changes (Pontius et al., 2004).

The diagonal entries of the transition matrix show the total amount of persistence, while entries off the diagonal show transition from one category to another. However, to report the net change of a category only underestimates the "total change", as it cancels a gross gain (column total minus persistence) of the category in one location and a gross loss (row total minus persistence) in another location. This type of change is termed "swap change" and results from the subtraction of the net change from the total change (Manandhar et al., 2010; Pontius et al., 2004). Finally, the total change is the sum of the gross gain and the gross loss.

4.3. Intensity analysis

Although transition matrices, and the measures of loss, gain, swap, and persistence, provide valuable information, they do not allow the consideration of all time points simultaneously, and so they do not enable full understanding of the land change process (Huang et al., 2012). The multi-scale intensity analysis (Aldwaik and Pontius, 2012) is organized into three levels in a top–bottom approach: interval, category, and transition (Table 1).

The interval level, having one group of measurements, analyzes the time intervals that constitute the temporal extent. The interval level analysis examines how the annual area of overall change varies across time intervals, comparing the observed annual change intensity S_t (Eq. (1)) during each time interval [Y_t, Y_{t+1}] to a uniform annual change U (Eq. (2)), during the entire extent of the study (Aldwaik and Pontius, 2012, 2013).

The category level assesses how the intensities of change vary among categories, identifying active and dormant categories in each interval. Eq. (3) computes the G_{tj} intensity of a category's annual gross gains as a percent of the size of the category at the end of the time

Table 4
The transition matrix of the Penteli study site from 1945 to 1960 (a), from 1960 to 1996 (b), and from 1996 to 2007 (c). Values represent percent of landscape.

1945–1960	1960										
1945	ag/na	artif	d.ur	for	herb	perm	ann	shr	spar	w/sh	Total
ag/na	0.53			0.23	0.00		0.31			0.19	1.26
artif		0.5		0.03	0.00				0.04	0.12	0.69
d.ur			0.14								0.14
for	0.02	0.02	0.1	7.00	0.06		0.08		0.00	0.09	7.37
herb	0.01		0.19	0.54	0.15	0.00	2.44	0.2		0.27	3.8
perm	0.00		0.00	0.02		0.41	0.86			0.04	1.33
ann	0.57	0.03	0.06	0.24	0.02	0.34	15.39	0.06		0.14	16.85
shr	0.22	0.2	0.22	8.37	0.42	0.05	2.58	3.12	0.01	33.5	48.69
spar				0.01	0.01				0.01	0.00	0.03
w/sh	0.36	0.15	0.26	7.72	0.28	0.04	1.27	0.55	0.00	9.21	19.84
1960–1996	1996										
1960	ag/na	artif	d.ur	for	herb	perm	ann	shr	spar	w/sh	Total
ag/na		0.01	1.07	0.05	0.01		0.48	0.10			1.72
artif		0.78	0.00	0.03			0.03	0.01		0.05	0.90
d.ur	0.00	0.09	0.82	0.02		0.00	0.01	0.03			0.97
for	0.05	0.46	4.94	7.45	1.00	0.21	0.14	3.81	0.08	6.01	24.15
herb		0.01	0.39	0.08	0.02	0.02		0.24		0.19	0.94
perm	0.02	0.02	0.56	0.02	0.01	0.10	0.09	0.03		0.00	0.84
ann	1.14	1.25	9.51	0.31	0.42	3.42	3.28	3.35		0.24	22.93
shr	0.00	0.22	1.78	0.32	0.01	0.00	0.05	1.28		0.26	3.92
spar				0.00					0.06		0.06
w/sh	0.01	1.03	5.55	7.83	1.50	0.10	0.13	13.59	0.95	12.89	43.57
1996–2007	2007										
1996	ag/na	artif	d.ur	for	herb	perm	ann	shr	spar	w/sh	Total
ag/na	1.09				0.11	0.02	0.01	0.00			1.22
artif		3.66		0.00				0.01	0.00	0.17	3.85
d.ur		0.03	24.59								24.62
for		0.02	0.12	5.45	0.03		0.04	5.79	0.30	4.39	16.13
herb	0.01				0.45	0.00	0.01	1.35	0.02	1.14	2.98
perm	0.09	0.06	0.23	0.02		2.80	0.64	0.01			3.84
ann	0.01	0.16	0.03		0.05	0.10	3.81	0.05		0.00	4.21
shr	0.09	0.07	0.14	0.33	1.17	0.02	0.29	15.76	0.99	3.58	22.43
spar									1.08		1.08
w/sh		0.01	0.22	0.47	0.17		0.02	8.58	0.51	9.66	19.65
Total	1.29	4.00	25.33	6.27	1.97	2.94	4.81	31.55	2.90	18.95	

ag/na: Agricultural–natural; artif: Artificial surfaces; d.ur: Discontinuous urban fabric; for: Forest; herb: Herbaceous vegetation; perm: Permanent crops; ann: Annual crops; shr: Shrublands; spar: Sparsely vegetated areas; w/sh: Transitional woodland-shrub.

interval [Y_t, Y_{t+1}] and Eq. (4) gives the L_{ti} intensity of a category's annual gross loss as a percent of the size of the category at the beginning of the time interval. The intensities obtained from Eqs. (3) and (4) for each interval, are compared to the interval-specific uniform hypothesized intensity of change S_t (Eq. (1)), computed at the interval level of analysis. This S_t intensity would exist, if the overall interval change had been distributed uniformly across the landscape (Aldwaik and Pontius, 2012, 2013).

The transition level, which also consists of two groups, with one group examining intensities of transitions to the particular gaining category, and the other examining intensities of transitions from the particular losing category, assesses how the intensities of the transition among categories vary at each time interval. The transition intensity analysis of the gaining category examines sizes of the transitions of the specific category, given the amount of its gain, and the analysis of the losing category assesses the sizes of the transitions from the losing category relative to the stock of the other categories (Aldwaik and Pontius, 2012, 2013).

Considering the observed gross gain of category n Eqs. (5) and (6) identify which other categories are intensively avoided versus targeted for gaining by category n in a given time interval. Eq. (5) gives the observed intensity R_{tin} of annual transition from category i to category n during interval [Y_t, Y_{t+1}] relative to the size of category i at the

Table 5
Components of land change (% of landscape) in Parnitha (white cells) and Penteli (gray cells) during the first (1945–1960), second (1960–1996) and third (1996–2007) period of the analysis.

	Gross loss		Gross gain		Persistence		Total change		Net change		Swap change	
	1945–1960											
Agricultural/natural	0.03	0.73	0.02	1.18	0.12	0.53	0.05	1.91	0.01*	0.45	0.04	1.46
Artificial surfaces	0.01	0.19	0.04	0.4	0.01	0.5	0.05	0.59	0.03	0.21	0.02	0.38
Discontinuous urban fabric	0.00	0.00	1.05	0.83	0.15	0.14	1.05	0.83	1.05	0.83	0.00	0.00
Forest	4.17	0.37	21.88	17.16	30.89	7.00	26.05	17.53	17.71	16.79	8.34	0.74
Herbaceous vegetation	3.73	3.65	1.52	0.79	4.00	0.15	5.25	4.44	2.21*	2.86*	3.04	1.58
Permanent crops	0.10	0.92	1.06	0.43	0.71	0.41	1.16	1.35	0.96	0.49*	0.20	0.86
Annual crops	2.10	1.46	1.85	7.54	9.51	15.39	3.95	9.00	0.25	6.08	3.70	2.92
Shrublands	24.11	45.57	0.82	0.81	6.01	3.12	24.93	46.38	23.29*	44.76*	1.64	1.62
Sparsely vegetated	0.12	0.02	0.04	0.05	0.57	0.01	0.16	0.07	0.08*	0.03	0.08	0.04
Transitional woodland-shrub	6.98	10.63	13.07	34.35	6.69	9.21	20.05	44.98	6.09	23.72	13.96	21.26
	1960–1996											
Agricultural/natural	0.13	1.72	0.28	1.22	0.00	0.00	0.41	2.94	0.15	0.50*	0.26	2.44
Artificial surfaces	0.02	0.12	3.87	3.07	0.03	0.78	3.89	3.20	3.84	2.95	0.04	0.24
Discontinuous urban fabric	0.00	0.15	0.09	23.80	1.19	0.82	0.08	23.95	0.09	23.65	0.00	0.30
Forest	3.68	16.70	1.90	8.67	49.10	7.45	5.57	25.37	1.78*	8.03*	3.80	17.34
Herbaceous vegetation	1.07	0.92	0.16	2.96	4.45	0.02	1.24	3.88	0.91*	2.04	0.33	1.84
Permanent crops	0.24	0.74	0.02	3.74	1.53	0.10	0.26	4.48	0.22*	3.00	0.04	1.48
Annual crops	2.50	19.65	0.10	0.92	8.87	3.28	2.60	20.57	2.40*	18.73*	0.20	1.85
Shrublands	0.68	2.64	6.48	21.15	6.13	1.28	7.16	23.79	5.80	18.51	1.36	5.28
Sparsely vegetated	0.00	0.00	0.00	1.02	0.62	0.06	0.00	1.03	0.00	1.02	0.00	0.00
Transitional woodland-shrub	6.10	30.68	1.52	6.76	13.67	12.89	7.62	37.43	4.58*	23.92*	3.05	13.51
	1996–2007											
Agricultural/natural	0.01	0.13	0.00	0.21	0.27	1.09	0.01	0.34	0.01*	0.07	0.00	0.27
Artificial surfaces	0.02	0.19	2.54	0.35	3.88	3.66	2.56	0.54	2.52	0.15	0.04	0.38
Discontinuous urban fabric	0.00	0.03	2.47	0.74	1.28	24.59	2.47	0.77	2.47	0.71	0.01	0.06
Forest	13.23	10.68	0.04	0.82	37.76	5.45	13.27	11.51	13.19*	9.86*	0.07	1.65
Herbaceous vegetation	0.40	2.53	0.28	1.52	4.21	0.45	0.67	4.05	0.12*	1.01*	0.56	3.05
Permanent crops	0.01	1.04	0.00	0.14	1.55	2.80	0.02	1.18	0.01*	0.90*	0.00	0.28
Annual crops	4.10	0.40	0.03	1.00	4.87	3.81	4.13	1.40	4.07*	0.60	0.06	0.81
Shrublands	0.13	6.67	1.03	15.79	12.48	15.76	1.16	22.46	0.90	9.12	0.26	13.34
Sparsely vegetated	0.15	0.00	12.15	1.81	0.47	1.08	12.31	1.81	12.00	1.82	0.31	–0.01
Transitional woodland-shrub	0.94	9.99	0.46	9.29	14.25	9.66	1.40	19.27	0.49*	0.70*	0.91	18.57

Asterisk in net change column indicates a negative net change.

beginning of the interval. Eq. (6) calculates a uniform intensity W_{tn} for category n for each interval that defines the intensity of annual transition to category n assuming that category n gains uniformly across the landscape.

Regarding the loss of category m, Eq. (7) gives the observed V_{tm} intensity of annual transition from category m to category j during interval $[Y_t, Y_{t+1}]$ relative to the size of category j at the end of the interval time. Eq. (8) gives the hypothesized Q_{tmj} uniform intensity of annual transition from category m to all non-m categories during each interval relative to the size of all non-m categories at the later time point within each time interval.

A transition is said to be uniform when a land-cover type gains from other categories in proportion to the availability of those other categories at the starting point of the analysis or when a land-cover type loses to other categories in proportion to the sizes of those other categories at the end point of the analysis (Aldwaik and Pontius, 2013). A transition from category m to category n is a systematically targeting transition when the gain of n targets m, while n targets the loss of m, that is, when $R_{mn} > W_n$ while $Q_{mn} > V_m$. The transition from category m to category n is a systematically avoiding transition when the gain of n avoids m, while n avoids the loss of m, that is, when $R_{mn} < W_n$ while $Q_{mn} < V_m$ (Aldwaik and Pontius, 2013; Pontius et al., 2013). We characterized as stationary those changes over intervals, across categories and among transitions, with intensities presenting the same pattern across different time intervals.

4.4. Error analysis

To assess the strength of changes indicated through intensity analysis, Aldwaik and Pontius (2013) formulated an approach to quantify the hypothetical errors that could account for the deviations between the observed and the hypothesized uniform change intensity at all three levels of the intensity analysis.

At interval, category and transition levels, when the observed intensity of change is greater than the uniform hypothesized intensity, then commission error arises (observed minus uniform change), while when the observed intensity is less than the uniform intensity, omission error occurs (uniform minus observed change). A larger hypothetical commission or omission error presents stronger evidence against the null hypothesis of uniform change at interval, category and transition levels.

At the interval level (Table 2) and given that the observed (S_t) change is greater than the uniform (U), hypothesized error intensity is calculated by the commission error relative to the size of the observed change (Eq. (9)), whereas if the observed change is less than the uniform, hypothesized error intensity is calculated by the omission error relative to the cumulative size of the observed change and the omission error (Eq. (10)).

At the category level and for the category j gains, the hypothetical error intensity at the end point $t + 1$ for active categories ($G_{tj} > S_t$), corresponds to the ratio between the hypothesized commission and the size of observed gain of j (Eq. (11)). On the other hand for dormant categories ($G_{tj} < S_t$), the hypothetical omission intensity at the end point of the period is given by Eq. (12).

When considering losses from category i, the hypothetical error intensity at the starting point t of the period for active categories ($L_{ti} > S_t$), is computed from the ratio between the hypothesized commission error and the size of the observed loss of category i (Eq. (13)). Respectively, the hypothetical omission intensity for losses with lower than uniform observed change, corresponds to the ratio between the hypothesized omission error and the hypothesized gain of the category i computed though Eq. (14).

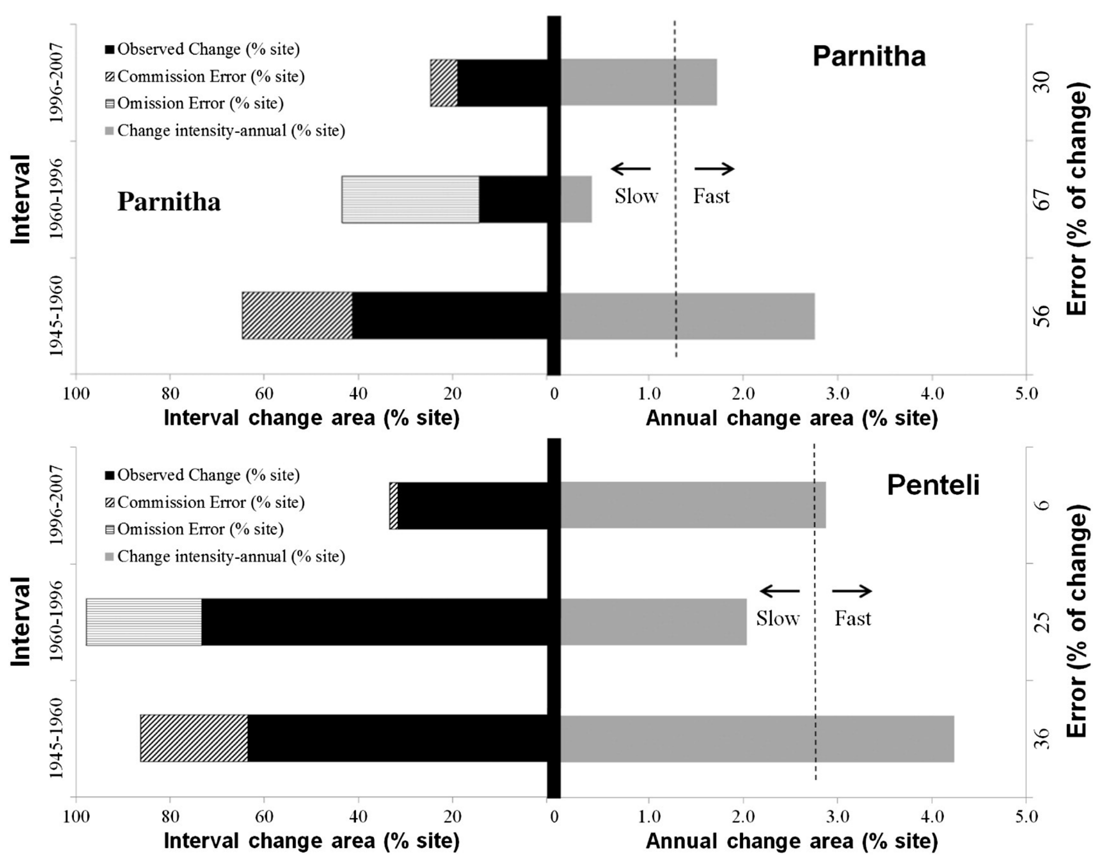

Fig. 4. Time intensity analysis for the three time intervals in Parnitha and Penteli sites. The bars located left from the middle axis, plot the observed change and the hypothesized change error as percent of the sites that are plotted. The bars that extend to the right from the middle axis depict the observed change intensity while percentage on the right vertical axis indicates hypothesized error intensity.

Similarly when examining transitions from *i*, the hypothetical error intensity for targeting transitions corresponds to the commission error of category *i* (R_{tin} minus W_{tn}) relative to the size of the observed transition from *i* to *n* (Eq. (15)) while in the case of avoiding transitions, the hypothetical omission intensity is given by Eq. (16), quantifying the ratio between omission error (W_{tn} minus R_{tin}) and the size of the hypothesized transition from *i* to *n*.

Finally for the transitions to *j*, the hypothetical error intensity for transitions with larger than uniform observed change, corresponds to the commission error of category *j* at $t + 1$ (Q_{tmj} minus V_{tm}) relative to the size of the observed transition from *m* to *j* (Eq. (17)). In the case of avoiding transitions, the hypothetical omission intensity is given (Eq. (18)) and is based on the ratio between omission error (V_{tm} minus Q_{tmj}) and the size of the hypothesized transition from *m* to *j*.

For further information on hypothesized error methodology as part of the intensity analysis the readers are referred to the works of Aldwaik and Pontius (2013) and Pontius et al. (2013).

5. Results

5.1. Landscape composition

Figs. 2 and 3 represent the spatially explicit distribution and the relative percentage of the different LULC categories for the two study areas, respectively. At the Parnitha study site (Fig. 2), forest (35.06%) and shrublands (30.12%) were the prevailing categories of the landscape in 1945, while non-natural areas, including artificial and discontinuous urban fabric patches, represented only 0.17% of the landscape (19 ha). Interpretation of the 1960 aerial photographs revealed a major landscape transformation, compared to 1945. Forest areas dominated, with coverage of 52.77% of the landscape (Table 3), followed by transitional woodland/shrubland areas (19.77%) and shrublands (6.81%). We observed a change in the 1996 map, such that an expansion of the artificial surfaces, then occupying almost 3.90% of the landscape, was evident. Forest areas continued to predominate, then covering 50.99% of the site, followed by transitional woodland/shrubland areas (15.19%). Finally, in 2007, forest was still the dominant class, although with a lower presence (37.80%), while we observed a rise in sparsely vegetated areas (12.62%), which had a presence almost equal to shrubland areas at that time (13.51%). Non-natural classes had increased, being 10.17% in total, with the artificial surfaces representing 6.42%, and the discontinuous urban fabric areas occupying 3.75% of the landscape, respectively.

At the Penteli study site (Fig. 3) shrublands (48.69%) and transitional woodland/shrubland (19.84%) areas dominated the landscape at the starting point (1945) of our analysis (Table 4). In 1960, the presence of transitional woodland/shrubland areas on the land had increased to 43.57%. After 36 years, in 1996, the most evident class was

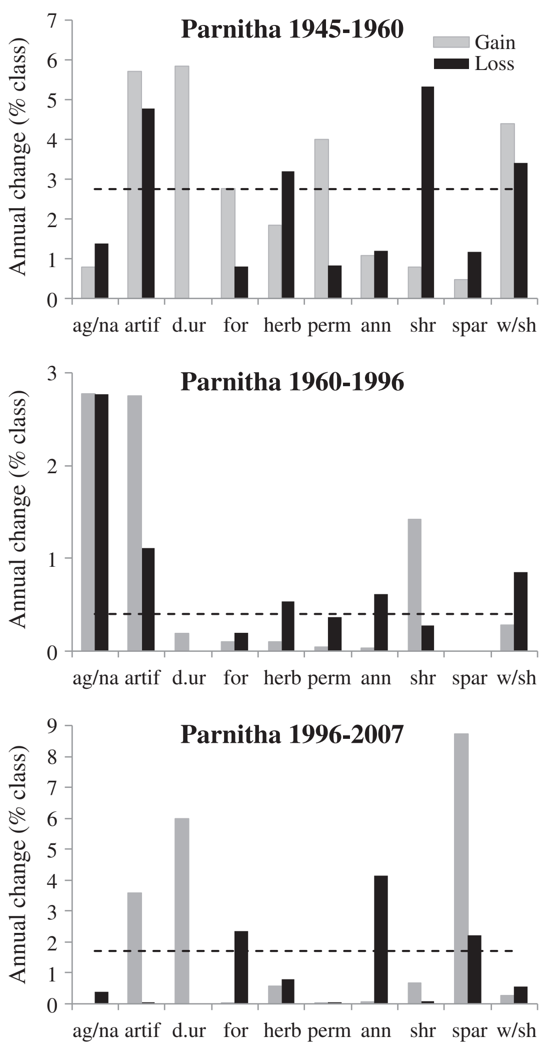

Fig. 5. Category-level intensity analysis for the three time intervals in Parnitha (left), and Penteli (right), both for category level gains (gray bars) and losses (black bars). ag/na: Agricultural–natural artif: Artificial surfaces d.ur: Discontinuous urban fabric for: Forest herb: Herbaceous vegetation perm: Permanent crops ann: annual crops shr: Shrublands spar: Sparsely vegetated areas w/sh: Transitional woodland-shrub.

discontinuous urban fabric, representing 24.62% of the landscape at that time, in the south and east of the site. Natural area classes showed a decrease, with shrublands occupying 22.43% of the landscape, while this figure was 19.65% for transitional woodland/shrubland areas, and 16.13% for forest. In the final time point of our analysis (2007) forest areas occupied only 6.27% of the landscape while, 31.55% of the landscape was covered by shrublands, and 18.95% was covered with transitional woodland/shrubland areas.

5.2. Components of LUCC

During the first period of the analysis (1945–1960), 58.66% of the Parnitha landscape showed persistence (Table 5), resulting primarily from the fact that 30.89% of the forest areas remained intact. However, there were significant gross gains of forest, resulting in an overall increase in its area of 17.71% of the landscape (Table 2), contrary to the net decrease observed for the shrublands (23.29%). For the subsequent period of the analysis (1960–1996), persistence accounted for 85.58% of the Parnitha landscape, primarily linked with the persistence of forest (49.10%). For the 1996–2007 period, we observed persistence of LULC in 81.01%, and we observed total change in up to 38% of the site. However, this change came almost exclusively from the net changes observed in this period, which covered 35.76% of the area, in contrast with the 1945–1960 and 1960–1996 periods, during which approximately 38% and 31%, respectively, of the overall change was attributed to swap changes. At the class level, we observed the largest net changes with regard to increased sparsely vegetated areas (12%) and decreased forest areas (13.19%).

Between 1945 and 1960, the net change at the landscape level of the Penteli study site corresponded to 96.22%, and the persistence to 36.46% of the landscape. We observed significant net decrease of shrubland (44.76%), mainly due to its replacement by transitional woodland/shrubland areas and forest areas (Table 3). Swapping changes were high for the transitional woodland/shrubland areas (21.26%). During the second period of the analysis (1960–1996), the net (102.35%) and swap (44.29%) changes were even higher than in the prior period, in contrast with the lower persistence (26.68%). At the class level in Penteli, we observed the largest net decrease change for transitional woodland/shrubland areas (23.92%) and annual crops (18.73%) while large net increases were observed for discontinuous urban fabric (23.65%), shrubland (18.51%) and artificial (2.95%) categories. Forest areas showed the largest swap component (17.34%), followed by transitional woodland/shrubland areas (13.51%). For the final period (1996–2007), the total change was 63.34%, with the swap changes accounting for almost two thirds of the total, that is, 38.41% of the landscape. Persistence was up to 68.34% of the landscape, with discontinuous urban fabric (24.59%) and shrubland (15.76%) making the largest contributions. Shrublands also showed the largest total change (22.46%), along with transitional woodland/shrubland areas (19.27%), which also experienced higher reallocation changes (18.57%).

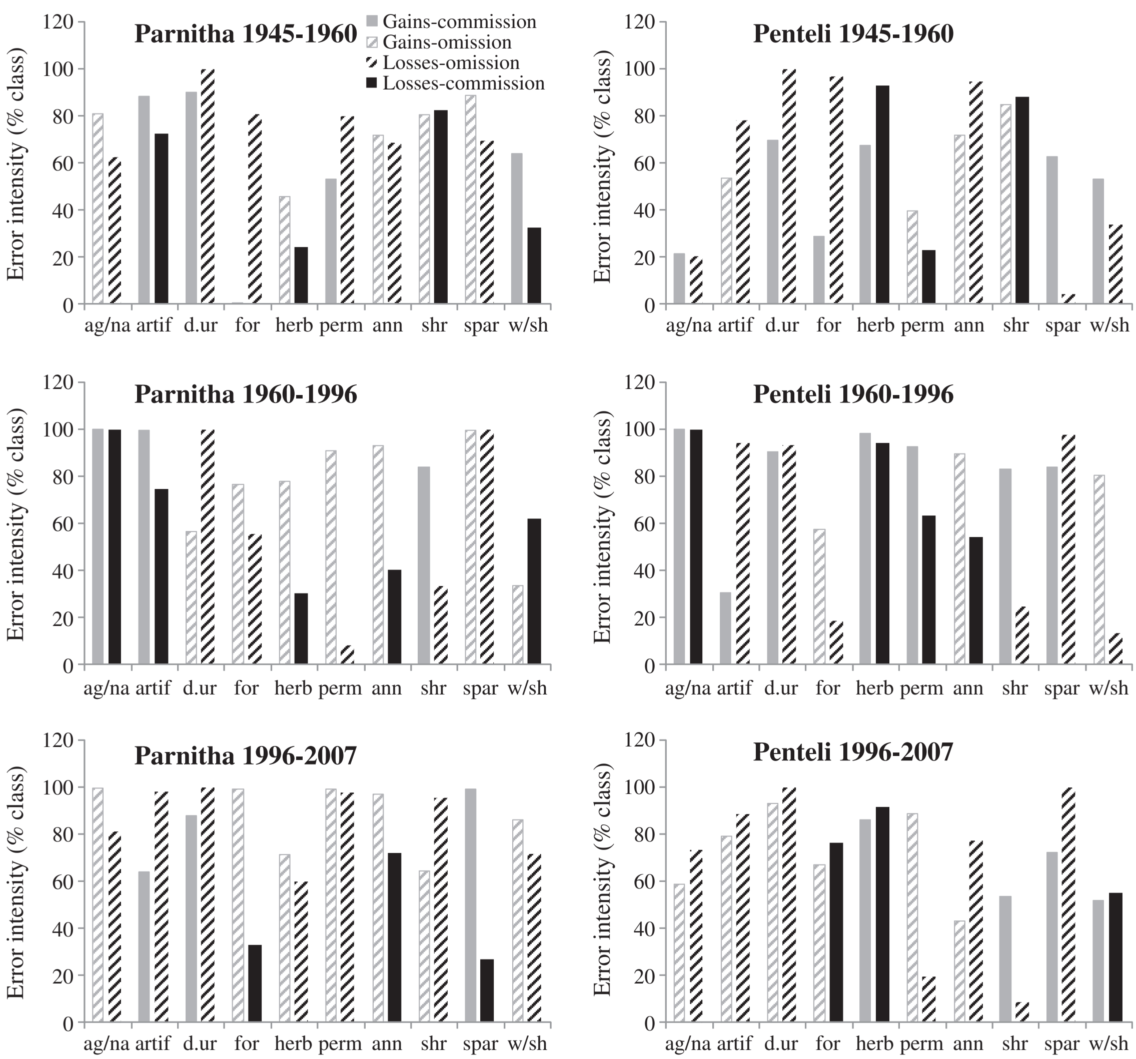

Fig. 6. Hypothetical error intensity at category level, as percent of each class at the $t + 1$ point (for the gains) and t points (for the losses).

5.3. Multi-level analysis of the processes in the two sites

Results of the interval level intensity analysis are presented in Fig. 4. As it can be seen, in both Parnitha and Penteli during the first interval (1945–1960), change appears more active than uniform with commission errors in 23.27% and 22.77% of the domain respectively supporting this evidence. During the second time interval annual change is slower than uniform with omission errors in Parnitha (28.99%) and Penteli (24.53%), accounting for this pattern. During the third interval the annual change in both areas, seems higher than uniform. Yet, the hypothetical commission error for the Penteli site corresponds to only 1.77% of the site, implying that the commission of change error is only up to 5.58% of the hypothesized change during this period in Penteli.

Table 6
Transition intensity analysis results at the Parnitha study site. Values represent percentage of each category. Superscripts *t* and *a* indicate targeting and avoiding transitions, respectively, while common superscripts on both sides of the diagonal indicate a systematic targeting or avoiding transition between categories. Highlighted gray cells correspond to stationary, targeting transitions, while bolded fonts correspond to stationary, avoiding transitions throughout the three periods.

1945-1960

Rtin / Qtmj	ag/na	artif	d.ur	for	herb	perm	ann	shr	spar	w/sh	Vtm
ag/na				1. 067^a / 0.003^t	0.320^t / 0.009^t						0.002
artif				4.045 ^{t} / 0.002^t			0.744^t / 0.002^t				0.001
d.ur											0.580
for		0.004^t / 2.968^t	0.000^a / 0.006^a		0.039^a / 0. 247^a	0.002^a / 0.032^a	0.004^a / 0.013^a	0.014^a / 0.070^a		0.733^a / 1.300^t	0.590
herb			0.187^t / 1.211^t	0.978^a / 0.143^a		0.154^t / 0.670^t	0.923^t / 0.626^t	0.394^t / 0.446^t		0.577^a / 0.225^a	0.262
perm			0.066^a / 0.044^t				0.755^t / 0.053^t				0.007
ann	0.004^t / 0.318^t		0.251^t / 2.447^t	0.039^a / 0.009^a	0.324^t / 0.681^t	0.405^t / 2.654^t		0.158^t / 0.269^t		0.024^a / 0.014^a	0.158
shr	0.002^t / 0.467^a	0.004^t / 2.750^t	0.084^t / 2.134^t	3.118^t / 1.780^t	0.058^a / 0.314^a	0.038^a / 0.643^a	0.149^t / 0.395^a			1.884^t / 2.871^t	1.725
spar					1.178^t / 0.149^t						0.008
w/sh				3.199^t / 0.829^t	0.179^t / 0.443^a	0.001^a / 0.006^a	0.000^a / 0.000^a	0.003^a / 0.006^a	0.021^t / 0.469^a		0.580
Wtn	0.001	0.003	0.070	2.247	0.110	0.071	0.140	0.077	0.003	1.010	

1960-1996

Rtin / Qtmj	ag/na	artif	d.ur	for	herb	perm	ann	shr	spar	w/sh	Vtm
ag/na		0.612^t / 0.021^t								2.166^t / 0.019^t	0.004
artif								1.113^t / 0.004^t			0.001
d.ur											0.580
for		0.008^a / 0.104^a	0.001^a / 0.036^a	0.147^t / 0.000^a				0.158^a / 0.661^t		0.027^a / 0.094^a	0.208
herb		0.078^a / 0.111^t	0.001^a / 0.005^a	0.001^a / 0.016^a		0.003^t / 0.012^a		0.054^a / 0.024^a		0.257^t / 0.093^t	0.031
perm	0.372^t / 2.316^t										0.007
ann	0.010^t / 0.395^t	0.489^t / 1.428^t	0.009^t / 0.076	0.015^a / 0.003^a	0.031^t / 0.076^a	0.004^t / 0.028^a		0.034^a / 0.031^a		0.021^a / 0.016^a	0.076
shr	0.003^a / 0.066^t	0.120^t / 0.211^t	0.013^t / 0.070^t	0.016^a / 0.002^a						0.127^t / 0.057^t	0.022
spar											0.000
w/sh		0.174^t / 0.883^t		0.212^t / 0.082^a	0.005^t / 0.022^a		0.014^t / 0.031^a	0.452^t / 0.708^t			0.200
Wtn	0.008	0.107	0.002	0.112	0.005	0.001	0.003	0.193	0.000	0.053	

Table 6 (*continued*)

1996-2007

Rtin \ Qtmj	ag/na	artif	d.ur	for	herb	perm	ann	shr	spar	w/sh	Vtm
ag/na								0.381[t] / 0.008[t]			0.001
artif									0.034[a] / 0.010[t]		0.001
d.ur											
for		0.108[a] / 0.859[a]	0.009[a] / 0.117[a]		0.016[a] / 0.185[a]			0.073[a] / 0.275[a]	2.076[t] / 8.388[t]	0.078[t] / 0.269[a]	1.934
herb				0.031[t] / 0.004[a]			0.055[t] / 0.051[t]	0.638[t] / 0.218[t]	0.058[a] / 0.021[a]		0.038
perm		0.045[a] / 0.011[t]									0.001
ann		1.477[t] / 2.065[t]	2.455[t] / 5.875[t]		0.019[a] / 0.037[a]	0.002[t] / 0.011[a]		0.201[t] / 0.133[a]			0.392
shr		0.076[a] / 0.148[t]					0.001[a] / 0.003[a]			0.015[a] / 0.013[a]	0.013
spar					2.211[t] / 0.304[t]						0.016
w/sh		0.215[a] / 0.508[t]		0.013[t] / 0.005[a]	0.011[a] / 0.039[a]			0.051[a] / 0.057[a]	0.278[a] / 0.334[t]		0.101
Wtn	0.000	0.240	0.227	0.007	0.027	0.000	0.003	0.107	1.111	0.049	

ag/na: Agricultural–natural; artif: Artificial surfaces; d.ur: Discontinuous urban fabric; for: Forest; herb: Herbaceous vegetation; perm: Permanent crops; ann: Annual crops; shr: Shrublands; spar: Sparsely vegetated areas; w/sh: Transitional woodland-shrub.

At the category level of analysis (Fig. 5), several categories occupying a small portion of the landscape experience change more intensively than the other categories. During the first interval in both sites, discontinuous urban fabric, transitional woodlands and forest (with lower evidence as commission error below 30% in both sites as it can be seen in Fig. 6.), are active in terms of gains while herbaceous vegetation and shrublands are active in terms of losses. During 1960–1996, both in Penteli and Parnitha, agricultural/natural, artificial and shrublands areas, are more active than uniform in terms of gain while agricultural–natural areas, herbaceous vegetation and annual crops present change lower than uniform. Finally, during the later period of analysis, sparsely vegetated areas are active gainers in both sites while forest experience losses more intensely than uniform. Overall in both sites during the whole period of the analysis (1945–2007), discontinuous urban avoid losing as expected while on the other hand, annual crops avoid gaining areas.

Table 6 presents the results of the intensity analysis at the transition level for the Parnitha site. During the first period of the analysis, we identified 20 systematically targeting transitions and 14 systematically avoiding transitions. Stronger evidence according to the results of the error analysis and the intensities of the hypothetical errors (Tables A.2 and A.3) exist for the transformation of sparsely vegetated areas to herbaceous areas and the transformation of annual cultivations to discontinuous urban fabric areas and permanent crops cultivations.

With regard to the 1960–1996 period, we identified 12 systematically targeting transitions and 10 systematically avoiding transitions, with the most evident in terms of error intensity being the encroachment of artificial areas, and the systematic targeting of permanent crops and agricultural/natural areas from agricultural/natural and woodland/shrublands areas respectively (Tables A.2 and A.3). Finally, in the third and final period for Parnitha, we identified 7 systematically targeting transitions and 10 systematically avoiding transitions. Larger intensity of commission errors among the targeting transitions are noticed for the transformation of annual cultivations to discontinuous urban fabric areas.

In all three periods, discontinuous urban areas systematically targeted annual crops, while the gaining pattern of forest with respect to transitional woodland/shrublands and the gaining pattern of permanent crops to annual crops, exhibits stationarity across the three time intervals.

With regard to the findings of the Penteli study site (Table 7), in a similar manner to Parnitha, we identified 15 systematically targeting transitions and 28 systematically avoiding transitions during the first time window, with stronger evidence existing for the transformation of sparsely vegetated areas to herbaceous areas (Tables A.2 and A.3). In the second period, there were 22 systematically targeting transitions and 39 systematically avoiding transitions.

We detected a major difference compared to the processes identified in Parnitha in the third period of the analysis, whereby we identified 16 systematically targeting transitions and 26 systematically avoiding transitions. Finally, in Penteli systematically targeting transitions from annual to permanent and from permanent to annual cultivations were evident during all three periods while the gaining pattern of forest with respect to transitional woodland/shrublands exhibited stationarity, similar to Parnitha.

6. Discussion

Within this study we analyzed and compared landscape patterns and systematic changes in two mountainous Mediterranean areas in the outskirts of the Athens metropolitan area in Greece. While several studies have quantified and analyzed the patterns of changes in rural, Mediterranean mountainous areas of marginal low-intensity agricultural land (Lasanta-Martínez et al., 2005; MacDonald et al., 2000; Schulz et al., 2010; Serra et al., 2008), and the associated effects in wildfire risk, biodiversity, and soil degradation, our study focused on two mountainous areas adjacent to one of the most densely populated urban areas in Europe. Within the systematic framework of intensity analysis we identified non-random transitions among different time periods and

Table 7
Transition intensity analysis results at the Penteli study site. Values represent percentage of each category. Superscripts *t* and *a* indicate targeting and avoiding transitions, respectively, while common superscripts on both sides of the diagonal indicate a systematic targeting or avoiding transition between categories. Highlighted gray cells correspond to stationary, targeting transitions, while bolded fonts correspond to stationary, avoiding transitions throughout the three periods.

1945 -1960

Rtin / Qtmj	ag/na	artif	d.ur	for	herb	perm	ann	shr	spar	w/sh	Vtm
ag/na				1.223^a / 0.064^t	0.006^a / 0.008^a		1.646^t / 0.091^t			0.998^a / 0.029^a	0.050
artif				0.284^a / 0.008^a	0.022^a / 0.016^t				0.351^t / 3.888^t	1.170^a / 0.019^t	0.013
d.ur											
for	0.014^a / 0.059^t	0.022^a / 0.180^t	0.090^t / 0.687^t		0.051^a / 0.396^t		0.072^a / 0.0 23^a		0.001^a / 0.147^t	0.084^a / 0.014^a	0.032
herb	0.019^a / 0.041^a		0.329^t / 1.298^t	0.947^a / 0.149^a		0.006^a / 0.029^a	4.271^t / 0.708^t	0.355^t / 0.344^t		0.480^a / 0.042^a	0.246
perm	0.009^a / 0.00 7^a		0.009^a / 0.013^a	0.089^a / 0.005^a			4.301^t / 0.251^t			0.216^a / 0.007^a	0.063
ann	0.227^t / 2.232^t	0.011^a / 0.213^t	0.024^a / 0.416^t	0.096^a / 0.067^a	0.007^a / 0.125^a	0.133^t / 2.669^t		0.022^a / 0.096^a		0.056^a / 0.022^a	0.126
shr	0.030^a / 0.853^a	0.027^a / 1.451^a	0.030^a / 1.497^a	1.146^a / 2.310^a	0.058^t / 2.984^a	0.007^a / 0.393^a	0.353^a / 0.749^a		0.001^a / 1.036^a	4.588^t / 5.126^t	3.161
spar				1.217^a / 0.001^t	2.769^t / 0.086^t	0.000^a / 0.000^a				0.182^a / 0.418^a	0.001
w/sh	0.122^t / 1.407^t	0.051^t / 1.121^a	0.086^t / 1.774^t	2.595^t / 2.131^t	0.095^t / 2.000^t	0.013^a / 0.313^a	0.426^a / 0.368^a	0.184^t / 0.928^a	0.001^a / 0.418^a		1.256
Wtn	0.080	0.027	0.055	1.235	0.055	0.029	0.604	0.105	0.003	2.858	

1 960 -1996

Rtin / Qtmj	ag/na	artif	d.ur	for	herb	perm	ann	shr	spar	w/sh	Vtm
ag/na		0.017^a / 0.008^a	1.729^t / 0.120^t	0.086^a / 0.009^a	0.016^a / 0.009^a		0.773^t / 0.315^t	0.157^a / 0.012^a			0.048
artif			0.002^a / 0.000^a	0.093^a / 0.005^t	0.004^a / 0.001^a		0.086^t / 0.018^t	0.036^a / 0.001^a		0.159^a / 0.007^t	0.580 / 0.004
d.ur	0.002^a / 0.002^a	0.250^t / 0.063^t		0.062^a / 0.004^a	0.000^a / 0.000^a	0.010^a / 0.003^a	0.024^a / 0.005^t	0.071^a / 0.003^a			0.005
for	0.006^a / 0.122^a	0.052^a / 0.329^a	0.568^a / 0.558^t		0.115 / 0.937	0.024^a / 0.151^a	0.016^a / 0.093^a	0.438^a / 0.472^a	0.009^a / 0.202^a	0.691^t / 0.849^t	0.580 / 0.553
herb		0.016^a / 0.004^a	1.136^t / 0.043^t	0.240^a / 0.014^a		0.048^a / 0.012^a		0.714^t / 0.030^t		0.568^t / 0.027^t	0.026
perm	0.054^t / 0.037^t	0.049^a / 0.011^a	1.858^t / 0.063^t	0.056^a / 0.003^a	0.023^a / 0.006^a		0.305^t / 0.061^t	0.102^a / 0.00 4^a		0.003^a / 0.0 00^a	0.021
ann	0.139^t / 2.604^t	0.152^t / 0.904^t	1.152^t / 1.073^t	0.038^a / 0.054^a	0.051^a / 0.393^a	0.414^t / 2.470^t		0.406^a / 0.415^a		0.030^a / 0.034^a	0.570
shr	0.001^a / 0.002^a	0.153^t / 0.156^t	1.259^t / 0.201^t	0.227^a / 0.055^a	0.010^a / 0.013^a	0.001^a / 0.001^a	0.037^t / 0.035^a			0.184^a / 0.037^a	0.095
spar				0.149^a / 0. 001^t							0.000
w/sh	0.000^a / 0.011^a	0.066^a / 0.743^a	0.354^a / 0.626^a	0.499^t / 1.349^t	0.096^t / 1.401^t	0.006^a / 0.071^a	0.008^a / 0.082^a	0.866^t / 1.683^t	0.060^t / 2.424^t		1.060
Wtn	0.034	0.086	0.668	0.318	0.083	0.105	0.033	0.612	0.028	0.333	

1996-2007

Rtin / Qtmj	ag/na	artif	d.ur	for	herb	perm	ann	shr	spar	w/sh	Vtm
ag/na		0.000^a / 0.000^a			0.790^t / 0.489^t	0.142^t / 0.059^t	0.044^a / 0.011^a	0.019^a / 0.001^a			0.012
artif				0.007^a / 0.004^a				0.029^a / 0.004^a	0.005^a / 0.007^a	0.411^a / 0.083^t	0.580 / 0.018
d.ur		0.011^a / 0.070^t									0.004
for	0.002^a / 0.020^a	0.009^a / 0.038^a	0.066^a / 0.042^a		0.019^a / 0.157^a		0.021^a / 0.069^a	3.263^t / 1.668^t	0.167^t / 0.932^t	2.473^t / 2.105^t	0.580 / 1.036
herb	0.033^t / 0.075^a					0.007^a / 0.007^a	0.030^a / 0.019^a	4.113^t / 0.388^t	0.048^a / 0.050^a	3.485^t / 0.547^t	0.234
perm	0.215^t / 0.637^t	0.142^t / 0.137^t	0.531^t / 0.081^a	0.044^a / 0.027^a			1.519^t / 1.214^t	0.020^a / 0.002^a			0.098
ann	0.017^t / 0.055^t	0.343^t / 0.360^t	0.070^a / 0.012^a		0.110^a / 0.235^a	0.210^t / 0.300^t		0.104^a / 0.014^a		0.008^a / 0.002^a	0.038
shr	0.038^t / 0.664^a	0.026^a / 0.148^a	0.058^a / 0.051^a	0.132^t / 0.474^a	0.473^t / 5.372^t	0.009^a / 0.070^a	0.117^t / 0.548^a		0.400^t / 3.096^t	1.451^t / 1.718^t	0.886
spar											0.000
w/sh		0.006^a / 0.030^a	0.104^t / 0.081^a	0.220^t / 0.688^a	0.077^a / 0.767^a		0.007^a / 0.029^a	3.971^t / 2.474^t	0.237^t / 1.607^t		1.120
Wtn	0.019	0.033	0.089	0.089	0.143	0.013	0.095	1.850	0.167	1.051	

ag/na: Agricultural–natural; artif: Artificial surfaces; d.ur: Discontinuous urban fabric; for: Forest; herb: Herbaceous vegetation; perm: Permanent crops; ann: Annual crops; shr: Shrublands; spar: Sparsely vegetated areas; w/sh: Transitional woodland-shrub.

sites as a first step to identify transition drivers and develop management scenarios (Teixeira et al., 2014).

Our findings suggest similarities, as well as important differences, both within and between the areas, across the 62 years of the study. The overall land transformation accelerated in all three intervals at both sites, according to the results of the intensity analysis, with strong evidence for relatively faster changes during the first interval (1945–1960) based on the hypothetical commission errors. The rapid changes during this interval are primary linked to the process of forestation in Parnitha and Penteli as a result of natural succession, following the major disturbances in forest areas shortly before and during the Second World War. This extensive afforestation that took place between 1945 and 1960 is indicated at first place by the gross gain and positive net changes of both forest and transitional woodland classes. The afforestation process is further identified by the systematic targeting transitions of sparsely vegetated areas to herbaceous areas, of herbaceous areas to shrublands, and of shrublands to transitional woodland/shrublands which, in turn, were systematically targeted by forest areas in both sites.

In the same period, the results of the category level intensity analysis in both sites, reveal that several other categories with minor presence, were relatively active at both sites between 1945 and 1960, presenting higher intensities of changes than the uniform of the interval such as the permanent and annual crops. These two classes systematically targeted each other in both sites, presumably due to diversified needs for agricultural products after the war and population re-allocation.

Both sites presented slower than uniform change during the second interval (1960–1996). The smaller omission intensity in Penteli relative to Parnitha is complementary to the higher net and swap changes identified during the second period for Penteli.

Differences in the amount and the rate of interval change between sites, influence category level analysis findings, as indicated by the fewer active LULC classes in Parnitha. At both sites and especially in Penteli, there is evidence of shrub encroachment (higher than uniform gain of shrublands) and urbanization (higher than uniform gain of artificial and discontinuous urban fabric), confirmed also by a positive net change observed in these categories.

At both sites during this period, there is a strong evidence that gain of artificial and discontinuous urban fabric targeted annual crops but not permanent crops (except from discontinuous urban fabric in Penteli) as well as shrublands. There are several socioeconomic factors that might well be related with this urbanization trend. Demographic tendencies and changes (Fig. 8) during this period, in both sites indicate a sharp increase in population and an expansion of road infrastructure, along with a rapid decline in agrarian active population. In several other studies over the Mediterranean region it was noted that in the case of urbanization, agricultural land accounts for the highest losses in area terms, due to the temporal flexibility of utilization, historically established locations next to already existing settlements and the low preservation status (Zasada et al., 2010). In addition, building permissions during the 1960–1991 within Athens metropolitan area increased over 200% while during the period from 1960 till early 80s, the Athens metropolitan area was the primary hosting region of small to large-size enterprises (Aggelidis, 2000). An interesting finding of the transition level intensity analysis was the preference indicated by discontinuous urban fabric and artificial classes of annual cultivations over permanent crop land. This selectivity pattern can be well explained by the succession of Greece to the European Union in 1981, and the adoption of the Common Agricultural Policy (CAP). CAP regulations especially prior to the 1992 reform, promoted plantation arboriculture such as olive yards and vineyards at the expense of annual crops (i.e. cereals) which have been subsidized to be left aside (Caraveli, 2000).

Intensity analysis during the later period (1996–2007), indicated that strong evidence for change (i.e. larger than uniform) existed only in Parnitha, in agreement with the larger absolute net change. In respect to the urbanization process identified during the previous period, discontinuous urban and artificial areas appear active at category level only in the case of Parnitha. Recent published statistics from the 2011 national census (Fig. 7), verify that population in Penteli is stabilized during the first decade of the 21st century, contrary to the continuous increase observed in Parnitha. A distinct feature observed during this period of the analysis was the very high ratio of net to swap changes in Parnitha while the opposite trend was observed in Penteli. In the former case, this related mainly to the systematic targeting of forest areas from sparsely vegetated areas as a result of a major fire in early 2007, which also corresponds to an important transition in terms of site's area (11.64%). In Penteli, large swap changes are observed especially for the shrublands and transitional woodland categories. These swap changes are linked to a primary ecological succession process which is expressed though the systematic targeting of shrublands and

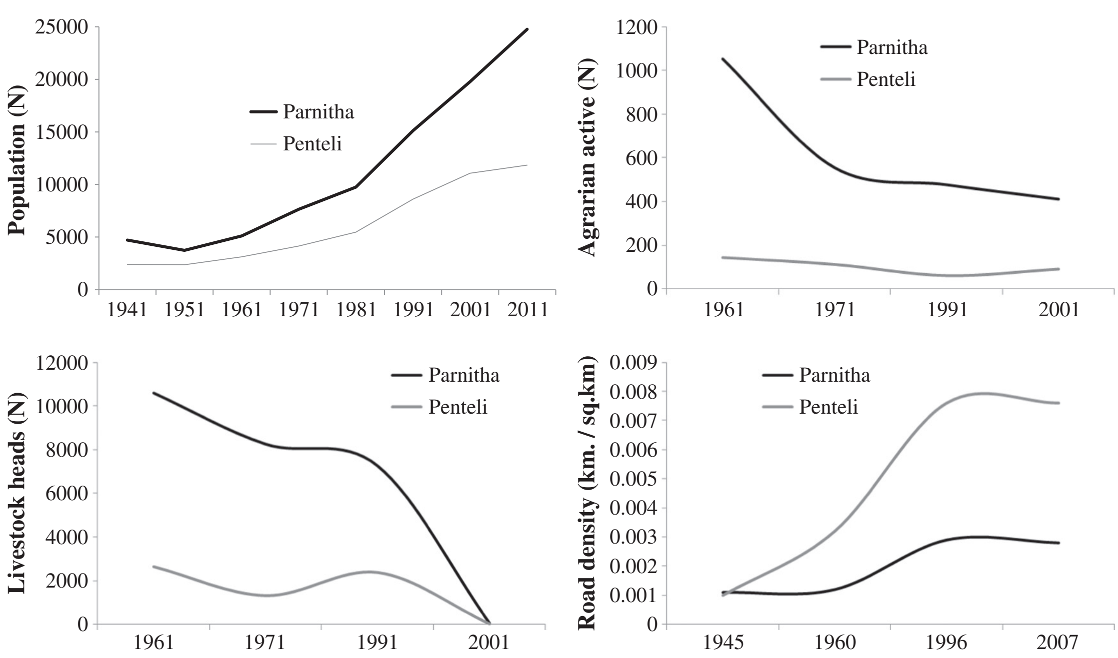

Fig. 7. Population, agrarian active population, livestock heads and road density during the period of our analysis in the two study areas.

herbaceous areas from transitional woodlands as well as from the systematic targeting of herbaceous areas from shrublands. On the other hand through a secondary succession shrublands systematically targeted transitional woodlands and forest areas while herbaceous areas systematically replaced shrubs. The agent that effectively shaped this pattern of change is forest fires (Fig. 8).

While technological, social and economic changes as well as European common policies can be perceived as the explanatory mechanisms for the common trends observed in the two sites, forest fires should be considered as a major agent of the diversity of changes occurred. Forest fires in the Mediterranean landscape are disturbances that can lead to the biggest changes in vegetation in the short term, conditioning forest structures, fire behavior, and fire types for the future (Alvarez et al., 2012). The higher fire frequency and the fire recurrence (Fig. 8) observed in Penteli during the entire 1960–2007 period affected the components of landscape change, with transitional woodlands, shrublands, and forest all revealing significant amounts of swap changes and intensive gains, especially during the two latter periods of analysis. An additional effect of the extended burned areas and short fire interval in Penteli was the decrease of the forest areas covered mainly by *P. halepensis* trees (Pausas and Vallejo, 1999). Indeed, it has been found that the frequent wildfire increases persistence of fire-prone classes in the landscape, and leads to a decline in the resilience of some Mediterranean plant communities (Romero-Calcerrada and Perry, 2004). This is because *P. halepensis* fails to naturally regenerate in the case of frequent fires over a short space of time, and with the immaturity risk, the species may be locally eliminated. On the other hand, the absence of frequent fires in Parnitha facilitated natural ecological process as indicated by the stationarity in the targeting of transitional woodlands from forest in all three periods and the targeting of shrublands from transitional woodlands during 1945–1996.

At the same time, the high fire frequency observed in Penteli from 1960 to the present day, may be at least partially explained by the extensive afforestation that took place between 1945 and 1960. Increased fire hazard is a major implication of the increased cover of forest and shrublands in areas with formerly lower fuel loads (Moreira et al., 2011; Moreno et al., 2011).

The higher persistence, the detection of less stationary and systematic changes, and even the lower fire frequency in Parnitha, might be linked to the fact that it was declared as a National Park back in 1961. This special protection regime appears to have restricted extended transformations of LULC as well targeting transitions from forest areas to non-natural classes. On the other hand we noticed that in both areas, artificial and discontinuous fabric areas systematically targeted shrublands during the second period. This is clearly linked to the fact that Greek forest law includes a less strict protection regime for shrublands, contrary to forest areas. Yet, a large fire in early 2007 in Parnitha had significant impacts in landscape dynamics as it was indicated by the intensity analysis. Conversely, as recently as 1988, a Presidential Decree was published, which designated special protection zones and zones with allowance of human activities for Mt. Penteli. Other studies in Mediterranean mountainous areas (Gracia et al., 2011), and elsewhere (Alo and Pontius, 2008; Gaveau et al., 2009), have also identified diversification in type and rates of LUCC, resulting from the establishment of different conservation status and protection levels in adjacent areas. Introduction of the special protection zones regime in Penteli in the early 1990 is therefore expected to halt, or at least decrease, uncontrolled loss of natural areas and associated LUCC. However, due to the time lag between ecosystem response and socio-economic changes (Gracia et al., 2011), the effects of this management policy are unlikely to be detected in the near future.

7. Conclusions

We detected major LUCC in two mountainous areas, located within 20 km distance of the center of Greece's capital, using historical aerial photography. In depth analysis of the transition matrix can reveal simultaneous gains and losses of a given land cover type in different locations, as well as gross gains and gross losses, and can identify systematic and temporal stationary transitions. We systematically evaluated and quantified change trajectories among LULC types on the basis of the framework of the multilevel intensity analysis that was recently introduced by Pontius et al. (Aldwaik and Pontius, 2012, 2013; Huang et al., 2012).

We identified both similarities and differences in the two landscape transformations through time. Originally, the annual rate of change seemed similar and faster than the uniform over the first and third intervals in both sites. However, the hypothesized error analysis indicated

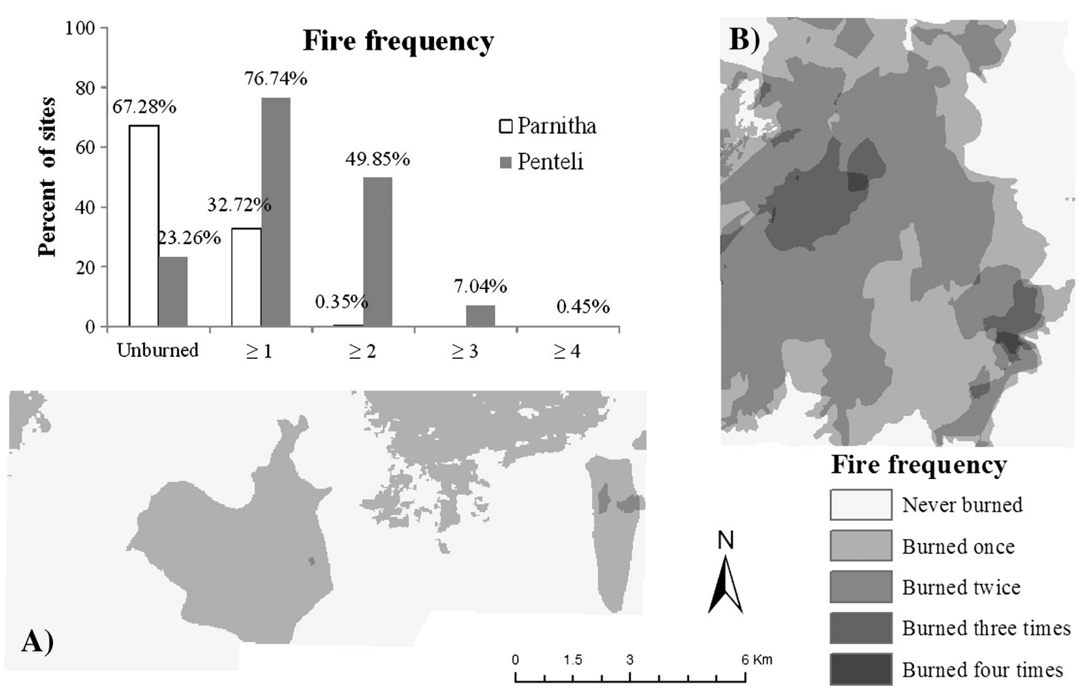

Fig. 8. Fire frequency observed in the two study sites between 1960 and 2007.

that in Penteli there is no strong evidence for change faster than uniform. In the category and transition levels, we obtained significantly different results between the two sites for each period.

Fire regime was the major factor shaping the landscape and resulting in the differences observed between the two sites. At the same time, previous disturbances observed in the areas influenced and determined fire behavior. Establishment of special protection in Parnitha in the early 60s appears to have prohibited recurrent fires and uncontrolled landscape transformations.

The analysis of LUCC is a prerequisite in order to define effective strategies for natural resources management and biodiversity conservation. Our research demonstrates the need for site-specific studies when it comes to large scale protection and restoration of fragile ecosystems, where natural or anthropogenic disturbances, and not the environmental gradients, might be the predominant factors determining ecosystem composition and structure.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2014.04.129.

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