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Spatial–Temporal Monitoring of Ecotonal Belt Using Landscape Ecological Indices in the Central Elburz Region: Remote Sensing and GIS Analysis

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ABSTRACT: Iran has mountainous landscapes and half of its surface is occupied by highlands. Moreover, Iran is an arid country and deserts are located at lower altitudes. Most metropolitan areas are positioned in mid-altitudes between mountain and desert. Cities grow upwardly toward the highlands under pressures of urbanization and desertification. Foothill ecotones are a zone between upland mountains and midland plains. Upwardly sprawl of urban centers has transformed the structures and functions of these ecologically strategic belts. In this article, we analyzed the transformational trend of the ecotonal zone in the southern slopes of the central Elburz (Tehran-Karaj urban region). Landsat 7 ETM+ (2000) and 8 OLI (2013) are used to monitor spatial and temporal variability of landscape metrics. The land covers are grouped into four classes: vegetation cover, open space, built area, and water body. Seven landscape metrics are used including: NP, CAP, MPS, AW-MPS, MNND, PARA, and TE. Our results indicate that NP, AW-MPS, TE, and PARA increased whereas CAP and MPS decreased. These results are a sign of the fragmentation process across the ecotonal strip.

Keywords: Environmental Quality, Central Elburz, Urban Region of Tehran-Karaj, Ecotone, Landscape Transformation

INTRODUCTION

Advances of environmental planning and management in the last decades can be described in two dimensions (Spellerberg, 2005): 1. theoretical shift that has happened in the methodologies of the study of natural and cultural systems. Systems approach and nested hierarchical organizations (Naveh, 2007) are the core concepts of this novel paradigm. Moving across scales is the most important strategy to cope with complexity, nonlinearity, and copious feedback loops of ecological systems (Farina, 2010). 2. The technological developments that have enhanced the efficiency of data collection, surveying, analysis, and synthesis. Remote sensing and satellite imagery technology has granted synoptic and updated digital data and improved availability and accessibility of materials for spatial and temporal investigations (Burel and Buadry, 2003). Geographic information systems (GIS) and spatial information systems have promoted the application of techniques of analysis, simulation, and modeling (Ingegenoli, 2002). In this research, we used landscape ecological paradigm along with remote sensing and GIS tools to prepare a monitoring plan for sustainable environmental management.

Monitoring Environmental Quality

Monitoring is the observation and

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recording of the values of the given variables vis-à-vis particular goals (Spellerberg, 2005; Lausch et al., 2013). Sometimes monitoring is carried out to guarantee regulations or performance standards (Wristen and O'Reilly, 2002). Therefore, monitoring can be defined as a systematic observation of relevant parameters focusing on certain themes or objectives (O'Neill et al., 1997; Bila et al., 2011). Monitoring does not only take into account the disturbance factors but also the impacts, consequences, results, and feedbacks too (EPA, 1994; Sharma et al., 2013). As a matter of fact, monitoring includes compliance, auditing, evaluation, and assessment. Four types of monitoring are distinguished (Spellerberg, 2005):

1. The simple monitoring, that is, the observation and recording of the values of the variables over specific time and space range without iteration.
2. The complementary monitoring is to offset the previous inventories which are deficient.
3. The surrogate monitoring that is performed as a substitute for a detailed investigation of variables that are difficult to quantify.
4. The integrative monitoring that is performed to provide the data and information that can be used for many purposes and in different ways. In this article, our monitoring scheme is the integrative one that can be used in diverse works.

Environmental changes can be monitored at many scales, but the scale of landscape and region has more information in support of sustainable spatial planning (Forman, 1995; Forman and Collinge, 1997). The availability of remote sensing imagery provides multiscale observation with periodic repetitionsover time (Lausch and Herzog, 2002; Lausch et al., 2013). Landscape and regional scales are called coarsescale and adequately covered by satellite images. Remote sensing images provide nonaverage and disaggregated data suitable for sustainable environmental planning (O'Neill et al., 1997; Syrbe and Walz, 2012). The spatial arrangement of elements impacts on horizontal flows and movements across land mosaics (Forman and Godron, 1986). Hence, modification of landscape directly affects ecological processes, flows, and movement (Burel and Buadry, 2003). Coarse-scale monitoring focuses on the structural composition and spatial configuration at the scale of landscape or region.

Monitoring activities have priority inenvironmental studies for two reasons (Becker et al., 2007): (1) monitoring data is needed to understand the ecological and cultural processes, and in addition, (2) monitoring information is essential for modeling and scenario-making.

Landscape Indices

Planning processdemands options and decisions (Forman, 1995); decision making is a kind of judgment (Ahern, 2005); judgment requires an evaluation; and indices are tools for rating and assessment (Botequilha and Ahern, 2002). So, definition and determination of indices are the central part of each planning process. Indices and indicators are the most useful tools for measuring a concept as complex as sustainability (Odermatt, 2004). Quantification of the spatial structure and its changes over time using landscape indices is a prerequisite for coarse-scale monitoring, and historical information of land conversions can help restoration activities (Plexida et al., 2014). Coarse-scale monitoring (i.e. monitoring at the scale of landscape and region) enhances land planning and management (Bila et al., 2011).

Spatial indices are quantitative tools for detecting structural pattern of land mosaics (Uuemaa et al., 2013). The indices indicate three main aspects of landscape transformation including loss, degradation, and fragmentation. The structural pattern of the landscape can be measured in two main dimensions, that is, composition and configuration (Botequilha and Ahern, 2002). Composition indices quantify number, type, and extent of elements, but the configuration indices measure spatially explicit attributes, namely, arrangement and layout of elements in the mosaic. The temporal dynamics of land mosaics could be monitored by means of a comparative approach and variability of the landscape indices (Lausch and Herzog, 2002). The variability of the indices over space–time dimensions could serve as a bridge between spatial pattern and ecological functioning.

The spatial–temporal monitoring of landscape can act as a decision support system and is a prerequisite for diagnosis of adaptivity and resilience (Farina, 2010; Aithal and Sanna, 2012). Coarse-scale monitoring of heterogeneous environment by measuring landscape ecological indices can help to enhance the efficiency and the effectiveness of land use decisions (Weng, 2007).

"Landscape clinical pathology" applies a medical approach into the coarse-scale monitoring (Ingegnoli, 2002). Status and trend of a landscape can be recognized on the basis of the following signs (Burel and Buadry, 2003):

- Signs of landscape integrity: number of pixels with changed land cover/decreases in original or rare covers/change of the rate of matrix connectivity/state of corridors (using length to edge ratio).
- Signs of the structural health of watersheds: state of catchment surfaces correlated with water quality/ type and size of riparian zones/specific areas relating to the slope and soil attributes.
- Signs of persistence and resilience: permeability rate/habitats quality/connection rate/land covers proportion/roads length/economic activities/contextual connectivity.

Ecotonal belts

Ecotone is called as an interface or transition zone between two ecological systems. Ecotones are discontinuities in the physical or biological structure along a gradient. Ecotones exist at all scales, from a few centimeters to biomes and thousands of years to a temporary lake. Ecotone could be seen from different point of views (Farina, 2010): boundary zone between two patches; boundary between two levels of dynamics; border between two different levels of biological complexity.

Structural attributes of an ecotone in relation to physical composition include (Burel and Buadry, 2003) size, shape, biological structure, structural constraints, internal heterogeneity, fractal dimension of edges, patches diversity, and patch dimensions. Function of an ecotone can be measured by persistency, resilience, functional constraints, and porosity (Farina, 2010).

A characteristic feature of high mountains is their vertical zonation into elevational belts (the treeline, snowline, knick line, etc.) (Becker et al., 2007). Spatial and temporal distribution of natural resources (water, soil, landform, and vegetation) in the continuum system of upland–lowland has produced a particular pattern of spacing (Korner and Ohsawa, 2005). Changes in humidity and temperature with altitude formed different belts with various conditions, capacities, and capabilities (Korner, 2007) in which, the uplands are a source of fresh water and air, medium altitudes are area of reproductive and fertile soil, and low altitudes are the final sink of matters (Bogachev, 2004). Altitudinal belts in arid mountainous landscape of Iran are a good example of the formation of ecotones (Yavari et al., 2012).

Iranian landscapes

The high, arid plateau of Iran is composed of diverse and contrasting environments (Firouz, 1974). Iran's diversity in climatic conditions and its rich biodiversity and ecosystems are rooted in its unique geography (Yavari et al., 2012). Iran is a typical high-mountain country situated within the dry belt of Asia. Half of Iran is composed of high mountains. The Iranian high mountains are a rather continuous chain, especially at the Elburz and Zagros which enclose Iran in northwest–northeast and northwest–southeast directions. The area within the mentioned mountain ranges is high plateau, and it gradually slopes down to become desert which continues into southern part of Afghanistan and near the Pakistan border (Naqinezhad et al., 2009). The Elburz cordillera with an average altitude of 3,000–3,500 m extends like a great arc of 650 km between Hindu Kush and Himalaya Mountains in the east and Anatolia and Caucasus Mountains in the west. Mt. Damavand (5,670 m) is the highest peak in whole Eurasia and west of the Hindu Kush (Firouz, 1974). Elburz massif is a narrow but high range. The maximum width of Elburz is 130 km, but its average is 100 km (Hadisi and Jafarpoor, 2002). Contrary to the Zagros range, Elburz has smaller watersheds, narrower valleys, shorter and faster rivers, and steeper slopes (Shahidi and Nazeri, 2011). Elburz has many gradients: temperature and moisture are decreasing from east to west and from north to south. Temperature, humidity, and rain have also risen by increasing height (Yavari et al., 2012). Elburz range can be divided longitudinally into three parts, given large rivers dissecting it: eastern, central, and western. The central part also is divided into three sections: northern, median, and southern (see Figure 1). There are two major rivers on the southern slopes of central Elburz: Jajrood and Karaj.

The temperature in Iran is characterized by relatively large annual range of about 22°C to 26°C. The rainy period in most of the country is from November to May followed by dry period between May and October with rare precipitation. The average annual rainfall of the entire country is about 240 mm.

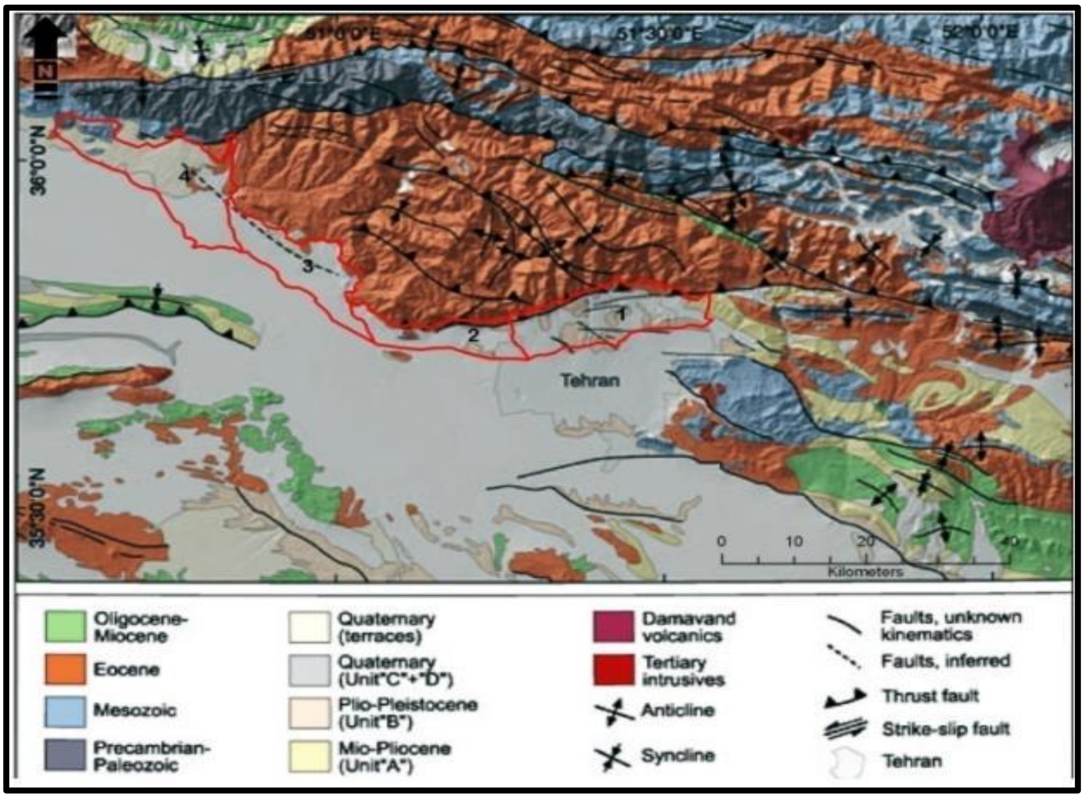

Fig. 1. Simplified map of geological structure of southern slope of central Elburz (Adapted from Landgraf et al., 2009)

Objectives

The mountainous matrix in Iran has created specific conditions, constraints, opportunities, and advantages (Yavari et al., 2012). Sequence of different altitude zones in the upland to lowland (or mountain to desert) continuum can be regarded as an association of landscapes (Yavari et al., 2007).Most human settlements and large metropolitan areas are placed on the midaltitudes between mountain and desert (Firouz, 1974). Current share of urbanization in Iran is more than 71.4%and the annual growth rate of urban population in the last decade was 4.69% (Statistical Center of Iran, 2014). Urbanization growth has caused the sprawl of urban areas upwardly into the ecotonal foothills (the zone between high and midlands) and has transformed the structure and function of this strategic zone (Yavari et al., 2007). These foothill zones connect mountains in the upland to the plains in the midlands (Korner, 2007). This ecotonal band serves as an interrelation joint between high and mid altitudes. The main goal of this study is to investigate the ways of connection, relation, and change in this ecotonal strip. However, specific objectives of this study are: (1) applying landscape ecological concepts in the evaluation of the ecotonal environment; (2) retrieval of land covers using Landsat images of 2000 and 2013; (3) measurement of spatial indices of landscape and analysis of spatial distribution of patches mosaic; and (4) monitoring and tracking the landscape changes over time by means of spatial indices.

MATERIALS & METHODS

Study area

Study area of this research is the ecotonal zone between upland mountain and midland plainin the southern slopes of the central Elburz region (Figs. 1, 2, and 3).

Tehran-Karaj region placed on the southern slopes can be partitioned to three main geomorphologic units (Mahmoodi, 1990):

1. The highlands and mountains of the North: areas with elevations above 1,800 m or with slopes greater than 16%.
2. The mid altitudes include: I. The northern badlands (the alluvials of the first phase); II. Conglomerate hills (the second phase); III. Recent fans (the third phase); and IV. New alluvial deposits and floodplains (the fourth phase).
3. Southern plains.

The growth of the Tehran city, capital of Iran, has launched from the Qajar era (circa 200 years ago) and has accelerated since 1970s, has not yet stabilized (Saeednia, 1989). Tehran's population has grown from 0.1 million in 1891 to 8 million in 2012, a drastic increase of 80 times (Statistical Center of Iran, 2014). Tehran has a still-growing population of 10 million, 8 million permanent residents, and 2million

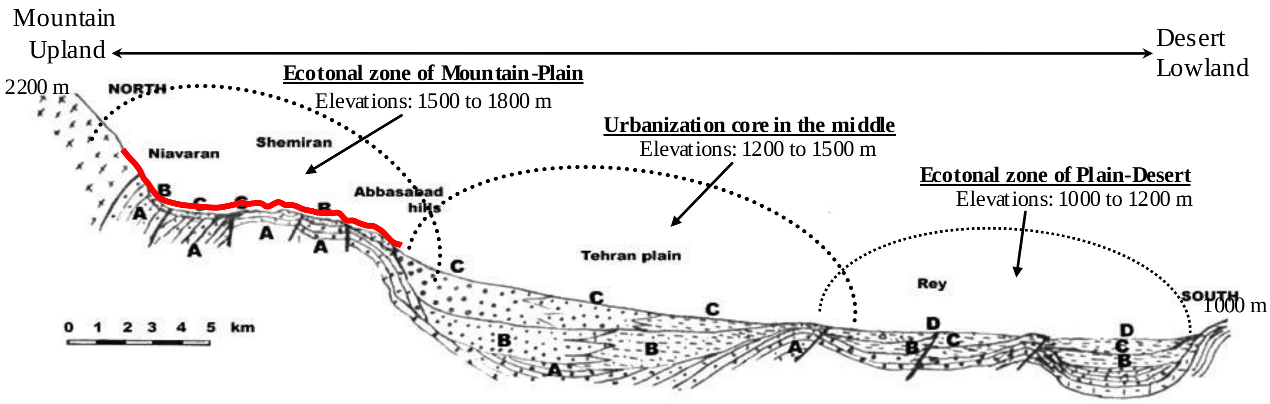

Fig. 2. North–South section of high, mid and lowelevation along the southern slopes of Elburz in Tehran plain (After Jahani and Reyhani, 2006).

nonresident commuters. Karaj city has a population of 1.4 million, and it is the fifth rank of the highest population after Tehran, Mashad, Isfahan, and Tabriz in Iran.

Tehran is the strongest sink of the population, and Karaj (as a satellite city of Tehran) is placed in the second position. Tehran Province has a population of over 12 million (16.2% of the entire country), and its population average annual growth during 2006–2011 was 1.44%. Karaj Province has a population of over 2.4 million (3.2% of the entire country), and its population average annual growth during 2006–2011 was 3.04% (Statistical Center of Iran, 2014). More than 90% of people living in Karaj and Tehran Provinces are in the urban area. The city of Tehran is positioned between Shahre-Rey plains in the South and Elburz Mountains in the North (Yavari et al., 2007). The slope and elevation are decreasing from north to south (Figure 2). The Increasing rates of population and urbanization in Tehran, Karaj, and their satellite areas have generated numerous ecological, economical, and social problems. Therefore, the coarse-scale monitoring can serve as a decision support system for spatial–physical planning and land management.

Data

Two satellite images of Landsat 8 OLI (2013) and two images of Landsat 7 ETM+ (2000) were used to capture land cover classes (Table 1; Figure 3). The images have cloud cover under 10% and are provided by the United States Geological Survey's (USGS) website with the GeoTiff format and the spatial resolution of 30 m. The months of May to July are selected for better recognition of the land covers. Years 2000 and 2013 are chosen because of the availability of data and the objectives of this study.

Rock formations, geomorphic, and landform characteristics are acquired by a geological map (Geological Survey of Iran), aerial photo (National Geographical Organization of Iran), and map of land suitability (Soil and Water Institute of Iran). Topographic map (National Cartographic Center of Iran) and DEM (Aster GDEM) is used to obtain the elevational attributes and to supplement other data.

All data and maps are registered to the same coordinate reference system: Universal Transverse Mercator (UTM) WGS 1984 Zone 39 N. Each satellite image is cropped and geometrically referenced using 30GCPs on the topographic map. Total Root Mean Square Error (TRMSE) of registration for all images was less than 0.50 pixels.

Table 1. Characteristics of Satellite images

Sensor	Acquired Date	Radiometric resolution	Local Time	Used Bands	Spatial resolution	Sun Azimuth Angle	Path and Row
ETM+	18 July 2000	8 bit	10:29:31	1-2-3-4-5-7	30 m	118.31	PATH = 164 ROW = 035
ETM+	25 July 2000	8 bit	10:35:30	1-2-3-4-5-7	30 m	120.51	PATH = 165 ROW = 035
OLI_TIRS	11 May 2013	16 bit	10:40:01	2-3-4-5-6-7	30 m	130.91	PATH = 164 ROW = 35
OLI_TIRS	19 June 2013	16 bit	10:36:01	2-3-4-5-6-7	30 m	119.03	PATH = 165 ROW = 35

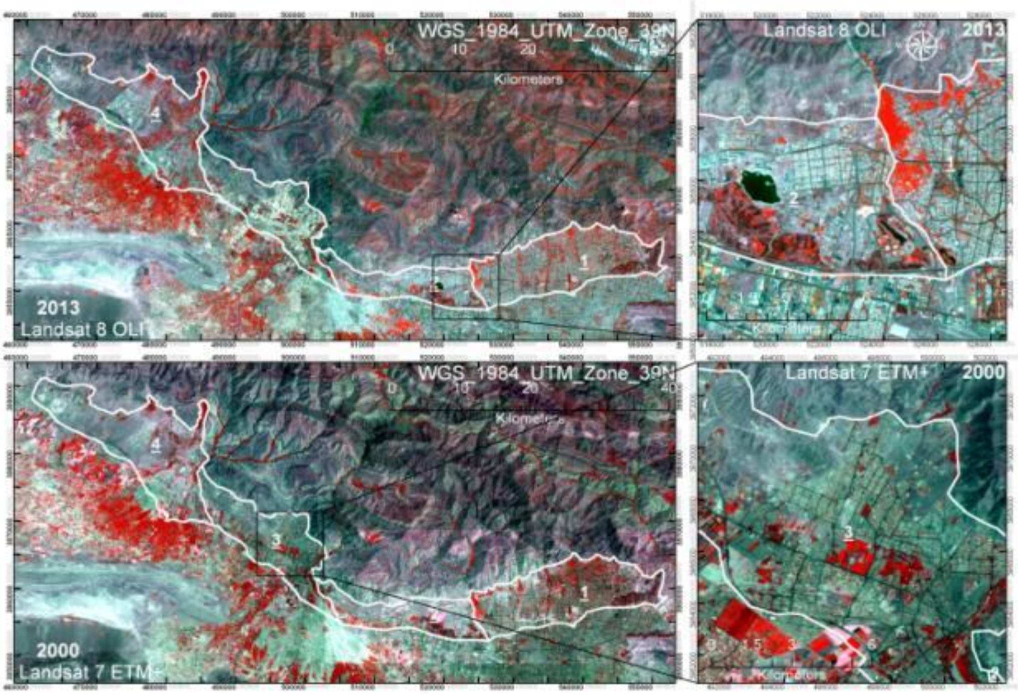

Fig. 3. Landsat 8 OLI/TIRS (2013) images at top, and Landsat 7 ETM+ in bottom; shown by false color 4-3-2

Delimiting the Ecotone

The ecotonal band is a narrow transition zone between mountain and plain in the continuum system of upland–lowland. The upper line of the foothill ecotone (northern border) is coinciding with Knick line, a line separating mountain and plain (Ahmadi, 2008).The lower line (southern border) is corresponding to the alluvial formation of A++. The eastern limit line is analogous to the Tehran municipality administrative boundary, and western limit is the Elburz Province administrative boundary.

Determining ecologically homogeneous units of land is a fundamental concept in environmental planning (Zonneveld, 2005). Considering natural conditions and urbanization impacts, the ecotone strip is longitudinally divided into four zones:

1. north Tehran to Kan River,
2. Kan River to Karaj River,
3. Karaj River to Kordan River, and
4. Kordan River to Abyek. Analysis and results are performed zone-specifically using ArcMap (version 9.3, ESRI) Zonal Statistics in Spatial Analyst Extension.

Land Cover Classification

Because of the lack of a standard typology for urban land-cover classes, and the confirmed ability of the Vegetation-Anthropogenic Impervious Surfaces (V-I-S)-soil model (Gluch and Ridd, 2010),which is suitable for remote sensing of urban regional environment, we classified land covers into four main groups: vegetation covers, anthropogenic impervious surfaces, open spaces, and water bodies. The supervised method with a maximum likelihood algorithm (Alavipanah, 2010) is applied to classify the satellite images (Fig. 3 and 4). Classification is performed by using the ERDAS Imagine system (version 8.4), and 40 training samples are used for each image. In the land cover map, areas less than 0.27 ha (3 pixel × 1 pixel) are eliminated in the larger nearby patch. Accuracy assessment is done, and the Kappa coefficient (Equation 1) for all the images was greater than 81%. Kappa coefficient is computed as:

$$k = \frac{N\sum_{i=1}^{r} x_{ii} - \sum_{i=1}^{r}(x_{i+} \times x_{+i})}{N^2 - \sum_{i=1}^{r}(x_{i+} \times x_{+i})} \qquad (1)$$

where N is the total number of sites in the error matrix, r is the number of rows in the matrix, x_{ii} is the number in row i and column i, x_{+i} is the total for row i, and x_{i+} is the total for a column I (Jensen, 1996). The main source of error was in the open spaces due to the broader definition of the class including sand, bare soil, exposed rock, rock outcrop, abandoned land, and sparse vegetation cover.

Calculation of Landscape Indices

We used the eight landscape indices to quantify the spatial pattern of the ecotone zone in the southern slope of Elburz (Table 2). This study considers each land cover as a patch. Landscape indices are as follows: number of patches (*NP*), class area proportion (*CAP*), mean patch size (*MPS*), area-weighted mean patch size (*AW-MPS*), total edge (*TE*), perimeter to area ratio (*PARA*), and mean nearest neighbor distance (*MNND*).

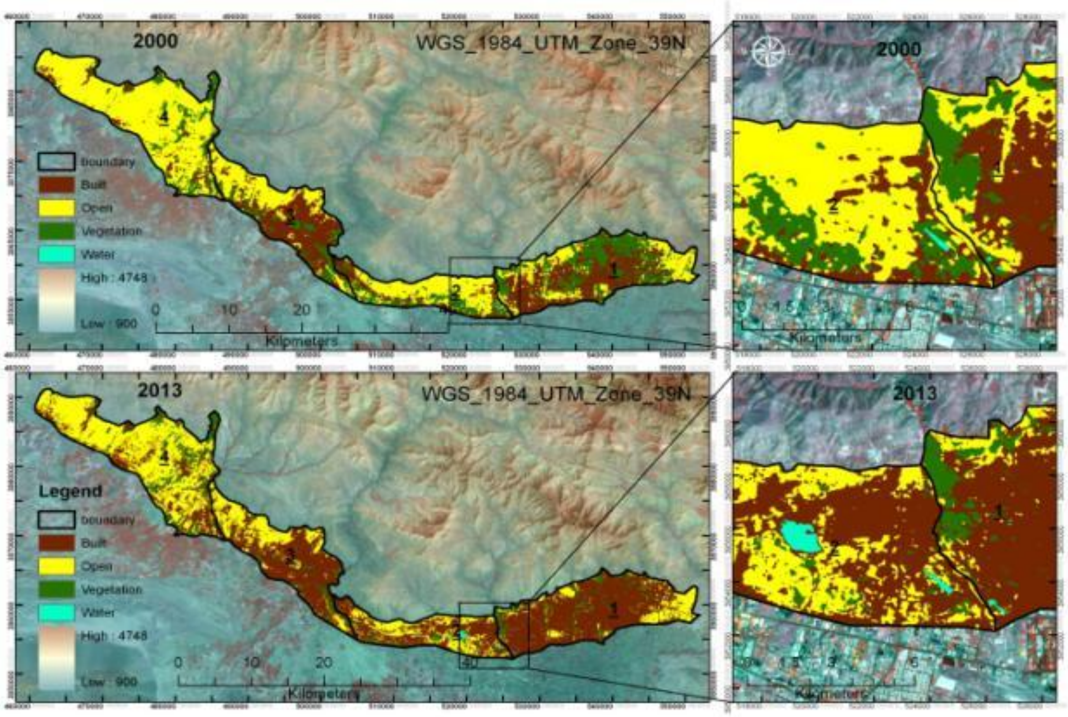

Fig. 4. Classified land cover map of foothill zone in 2000 (top) and 2013 (bottom)

Table 2. Definitions of landscape indices and calculation method

Indices	*NP*	*CAP*	*MPS*	*AW-MPS*	*TE*	*PARA*	*MNND*
Formula	n_i	$\sum_{j=1}^{n} a_{ij}\left(\frac{1}{10000}\right)$	$\frac{\sum_{j=1}^{n} x_{ij}}{n_i}$	$\sum_{j=1}^{n}\left[x_{ij}\left(\frac{a_{ij}}{\sum_{j=1}^{n} a_{ij}}\right)\right]$	$\sum_{k=1}^{n} e_{ik}\left(\frac{1}{1000}\right)$	$\left(\frac{100\, p_{ij}}{a_{ij}}\right)$	h_{ij}
Range	*NP*≥ 1, without limit	*CAP*> 0, without limit	*MPS* > 0, without limit	*AW-MPS*> 0, without limit	*TE*≥ 0, without limit	*PARA*> 0, without limit	MNND > 0, without limit
Description	Number of Patches	Class Area Proportion (ha)	Mean Patch Size (ha)	Area Weighted Mean Patch Size (ha)	Total Edge (km)	Perimeter to Area Ratio	Mean Nearest Neighbor Distance (m)

RESULTS & DISCUSSION

Table 3 indicates the measurement of indices for the years 2000 and 2013 in total landscape and sublandscape as well as class levels. Land covers in the 13-years' period, from 2000 to 2013, in the ecotonal belt have changed as follows: vegetation changed from 12.8 to 8.53%; open class from 51.43 to 38.55%; and built class from 28.73 to 52.59%. Class area proportion of vegetation (*CAP_Veg*) in the entire area declined from2000 to 2013.Similartrend has occurred in all the zones. Maximum and minimum changes of vegetation class have taken place, respectively, in zone 1 (North of Tehran) with 22.61% and zone 4 (Suburb of Karaj-Qazvin) with 14.07%.

The total share of open spaces (*CAP_Opn*) fell from 2000 to 2013; the trend is common to all zones. Zone 2 (Suburbs of Tehran-Karaj) and zone 3 (North of Karaj) indicated correspondingly highest and lowest changes of *CAP_Opn*. Regarding *CAP_Opn*, zones 1, 2, 3, and 4were 25.67, 59.44, 37.61, and 79.21%, respectively, in 2000; later it changed to, 16.49, 34.28, 31.20, and 64.42%, respectively, in 2013.

The relative contribution of the built-ups (*CAP_Bui*) increased in all four zones. *CAP_Bui* in zones 1, 2, 3, and 4 has increase of 31.65, 37.99, 14.91, and 16 %, respectively. A maximum increase of *CAP_Bui* occurred in zone 2 and minimum increase was in zone 3. The 13-year trend of our study indicated that 32.93% of the entire area of the ecotone had changed.

NP increased from 1,836 in 2000, to 3,463 in 2013 in the total area, which is a sign of fragmentation (Table 4). In 2000, the zone 1 with 732 and zone 2 with 317 each have the largest and smallest values of *NP*. However, zone 4 with 1,365 and zone 3 with 567 had the maximum and minimum values for *NP* in 2013, respectively.

Table 3. Landscape indices: *CAP, NP, MPS, AW_MPS, MNND, TE*, and *PARA*

Zone	Area (ha)	Year	*CAP_Veg (%)*	*CAP_Opn (%)*	*CAP_Bui (%)*	*NP*	*MPS (ha)*	*AW-MPS (ha)*	*MNND (m)*	*TE (Km)*	*PARA*
1	17992611	2000	30.92	25.67	43.12	732	27.47	3561.65	173.39	1611.02	3.61
		2013	8.31	16.49	74.96	966	20.85	11104.00	186.55	1395.71	4.70
2	9107235	2000	19.64	59.44	20.26	317	32.17	2915.71	243.30	713.84	3.60
		2013	5.57	34.28	58.59	572	17.89	3476.89	180.61	1049.82	4.43
3	13149216	2000	14.19	37.61	47.86	353	41.61	3518.78	236.17	876.55	3.24
		2013	5.74	31.20	63.01	567	25.94	5413.86	200.35	1054.77	4.29
4	20596761	2000	12.80	79.21	7.69	447	51.48	13328.09	387.02	1016.54	3.58
		2013	11.82	64.42	23.74	1365	16.87	7954.71	231.93	2257.70	4.53
Total	60845823	2000	12.80	51.43	28.73	1836	36.97	8998.78	269.73	4139.24	3.58
		2013	8.53	38.55	52.59	3463	19.62	16685.13	204.01	5628.14	4.53

Table 4. Number of patches (*NP*) at total and class levels

Zone	Year	*NP*	*NP_Veg**	*NP_Opn**	*NP_Bui**	*NP_Wat**
1	2000	732	342	186	202	2
	2013	966	482	339	140	5
2	2000	317	116	101	99	1
	2013	572	163	257	149	3
3	2000	353	134	93	126	0
	2013	567	185	251	131	0
4	2000	447	180	55	212	0
	2013	1365	361	267	737	
Total	2000	1836	765	432	636	3
	2013	3463	1187	1113	1155	8

**NP_Veg*: number of vegetation patches; *NP_Opn*: number of open patches; *NP_Bui*: number of built patches; *NP_Wat*: number of water patches.

Total *NP* of vegetation (*NP_Veg*), open spaces (*NP_Opn*), and built area (*NP_Bui*) increased from 765, 432, and 636, respectively, in 2000 to 1,187, 1,113, and 1,155 in 2013. The highest change of *NP_Veg* happened in the zone 4 and the lowest was in the zone 2. Descending rank of *NP_Opn* in 2000 was zone 1 (with value of 186) > zone 2 (with value of 101) > zone 3 (with value of 93) > zone 4 (with value of 55), converted to zone 1 (339) > zone 4 (267) > zone 2 (257) > zone 3 (251) in 2013.

Total *NP_Bui* climbed from 636 to 1,155 during the period of 13 years. Interesting point was the reduction of *NP_Bui* in the zone 1 (from 202 in 2000 to 140 in 2013), contrary to the general trend of increase in other zones. This is due to the expansion of the built patches and then joining them together. This change is called, a transformation of the contextual matrix. The highest value of *NP_Bui* was in zone 4 (212 for 2000 and 737 for 2013).

MPS is calculated as the division of the total area to the number of patches. Throughout the area, *MPS* descended from 36.97 in 2000 to 19.62 ha in 2013, which is a result of the elevated numbers and the declined areas of patches. These are also signs of fragmentation process. As Figure 5 shows, *MPS* in zones 1, 2, 3, and 4, respectively, were 27.47, 32.17, 41.61, and 51.48 ha in 2000, decreased to 20.85, 17.89, 25.94, and 16.87 in 2003, in the aforementioned order. During the period of 13 years throughout the study area, *MPS* of vegetation covers (*MPS_Veg*), open spaces (*MPS_Opn*), and built-up areas (*MPS_Bui*) went from 17.25, 81.08, and 30.87 ha in 2000 to 47.6, 23.56, and 31.10 ha in 2013, respectively. For all zones, *MPS_Veg* and *MPS_Opn* had smaller quantity in 2013 when compared to 2000 (Figure 5). But, *MPS_Bui* increased from 2000 to 2013, except for zone 4. *MPS_Bui* in zones 1, 2, 3, and 4were 43.22, 21.42, 55.87, and 8.26, respectively, in 2000 that turned to 108.85, 40.77, 71.05, and 7.31 ha in 2013. Descending rank of *MPS_Opn* in 2000 was the zone 4 (332.82) > zone 2 (60.08) > zone 3 (59.90) > zone 1 (27.88 ha) that changed in 2013 as zone 4 (55.92) > zone 3 (18.27) > zone 2 (13.53) > zone 1 (9.77 ha).

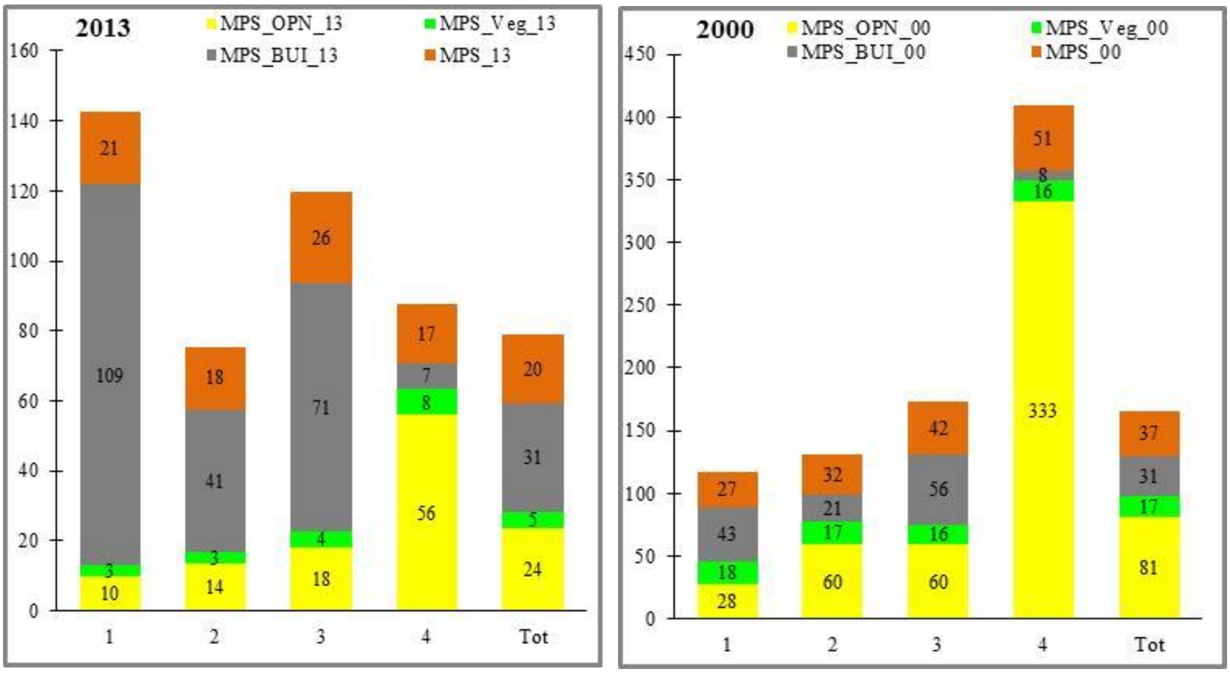

Fig. 5. *MPS*, *MPS_Veg*, *MPS_Opn*, *and MPS_Bui* in 2000 and 2013. Veg: Vegetation; Opn: Open; Bui: Built up.The numbers, 00 and 13 means2000 and 2013, respectively

The arithmetic *MPS* carries the same weight for all patches, but the *AW_MPS* exerts the weight of each patch through the ratio of the patch area to the total area. When the variance of sizes is high, the arithmetic mean cannot be a good description of the actual condition, but area-weighted mean can offer the better understanding of the landscape state. *AW_MPS* in the entire area was 8,998.87 ha in 2000 increased to 16,685.13 ha in 2013. The extremes of *AW_MPS* in 2000 were zone 4 (with a value of 13,328.09 ha) and zone 2 (2,915.71 ha), which changed to zone 1 (with a value of 11,104 ha) and zone 2 (with 3,476.89 ha) in 2013, accordingly. *AW_MPS* in vegetation covers (*AW_MPS_Veg*), open spaces (*AW_MPS_Opn*), and built-up areas (*AW_MPS_Bui*) in 2000 were 493.90, 14,060.59, and 5695.76 ha, respectively, which changed to 65.81, 7,063.78, and 26,394.66 ha in 2013, respectively. In the period between 2000 and 2013, the *MPS* trend was descending in zones 1, 2, and 3, but *AW_MPS* had ascending trend, showing the different sensitivity of the two indices. Yet, *MPS* and *AW_MPS* in the zone 4 indicated the similar pattern of decline.

Mean nearest neighbor distance (*MNND*) is an index of the connectivity, distribution, and arrangement of patches across the landscape. The lower amount of *MNND* implies the higher connectivity of patches and vice versa. *MNND* in the entire area decreased from 269.73 m in 2000, to 204.01 m in 2013 (Figure6).During the 13-year period, *MNND* in vegetation class (*MNND_Veg*) had increased value in all the zones, except in zone 4. In the whole area, *MNND_Veg* rose from 350.56 m in 2000to 390.47 m in 2013; this is a sign of reduced patch size, increased patch segregation, and high-fragmentation process. *MNND* in the open class (*MNND_Opn*) grew in all zones, except in zone 3.Peak and valley of *MNND_Opn* in 2000were 284.44 (zone 1) and 24.80 (zone 4), respectively; increased to 309.32 (zone 1) and 34.25 (zone 4) in 2013, with the same pattern. *MNND_Bui* reduced in all zones, because of expansion of built patches, jointed patches, and greater connectivity between them. The ascending trend of *MNND_Bui* in 2000 was, zone 1 (112.46) < zone 3 (116.99) < zone 2 (378.56) < zone 4 (565.86 m); changed in 2013 as zone 1 (23.86) < zone 1 (37.59) < zone 3 (50.19) zone 4 (130.36 m). In 2000, the lowest value of *MNND* at the class level was in the open spaces of the zone 4 (with mean distance of 24.80 m), and the highest was for the vegetation of the zone 4 (with mean distance of570.39 m). In 2013, the minimum distances of classes happened in zone 1 for the built-ups with 23.86 m (highly connected) and the maximum occurred in zone 4 for vegetation with 531.19 m (very fragmented).

TE is quantified by the sum of the boundaries on the landscape. The greater the length of boundaries, produces the finer grain-size pattern resulting in higher environmental resistance to ecological processes. This index is also a sign of fragmentation of the landscape. During the 13-year period of our study, *TE* rose from 4,139.24 to 5,628.14 km on the entire area, which signifies increasing the boundaries, decreasing the patch size, and higher fragmentation. The highest *TE* in 2000 and 2013 were in zone 1 (16,111.02) and the zone 4 (2,257.70 km), respectively; the lowest *TE* was in the zone 2 with 713.84 km (in 2000) and 1,049.82 km (in 2013).

The *PARA* is an index of the form of patches that show the amount of edge effect and interior area. The higher value of the *PARA* is an indication of narrow and elongated shape with lobes and corners. By decreasing the *PARA*, forms will go toward circular shapes having a greater area of interior part. The *PARA* index on the whole area increased from 3.58 in 2000 to 4.53 in 2013, which is a sign of complexity of shapes (with higher convex and concave forms), increase of edges, and decrease of the area. The smallest amount of *PARA* in

2000 and 2013 was in zone 3 with 3.24 and 4.29, respectively. This indicates the lower complexity and diversity of patch forms in zone 3. The largest quantity of the *PARA* in 2000 and 2013 were in zone 1 with 3.61 and 4.70, respectively, showing the more complex shapes and more various forms of this zone.

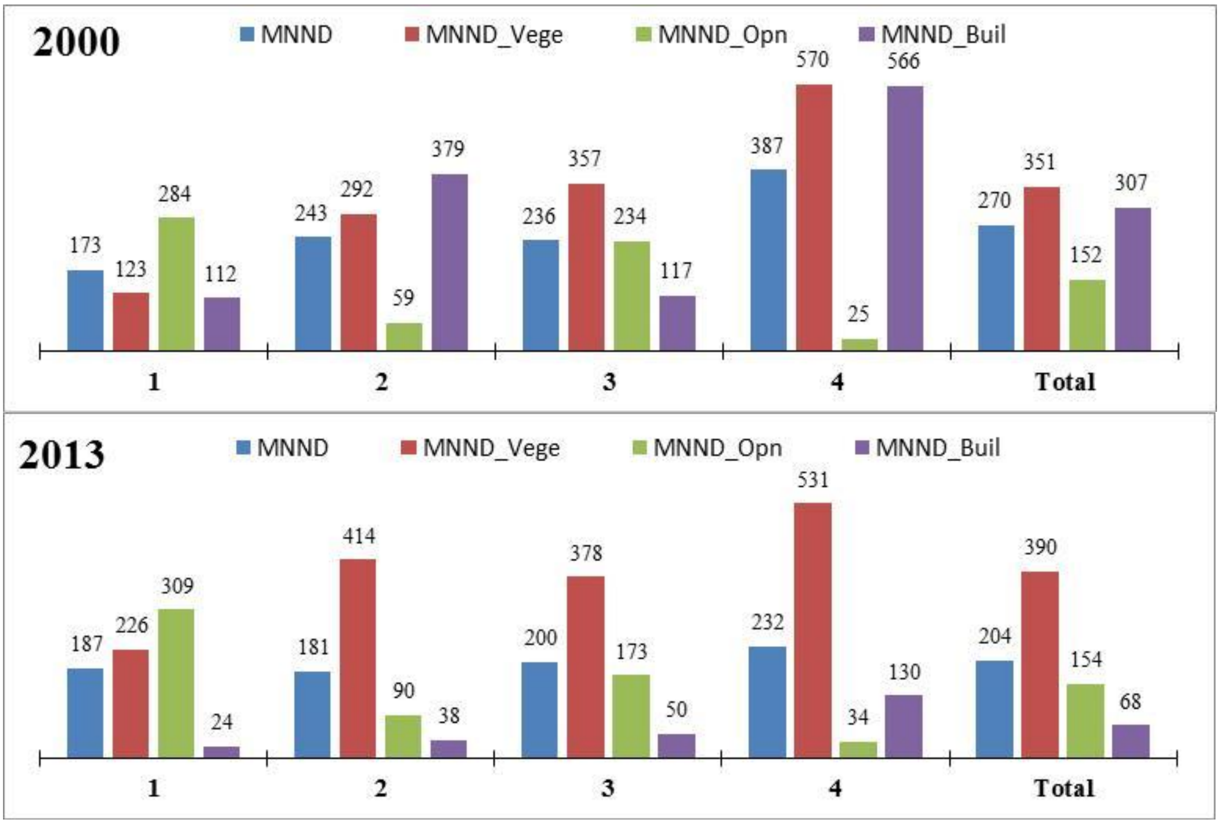

Fig. 6. Mean nearest neighbor distance (MNND) in 2000(top) and 2013(below). Veg: Vegetation; Opn: Open; Bui: Built up.

Conclusion

In general, the landscape indices *NP*, *CAP_Bui*, *AW-MPS*, *TE*, *PARA*, and *MNND* had increasing trends during this period, but *MPS*, *MNND*, *CAP_Veg*, and *CAP_Opn* declined from 2000 to 2013. *MNND_Veg* and *MNND_Opn* rose over the time indicating the highest degree of fragmentation, but *MNND_Bui* is decreased showing that connectivity increased. In the whole area *NP_Veg*, *NP_Opn*, and *NP_Bui* had increased value between 2000 and 2013, which is a sign of fragmenting.

Our results show that 32.93% of the ecotonal zone has changed during the past 13 years (2000 to 2013). Vegetation covers and open spaces were the main source of land cover conversions and built-up area was the ultimate sink of conversions. The explosive trend of urbanization in the ecotonal zone signifies that regional interrelations within upland–lowland continuum (Becker et al., 2007) have been altered.

Vegetation covers in the ecotone zone based on urban green space functions, land use type, and ownership can be grouped into four main types: (1) urban parks and public green spaces with formal rectangular geometry, (2) vegetation covers in private or semi-public spaces with various formal geometries,(3) orchards and natural green areas, and (4) cultivated green spaces without tree cover. Most vegetation cover changes during this period (2000–2013) have succeeded in orchards. Orchards of this ecotonal zone are in the valley floors, alluvial fans, and riparian areas that play an important role for the ecological integrity of the whole landscape; these green areas are visible on aerial or satellite images with ⋏-shaped forms in the foot of the mountain and in the mouth of river valleys. Green spaces on the entire area declined from 12.8 in 2000 to 8.53% in 2013.

Most of the rain in Iran comes in a few days, with a small number of rain days contributing a large proportion of the annual rainfall. For the entire country, 44% of rainfalls occur in 10% of the days. High-intensity days are 15% of the rain days but produce 41% of the rain (Alijani et al., 2008).Flash floods cause severe soil erosion, agricultural damage, road and bridge destruction, street runoff, car accidents, and traffic jams. In our study area, the total share of the impervious surfaces in 2000 was 28.73% which increased to 52.59% in 2013. Decreased amount of vegetation cover and increased proportion of impervious surface result in increased surface runoff and flash floods across the landscape. Consequently, Based on Paul and Meyer (2001), we can expect that surface runoff have increased by three times.

Open spaces of the ecotonal area are in four groups: (1) mountain slopes with ⋎-shaped surfaces, exposed rock, steep slopes, and thin layer of soil and colluvial deposits, placed in the upper part of the ecotone; (2) hilly areas with circular and oval-shaped surfaces placed in the middle of the ecotone; (3) sparsely vegetated pastures with gentle slope and semi-deep soil; and (4) Oued, Wadis, and flooding areas. In zones 1 and 3 (north of Tehran and Karaj) the direct driving force of change is urbanization, and the mountain slopes and the flooding plains are at greater risk of urbanizing. But in zones 2 and 4 (suburbs of Tehran and Karaj), pasture lands and hilly areas are mostly in risk of transformation and construction of buildings. River valleys and orchards are also two strategic elements, considering the structure of the ecotonal landscape.

The upper boundary line of the ecotone (Knick line) has a generally curved shape and can be simplified as a sequence of two basic surfaces: (1) a concave form and (2) a convex form. Concave surfaces are like a funnel or ⋎-shaped (wide at the top and narrow at the bottom) including colluvial deposits in base of the mountain. But, convex ⋏-shaped surfaces contain the valleys extending downward into the plain. Convex forms include alluvial fans with a river in the middle; and also, rural orchards in the riparian peripheries have taken here.

Determining the state and trends of landscape elements are necessary for a better understanding of the ecological resources. The processes of transformation in our study area can be described using a sequence of landscape succession described by Forman (1995) in the five series. Zones 1 and 3 are in the final phase of land transformation (nearly between the shrinkage and attrition); zone 2 is nearly in the middle (between the fragmentation and shrinkage); and zone 4 is approximately in the primary levels (the perforation and fragmentation). Considering the state and trend of each zone in terms of land transformation processes, different strategies can be taken for planning activities. Ahern (2005) demonstrated planning methods and strategic orientation in four types: protective, defensive, offensive, or opportunistic. These strategies, in essence, define the planning context with respect to the macrodrivers of change in a given landscape and the strategic nature of the planners' response (Ahern, 2005).

Current technical tools of remote sensing and GIS along with a theoretical base of the landscape ecological approach can provide an appropriate framework for monitoring the environmental quality. The application of methods and techniques of remote sensing and GIS are critical for coarse-scale monitoring of land use/cover changes, and standardized techniques of processing is a necessary condition for the comparative studies (Laush and Herzog, 2002; Lausch et al., 2013).

Local scale changes could only be perceived if the wider geographical context and its choric relations are taken into account. Broad-scale monitoring with satellite images can be linked to a local-scale monitoring to form a monitoring network of environment on many scales (Lausch and Herzog, 2002; Lausch et al., 2013). Monitoring of landscape condition and its changes through the time is a necessary tool for land use decision and spatial planning. Determining the state and trends of landscape elements are necessary for a better understanding of the ecological resources.

The ecotonal zone between two major landscapes (mountain and glacis) along highland–lowland continuum system acts as an intermediate connector having many ecological services at several scales. Ecotones are ecologically significant area for monitoring of environmental quality (Forman, 1995). Ecotonal belt formed at the foot of the mountain is more diverse than the surrounding context and have to be treated as a strategic location (Farina, 2010) for monitoring environmental quality.

Each altitudinal belt has particular ecological and socioeconomic services (Bogachev, 2004). Alluvial fans located in the base of the mountains have fertile and reproductive soils that are suitable for settling the urban centers and horticultural activities like orchards. This ecotone of mountain plain have located in the way of winds flowing from mountain toward plain in the night and from plain to mountain during day; therefore, the ecotone is playing an important role for the refinement of urban air condition.

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