



Research paper

Spatial and temporal deforestation dynamics of Zagros forests (Iran) from 1972 to 2009

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H I G H L I G H T S

- We developed two spatial measures to quantify the changes across time and space.
- Loss of connecting patches decreased connectivity more than forest area.
- Southern Zagros had more connectivity loss due to seed based management.
- Different restoration approaches should be used in northern and southern districts.

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A B S T R A C T

The emerging interest in sudden losses in vegetation and forest cover in semi-arid areas has led to a new understanding of the patterns and processes of deforestation. The Zagros oak forests in western Iran have undergone dramatic changes in cover and structure in recent decades, with negative consequences for the communities that depend upon them. This study had three objectives: (1) evaluate the nature and magnitude of these changes from 1972 to 2009 through trends in forest area and connectivity; (2) evaluate the changes in forest area and landscape connectivity across a climatic gradient; and (3) evaluate the effect of topographical variations. Landsat MSS, TM, and ETM+ images for the region were preprocessed and corrected prior to classification of 167 landscape units (LU; 400 km² each). We developed two measures – deforestation sensitivity (DS) and connectivity sensitivity (CS) – for each LU. A considerable but relatively linear loss in forest area and connectivity was detected. Connectivity loss occurred more rapidly than forest loss due to the loss of connecting patches. More connectivity was lost in southern Zagros due to climatic differences and different forms of traditional land use. Steep slopes and high elevations experienced more forest loss and connectivity. In northern Zagros the coppice form of forest management should be supported as a method that maintains connectivity. In southern Zagros, restoration projects should focus on regeneration in forest gaps to restore connectivity between isolated forest fragments. The study provides large scale information for restoration projects across a spatial climatic gradient.

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1. Introduction

For millennia, semi-arid savannas and woodlands have been some of the most important ecosystems for human cultures; their resilience and dynamics are an active area of research at multiple scales (Hirota, Holmgren, Van Nes, & Scheffer, 2011; Mayer & Henareh Khalyani, 2011; Staver, Archibald, & Levin, 2011). Trends

in vegetation cover in these ecosystems have been examined for the existence of nonlinear declines in the amount and kinds of vegetation cover (e.g., Carmel & Kadmon, 1999; Hirota et al., 2011; Rietkerk & Van de Koppel, 1997; Rietkerk, van den Bosch, & Van de Koppel, 1997; Staver et al., 2011). In the case of nonlinear vegetation loss, once the ecosystem transitions to another state, recovery will be slow or even irreversible because of new internal feedbacks that reinforce the resilience of the new state (Mayer & Rietkerk, 2004; Scheffer, 2009; Walker, Holling, Carpenter, & Kinzig, 2004). These sudden, catastrophic declines in vegetation cover have dire consequences for the human communities that depend upon the vegetation for livestock grazing, fuel, and other demands. Similar to other woodlands around the world, Zagros semi-arid oak forests in western Iran have been subject to dramatic changes in

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forest cover and structure in recent decades (Henareh Khalyani, Falkowski, & Mayer, 2012a; Henareh Khalyani, Mayer, Falkowski, & Muralidharan, 2012b; Jazirehi & Ebrahimi Rostaghi, 2003). The rapid decrease in forest area in Zagros suggests the possibility of similar dynamics behind critical shifts that have been found in other semi-arid areas of the world (e.g., Rietkerk and Van de Koppel, 1997; Rietkerk et al., 1997). Given the national and regional importance of Zagros forests, it is extremely useful for restoration management to identify irreversible critical shifts by retrospective studies, and to evaluate some indices, which might signal impending shifts.

Zagros forests have critical national importance. These forests capture over one third of the country's annual precipitation, and are the headwaters for 40% of the country's rivers and streams (providing 50 billion m³) which water the dry central plateau of Iran (Jazirehi & Ebrahimi Rostaghi, 2003). However, these forests have rarely been studied through spatially explicit landscape studies. Saei (1942) delineated the geographic extension of Zagros forests for the first time and reported dense forest stands in Kurdistan (northern Zagros). Forest stands were generally sparse in the other areas of Zagros, except some remote and isolated patches. Three forms of forest management and regeneration are practiced in Zagros due to climatic differences north to south: coppice form, seed-based form, and in some areas a combination of these two (Jazirehi & Ebrahimi Rostaghi, 2003). These three forms appear unequally north to south, with more coppice form appearing in northern Zagros. This is due to the climatic gradient and to differences in local management traditions from north to south (Jazirehi & Ebrahimi Rostaghi, 2003). Therefore, the changes in traditional management in Zagros from north to south might cause different patterns of changes in forest area and structure across space. Ghazanfari, Namiranian, Sobhani, & Marvi Mohajer (2004) found that the rapid growth (in height) of sprouts in the coppice traditional system in northern Zagros helped regenerated stands to quickly pass the grazing height. Henareh Khalyani (2005) found that small scale protection from grazing and gradual amendment of traditional utilization was required to re-establish the seed-based regeneration (Henareh Khalyani, 2005; Namiranian, Henareh Khalyani, Ghazanfari, & Zahedi Amiri, 2007).

The first step to evaluate forest changes across space and through time is to select the appropriate spatial metrics that can be reliably used at the Zagros forests' scale. Common landscape metrics (Macgrail, Cushman, Neel, & Ene, 2002) and patch-size distributions (Clauet, Shalizi, & Newman, 2009) have been used in combination in previous studies to examine forest loss and structural changes in Zagros (Henareh Khalyani et al., 2012b; Henareh Khalyani, Mayer, Webster, & Falkowski, 2013). However, common landscape metrics may have shortcomings, including inconsistency in capturing certain changes in landscape structure and interpretation difficulty (Li & Wu, 2004), overly complex for use in applied situations (e.g., Sarkar et al., 2006), and requiring data reduction methods due to their high correlation with each other (e.g., Henareh Khalyani et al., 2012b, 2013; Riitters et al., 1995). While they have proved useful at the local scale, landscape metrics are likely to suffer the same shortcomings in this ecosystem as in others when applied at the regional scale.

Landscape connectivity represents the flow of genes, energy, and species dispersal across space, and can therefore measure several dimensions of landscape stability and sustainability (Jordán, Báldi, Orci, Racz, & Varga, 2003; Minor & Urban, 2007; Pascual-Hortal & Saura, 2006; Urban & Keitt, 2001). Different connectivity metrics based on habitat availability, habitat connectivity, and graph structure were developed and tested by previous studies (Minor & Urban, 2007, 2008; Pascual-Hortal & Saura, 2006; Rothley & Rae, 2005; Saura & Pascual-Hortal, 2007; Urban & Keitt, 2001). However, most of these metrics were not problem-free. They did not react consistently to landscape changes and lacked an adequate

response to connectivity changes. Two metrics did not suffer these problems: integral index of connectivity (ICC), and the probability of connectivity (PC), which are both based on habitat availability (Pascual-Hortal & Saura, 2006). These metrics are integrated measures, incorporating both within patch connectivity (patch areas are measured as the spaces where connectivity occurs), and connectivity between patches (distance between patches and the permeability of the landscape matrix between the patches). Habitat availability in these metrics is an integrated combination of within patch and between patch connectivity (Pascual-Hortal & Saura, 2006; Saura & Rubio, 2010). Connectivity metrics in general are suitable for large-scale studies, are more robust to the detail in input data, and are applicable to sparse landscapes (Saura & Rubio, 2010; Saura, Estreguil, Mouton, & Rodríguez-Freire, 2011a). Since this study is focused on the entire Zagros forest and encompasses a larger extent than previous landscape structure studies, which used common landscape metrics (Henareh Khalyani et al., 2012b, 2013), we can therefore capture the regional north–south gradient in vegetation dynamics using connectivity metrics. Zagros forests are open canopy, sparse oak forests which have experienced a long history of disturbances and habitat fragmentation (Henareh Khalyani et al., 2012b, 2013; Jazirehi & Ebrahimi Rostaghi, 2003). These two characteristics (large extent and sparse forests) make connectivity metrics based on graph theory valuable indicators for monitoring the dynamics of forest cover and connectivity change across the entire Zagros region.

In this study we examined the changes in forest area and connectivity through time and across space to address three main objectives: (1) examine trends in Zagros forest cover and connectivity from 1972 to 2009 to test for critical transitions against the null hypothesis of gradual changes in forest area and connectivity; (2) investigate the changes in forest area and connectivity across the entire Zagros forests, examining the climatic gradient of changes from north to south (this allows us to evaluate the hypothesis that climate is a primary driver of forest change; Jazirehi & Ebrahimi Rostaghi, 2003); (3) evaluate the changes in area and connectivity in relation to variations in elevation and slope across Zagros. The area has a rugged topography with high variation in elevation and slope (Henareh Khalyani et al., 2012a). Elevation and slope provide variation both in local climatic condition in terms of rainfall and temperature and also in local communities' utilizations, and may drive differences in the changes observed in forest area and connectivity. High elevations and steep slopes on one hand imply a lower likelihood of forest conversion or other human induced disturbances (due to physical difficulties of working in these areas), but alternatively they may represent areas of lower access for the governmental management agency to control the traditional usages and other damages.

2. Methods

2.1. Zagros forests' northern and southern districts

The Zagros region extends along a climatic gradient in temperature and precipitation from northwest Iran toward the southeast (Fig. 1). Jazirehi and Ebrahimi Rostaghi (2003) described the position of Zagros forests in the phytogeographic regions of the northern hemisphere as the Zagrosian sector in the Irano-Anatolian sub-region, Irano-Turanian region, and Holarctic Kingdom. The endemic species of Zagrosian sector is *Quercus brantii* var. *persica*, and the sector is composed of two northern and southern districts with unique species (Jazirehi & Ebrahimi Rostaghi, 2003). The forest cover is ~5 million ha, and occurs at 1000–2300 m above sea level (Jazirehi & Ebrahimi Rostaghi, 2003). The area has a rugged topography including all possible ranges of slopes (Henareh

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