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Landscape trajectories and their effect on fragmentation for a Mediterranean semi-arid ecosystem in Central Chile

Angela Hernández [a, *], Marcelo D. Miranda [a, b], Eduardo C. Arellano [a, b], Cynnamon Dobbs [a]

[a] Departamento de Ecosistemas y Medio Ambiente, Pontificia Universidad Católica de Chile, Ave. Vicuña Mackenna, 4860, Santiago, Chile
[b] Center of Applied Ecology & Sustainability (CAPES), Pontificia Universidad Católica de Chile, Alameda, 340, Santiago, Chile

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ABSTRACT

Changes in land use and land cover reflect anthropogenic effects in areas with a long history of human occupation, such as Mediterranean regions. To understand the landscape dynamics of a semi-arid Mediterranean ecosystem in Chile, we evaluated land-cover trajectories and their effects on landscape spatial patterns over a period of 36 years (1975–2011). We used landscape metrics combined with surveys of landowners to distinguish the main drivers of landscape change. General results indicated that changes in forest area followed both natural (64%) and human-induced (36%) trajectories. At the landscape level, fragmentation for all forest cover types increased, whereas at the class level, fragmentation of Native Forest decreased. The landscape changed from a homogeneous mosaic dominated by grazing and agriculture to a more heterogeneous environment, where natural cover had become more dominant. Thus, the use of a landscape ecology approach together with field information improved our understanding of the spatiotemporal dynamics in this landscape. This study is one of the first to assess landscape dynamics of the Mediterranean semi-arid region of Chile. This is important because it aids decision-making for biodiversity conservation in a global hotspot and land-use planning.

1. Introduction

A landscape is a dynamic entity constantly changing its spatial, biotic, and abiotic patterns (Forman, 1995). Many of the dynamics occurring at the landscape level have profound consequences for the structure and function of ecosystems (Forman, 1995; Gustafson, 1998; Parcerisas et al., 2012). Major landscape changes have occurred as a consequence of changes in land use and land cover (Foley et al., 2005). Land use is defined by its anthropogenic use, such as agriculture, forestry, built-up areas, pasture, and others, which all alter the structure and function of the landscape. Land cover refers to the physical and biological surface cover of the land, including water, vegetation, bare soil, and/or artificial structures (Meyer and Turner, 1994). This is particularly relevant for areas with a long history of human occupation (Foley et al., 2005; Mitsuda and Ito, 2011), such as Mediterranean landscapes.

In Mediterranean landscapes, changes in cover and land use have been profound, particularly because these ecosystems are considered particularly vulnerable to land changes given their semi-aridity and high biodiversity (Sala et al., 2000). Mediterranean landscapes represent <5% of the surface of the Earth; however, they support nearly 20% of the plant species of the world, many of which are endemic (Cowling et al., 1996). Research on landscapes dynamics in Mediterranean ecosystems and the ecological consequences of changes in cover and land use have mainly occurred in Europe (Foggi et al., 2014; Geri et al., 2010; Preiss et al., 1997; Saura et al., 2011), with some examples from North America (Gerlach, 2004) and Australia (Seabrook et al., 2007). In South America, the only Mediterranean ecosystem occurs in Central Chile and has received little attention from landscape ecologists.

Research on landscape changes in Mediterranean landscapes in Chile are still in their infancy. Patterns in the reduction of natural vegetation have been qualitatively described by Armesto et al. (2007) and Aronson et al. (1998) and, more recently, Schulz et al. (2010) explored the landscape dynamics (2010). These studies highlight the importance of understanding landscape changes at the local scale to provide a robust understanding of the processes

* Corresponding author. Ave. Vicuña Mackenna 4860, ZC 7820436, Santiago, Chile.
E-mail addresses: angelahernandez@uc.cl (A. Hernández), mmirands@uc.cl (M.D. Miranda), eduardoarellano@uc.cl (E.C. Arellano), cdobbsbr@gmail.com (C. Dobbs).

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and effects resulting from changes in landscape dynamics.

Understanding historical changes of land use and cover shed light on the environmental and social impacts that result from the new landscape configuration (Mitsuda and Ito, 2011). One of the most common ways of analyzing landscape configuration is to distinguish the spatial pattern of land cover in an area. Changes in the spatial patterns and ecological processes of a landscape can have positive effects on anthropogenic land use by increasing habitat connectivity; however, they can also have negative effects by fragmenting natural landscapes, with substantial consequences for biodiversity (Elena-Rosselló et al., 2013; Forman, 1995; Gustafson, 1998).

Land-cover trajectory analyses have been used to better understand how historical processes have driven changes in cover and land use. This type of analysis enables us to identify the direction of change for different land-cover and land-use types to determine how landscapes change temporally (Ruiz and Domon, 2009), and how the local context and public policies shape those trajectories (Wang et al., 2013). Land-cover trajectory analysis has been used previously in Chile by Carmona and Nahuelhual (2012) to evaluate landscape dynamics in Southern Chile, where the main trajectories associated with fragmentation were derived from landscape conversion to agricultural land.

To our knowledge, little is known about the impacts of historical changes in cover and land use on semi-arid Mediterranean landscapes of Central Chile, determinant factor for land-use planning. This study evaluated changes in cover and land use and their trajectories over a period of 36 years (1975–2011), assessing the effects of fragmentation on natural vegetation for this type of landscape. Remote-sensing data, in combination with Geographic Information Systems (GIS), were used to obtain land-use and/or land-cover maps to analyze the main trajectories of change. To evaluate the spatial patterns of the landscape, we quantified commonly used metrics for fragmentation analysis.

2. Materials and methods

2.1. Study area

This research was conducted in the semi-arid Mediterranean zone of Chile, specifically in the rural area of Catapilco (32°34′6.20′S − 71°16′31.48′W), Valparaíso Region (Fig. 1). The study area covered approximately 10,000 ha. The climate is typically Mediterranean, characterized by irregular and intense rainfall events and a harsh dry summer period (Luebert and Pliscoff, 2012). The average annual precipitation is 547.8 mm, distributed mainly between May and August, with a prolonged dry season of 6 months between October and March. The average annual temperature is 15.4 °C; the warmest month is January, with a maximum average temperature of 27.6 °C, and the coldest month is July, with a minimum average temperature of 5.4 °C.

This area was selected because it has a long and known history of changes in land cover and land use. We used it as a case study because it is representative of land cover and land use in most Mediterranean landscapes of central Chile. The vegetation mosaic is typical of this ecosystem, where the highest elevations are dominated by sclerophyll forest, hillsides by arborescent shrubland, and the valleys by extensive *Acacia caven* (espinal) scrubland, and agriculture, livestock, and urban areas.

2.2. Analysis of spatial data

The assessment of change in land use and land cover was performed over a 36-year period (1975–2011). A set of four classified Landsat images: one MSS image (1975) and three TM5 images (1992, 2001, and 2011) were used in the study. Details of image processing and classification, in addition to accuracy assessment, can be found in Hernández et al. (2015). Land-cover and land-use types were identified in Hernández et al. (2015) and corresponded to: (1) Native Forest; (2) Arborescent Shrubland; (3) Dense Espinal; (4) Espinal; (5) Grassland; (6) Agricultural; (7) Water; (8) Urban and Bare Land; and (9) Plantations (Table 1, Appendix B).

2.3. Trajectories and drivers of change

Two steps were followed to determine the trajectories of change for land use and land cover. First, land-use and land-cover maps for the four years previously mentioned were obtained from the previously classified Landsat images, using ArcGIS 10 (ESRI, Redlands, Calif.). Second, changes in land cover and land use were evaluated

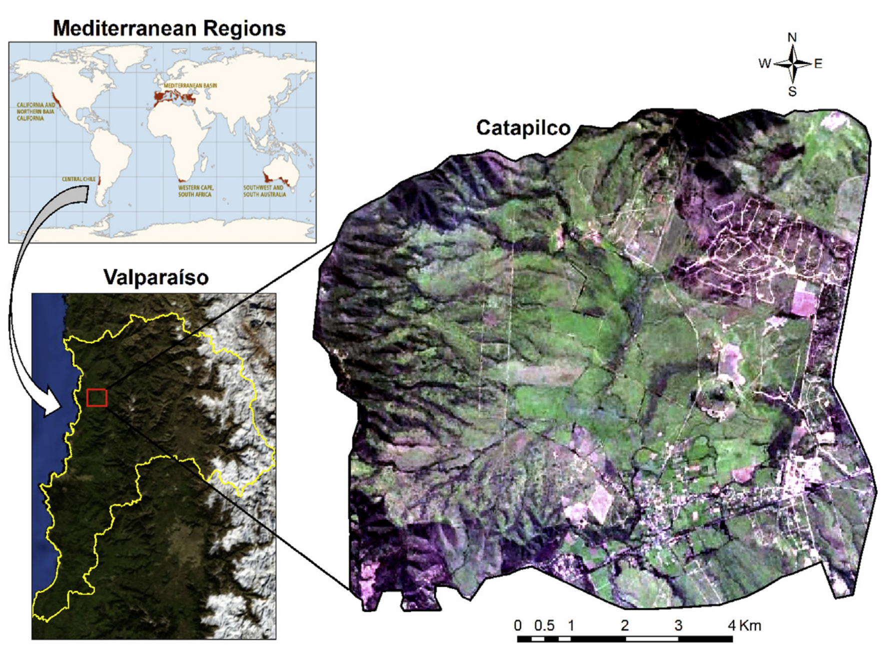

Fig. 1. Study area, with the visible spectrum (image composite RGB bands 3, 2, 1) of the Landsat image from 2011.

Table 1
Description of land-use and land-cover types for Catapilco, Valparaiso Region, Chile.

Class	Description
Native forest	Advanced succession stage of sclerophyll forest, with species such as *Cryptocarya alba, Peumus boldus, Quillaja saponaria, Lithraea caustica*, among others; 80%–98% woody cover
Arborescent shrubland	Intermediate succession between the matorral and the sclerophyll forest; cover by arborescent species such as *Acacia caven, Maytenus boaria, Prosopis chilensis, Trevoa trinervis, Colliguaja odorífera*, and second-growth sclerophyll species; 35%–75% woody cover
Dense espinal	Thick *A. caven* cover in arboreal stage, together with second-growth *Quillaja saponaria*; 51%–80% woody cover
Espinal	Cover showing high density of shrubby *A. caven* and *T. trinervis* together with herbaceous cover; 26%–50% woody cover
Grassland	Herbaceous cover with isolated *A. caven* and *T. trinervis* shrubs; 0–10% woody cover
Agricultural	Dry farming and irrigation cultures, vineyards, and olive groves
Urban/bare land	Urban zones, rocks, barren lake beds, recently cleared lands, roads, and highways
Plantation	Ornamental trees and plantations of *Pinus radiata* and *Eucalyptus globulus*
Water	Rivers, lakes, and reservoirs

by identifying the changes that occurred in each cover and between the years 1975–1992, 1992–2001, and 2001–2011. The trajectory analysis for each period was done using the transition matrix (Appendix A) in IDRISI Selva (Eastman, 2012). Transition matrices represent the area of landscape that undergoes a conversion from class *i* to class *j* between two consecutive times (Pontius et al., 2004).

The spectrum of possible trajectories was grouped into two generic classes: human-induced trajectories and natural trajectories, following Geist et al. (2006). Song et al. (2009) found that the processes responsible for changes in land cover and land use can be generally divided between these two groups. Human-induced trajectories include: urbanization; conversion of forest to cropland; conversion of grassland to cropland; change of crop on existing cropland; conversion of cropland to pasture; and conversion of pasture to cropland. They are often irreversible because they involve major impacts on the function and structure of the landscape. Natural trajectories result from natural ecosystem processes and include natural regeneration from land abandonment, natural succession, and natural cover expansion (e.g., dispersion).

To establish the drivers of the trajectories of change, informal interviews with landowners, land managers, municipal authorities, and other key informants were conducted, because they could provide valuable complementary information for interpreting the dynamics of change and their drivers. Ancillary information from historical files and the Forestry Agricultural census of the National Institute of Statistics of Chile (INE, 2007) were consulted.

2.4. Analysis of spatial patterns of forest cover

The land-use and land-cover maps were used to estimate the changes in spatial patterns during the 36-year period. Landscape metrics were analyzed for Native Forest, Arborescent Shrubland and Espinal covers (Appendix B) to understand their spatial patterns. We selected the following commonly used nonredundant metrics at landscape and class levels: (1) the number of patches or number of fragments of different covers; (2) mean patch area; (3) the largest patch index, (i.e., the percentage of the landscape occupied by the largest patch); and (4) proximity index within 500 m. Quantification of metrics was performed using FRAGSTATS (McGarigal et al., 2012).

3. Results

3.1. Trajectories of change

The greatest net change between 1975 and 1992 was the trajectory from Espinal to Arborescent Shrubland (31%). Other important trajectories were 26% of Grassland converted to Espinal and 23% of Arborescent Shrubland converted to Grassland (Fig. 2). Between 1992 and 2001, Espinal loss was the largest, with 29% converted to Grassland and 26% to Arborescent Shrubland (Fig. 2) and this major increase in Espinal resulted from Grassland conversion. From 2001 to 2011, 26% of Grassland and 20% of Arborescent Shrubland were converted to Espinal (Fig. 2). The greatest increment in Native Forest (24%) resulted from Arborescent Shrubland conversion, between 1992 and 2001. Over the whole study period, 64.4% of forest areas followed a natural trajectory, whereas the remaining 35.6% followed a human-induced trajectory (Fig. 2).

3.2. Changes in landscape fragmentation

Results demonstrated that the landscape of Catapilco has undergone constant temporal and spatial changes that have transformed its structure and configuration (Fig. 3). At the landscape level, the number of patches increased significantly over time (Fig. 4a), with the largest increase (64%) occurring between 2001 and 2011. Conversely, mean patch area declined steadily from 7.2 ha in 1975 to 3.2 ha in 2011 (Fig. 4b). Although the largest patch index decreased over the first 26 years, it increased from 2.8% in 2001 to 5.5% in 2011 (Fig. 4c). The proximity index decreased after 1992 (Fig. 4d), showing a greater degree of isolation among patches in the landscape.

At the class level over the whole study period, the number of patches increased in Native Forest, Arborescent Shrubland and Espinal, being greatest in Native Forest, which increased fourfold compared with values in 1975 (Fig. 5a). However, the mean patch area declined for all three cover types (Fig. 5b). The largest patch index for Native Forest showed a constant increase from 1992 onwards, having reached 5.5% by 2011 (Fig. 5c). The proximity index of Native Forest increased, reflecting an increase in forest connectivity. Conversely, Arborescent Shrubland showed a continuous dispersion of its patches within the 36-year period, with a reduction in its proximity index from 17.2% in 1975 to 4.6% in 2011. Similarly, Espinal patches became more dispersed over the same period (Fig. 5d).

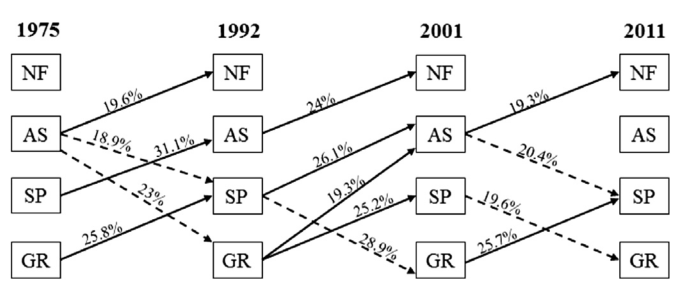

Fig. 2. Trajectories of change for forest cover and Grassland: NF: Native Forest, AS: Arborescent Shrubland, SP: Espinal, GR: Grassland. The lines represent natural processes (solid line) and anthropogenic processes (dashed line). Net changes represented >4% of the study area.

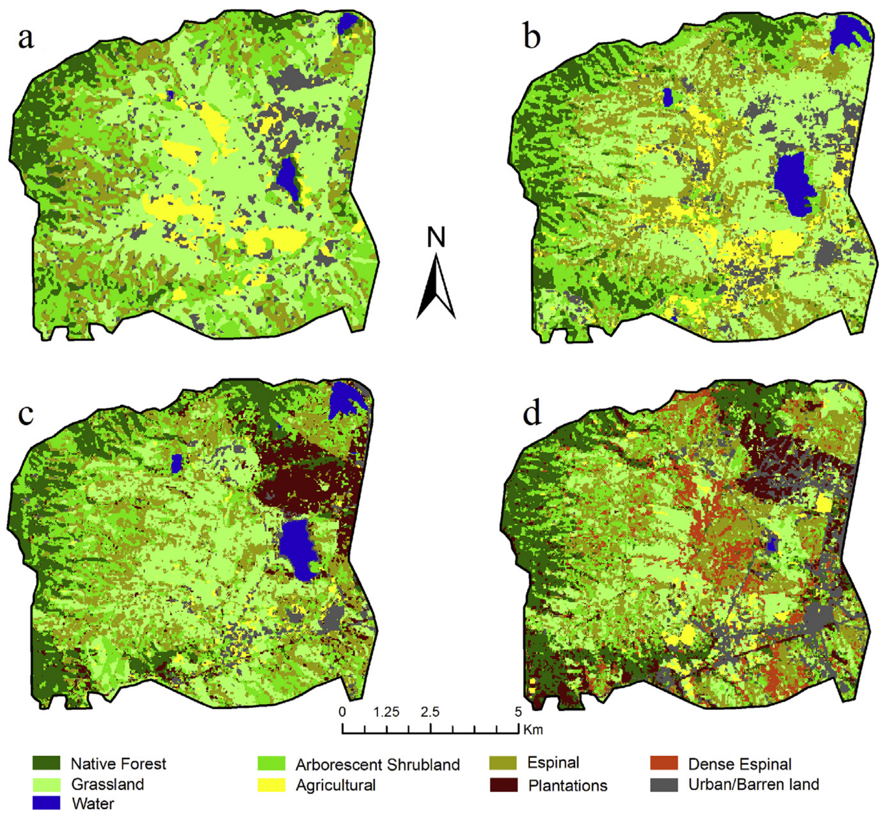

Fig. 3. Land-cover and land-use change based on interannual satellite images: (a) 1975, (b) 1992, (c) 2001, and (d) 2011.

4. Discussion

4.1. Trajectories of land-use and land-cover change and their effects on the landscape

The changes described above reflect the temporal-spatial dynamics of the Catapilco landscape over a period of 36 years. Natural trajectories occurred mainly from Espinal to Arborescent Shrubland and from Arborescent Shrubland to Native Forest, with fewer resulting from land abandonment after farming and grazing, explaining the net increase in Native Forest and Dense Espinal. The area under Espinal also recorded a net increment, mainly through

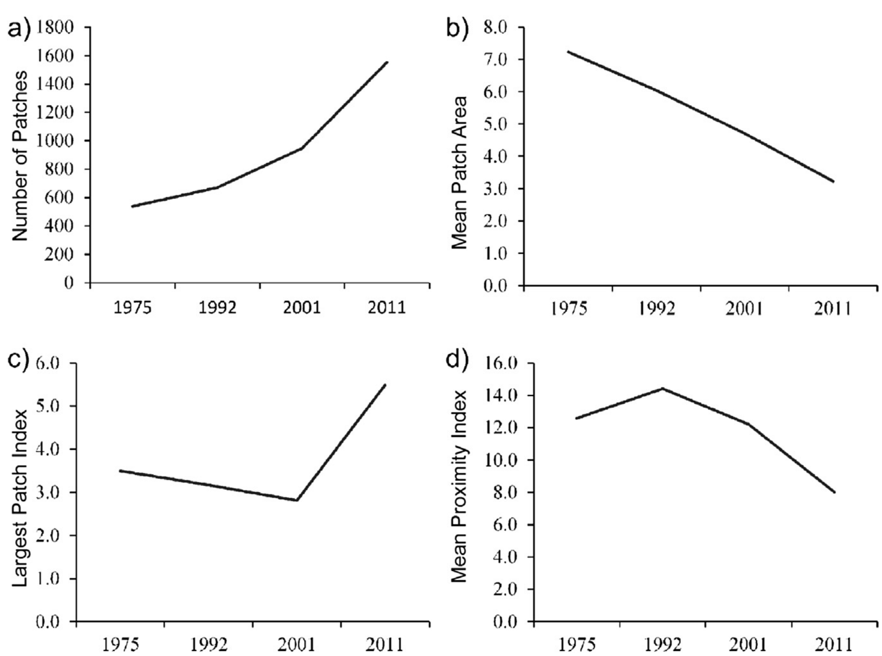

Fig. 4. Temporal changes in metrics at the landscape level applied to forest cover 1975, 1992, 2001, and 2011. (a) Number of patches, (b) Mean patch area, (c) Largest patch index, (d) Mean proximity index.

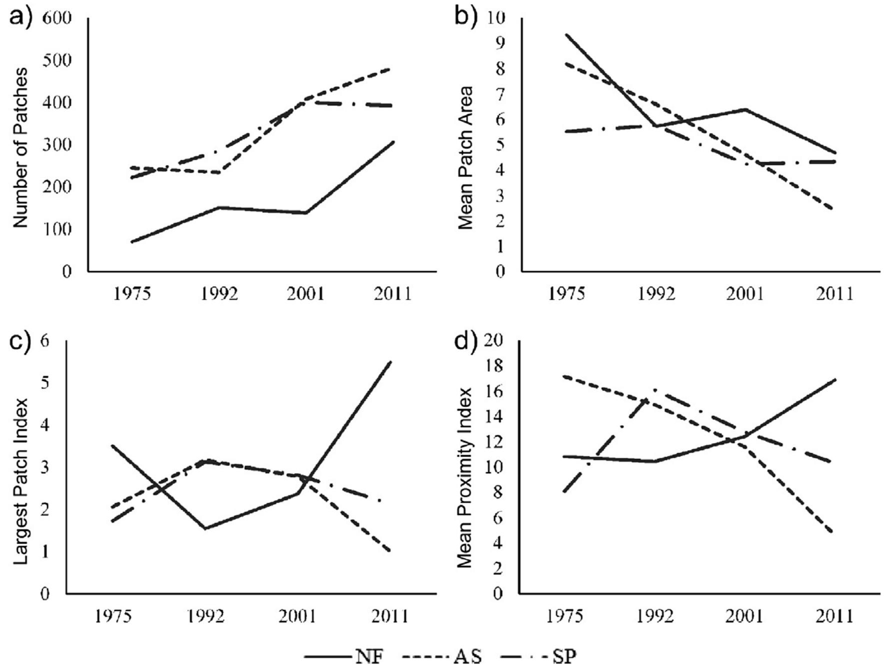

Fig. 5. Temporal changes in metrics at the class level for Native Forest (NF), Arborescent Shrubland (AS) and Espinal (SP). (a) Number of patches, (b) Mean patch area, (c) Largest patch index, (d) Mean proximity index.

the abandonment of Grassland used for grazing, leading to natural regeneration. Human-induced processes were mainly represented by the abandonment of agricultural land and the generation and subsequent abandonment of pasture. These processes explain the decreases recorded in the Agricultural and Grassland classes (Table 2). Several authors have reported similar trends of increasing natural cover, mainly forest, resulting from the reduction in farmland in different parts of the world (e.g., Díaz et al., 2011; Preiss et al., 1997; Saura et al., 2011; Taillefumier and Piegay, 2003). However, this is the first time this trend has been reported in Mediterranean Chile. Abandonment of agriculture has consequences for the environment and rural livelihood (Díaz et al., 2011). Negative impacts include the disappearance of traditional agricultural practices, long-term loss of habitats of high ecological value (Díaz et al., 2011; Zavala and Burkey, 1997), greater vulnerability to forest fires (Romero-Calcerrada and Perry, 2004), and invasion of exotic species (Schneider and Geoghegan, 2006). Conversely, positive outcomes occur when abandonment is followed by natural vegetation regeneration, resulting in the recovery of ecosystem services and, therefore, enhancement of human and environmental well-being (Izquierdo and Grau, 2009). Natural succession and vegetal regeneration are considered positive effects with respect to overcoming forest loss and fragmentation (Díaz et al., 2011).

Trajectory and pattern analysis showed that the landscape changed from a homogeneous mosaic dominated by grazing and agriculture to a more heterogeneous environment where natural cover also became dominant (Fig. 3; Table 2). In 1975, six land-use and land-cover classes dominated the landscape, with Grassland most dominant. In 1992, landscape composition was relatively similar, although Grassland had slightly decreased and Espinal slightly increased. Between 2001 and 2011, the landscape composition increased from seven to nine cover classes, with the appearance of Plantation and Dense Espinal as new classes. Most studies have reported that land-use and land-cover change homogenizes the landscape, primarily because of increased cropland (Mottet et al., 2006; Papastergiadou et al., 2007) and forest plantations (Echeverría et al., 2012). However, a recent study showed that an increase in anthropogenic cover led to greater landscape heterogeneity (Cayuela et al., 2006). Brotons (2007) stated that Mediterranean landscape patterns should have open areas, such as farming, grazing, forestry, and other spaces, leading to a heterogeneous landscape. In addition, Estrada et al. (2004) suggested that, by reducing landscape heterogeneity, birds and other terrestrial vertebrates might decline because of their need for open spaces.

Table 2
Land-cover and land-use type (ha) estimated for 1975, 1992, 2001, and 2011 in Catapilco, Valparaiso, Region, Chile.[a]

Cover	1975		1992		2001		2011		Loss (1975–2011)	Gain	Net change
	ha	%	ha	%	ha	%	ha	%	ha	ha	ha
Native forest	617	8	895	11	984	12	1307	16	288	978	689
Arborescent shrubland	1996	25	1451	18	1916	24	1252	15	1662	918	−744
Dense espinal	0	0	0	0	0	0	777	10	0	777	777
Espinal	1271	16	1684	21	1705	21	1632	20	1030	1391	361
Grassland	2774	34	2476	30	1847	23	1501	18	2187	914	−1273
Agricultural	581	7	731	9	216	3	231	3	527	177	−350
Urban/bare land	841	10	691	8	345	4	682	8	710	552	−158
Plantation	0	0	0	0	932	11	756	9	0	756	756
Water	65	1	216	3	199	2	6	0	60	1	−59

[a] The last three columns indicate gain, loss and net change in area from 1975 to 2011.

Our results confirm that the Catapilco landscape has been dynamic, becoming more heterogeneous as a result of pattern configuration changes over time.

4.2. Drivers of change in trajectories

The trajectories described above resulted in different landscape patterns that depended on drivers of change generated by regional contexts and government policies (Wang et al., 2013). Landscape change resulted mainly from socioeconomic, local, regional, and political drivers. In 1975, the National Government introduced agricultural policies that resulted in increased agricultural and livestock exploitation, leading to the conversion of large areas of land during the late 1970s (Fig. 3a, Table 2). Between 1992 and 2001, changes in agricultural policies resulted in the abandonment of agricultural land and a reduction in livestock numbers, leading to an increase in Espinal, Arborescent Shrubland and Native Forest. For the last period, 2001–2011, incentives for new export-oriented crops, the introduction of new intensive practices, and improvements in road infrastructure (Valdés and Foster, 2005) encouraged plantations, vineyards, and olive companies. These socioeconomic aspects, together with interannual climate variability, resulted in the abandonment of agricultural land and its replacement with subsistence crops and some cattle grazing in small paddocks. These land-abandonment dynamics explain the increase in natural cover and the emergence of new land-cover types, such as Dense Espinal, increasing landscape heterogeneity.

4.3. Dynamic landscape spatial pattern

Changes in land cover resulted in the modification of spatial patterns, as confirmed by landscape-and class-level metrics. The results from landscape-level metrics indicated the presence of smaller and more isolated patches, suggesting fragmentation, similar to results from Turkish Mediterranean landscapes (Coskun Hepcan, 2013) and Mexican native forests (Cayuela et al., 2006). Landscape fragmentation is not a random process, but follows a specific pattern (Echeverría et al., 2012; Lindenmayer and Fischer, 2006). Pattern change impacts plant species composition, varying in space and time because of factors such as land use, fire, and rain (Odiwe et al., 2012). For example, anthropogenic impacts are greater in valleys because of agriculture and pasture, followed by subsequent abandonment. Similar results were observed in the Mediterranean zone of Greece, where forests and grasslands were scarce in valleys because of intensive agriculture (Plexida et al., 2014).

The class-level analysis indicated that the increase in the number of patches was related to the reduction in the average patch size, leading to fragmentation and habitat loss (Echeverría et al., 2006). Native Forest metrics showed that, although the number of patches increased, the largest patch did not decrease in size. The proximity index among patches also increased over the period of analysis, suggesting that, despite increases in the number of patches, the connectivity of Native Forest patches had also increased. This suggests that the patch number increase resulted from the appearance of new small patches rather than from the fragmentation of older patches, showing an effect of natural trajectories, such as natural regeneration. Previous research in the area showed that, for the same period, there was an improvement in the structural and functional connectivity of this landscape for the dispersion of seeds of sclerophyllous tree species (Hernández et al., 2015). Echeverría et al. (2012) and Altamirano et al. (2007) suggested that forest regrowth led to the fragmentation reduction of forest patches on marginal lands.

5. Conclusions

This study demonstrated the importance of incorporating the landscape history using land-use and land-cover change trajectories to understand the patterns generated by these changes. Integration of landscape analysis and historical information improves our understanding of spatial temporal dynamics. Evaluating trajectories and spatial patterns together produced a more comprehensive approach to understanding semiarid Mediterranean landscape dynamics. Overall, landscape trajectories were strongly influenced by natural processes, such as natural regeneration, and human-induced processes, such as abandonment of agricultural and grazing land.

Spatial patterns led to the fragmentation of the landscape, particularly in the valleys. However, class-level metrics showed that Native Forest fragmentation decreased because of an increased in its area, mainly as a result of the formation of small new patches.

Our study provides a greater understanding of the dynamics of the semiarid Mediterranean landscape of Chile, useful for improving decision-making in landscape planning.

Acknowledgments

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Appendix A

Transition matrices.

	Year 1992								
	Class	Native forest	A. Shrubland	Espinal	Grassland	Agricultural	Urban/bare land	Water	Total 1975
Year 1975	Native forest	**352.6**	203	9.6	15.8	7.5	2.3	26.3	617
	A. shrubland	392	**493**	377.5	458.2	124.7	123.2	27.3	1995.8
	Espinal	112.7	395	**317.4**	269.2	85	73.2	18.8	1271.3
	Grassland	12.6	235.2	715.3	**1236.5**	254.6	284.2	35.6	2774.1
	Agricultural	2.2	37.5	112.9	111.1	**199.7**	89.8	27.8	581
	Urban/bare land	22.8	86.7	151	385.4	59.9	**118.5**	16.3	840.6
	Water	0	0.4	0	0	0	0	**64.2**	64.5
	Total 1992	894.8	1450.8	1683.72	2476.1	731.3	691.2	216.3	8144.2

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(*continued*)

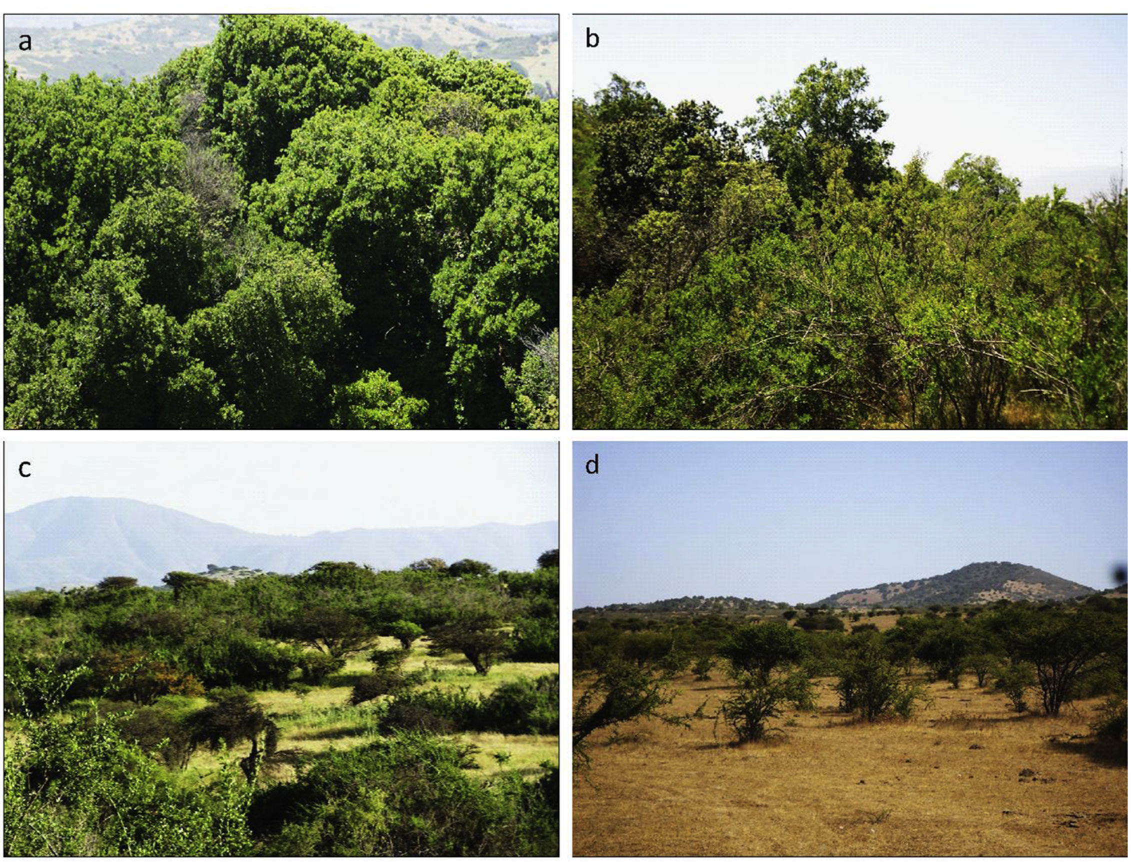
	Year 2001									
	Class	Native forest	A. Shrubland	Espinal	Grassland	Agricultural	Urban/bare land	Water	Plantation	Total 1992
	Year 2001									
	Class	Native forest	A. Shrubland	Espinal	Grassland	Agricultural	Urban/bare land	Water	Plantation	Total 1992
Year 1992	Native Forest	**369.6**	290	100.4	51	7.6	15.9	6.2	54.1	894.8
	A. shrubland	348.6	**449.9**	248.6	190.9	27.2	38.3	28.4	119	1450.8
	Espinal	74.6	438.8	**451.7**	487	40.7	54.5	5.1	131.4	1683.7
	Grassland	119.3	478	625.1	**708.2**	52	93.3	4.9	394.7	2476.1
	Agricultural	27.8	141.2	153.4	241.7	**47.2**	50	2.3	67.7	731.3
	Urban/bare land	42.8	104.1	117	157.7	37.9	**75.7**	1.5	154.5	691.2
	Water	0.8	14.4	9	10.6	3.9	17	**150.3**	10.3	216.3
	Plantation	0	0	0	0	0	0	0	0	0
	Total 2001	983.5	1916.4	1705.1	1847.2	216.4	345.3	198.7	931.7	8144.2

	Year 2011										
	Class	Native forest	A. Shrubland	Espinal	Grassland	Agricultural	Urban/bare land	Water	Plantation	Dense espinal	Total 2001
Year 2001	Native Forest	**469.9**	143.8	49.4	46	12.6	35.4	0	188.7	37.7	983.5
	A. shrubland	370.2	**344.3**	390.7	273.8	36.9	112.7	0.4	189.2	198.4	1916.4
	Espinal	176	300.2	**446**	334.4	42	117.4	0.5	91.5	196.9	1705.1
	Grassland	110.8	272.6	474.8	**515.7**	74.3	108.2	0.4	56.7	233.6	1847.2
	Agricultural	21.5	21	36	49.9	**15.5**	43.5	0.1	11.8	17.2	216.4
	Urban/bare land	35.7	38.9	61.5	58.1	15.5	**87.8**	1.6	21	25.3	345.3
	Water	15.1	33.2	21.2	93.1	10.3	11.3	**2.1**	2.6	9.8	198.7
	Plantation	107.3	97.8	152.6	130.1	23.6	166.2	0.8	**194.9**	58.3	931.7
	Dense espinal	0	0	0	0	0	0	0	0	0	0
	Total 2011	1306.5	1251.8	1632.2	1501	230.7	682.4	5.9	756.4	777.2	8144.2

Transition matrices of changes in land cover and land use between the years 1975–1992, 1992–2001, and 2001–2011.

Appendix B

Natural land cover: (a) Native Forest; (b) Arborescent Shrubland; (c) Dense Espinal; and (d) Espinal.



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