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Factors influencing vegetation cover change in Mediterranean Central Chile (1975–2008)

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Keywords
Deforestation; Driving forces; Forest regeneration; Land-cover change; Shrubland regeneration.

Abbreviations
AIC = Akaike information criterion; AUC = area under curve; ROC = receiver operating characteristic.

Nomenclature
Zuloaga et al. (2008)

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Abstract

Questions: Which are the factors that influence forest and shrubland loss and regeneration and their underlying drivers?

Location: Central Chile, a world biodiversity hotspot.

Methods: Using land-cover data from the years 1975, 1985, 1999 and 2008, we fitted classification trees and multiple logistic regression models to account for the relationship between different trajectories of vegetation change and a range of biophysical and socio-economic factors.

Results: The variables that most consistently showed significant effects on vegetation change across all time-intervals were slope and distance to primary roads. We found that forest and shrubland loss on one side and regeneration on the other often displayed opposite patterns in relation to the different explanatory variables. Deforestation was positively related to distance to primary roads and to distance within forest edges and was favoured by a low insolation and a low slope. In turn, forest regeneration was negatively related to the distance to primary roads and positively to the distance to the nearest forest patch, insolation and slope. Shrubland loss was positively influenced by slope and distance to cities and primary roads and negatively influenced by distance to rivers. Conversely, shrubland regeneration was negatively related to slope, distance to cities and distance to primary roads and positively related to distance from existing forest patches and distance to rivers.

Conclusions: This article reveals how biophysical and socioeconomic factors influence vegetation cover change and the underlying social, political and economical drivers. This assessment provides a basis for management decisions, considering the crucial role of perennial vegetation cover for sustaining biodiversity and ecosystem services.

Introduction

Landscapes are influenced by both ecological factors and the presence of humans and can therefore be considered as the joint effect of natural events and human intervention on the environment (Naveh & Lieberman 1994). In inhabited areas, it is the human element that is increasingly playing the most significant role in the creation, transformation and evolution of landscapes, mostly through land-use and land-cover change that ultimately affect the natural vegetation (Burel & Baudry 2003; Serra et al. 2008). As vegetation contributes to carbon storage, water cycle regulation and other ecosystem functions, these changes can have profound impacts on human well-being (Millennium Ecosystem Assessment 2005). It is therefore important to identify how these changes

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occur (patterns) and to understand the underlying driving forces that influence them (processes). Most studies have focused on the documentation and analysis of spatial patterns of vegetation change, particularly deforestation (Cayuela et al. 2006; Echeverría et al. 2006), while little attention has been paid to the underlying processes generating such change (Bürgi et al. 2004). Understanding the processes that act as driving forces of vegetation dynamics is also useful to predict trajectories of change and mitigate future impacts that may otherwise have a negative effect on the provision of ecosystem services. This is a challenging issue as changes in vegetation cover can be influenced by a complex set of factors, ranging from global external drivers (e.g. demand from international markets and environmental policies) to local conditions and pressures (e.g. population increase and infrastructure development; Geist & Lambin 2002).

In Latin America, many countries face growing conflicts between resource development and environmental degradation (Grau & Aide 2008). Vegetation and land-cover change are therefore critical issues for landscape conservation, management and planning. Despite the increasing number of studies investigating land-cover change over the last two decades, most of the studies in Latin America have focused mainly on: patterns (Sandoval & Real 2005; Echeverría et al. 2008) rather than on processes (but see Baldi & Paruelo 2008); tropical (Geist & Lambin 2002; Armenteras et al. 2006; Chowdhury 2006), rather than on temperate regions (but see Sandoval & Real 2005; Grau et al. 2008); deforestation (Armenteras et al. 2006; Cayuela et al. 2006; Echeverría et al. 2006, 2008; Zak et al. 2008; Gasparri & Grau 2009) rather than on afforestation (but see, Munroe et al. 2002; Etter et al. 2006; Calvo-Alvarado et al. 2009; Clement et al. 2009; Redo et al. 2009); and; forests (Armenteras et al. 2006; Echeverría et al. 2008) rather than on vegetation as a whole, including other vegetation types such as shrubland or pastureland. There are therefore important gaps that need to be addressed in the Latin American context. This study aims to fill one of such gaps in Mediterranean Central Chile. Previous studies have attempted to describe patterns of landscape change in the region rather qualitatively (Aronson et al. 1998; Armesto et al. 2007) and, more recently, also quantitatively (Schulz et al. 2010). However, as far as we know, no study has yet investigated the underlying factors influencing loss and gain of forest and shrubland cover in this dryland forest landscape.

Central Chile is acknowledged as one of the 25 world biodiversity hotspots (Myers et al. 2000). At the same time, this area concentrates about one-third of the Chilean human population and it is important for agricultural production. Historical records indicate that this region has experienced profound landscape transformations resulting from logging, agriculture expansion and livestock overgrazing since the mid-sixteenth century (Elizalde 1970; Vogiatzakis et al. 2006). Such transformations have been particularly intense in the last three decades, resulting in a continuous reduction of forest and shrubland cover. This reduction has taken place as a progressive degradation of forest to shrubland and a highly dynamic conversion between shrubland and human-induced types of land cover, such as cropland and pastures (Schulz et al. 2010).

The main objective of this study is to investigate the influence and relative importance of different biophysical and socio-economical factors on loss and gain of forest and shrubland in Central Chile in three study intervals spanning 33 yr. To achieve this, we relied on land-cover maps derived from remote sensing imagery and the analysis of the main trajectories of vegetation cover change (Schulz et al. 2010) using multivariate statistical tools. A major motivation for studying the factors that influence vegetation change is to help incorporate such factors within local and regional policies and planning approaches.

Methods

Study area

The study area is located in the Mediterranean bioclimatic zone of Central Chile (Amigo & Ramírez 1998) between 33°51′00″ to 34°07′55″ S and 71°22′00″ to 71°00′48″ W. It extends over 13 175 km^2 and is home to around 5.2 million people (INE 2003). The area exhibits a high climatic variability because of the varied topography from sea level to 2260 m a.s.l., which results in a spatially heterogeneous mosaic of vegetation. Major vegetation formations found in the area are evergreen sclerophyllous forest, commonly associated with the woody taxa *Cryptocarya alba*, *Quillaja saponaria*, *Lithrea caustica*, *Peumus boldus* and the mostly deciduous and xerophytic *Acacia caven* shrubland, commonly associated with the woody taxa *Prosopis chilensis*, *Cestrum parqui* and *Trevoa trinervis* (Rundel 1981; Arroyo et al. 1995; Armesto et al. 2007). In the last decades, *A. caven* shrubland has been predominant and covers most of the lower hill slopes, whereas evergreen sclerophyllous forest remains on steeper slopes with southern aspect and in drainage corridors. Major agricultural land-use activities are vineyard and fruit cultivation as well as corn and wheat cropping, which are mostly concentrated in flat valleys. Important uses of vegetation resources by local communities are extraction of fuel wood from native tree and shrub species, and extensive livestock husbandry on pastures, in shrublands and in forests. In the flat coastal zone, conversions to commercial timber plantations of exotic species such as *Pinus radiata* and *Eucalyptus globulus* have occurred since the 1970s

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(Aronson et al. 1998), but they do not represent a major land-cover change in terms of extent (Schulz et al. 2010).

Measures of land-cover change

We used pre-existing land-cover maps derived from Landsat images taken in 1975 (MSS), 1985 (TM), 1999 (ETM+), and 2008 (TM), which were classified by means of a supervised procedure and post-classification improvements through the use of ancillary data (Schulz et al. 2010). The following eight land-cover classes were present: (1) forest, (2) shrubland, (3) pasture, (4) bareland, (5) agricultural land, (6) timber plantations, (7) urban areas and (8) water. Classification accuracy was 65.8, 77.3, 78.9, and 89.8% for the 1975 MSS, 1985 TM, 1999 ETM+ and 2008 TM images, respectively (Schulz et al. 2010). A full description of the classification procedure and accuracy assessment is provided in Schulz et al. (2010).

Over the whole study area, a grid of sampling points separated at a regular distance of 1000 m was generated in order to obtain a representative set of samples. This grid was overlapped with all four land-cover maps, and samples of all trajectories of land-cover change were extracted for the three change intervals (1975–1985, 1985–1999, 1999–2008) and for the entire study interval (1975–2008). To investigate in detail vegetation loss and gain, sampling points were extracted with the same grid and reclassified into four independent datasets with binary response variables for the following change trajectories: (1) forest to no forest (FNF, i.e. deforestation), (2) shrub to no natural vegetation (SNV, i.e., shrubland loss), (3) no natural vegetation to shrubland (NVS, i.e. shrubland regeneration) and (4) shrubland to forest (STF, i.e. forest regeneration). For our aims here, the class 'no natural vegetation' included agricultural land, pasture, bareland and urban areas. The number of sample points that were analysed for changes from any of the eight land-cover classes to any other class and the sample points that changed or did not (i.e. change versus no-change) for the four specific trajectories of vegetation change in all study intervals are shown in Appendix S1. Each of the vegetation change trajectories is based on an independent dataset and contains no overlapping points in space; thus, it was not necessary to perform multiple test corrections of results (see below). An overview of the analysis procedure is shown in Fig. 1.

Explanatory variables

Two sets of explanatory variables were used in the analyses of vegetation change, namely biophysical and socio-economic variables. Six biophysical variables were selected for all change trajectories. These were: (1) elevation (m); (2) slope (degrees); (3) potential insolation ($W\,h\,m^{-2}$), which was elaborated by means of an ArcGIS (version 9.2; ESRI Inc. Redlands, CA, USA) algorithm that incorporates topography based on a digital elevation model (1:50 000 scale) and solar angle based on the geographical position. Insolation serves as a proxy for the effects of aspect on incoming radiation, which has an important influence on vegetation in Central Chile (Armesto & Martínez 1978; Badano et al. 2005); (4) distance to rivers (m), calculated as the distance to the nearest river or stream. For the FNF change trajectory, we additionally used the variable (5) distance within nearest forest edge (m), which represents the distance from the nearest forest edge from sampling points situated inside a forest patch. For the NVS and STF change trajectories, the variable (6) distance to nearest forest patch (m) was included, which represents the distance between a non-forest sampling point and the nearest forest patch.

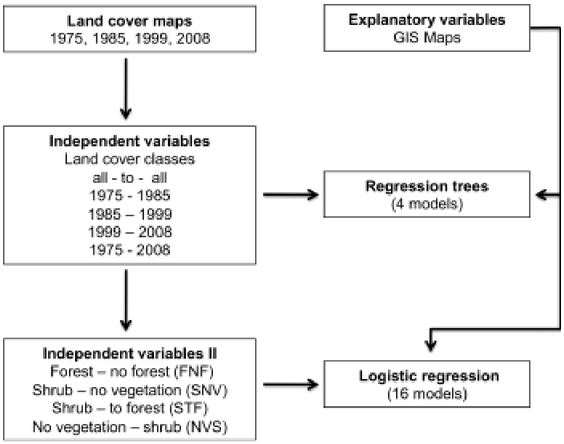

Fig. 1. Overview of the analysis procedure to investigate factors influencing vegetation cover change in Central Chile.

To account for the effects of human influence on vegetation change, we used the five socio-economic variables: (1) distance to cities $> 20\,000$ inhabitants (m); (2) distance to villages and towns $< 20\,000$ inhabitants (m); (3) distance to primary, paved roads (m); (4) distance to secondary roads (m); and (5) distance to agricultural land (m). All distances were Euclidean distances. Geographic information was handled in ArcGis (version 9.2; ESRI Inc.) and its extension Spatial Analyst. A more detailed description of the explanatory variables is provided in Table 1.

Statistical analyses

To analyse the explanatory variables of vegetation cover change, we employed two different modelling techniques in all study intervals, namely classification trees and multiple logistic regression. To avoid multicollinearity

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Table 1. Description of the biophysical and socio-economic explanatory variables used to assess factors that influence vegetation cover change in Central Chile for the interval 1975–2008. [1]Digital Elevation Model, Instituto Geográfico Militar de Chile, [2]Instituto Geográfico Militar de Chile (IGM 1990); [3]Ministerio de Planificación y Cooperación; [4]Instituto Nacional de Estadistica de Chile (INE 1982, 2003).

Variables	Description	Source
Biophysical		
Slope	Slope in degrees	DEM[1] 1:50 000
Insolation	Insolation on equinox, summer and winter solstice	DEM[1] 1:50 000
Dist_river	Distance from rivers Euclidian distance from first and second order rivers and streams	Hydrology, IGM[2] 1:50 000
Dist_edge	Distance within forest edge Euclidean distance from sampling points inside forest patches to the nearest forest edge	Land-cover maps (Schulz et al. 2010)
Dist_forest_patch	Distance to nearest forest patch Euclidean distance from sampling points outside forest patches to nearest forest patch	Land-cover maps (Schulz et al. 2010)
Socio-economic		
Dist_city > 20T	Distance to cities Euclidean distance from cities $> 20\,000$ inhabitants in 1982 and 2002 elaborated on the basis of shape files and city census data	MIDEPLAN[3], INE[4]
Dist_village < 20T	Distance to villages Euclidean distance from villages and towns $< 20\,000$ inhabitants in 1982 and 2002	MIDEPLAN[3], INE[4]
Dist_road_P	Distance to primary roads Euclidean distance to highways and paved roads with two or more lanes	Roads, IGM[2] 1:50 000
Dist_road_S	Distance to secondary roads Euclidean distance to unpaved roads with on one or two lanes, trails and tracks	Roads, IGM[2] 1:50 000
Dist_agri	Distance to agricultural land Euclidean distance to agricultural fields 1975, 1985, 1999	Land cover maps (Schulz et al. 2010)

effects, we first performed Pearson's correlation tests and discarded highly correlated variables ($r > 0.7$) for further analyses. For all change trajectories and intervals, there was a high positive correlation between elevation and distance to agricultural land. We used distance to agricultural land instead of elevation as, in contrast to elevation, distance to agricultural land changed throughout the three study intervals, thus providing a more descriptive picture of human land-use. Three initial variables representing potential insolation, namely equinox (e), summer (s) and winter (w) solstices, were also highly correlated (e–w $r > 0.9$; e–s $r > 0.6$; s–w $r > 0.4$). Furthermore, summer solstice was highly correlated with slope ($r > 0.7$) in half of the models. To avoid multicollinearity we selected equinox, as it represents medium rather than extreme values of insolation throughout the year. Nevertheless, random tests using winter and summer solstice instead of equinox were performed for the four change trajectories and showed that equinox was a good representative variable of the amount of insolation at a sampling point.

Classification trees

Classification trees allowed the investigation of factors that influence all possible trajectories of change in the landscape when they were considered simultaneously. This provides information on relevant trajectories of change over the entire landscape in each time interval, gives insights on the associated factors, and reveals tendencies of the spatial distribution of changes in relation to the explanatory variables. Classification trees were used to predict membership of samples in the classes of a categorical dependent variable (i.e. any possible trajectory of change) from their measured values on one or more predictor variables (i.e. the biophysical and socio-economical explanatory variables). Classification trees are built on binary recursive partitioning, an iterative process of splitting the data into partitions and then splitting them up further on each branch. Branches were not pruned and therefore show the full spectrum of significant correlations. These analyses were performed using the R 'tree' package (Ripley 2007).

Multiple logistic regression

Multiple logistic regression was used to explore the effects of the biophysical and socio-economical variables on specific trajectories of change in forest and shrubland cover (i.e. FNF, SNV, NVS and STF). It provides information on the probability and significance of occurrence of change (i.e. the dependent variable is a binary response variable, within the specific setting of explanatory variables. Four multiple logistic regression models simultaneously entering all explanatory variables were developed for each trajectory of change – no change in each time-interval (1975–1985, 1985–1999, 1999–2008 and 1975–2008).

To determinate the set of explanatory variables constituting the best model fit for each interval and change trajectory, we used the full set of explanatory variables and performed a backward stepwise model selection based on the Akaike information criterion (AIC) (Akaike

1973; Reineking & Schröder 2006). The AIC is actually equivalent to twice the log-likelihood of the model fitted plus two times the number of parameters estimated in its formation. Given that the model with the smallest log-likelihood is considered to be that with the best fit, the addition of two times the number of parameters means that AIC effectively includes a penalty for adding predictor variables to the model. Thus, AIC aids in identifying the most parsimonious model among a set of models that sequentially remove explanatory variables from a full model (Burnham & Anderson 2002). To evaluate performance, we calculated the area under the receiver operating characteristic (ROC) curve (AUC) (Swets 1988), after an internal validation using bootstrapping with 10 000 bootstrap samples (Hein et al. 2007). According to Hosmer & Lemeshow (2000) and Hein et al. (2007), AUC-values above 0.7 describe an acceptable model performance, values between 0.8 and 0.9 denote excellent performance, and values above 0.9 mean an outstanding performance.

Spatial autocorrelation

To account for possible effects of spatial autocorrelation, the residuals of the final logistic regression models were analysed using Moran's I correlograms (Dormann et al. 2007). We did not find any significant spatial autocorrelation (see the Supporting Information, Appendix S2) and, consequently, we did not apply further model corrections. All statistical analyses were performed with the R statistical software (R Development Core Team 2009).

Results

Trajectories of change and influencing factors

Classification trees for the four study intervals are shown in Fig. 2. For the entire study interval 1975 to 2008 (Fig. 2a), the first split was produced by distance to agricultural land. At close distances to agricultural land (i.e., < 15 m), change from agricultural land to shrubland was the main trajectory of vegetation change. Further than this distance, slope determined a second split. In flat areas (i.e., slope $< 5^{\circ}$), proximity to cities (third split) resulted in a change from shrubland to urban areas. At greater distances from cities, distance to agricultural land (fourth split) determined the conversion from shrubland to agricultural land at close distances (< 114 m), whereas further away the main change was conversion from shrubland to pasture. On steeper slopes (i.e., $> 5^{\circ}$), distance to agricultural land (fifth split) determined either the conversion from shrubland to pasture nearby agricultural land (i.e., < 737 m) or, conversely, a degradation from forest to shrubland further than this distance.

A similar pattern was consistently found in the intervals 1975–1985 (Fig. 2b), 1985–1999, (Fig. 2c), and 1999–2008 (Fig. 2d). The major noticeable difference was found for interval 1999–2008, when slope did not appear to be a significant variable, distance to agricultural land gained importance as an explanatory variable of change in vegetation cover and the transformation of pasture to shrubland emerged as a relevant trajectory of change mostly occurring near agricultural land located far away from cities.

Factors influencing change in forest and shrubland cover

The 16 multiple logistic regression models for the four change trajectories and four time-intervals resulted in 12 models with AUC value > 0.7 and four models with AUC values < 0.7 but > 0.66. The relationships between the explanatory variables tested and deforestation (FNF), forest regeneration (STF), shrubland loss (SNV) and shrubland regeneration (NVS) during the four study intervals are summarized in Table 2. The variables that most consistently showed significant effects on vegetation change across the four time-interval models were slope and distance to primary roads. Forest and shrubland loss on one side and regeneration on the other often displayed opposite patterns in relation to different explanatory variables. This is particularly the case for distance to primary roads; deforestation and shrubland loss tended to occur further away from primary roads, whereas forest and shrubland regeneration primarily occurred close to primary roads in almost all four time-intervals. A similar reverse pattern can be observed for forest loss and regeneration in relation to insolation and slope, as well as for shrubland loss and regeneration in relation to distance to rivers and slope.

Deforestation (FNF)

The logistic regression models indicated a consistent positive effect of distance to the nearest edge and to primary roads and a negative effect of slope and insolation on the probability of an area experiencing forest loss for the four study intervals (Table 2, Appendix S3a). Additionally, distance to agriculture was positively related to deforestation for all intervals, except for the 1975–1985 interval. Distance to rivers was negatively related to deforestation for the 1999–2008 interval, whereas distance to secondary roads was positively related to deforestation for the overall 1975–2008 interval (Table 2, Appendix S3a).

Shrubland loss (SNV)

Slope, distance to cities and distance to primary roads were positively related to shrubland loss, whereas distance to rivers was negatively related in all four time

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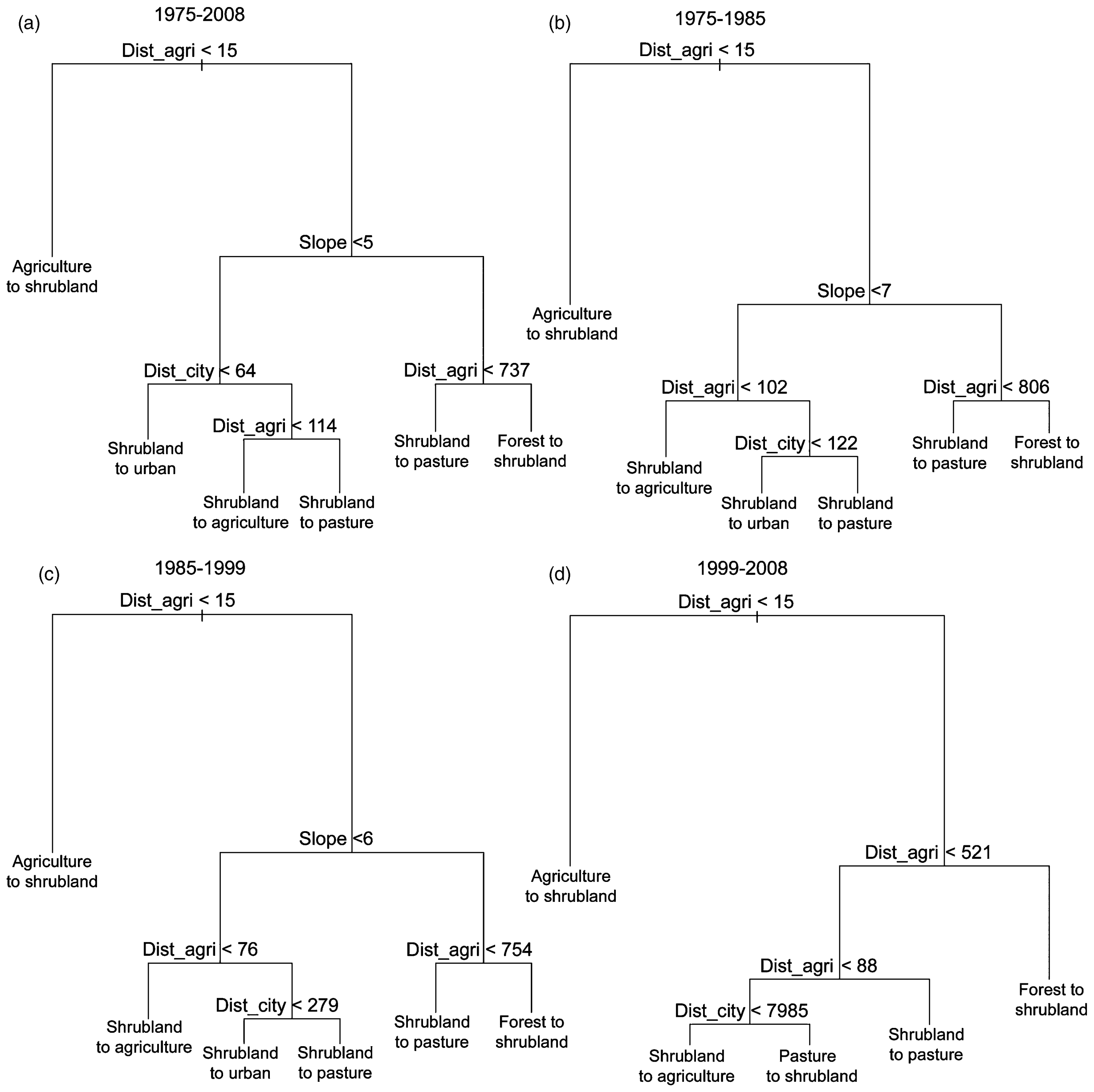

Fig. 2. Classification trees for (**a**) the entire study interval (1975–2008) and intervals (**b**) 1975–1985, (**c**) 1985–1999, and (**d**) 1999—2008. The root of each interval tree is at the top and each sequential split along each branch is labelled with the respective splitting criterion. Values that are true go left from the 'splitting point', whereas values that are false go right. The height of the vertical segment above each split is related the decrease in deviance associated with that split.

intervals (Table 2, Appendix S3b). Distance to secondary roads was positively related to shrubland loss in all intervals, except for the 1975–1985 interval. Distance to villages also had a positive effect on shrubland loss during the 1985–1999 and 1999–2008 intervals. Insolation and distance to agricultural land were statistically significant but did not show a clear pattern in three of the four time-intervals.

Forest regeneration from shrubland (STF)

Conversion of shrubland to forest was positively related to distance to the nearest forest patch and insolation in all four intervals and to slope in all intervals but in 1975 to 1985. It was consistently and negatively related to primary roads in all intervals and to distance to villages in all intervals except 1985–1999 (Table 2, Appendix S3c). Over

Table 2. Summary of results of the multiple logistic regression models showing the relationships between the explanatory variables tested and deforestation (FNF), shrubland loss (SNV), forest regeneration from shrubland (STF), and shrubland regeneration (NVS) for the intervals 1975–1985, 1985–1999, 1999–2008, and 1975–2008. Each sign (− , 0, or +) indicates the direction of significant effects ($P < 0.05$), i.e. a significant positive effect (+), a significant negative effect (−), or a non-significant effect (0) for each time-interval (one sign per interval, which are arranged in the order explained above). The symbol/indicates that the variable was not included in the model (see Explanatory variables in the Methods section). No sign means that the variable did not appear in the final model. A description of explanatory variables is found in Table 1.

Explanatory Variables	Trajectories of vegetation change 1975–1985, 1985–1999, 1999–2008, 1975–2008			
	Deforestation/shrubland loss		Forest/shrubland regeneration	
	FNF	SNV	STF	NVS
Slope	− − − −	+ + + +	0 + + +	− − − +
Insolation	− − − −	− + − 0	+ + + +	0 − 0 +
Dist_river	0 0 − 0	− − − −		+ + + +
Dist_edge	+ + + +	/	/	/
Dist_forest_patch			+ + + +	+ + + +
Dist_city > 20T		+ + + +	0 − + −	− 0 − −
Dist_village < 20T		0 + + 0	− 0 − −	0 + − 0
Dist_road_P	+ + + +	+ + + +	− − − −	0 − − −
Dist_road_S	0 0 0 +	0 + + +	− 0 − 0	0 − 0 −
Dist_agri	0 + + +	0 + + −	0 − − 0	0 − + −

the entire 1975–2008 interval, distance to cities was also negatively related to the probability of forest regeneration, but did not have a consistent effect in other intervals. Distance to agricultural land had a negative effect in the 1985–1999 and 1999–2008 intervals.

Shrubland regeneration (NVS)

Shrubland regeneration from areas with no natural vegetation was positively related to distance from existing forest patches and to distance from rivers in all time-intervals. In most time intervals, it was negatively related to slope, distance to cities and distance to primary roads (Table 2, Appendix S3d). Distance to secondary roads was negatively related to shrubland regeneration in the 1985–1999 and the overall 1975–2008 interval. Other variables significantly related to shrubland regeneration but with no clear pattern across time-intervals were insolation, distances to villages and agricultural land (Table 2).

Discussion

Statistical assessments of factors influencing vegetation cover change are limited by a number of uncertainties, including the accuracy of underlying land-cover maps and the partial lack of data on progressively changing factors, such as distance to roads. These uncertainties can affect the models' output. Nonetheless, model performance in this study, as evaluated by the AUC, can be regarded as acceptable. Gellrich et al. (2007), for example, considered AUC values of 0.67 for model predictions as satisfactory in a study of forest regrowth. Therefore, the investigation reported here contributes to understand some of the factors that explain vegetation cover change in Mediterranean regions.

Relative importance of factors influencing land-cover change

Land-cover change in Central Chile between 1975 and 2008 was strongly influenced by human land-use. Except for the spatial arrangement of agricultural fields and urban areas across the landscape, slope appears as the only biophysical variable to influence land-cover change. Areas very close (< 15 m) to existing agricultural fields appeared likely to be set aside and subjected to shrubland regeneration, which can be explained by rotational agricultural practices in the region. Next to these fallow fields (i.e. from 15 m to ca. 100 m), the pattern of conversion of shrubland to agriculture on flat areas rather than on steep slopes was detected (Fuentes et al. 1989; Zak et al. 2008). As expected, areas with gentle slopes had a tendency to be converted from shrubland to more intensive land-use types such as agriculture and pasture (Schulz et al. 2010). In steeper areas, these changes seem to take place progressively at closer distances from agricultural fields across the different time-intervals studied, which may indicate a remarkable expansion of the agricultural frontier upwards the hills.

In contrast to previous time-intervals, slope was not a relevant explanatory variable of change in the 1999–2008 interval, hinting that this natural constraint set by the abiotic landscape pattern was removed or reduced (Bürgi & Turner 2002). This seems plausible, as the lack of water availability, a limitation for agriculture on the hillsides in Central Chile, has been overcome owing to government programmes subsidizing small-scale irrigation systems since 1990 (Maletta 2000). As a result of agricultural expansion upwards the hills, forest remnants, mainly located on high elevations and steep slopes, became successively closer to human influence and therefore more prone to anthropogenic pressures. In the 1999–2008 interval, revegetation from pastures to shrubland was relevant further than 8 km away from the cities, which could indicate a tendency of reduced land-use pressure or land abandonment in remote areas.

Loss and regeneration of forest and shrubland

Unexpectedly, the probability of deforestation was higher within forest stands than at the edges in all study intervals. Consequently, we detected a higher probability of deforestation at larger distances to primary roads and agricultural fields. This pattern might reveal a hidden pressure through cattle grazing and illegal firewood collection and charcoal production (Armesto et al. 2007; Balduzzi et al. 1982; Fuentes et al. 1986; Rundel 1999). Such hidden pressures are not rare in Latin American countries such as Chile (Callieri 1996), Mexico (Ochoa-Gaona & Gonzalez-Espinosa 2000) and Colombia (Aubad et al. 2008), where rural population often depends on firewood for household consumption and illegal production of charcoal for income generation.

The probability of shrubland loss increased on steep slopes, further away from cities, villages, primary roads and agricultural land, and at closer distance to rivers. This can be explained by land-use history in the region. The occurrence of shrubland has predominated during the entire studied interval on areas with steep slopes such as foothills, whereas flat areas had been historically occupied by agriculture, roads, and human settlements. This finding also indicates that the pressure for land use has started to exceed available flat land, and more extensive land-use types such as cattle breeding have been pushed up the hills (Armesto et al. 2010). Conversely, agricultural expansion has been favoured by water availability in the vicinity to rivers and led to increased loss of shrubland and the elimination of almost all natural vegetation at the riverbanks during the last three decades (Schulz et al. 2010).

Forest regeneration from shrubland and shrubland regeneration, largely from agricultural land and pasture, mostly occurred on areas further away from existing forest patches. While forest regeneration was more likely to occur on steep slopes and on highly insolated areas, shrubland regeneration was more likely on flatter slopes and closer to rivers. Although agricultural land has been shown to be expanding up the hills, low productivity in these soils leads to crop abandonment following a few years of agricultural activity. Also, where forest and shrubland is not further used for free-ranging cattle, succession may lead to regeneration. In addition, forest and shrubland regeneration in Central Chile tended to occur nearby roads, villages and agricultural fields. These patterns have also been detected in northern Argentina (Grau et al. 2008), where secondary forests occur close to agricultural and urban sectors. Urban-led demands for conservation and recreational land uses (Lambin et al. 2001) and more off-farm opportunities in the vicinity of roads (Clement et al. 2009) are plausible explanations of these patterns.

Drivers underlying the factors that influence vegetation change

We have identified four major social, political, and economical changes that could partly explain the factors influencing vegetation cover change in our study, namely population increase, a new neoliberal market policy, technological innovations and lack of effective environmental policies.

Population density has increased in the study area by 53% between 1970 and 2002 (INE 1970, 2003). This has led to an increase in resource demand, as urbanization affects land-cover change elsewhere through the transformation of urban–rural linkages (Lambin et al. 2001). As a result, forces of vegetation change emerge in opposite directions, a general pattern found in many parts of the world (Antrop 2005). Whereas rural areas have experienced intensifications and an increase in area under production, some remote areas might have experienced land abandonment as a result of rural–urban migrations (rural population declined in 2002 to 93% of the 1970 population in the study area; INE 1970, 2003). These processes are responsible for the highly dynamic changes observed in shrubland cover.

Agricultural production has changed because of a new neoliberal market policy in Chile. The most important transformation in agriculture was the development of the fruit export sector in the 1980s and 1990s (Altieri & Rojas 1999). Since 1975, exports for two of the main agricultural products of the study region – wine and avocado – have increased at the national level by a factor of 27 and 25, respectively, and export market prices have increased by 242% for wine (1975–2007) and by 128% for avocado (1990–2007) (FAO 2009). This has led to an expansion of agriculture towards less favourable areas on steep slopes at the mountainsides, which has been facilitated by

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technological advancements. For example, there has been an increase of micro-irrigation and the use of water pumps by 425 and 197%, respectively, between 1997 and 2007 (INE 1997, 2007). In the same interval, a 989% increase in the use of large tractors was reported for the study area (INE 1997, 2007).

Altieri & Rojas (1999) argued that in Chile, the government's involvement in environmental matters was marginal until 1989, probably as a result of the authoritarian regime between 1973 and 1989. It was only in 1990 when systematic formulation of environmental policies began (Altieri & Rojas 1999). Although in 1992 negotiations for a new forest law started, it took until 2007 to approve the new forest legislation, including improvements for the preservation and sustainable use of the country's forests. Therefore, during the interval studied, native forests remained largely unprotected from human interventions, and environmental policies had no major influence on changes in vegetation cover.

Implications for management

The progressive degradation of the natural vegetation has generally negative impacts on ecosystem functions and services such as water provision, which are of outmost importance in Mediterranean regions such as Central Chile. Severe soil erosion and degradation have been reported to extend on agroecosystems from the rainfed coastal plains to the Central Valley in Chile (Altieri & Rojas 1999), and have been classified as severe to moderate desertification (CONAF 2006). An increase in bareland from 9 to 13% of the study area (Schulz et al. 2010) could be a result of such processes. Strategies to reduce pressure on natural vegetation cover and enhance passive restoration are therefore urgently needed. These could include the control or certification of fuelwood, recently implemented in areas further south in Chile, and the restriction of cattle to shrublands while banning grazing in forests. Strategies to accelerate the recovery of natural vegetation could involve restoration of small forest islands within less suitable agricultural lands, which could serve for the natural spread of seeds through wind and fauna (Rey Benayas et al. 2008). This study provides insights on the spatial configuration of processes of passive revegetation and indicates areas more prone to land-use pressures. Whatever strategies are being developed, integrative land-use planning is needed to optimize the spatial distribution of land-use types (Gao et al. 2010), taking into consideration the particular vulnerability of the landscape as well as the influencing factors and underlying circumstances that enhance change or stability.

To conclude, an integration of biophysical and human factors remains an important research task in the explanation of land-use and land-cover change (Sluiter & de Jong 2007). The analysis of the effects of factors influencing vegetation change trajectories unravelled which factors have been constant in the most recent history of Mediterranean Central Chile. Subtle phenomena such as the tendency of internal forest fragmentation and degradation remain. Although topography constrains the expansion of agriculture on the last remnants of natural vegetation, it is increasingly being overcome because of technical innovations. Forest and shrubland recovery is taking place at closer proximity to human settlements and roads, which might indicate a trend towards a new appreciation of forest in terms of recreation and landscape aesthetics. Nevertheless, as loss of vegetation cover has not yet been halted in the region, our assessment can help to develop environmental policies that limit human land-use to the most suitable areas, while enhancing the restoration of natural vegetation for the long-term maintenance of forest ecosystem services.

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Supporting Information

Additional supporting information may be found in the online version of this article:

Appendix S1. Number of sample points for the analysed trajectories of vegetation cover for the study intervals 1975–1985, 1985–1999, 1999–2008, and 1975–2008.

Appendix S2. Plot of Moran's I over Distance (m), for the change trajectories forest to no forest (FNF), shrubland to no natural vegetation (SNV), shrubland to forest (STF) and no natural vegetation to shrubland (NVS) for the change intervals 1975–1985, 1985–1999, 1999–2008 and 1975–2008.

Appendix S3. Results of the multiple logistic regression models of (a) deforestation, (b) shrubland loss, (c) forest regeneration, and (d) shrubland regeneration for the intervals 1975–1985, 1985–1999, 1999–2008, and 1975–2008. A description of explanatory variables is found in Table 1.

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