Landscape and Urban Planning 107 (2012) 12–20

Contents lists available at SciVerse ScienceDirect

Landscape and Urban Planning

journal homepage: www.elsevier.com/locate/landurbplan

Land-cover change to forest plantations: Proximate causes and implications for the landscape in south-central Chile

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ARTICLE INFO

Article history:
Received 10 August 2011
Received in revised form 7 April 2012
Accepted 10 April 2012
Available online 6 May 2012

Keywords:
Exotic species
Timber plantations
Afforestation
Autologistic regression
Land use change
Spatially explicit models

ABSTRACT

Timber plantation expansion is a significant form of landscape change with reported negative environmental and social impacts. We analyze the proximate drivers of plantation expansion in southcentral Chile, one of the countries in South America with the highest rates of afforestation and reforestation in the last decades. Satellite images from 1975, 1990 and 2007 were used to estimate autologistic regressions for the periods 1975–1990 and 1990–2007. Timber plantations (mostly *Pinus radiata*) increased from 29,213 ha in 1975 (5.5% of the landscape) to 224,716 ha in 2007 (42.4% of the landscape). We found a clearer pattern of expansion between 1975 and 1990 as compared to 1990–2007, associated with soils of forest suitability, steep slopes, and proximity to main cities, corporate landholding, and large farms. Between 1990 and 2007 some of these drivers lost significance as plantations expanded in all directions and became the predominant land cover. Additionally, 41.5% of new plantations in the 1975–1990 period and 22.8% in the 1990–2007 period were established by clearing secondary native forests, which corroborates that plantation expansion in Chile has been a direct cause of deforestation and biodiversity loss. Understanding the proximate drivers of plantation expansion is essential in order to advance our comprehension of the underlying patterns and causes of this landscape change, which will allow us to better predict which areas are more vulnerable to change, and help to prevent adverse environmental and social impacts as plantations expand to the southern regions of the country.

1. Introduction

The establishment of forest plantations, which includes the removal of native forest cover and its replacement with plantations as well as the establishment of plantations on cleared agricultural land, has caused significant landscape changes in both tropical and temperate areas (Bremer & Farley, 2010; Lindenmayer, 2010). Worldwide, forest plantations have increased from 178.3 million ha in 1990 to 264 million ha in 2010, with a further rise of 300 million ha expected by the year 2020 (FAO, 2010). This is due principally to the world's growing reliance on timber products sourced from plantations (Brockerhoff, Jactel, Parrota, Quine, & Sayer, 2008) and the attempts to reduce climate change effects by sequestering carbon in the terrestrial biosphere (Bremer & Farley, 2010; Strengers, van Minnen, & Eickhout, 2008).

The rapid expansion of forest plantations is one of the most contentious issues in contemporary sustainable development due to the significant environmental and social conflicts it is causing in many countries (Gerber, 2011; Gerber & Veuthey, 2011). The environmental impacts which result from plantation expansion are greatest when plantations are established by clearing native forest (Bremer & Farley, 2010; Lindenmayer, 2010). In this context, understanding the proximate drivers of plantation expansion is essential in order to advance our comprehension of the underlying patterns and causes of this landscape change, which will allow us to better predict which areas are more vulnerable to change and give us the tools needed to prevent adverse environmental and social impacts.

Chile offers an interesting case of study for this endeavor. Plantation establishment in Chile began in the mid-1940s (Clapp, 1995; Toro & Gessel, 1999). However, it was only after the neoliberal reforms undertaken after 1973 that Chilean forest policy strongly supported plantations, principally through Decree Law 701 (DL 701), which was enacted in 1974 (Niklitschek, 2007). This political

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http://dx.doi.org/10.1016/j.landurbplan.2012.04.006

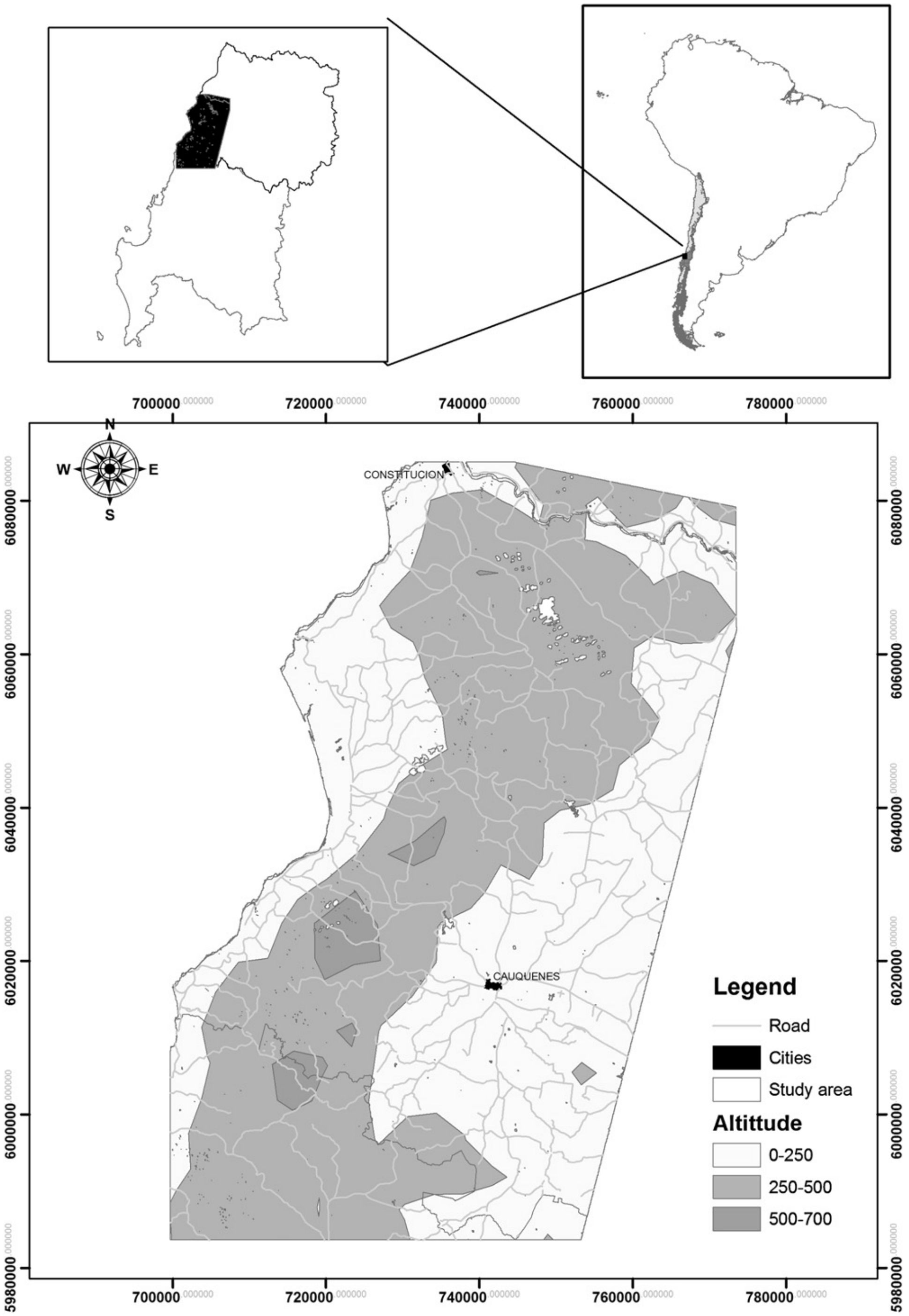

Fig. 1. Location of the study area in the Coastal Range of south-central Chile.

context added to Chile's comparative advantages for plantation forestry (Clapp, 1995), which include a favorable growing environment, especially for Radiata pine (*Pinus radiata*) and Eucalypts (*Eucalyptus globulus* and *Eucalyptus nitens*), advantageous market access, and land with low logging costs (Sedjo, 2005).

As a result of the favorable economic and political context, between 1995 and 2009 Chile exhibited one of the highest annual rates of afforestation (49,020 ha) and reforestation (53,610 ha) in South America (FAO, 2010; INFOR, 2010). This forest plantation model has been regarded as a success and many countries in the developing world have sought to emulate it (Lara, Reyes, & Urrutia, 2010; Lara & Veblen, 1993; Sedjo, Goetzl, & Moffat, 1999). Nonetheless, while this model has been seen as an economic accomplishment, the conversion to plantations is one of the greatest threats to native forest ecosystems, particularly temperate rainforests located in the south-central and southern regions of the country (35–41° S) (Aguayo, Pauchard, Azocar, & Parra, 2009; Echeverría et al., 2006; Lara, Little, Nahuelhual, Urrutia, & Díaz, 2011; Wilson, Newton, Echeverría, Weston, & Burgman, 2005). In this scenario, a better comprehension of the drivers of plantation expansion is not only a major challenge to land use planning and landscape management in Chile, especially as plantations advance toward the southern regions (Lara et al., 2010), but it is also relevant for other countries following the same forestry model.

At present land use/cover (LUC) change studies conducted in Chile have focused principally on deforestation, reporting plantation expansion as a direct cause of native forest loss (Aguayo et al., 2009; Altamirano & Lara, 2010; Echeverría et al., 2006). However, none of these studies has examined the specific drivers of LUC change to plantations. Furthermore, no such studies have tried to account for socioeconomic drivers. In this context, the goal of this research was to identify proximate natural and socioeconomic drivers influencing LUC change to timber plantations. Specifically, GIS coupled with an autologistic regression model was used to explore the significance and effect of a range of drivers on the probability of LUC change to plantations, taking the Coastal Range of south-central Chile for the periods 1975–1990 and 1990–2007 as a study case. We anticipate that not only biophysical factors, but also accessibility and farm structural variables would influence LUC change decisions. Specifically, we would expect a higher probability of plantation expansion to be related with large properties, which are better connected to main roads and cities. We also anticipate that these variables could have been more influential in initial stages of plantation expansion (1975–1990) than in later years (1990–2007), due to the more favorable institutional conditions during the former period. Specifically, during the 1990s a new law (Law 19,561 of 1998) aimed at modifying DL 701 by redirecting the policy emphasis from industrial growth toward the protection of fragile soils, rehabilitation of degraded lands, and the increasing participation of small landowners (Niklitschek, 2007), all which could have decreased plantation rates and modified the spatial patterns of expansion. Finally, we foresee that, as other studies elsewhere have documented, plantation expansion has preferentially occurred on soils covered by native vegetation instead of those covered by cleared agricultural land, with the consequent adverse effects on biodiversity and the landscape.

2. Study area

The study area (Fig. 1) covers 529,516 ha and is located in the Coastal Range of the Maule and Bio-Bio regions in south-central Chile (71°59′ W–35°20′ S and 72°49′ W–36°17′ S). The Coastal Range is a mountainous formation that ranges from 0 to 800 m a.s.l. It is mainly composed of granitic and metamorphic rocks. It presents a smooth wavy relief, low hills that smoothly descend toward the coast as a result of tectonic deformation. Most of the coastal towns and villages are built on low-lying coastal plains near the river mouths or on elevated terraces adjacent to the shore. Long segments are backed by rocky shores or elevated terraces that have steep nearshore slopes. According to FAO classification, the soil corresponds to chromic luvisol (FAO, 1998). Intense wheat crops at the beginning of the XX century caused a severe erosion of the study area. The soil profile does not contain a superficial layer of A horizon. The high content of clay causes a low field capacity and low water infiltration.

The area is characterized by rainfall concentrated during the winter, which leads to dry summers from September to April with little cloud cover and high solar radiation. The natural forest is mainly dominated by secondary forest of *Nothofagus* species (*N. obliqua* and *N. glauca*) (Fagaceae) and sclerophyllous species including *Acacia caven* (Mimosaceae), *Quillaja saponaria* (Rosaceae), and *Maytenus boaria* (Celastraceae). Also, several endangered species such as *N. alessandri*, *Pitavia punctata* (Rutaceae), and *Gomortega keule* (Gomortegaceae) (all of which are endemic to the Coastal Range of south-central Chile) can be found in the study area (Donoso, 1993).

Forest clearance, on a significant scale, began with the arrival of European colonizers in the XVI–XVIIth century. Throughout the Spanish colonial period (1700s), timber was extracted from forests without any concern for the renewal of this resource (Donoso & Lara, 1996). Widespread high-grading of the finest trees in old-growth forests led to rapid depletion of the most valuable timber species in south-central Chile (e.g. *N. nervosa*, *Persea lingue*, *Laurelia sempervirens*) (Armesto et al., 2010).

Then, in the mid-XIXth century a boom in the cultivation of wheat crops resulted in the elimination of extensive forest areas in the Coastal Range of the study area. More recently, (since the 1970s), the conservation of the last remnants of native forests has been seriously threatened by the expansion of forest plantations, mainly of Radiata pine (*P. radiata*) (Echeverría et al., 2006; Lara & Veblen, 1993).

At present, the main economic activities in the study area are based on plantation-based industry and agriculture, with the majority of the land classified as agricultural land dedicated to natural pastures that sustain cattle and sheep livestock (INE, 2007). According to the last population census in 2002, the eight municipalities comprised in the study area report high percentages of rural populations, with an average of 46.7% (INE, 2002). These municipalities also exhibit high levels of rural out-migration (17% on average between 1992 and 2002) and poverty (25% of the population in 2002) (INE, 2002).

3. Materials and methods

3.1. Remote sensing and land cover data

Data included a set of three Landsat scenes and supporting biophysical and socio-economic data of comparable quality. The Landsat images from March 22, 1975 (MSS) and January 22, 1990 (TM) had previously been classified and the details of image classification and accuracy assessment were reported in Echeverría et al. (2006). For the year 2007, a Landsat scene (ETM+), acquired on February 14, 2007, was subject to geometric, atmospheric and topographic corrections following Chuvieco (1996). Geometric correction was performed using the “full processing” module in PCI Geomatics and 65 ground control points (GCPs) sampled in field visits in July and August, 2007. The geometric accuracy ranged from 0.10 to 0.39 pixels corresponding to 3 m to 11.7 m, respectively. Atmospheric correction was conducted by transforming the original radiance image to a reflectance image (Chávez, 1996). The topographic correction was performed using the method proposed by Teillet, Guindon, and Goodeonugh (1982) in order to remove shadows in hilly areas. The elevation model data used for the correction was a 30 m × 30 m resolution digital elevation model (DEM) constructed through digital 50 m-elevation contours. We used bands 3, 4 and 5 to select training sites, while the entire set of spectral signatures was used to classify scenes.

Four resources were available to aid image classification: (i) the nationwide inventory of native forest cover (“Catastro”), which is a GIS-based data set of thematic maps derived from aerial photographs and satellite imagery developed between 1994 and 1997 (CONAF–CONAMA–BIRF, 1999); (ii) a set of 11 natural color digital aerial photographs (1:115,000) taken in 2007 and provided by the Laboratory of Landscape Ecology at Universidad de Concepción; (iii) the previously classified images from 1975 and 1990 (Echeverría et al., 2006); and (iv) the set of 65 GCPs used in geometric correction.

Owing to the availability of ground-based data sets, we chose to use a supervised classification method to classify the 2007 scene, following Echeverría et al. (2006). This method begins with a known set of classes that are separated or combined according to statistics or other properties of the image date. The supervised classification can be computationally implemented, allowing the specialist to choose and set up discrete classes (thus supervising the selection)

Table 1
Description of the independent variables used in the auto-logistic regressions estimated for the periods 1975–1990 and 1990–2007.

Variable name	Description	Source of data
Soilf	Dichotomous variable equal to 1 if the soil was of forest aptitude and zero otherwise	Digital soil map database at a scale of 1:100,000 (CIREN, 1997)
Soila	Dichotomous variable equal to 1 if the soil was of agricultural aptitude (cereal crops or pastures) with low to moderate limitations for farming, and zero otherwise	Digital soil map database at a scale of 1:100,000 (CIREN, 1997)
Slp	Slope (%)	30 m × 30 m DEM with a 50 m contour at a scale of 1:250,000 (IGM Chile) generated by a 3D analyst extension in ArcGIS
Alt	Altitude (m)	30 m × 30 m DEM with a 50 m contour at a scale of 1:250,000 (IGM Chile) generated by a 3D analyst extension in ArcGIS
Distr	Average Euclidean distance to the main paved roads	Base cartography of the study area
Distc	Average Euclidean distance to the cities of Constitución and Cauquenes	Base cartography of the study area
Firm	Dichotomous variable equal to 1 if the property corresponded to a corporate landholding and zero otherwise	1999 Cadastral Map of Rural Properties (CIREN & CORFO, 1999)
Sizef	Property size (ha)	1999 Cadastral Map of Rural Properties (CIREN & CORFO, 1999)
Prevf	Dichotomous variable equal to 1 if plantations were established on land previously covered by native forest and zero otherwise	1975 and 1990 satellite images
Preva	Dichotomous variable equal to 1 if the previous land use was agriculture and zero otherwise	1975 and 1990 satellite images

and then, assign them category names (Chuvieco, 1996). The statistical decision criterion of Maximum Likelihood was used in the supervised classification to assist in the classification of overlapping signatures, in which pixels were assigned to the class of highest probability. The Maximum Likelihood uses the Gaussian threshold of class signature to determine if a given pixel falls within the class or not. The entire set of spectral signatures from the supervised classification was inspected and signature separability and confusion matrices were examined. Accuracy assessment was conducted based on a stratified random sampling. A set of 583 sampling points were overlaid on the reference land cover maps and assigned to the respective class. Confusion matrices were constructed to compare the class identified for each sampling point with the land covers derived from the satellite image.

Five categories of land cover were identified based on Catastro (CONAF–CONAMA–BIRF, 1999): (i) agricultural land is a land cover including crops and pastureland (APL); (ii) shrubland (SH) corresponds to a land cover type where trees cover less than 10% and shrubs cover between 10% and 75% of the area; (iii) arboreous shrubland (ASH), is a land cover type in which tree species cover between 10% and 25% and shrub species, between 75% and 90%; (iv) native forest (NF), mainly secondary forests, which is a land cover where tree crowns cover over 25% and in most cases over 50%, composed of *Nothofagus* species; and (v) exotic plantations (PL), composed almost exclusively of Radiata pine (*P. radiata*). Plantations meet a minimum area requirement of 0.5 ha, a tree crown cover of at least 25% of the land area, and a total height of adult trees above 2 m (FAO, 2001).

It is difficult to detect and distinguish between afforested and reforested land given the rotation scheme of plantations and the consequent risk of classifying the bare ground between rotations as agricultural or pasture-land or fallow land. In order to avoid this problem, the change from plantation to agricultural and pastureland was ruled out and these areas were classified as “bare ground” between plantation rotations (BG). All land cover maps were analyzed to assess land cover change.

3.2. Land use and land cover change analysis

To gain general insight into the land cover change process, the following analyses were conducted: (a) a calculation of the land cover transition matrices for land cover for the periods 1975–1990 (hereafter the first period) and 1990–2007 (hereafter the second period) was done using the map cross-tabulation function of Idrisi GIS Vers.3.2 (Clark-Labs, 2006); the transition rate (p_{ij}) from land cover class i to class j was calculated using the formula $p_{ij} = A_{jt_2}/A_{it_1}$ where t_1 and t_2 correspond to the years of the satellite images and (b) a calculation of annual rates of change. For both periods land cover losses, gains and net changes were assessed for each category using the Land Change Modeler ArcGIS (9.3) extension (ESRI, 2009). Annual rates of change were calculated using the formula $P = [100/(t_2 - t_1)] \times \ln[S_2/S_1]$ proposed by FAO (1996), where P corresponds to the annual percent of change of a single land cover, and S_1 and S_2 represent the area of the specific land cover under analysis in times t_1 and t_2, respectively (corresponding to the years of the satellite images).

3.3. Measurement of the dependent and independent variables used in modeling LUC change to plantations

To create the binary dependent variable of the probabilistic regression models, land cover change maps for the periods 1975–1990 and 1990–2007 were constructed. While the unit of observation is generally the pixel (0.09 ha), land cover change to plantation was subjected to a minimum area of 0.5 ha. Of the 25 possible transitions, we isolated those that represented plantation expansion, namely the transitions from shrubland (SH), arboreous shrubland (ASH), native forest (NF) and agriculture and pastureland (APL) to plantations (PL). Boolean (0 and 1) images were created to account for these areas of expansion (1’s in the Boolean image) and for those areas of the remaining transitions where plantation expansion did not occur (0’s in the Boolean image). The areas of plantation persistence and reforestation were excluded from the LUC change analysis since our focus was on land use change to plantations.

For each time interval, we randomly selected a sample of 2000 points from the Boolean images using Hawth Tool ArcGIS (9.3) extension. This was performed with the stipulation that a distance of 1000 m separate the points in order to lessen the effect of spatial autocorrelation. A 50% of the sampling points corresponded to areas converted to forest plantations, and a similar proportion corresponded to areas converted to other land use category.

Table 2
Transition matrices for the periods 1975–1990 and 1990–2007. Percentage of the total landscape area.

1975	1990													
Category	PL (ha)	PL (%)	ASH (ha)	ASH (%)	APL (ha)	APL (%)	SH (ha)	SH (%)	NF (ha)	NF (%)	BG (ha)	BG (%)	Total ha 1975	Total (%)
PL	9620	1.8	9126	1.7	0	0	5211	1.0	4588	0.9	667	0.1	29,213	5.5
ASH	27,418	5.2	29,624	5.6	4190	0.8	33,202	6.3	16,995	3.2	0	0	111,428	21.0
APL	9990	1.9	6121	1.2	24,277	4.6	55,849	10.5	3027	0.6	0	0	99,264	18.7
SH	12,552	2.4	11,194	2.1	24,246	4.6	115,735	21.9	3989	0.8	0	0	167,716	31.6
NF	35,469	6.7	22,409	4.2	4415	0.8	22,787	4.3	36,813	7.0	0	0	121,895	23.0
BG	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total ha 1990	95,049	18.0	78,473	14.8	57,128	10.8	232,785	44.0	65,413	12.4	667	0.1	529,516	100

1990	2007													
Category	PL (ha)	PL (%)	ASH (ha)	ASH (%)	APL (ha)	APL (%)	SH (ha)	SH (%)	NF (ha)	NF (%)	BG (ha)	BG (%)	Total 1990 (ha)	Total 1990 (%)
PL	57,705	10.9	4033	0.7	0	0	3266	0.6	10,348	1.9	19,698	3.7	95,049	17.9
ASH	47,441	8.9	1811	0.3	17,773	3.3	2908	0.5	8540	1.6	0	0	78,473	14.8
APL	12,183	2.3	3900	0.7	27,447	5.1	11,226	2.1	2373	0.4	0	0	57,128	10.7
SH	68,689	12.9	12,608	2.3	91,473	17.2	48,899	9.2	11,116	2.1	0	0	232,785	43.9
NF	38,198	7.2	1721	0.3	11,173	2.1	1624	0.3	12,697	2.4	0	0	65,413	12.3
BG	501	0	9	0	64	0	5	0	87	0	0	0	667	0.1
Total 2007	224,716	42.4%	24,083	4.6%	147,929	27.9%	67,928	12.8%	45,162	8.5%	19,698	3.7%	529,516	100%

PL: plantations; ASH: arboreous shrubland; APL: agriculture and pasture-land; SH: shrubland; NF: native forest; BG: bare ground between plantation rotations.

Spatial data on all predictor variables (Table 1) were assembled from maps scaled to the 1:50,000 and converted to raster maps with 50 m × 50 m (0.25 ha) cell size. Predictor variables were grouped in three categories: (i) biophysical factors related to ecological and topographic conditions (*Soilf*, *Soila*, *Slp*, *Alt*), which account for the yield potential of land and the costs of farming as compared to planting, since they influence the degree of mechanization and on-foot accessibility (Gellrich, Baur, & Zimmermann, 2007); (ii) accessibility factors (*Distr*, *Distc*), which account for the access and opportunity costs of farm labor and the access to output and input markets; and (iii) farm-related factors (*Firm*, *Sizef*, *Prevf*, *Preva*), which account for farm structural variables. An important assumption in the case of *Firm* and *Sizef* is that farm structure remained constant over time; hence the property's structure in 1999 represents the type of property for the duration of the study. The description of the independent variables is provided in Table 1.

The independent variables chosen aimed at representing drivers of LUC change, which have been defined as the forces that cause observed landscape changes and have been classified as socioeconomic, political, technological, natural, and cultural driving forces (Bürgi, Hersperger, & Schneeberger, 2004). As in similar LUC change studies, the selection of variables was restricted to proximate rather than ultimate driving forces, such as national policies and market forces. Since proximate factors directly affect changes in LUC, their effect can be quantified, and they can be represented spatially (Wilson et al., 2005).

3.4. Autologistic regression

The presence of plantations was assumed as a binomial error distribution with a logit link function. As spatial autocorrelation was suspected, the probability of plantation expansion (Pr) was modeled using an autologistic regression which incorporates spatial dependence with binary response data (Augustin, Mugglestonet, & Buckland, 1996) and has the form $\log(p/(1-p)) = \alpha + \beta_1 x_1 + \cdots + \beta_n x_n + \beta_{n+1} autocov_{n+1}$ where $p = \Pr(y = 1|x)$ with $y = 1$ indicating the presence of plantations. The autocovariate (*autocov*) at pixel *i* is the weighted sum of observations in neighboring pixels in a defined neighborhood and can be expressed as $autocov_i = \sum_{j=1}^{k_i}(1/d_{ij})y_j$ where d_{ij} is the Euclidean distance between pixel *i* and pixel *j* for each pixel *i*, *k* is the number of pixels within a specified lag distance of pixel *i*, and *y* is the presence or absence of the specified land transition (plantation in this case) at pixel *j* (Augustin et al., 1996). The model was estimated in SAM (Spatial Analysis in Macroecology) version 4.0 (Rangel, Diniz-Filho, & Bini, 2010) using the independent variables (*x*'s) described in Table 1. These variables were checked for correlation, but no significant correlations were found. During the first period, the highest positive correlation coefficient equaled 0.35 (*Sizef* and *Alt*) and the highest negative coefficient equaled −0.35 (*Preva* and *Prevf*). During the second period the highest positive correlation coefficient equaled 0.27 (*Slp* and *Soilf*) and the highest negative coefficient was equal to −0.25 (*Soila* and *Soilf*).The performance of the model in both periods was evaluated through the percentage of correct predictions, the measures of sensitivity (percentage of 1's correctly predicted) and specificity (percentage of 0's correctly predicted), and the odds ratios. The significance of individual coefficients was evaluated through the *t*-test at 10%, 5% and 1% levels of significance.

4. Results

4.1. Patterns and rates of plantation expansion

Overall classification accuracy for the 2007 image was 90.9%, with the lowest value for arboreous shrubland (83.1%) and the

Table 3
Transition matrices for the periods 1975–1990 and 1990–2007 showing transition rates (p_{ij}) from land cover class i to class j calculated as $p_{ij} = A_{jt_2}/A_{it_1}$ where t_1 and t_2 correspond to the years of the satellite images.

1975	1990					
	PL	ASH	APL	SH	NF	BG
PL	0.329	0.312	0	0.178	0.157	0.022
ASH	0.246	0.265	0.037	0.297	0.152	0
APL	0.100	0.061	0.244	0.562	0.030	0
SH	0.074	0.066	0.144	0.690	0.023	0
NF	0.290	0.183	0.036	0.186	0.302	0
BG	0	0	0	0	0	0
1990	2007					
	PL	ASH	APL	SH	NF	BG
PL	0.607	0.042	0	0.034	0.108	0.207
ASH	0.604	0.023	0.226	0.037	0.108	0
APL	0.213	0.068	0.480	0.196	0.041	0
SH	0.295	0.054	0.392	0.210	0.047	0
NF	0.583	0.026	0.170	0.024	0.194	0
BG	0.751	0.013	0.095	0.007	0.130	0

PL: plantations; ASH: arboreous shrubland; APL: agriculture and pasture-land; SH: shrubland; NF: native forest; BG: bare ground between plantation rotations.

highest value for plantations (92.2%). Overall agreement for the 1975 and 1990 images was 82.7% and 83.3%, respectively (Echeverría et al., 2006).

The results confirm the rapid expansion of plantations during the period of study, from 29,213 ha in 1975 (5.5% of the landscape) to 95,049 ha in 1990 (17.9% of the landscape) and 224,716 ha in 2007 (42.4% of the landscape) (Table 2), at annual rates of 7.9% and 5.1%, for the periods 1975–1990 and 1990–2007, respectively.

During the period 1975–1990, net gains to plantations (gains minus persistence) reached 85,429 ha with a large contribution coming from native forests (35,469 ha; 41.5%) and arboreous shrubland (27,418 ha; 32%). In the period 1990–2007 gains to plantations reached 167,011 ha; the main contributor to plantation gains was shrubland (68,689 ha; 41.1%), followed by arboreous shrubland (47,441 ha; 28.4%) and native forests (38,198 ha; 22.8%). On the contrary, agricultural lands contributed only a small proportion of the gains in plantation cover in both periods, with 9990 ha (5.9%) and 12,183 ha (7.3%), respectively (Table 2).

Of the six major land cover classes between 1975 and 1990, shrubland had the highest rate of persistence in the first period (0.69), followed by plantations (0.32), native forest (0.30), arboreous shrublands (0.26) and agriculture and pasture-land (0.24) (Table 3). Regarding transitions to different land cover classes, approximately 29% of secondary native forests and 24% of arboreous shrublands in 1975 were converted to plantations in 1990. During the period 1990–2007, plantations still had the highest level of persistence (0.60) followed by agriculture and pasture-land (0.48), demonstrating a highly anthropic landscape. In this period, most of the bare ground present in 1990 was converted to plantations (0.75), while 60% of arboreous shrublands and 58% of the secondary native forest present in 1990 were also replaced by plantations.

In terms of their spatial distribution, in 1975 plantations were located mainly in three specific zones within the study area. By 1990, plantations had expanded rapidly across the landscape but were still mostly confined to the Coastal Range. By 2007 plantations had expanded further toward the relatively dry rainshadow area of the Coastal Range's oriental foothills, becoming the dominant land cover in this area (Fig. 2).

4.2. Model performance and estimation results

Table 4 shows the results of the autologistic regressions for the periods 1975–1990 and 1990–2007. For the first period, the autologistic model correctly predicted and classified 69.2% of the cases as indicated by the percentage of overall accuracy. The Chi square measure ($p < 0.0001$), and the odds ratios of the covariates corroborate the model's overall high-quality performance. Most odds ratios were larger than 1, indicating that plantation expansion had a very high probability of occurring. In turn, the percentage of correct predictions of 1's (sensitivity) and 0's (specificity) was 72.7% and 65.7%, respectively. In the period 1990–2007 the model exhibited a very similar performance to the model estimated in the first period.

Soilf and *Slp* were among the significant biophysical drivers that increased the probability of plantations between 1975 and 1990, which corroborates that in this period plantations were more likely to expand on soils of forest aptitude located at higher slopes. During this period, 65.1% of the new plantations (48,232 ha) were established on slopes between 0% and 15% (Appendix A).

Among accessibility factors, *Distc* corroborates that between 1975 and 1990 plantations were more likely to occur near cities. During this period, 43.5% of newly planted areas (37,138 ha) occurred within 5 km from Constitución or Cauquenes. Constitución is home to one of the largest pulp mills in the country, created in 1969 (as Celulosa Constitución S.A.), while Cauquenes is located in the rainshadow of the study area and is more oriented to agricultural activities and markets. Both cities are similar in size with populations of 52,000 and 50,914 people, respectively (INE, 2002).

Table 4
Coefficient estimates, p-values, and measures of performance from the autologistic regressions for the periods 1975–1990 and 1990–2007.

Variable	1975–1990			1990–2007		
	Coeff.	p value	Odds ratios	Coeff.	p value	Odds ratios
Constant	−6.730	<0.001	0.001	−6.386	<0.001	0.002
Soilf	0.183	0.088	1.201	0.469	<0.001	1.598
Soila	0.119	0.605	1.126	−1.126	<0.001	0.324
Slp	0.012	0.032	1.013	0.008	0.247	1.008
Alt	0.636	0.132	1.890	0.950	0.027	2.585
Distc	−0.025	<0.001	0.976	0.002	0.712	1.002
Distr	<0.001	0.959	0.999	0.045	0.015	1.046
Firm	0.265	0.034	1.304	0.212	0.108	1.236
Sizef	0.395	0.043	1.484	0.012	0.954	1.012
Prevf	0.405	<0.001	1.500	0.745	<0.001	2.106
Preva	0.027	0.848	1.028	0.532	0.007	1.703
Autocov	12.987	<0.001		10.963	<0.001	
Chi square	447.196	<0.0001		410.559	<0.0001	
Overall accuracy	0.692			0.680		
Sensitivity	0.727			0.700		
Specificity	0.657			0.650		

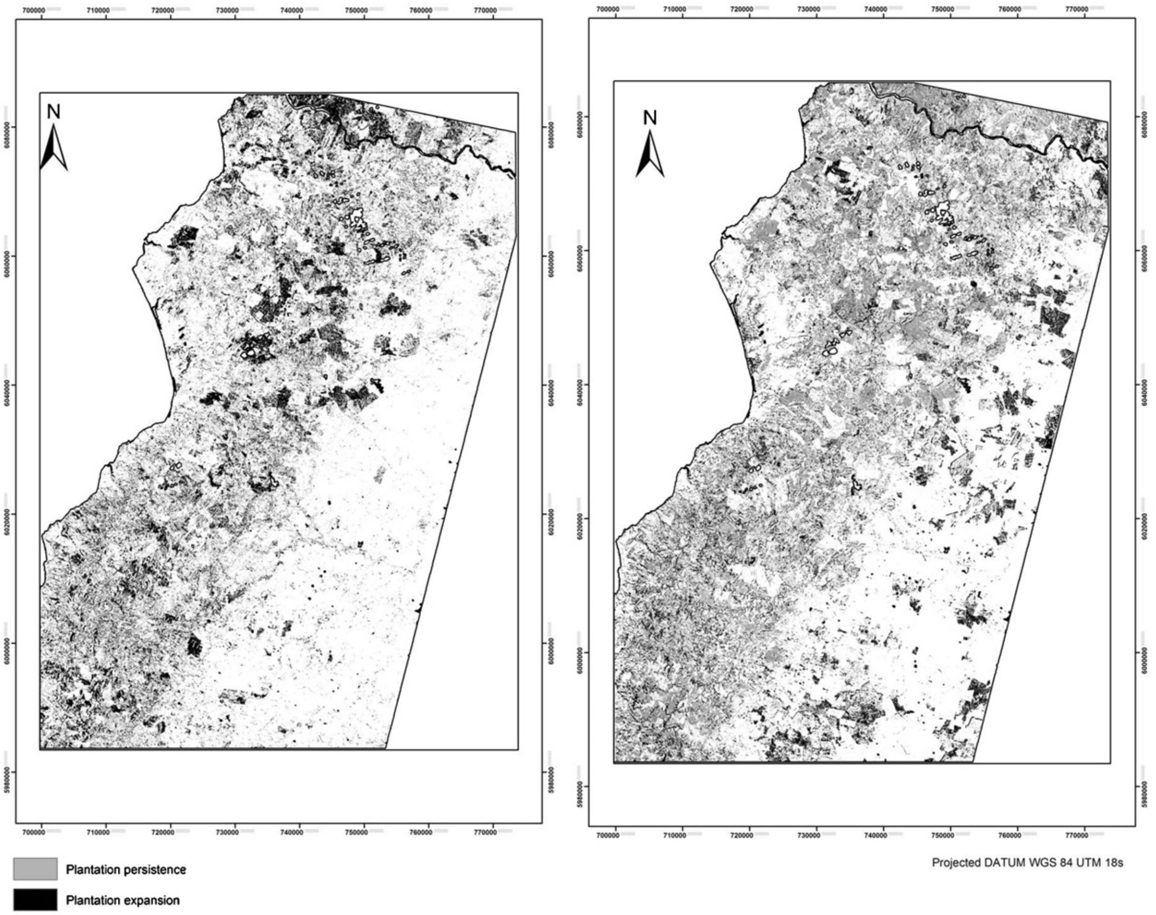

Fig. 2. Plantation expansion and persistence for the 1975–1990 and 1990–2007 periods.

Among farm structural factors *Firm*, *Sizef*, and *Prevf* were significant which confirms that between 1975 and 1990 plantations were more likely to occur on large corporate landholdings and were established on areas previously covered by native forest, becoming a direct cause of deforestation. Simultaneously, during this period 41.5% of the new plantations were established on land covered by secondary forests and only 11.7% were established on land previously dedicated to agriculture. By 1999, corporate landholdings comprised 2.1% of the properties in the study area and corporations owned nearly 32% of the plantations. They also coincided with the largest properties in the study area, with an average size of 214 ha and a maximum size of 4381 ha. By 2007, 236 of these corporate landholdings had more than 80% of their area planted.

In the period 1990–2007 plantations continued to expand on soils of forest suitability and at higher elevations as indicated by *Soilf* and *Alt*, respectively, but they were also likely to be established on soils suitable for agriculture and pastures as indicated by the significant coefficient of *Preva*. While *Disct* was no longer a significant predictor, *Distr* suggests that during this period it was more likely that plantations occurred farther from roads. This is consistent with the fact that, during this period, 40.5% of new plantations (67,615 ha) were established more than 20 km from a paved road (Appendix A). *Firm* lost significance suggesting that between 1990 and 2007 plantations expanded on different types of landholdings. Yet, they were still more likely to be established on areas covered by native vegetation as *Prevf* suggests, but also on areas previously covered by agriculture and pasture-lands as indicated by *Preva*. Between 1990 and 2007, 41.1% of the new plantations were established on shrublands, 28% on arboreous shrublands, 22.8% on native forest, and 7.5% on agricultural and pasture-lands.

5. Discussion of results

To understand how LUC change affects and interacts with the environmental system, we need information on what changes happen, where and when they occur, the rates of change, and the social and physical drivers of those changes (Lambin, Geist, & Lepers, 2003). This study aimed at providing some of this relevant information.

The results reveal that in the Coastal Range of south-central Chile, plantations have increased nearly ten-fold between 1975 and 2007 at an average annual rate of 6.4%, with important implications for biodiversity and the landscape. As a result, by 2007 this study area comprised near 10% of the country's plantation state in 2007 (INFOR, 2010). The modeling approach chosen in this study (autologistic regression) was capable of establishing causal relationships between the probability of LUC change and proximate drivers of change namely biophysical, accessibility, and farm structural factors. This approach has been found to be more effective in analyzing particular LUC changes than other approaches (e.g. Markov chains and cellular automata) (Huang, Zhang, & Wu, 2009; Munroe, Southworth, & Tucker, 2004). Yet, we are aware of the complex interactions among the underlying causes of LUC change to plantations, which cannot always be represented in a single model. In this sense, two considerations may help improve future versions of the model. Firstly, is to work with land trajectories over several observation years (e.g. native forest-shrubland-plantations) rather than two-year transitions. Secondly, is to use panel data estimation techniques, combining spatial time-invariant data with time-variant socio-economic data (e.g. land tenure, property size), as more accurate information becomes available.

The main findings can be summarized as follows. Firstly, we identify a clearer pattern of expansion between 1975 and 1990 as compared to 1990–2007, associated with soils of forest suitability, steep slopes, proximity to main cities, corporate landholdings, and large farms. On the contrary, during the period 1990–2007, some biophysical and farm structural factors were no longer important as plantations expanded in all directions, becoming the predominant land cover in the landscape. Besides timber forestry comparative advantages-large areas of land of low opportunity costs for farming and low establishment and accessibility costs for planting-, the fact that plantation expansion was more likely to occur on corporate landholdings can be attributed to the effect of government subsidization. This was particularly relevant between the 1970s and early 1990, before Law 19,561 was enacted in 1998 and modified the scope of DL701. Several authors have examined the Chilean plantation development program, concluding that the main beneficiaries were those with an initial capital base that enabled them to engage in tree planting (Beattie, 1995). Beattie (1995) observed that between the 1970s and early 1990s, 80% of the subsidy payments of DL 701 went to Chile's three largest forestry companies.

Secondly, we find a consistently higher probability of plantation expansion on areas previously covered by native forests and arboreous shrublands in both periods, which corroborates that plantation expansion in Chile, has been a direct cause of deforestation and biodiversity loss (Aguayo et al., 2009; Altamirano & Lara, 2010; Echeverría et al., 2006; Lara & Veblen, 1993). This finding coincides with the results reported in countries such as Indonesia (Obidzinski & Chaudhury, 2009), Australia (Kanowski, Catteral, & Wardell-Johnson, 2005; Mercer & Underwood, 2002), Spain (Teixido, Quintanilla, Carreño, & Gutiérrez, 2010), and New Zealand (Nagashima, Sands, Whyte, Bilek, & Nakagoshi, 2001).

The spatiotemporal dynamics resulting from the interaction of natural and socioeconomic drivers have important implications for biodiversity and the landscape. In terms of biodiversity conservation, the second-growth forests that have been converted to plantations belonged to the mixed sclerophyllous and the *N. obliqua*–*N. glauca* forest types (Donoso, 1993), including more than 15 tree species, one of which is listed as endangered (*P. punctata*) and another as vulnerable (*N. glauca*), both of which are endemic to the coastal region of south-central Chile (Lara, Donoso, & Aravena, 1996). These second-growth forests are typically 20–60 year old stands and are the result of human-set fires, land clearing for agriculture and pasture-land on a repeating cycle of clearing-abandonment-forest regrowth that has occurred in the area at least since 1900 (Donoso, 1993). Furthermore, this area is located within the Temperate Rainforest Eco-region, which has been classified by the World Wildlife Fund (WWF) and the World Bank's Global Initiative 200 as an ecosystem with one of the highest international conservation priorities (Olson & Dinerstein, 1998). This classification is due to the high degree of endemism, the threats from diverse human activities and the critical status of different species and ecosystems.

In terms of the landscape, plantations on such a large scale, because they are associated with corporate landholdings and large properties, has led to the homogenization of the landscape (large extensions of even-aged stands of the same species), which, in turn, has important implications for biodiversity (e.g. lack of connectivity, species loss), ecosystem services (e.g. water flows) and humans (e.g. fire risk) (González, Lara, Urrutia, & Bosnich, 2011; Little, Lara, McPhee, & Urrutia, 2009). Furthermore, since most planting under corporate landholding has been subject to DL 701, land conversion to plantations becomes an irreversible land trajectory since parcels subject to DL 701 are required to permanently remain in plantation forestry (Niklitschek, 2007).

According to modeling results, the areas more vulnerable to future change in the southern regions of Chile would be those located on soils which are marginal for agriculture (e.g. areas in the Andes and Coastal Ranges) which also concentrate high levels of rural poverty. These regions are already experiencing rapid transformation with LUC change to plantations coexisting with multiple land trajectories of deforestation, forest degradation and land abandonment (Aguayo et al., 2009; Carmona & Nahuelhual, 2012; Díaz, Nahuelhual, Echeverría, & Marín, 2011). Planning can be very difficult in these dynamic landscapes, especially where landscape change processes are unregulated as is the case of rural areas in Chile where most policy instruments are merely indicative rather than obligatory. Hence, effectively planning plantation expansion in order to avoid negative impacts will most likely require a combination of both market incentives (i.e. forest certification) and adequate enforcement of proscribed clearing.

These results highlight the need for adequate quantification and economic valuation of the social benefits and costs associated with conversion to plantations. On one hand, the true social value of the ecosystem services provided by native forests and other land cover types, which are being replaced, must be considered. On the other hand, private landowners engaging in plantation establishment should be required to adequately deal with negative environmental impacts, which is essential to have an effective plantation strategy in the long-term.

Acknowledgements

The research leading to these results has received funding from International Foundation for Science (Grant S/17587R) and the European Union's Seventh Framework Programme (FP7/2007–2013) under Grant Agreement No. 243888. The authors thank Miss Brenda Román for her important contribution to data collection, Mr. Rodrigo Fuentes from the Laboratory of Landscape Ecology at Universidad de Concepción de Chile for his assistance in satellite image classification and analysis, and Mr. Ian Kinney and Mrs. Christine Harrower for English editing.

Appendix A. Distribution of new plantations (%) in relation to slope, altitude, distance to cities, and distance to main paved roads in the periods 1975–1990 and 1990–2007

Slope (%)	Plantations (%)		Altitude (m)	Plantations (%)		Distance to cities (m)	Plantations (%)		Distance to roads (m)	Plantations (%)	
	1975–1990	1990–2007		1975–1990	1990–2007		1975–1990	1990–2007		1975–1990	1990–2007
0–15	65.1	33.7	0–150	14.4	5.4	1–5000	43.5	39.2	0–5000	35.5	18.2
15–30	28.8	25.9	150–300	35.8	13.3	5000–10,000	19.2	22.1	5000–10,000	30.0	16.7
30–45	5.6	15.4	300–450	36.1	16.6	10,000–20,000	21.6	21.1	10,000–15,000	22.2	14.0
>45	0.5	25.0	>450	16.2	64.7	20,000–50,000	15.7	17.5	15,000–20,000	11.6	10.6
						>50,000			>20,000	0.7	40.5

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