Forest Ecology and Management 345 (2015) 10–20

Contents lists available at ScienceDirect

Forest Ecology and Management

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

Native forest replacement by exotic plantations in southern Chile (1985–2011) and partial compensation by natural regeneration

Carlos Zamorano-Elgueta [a,*], José María Rey Benayas [a], Luis Cayuela [b], Stijn Hantson [c], Dolors Armenteras [d]

[a] Departamento de Ciencias de la Vida – UD Ecología, Edificio de Ciencias, Universidad de Alcalá, E-28871 Alcalá de Henares, Spain
[b] Área de Biodiversidad y Conservación, Departamento de Biología y Geología, Universidad Rey Juan Carlos, c/Tulipán s/n, E-28933 Móstoles (Madrid), Spain
[c] Karlsruhe Institute of Technology, Institute of Meteorology and Climate Research/Atmospheric Environmental Research (IMK-IFU), Garmisch-Partenkirchen, Germany
[d] Laboratorio de Ecología del Paisaje y Modelación de Ecosistemas, Departamento de Biología, Facultad de Ciencias, Universidad Nacional de Colombia, Bogotá, Colombia

ARTICLE INFO

Article history:
Received 6 October 2014
Received in revised form 21 January 2015
Accepted 15 February 2015
Available online 4 March 2015

Keywords:
Deforestation
Fragmentation
Land cover change
Temperate forest
Spatial patterns

ABSTRACT

Although several studies have reported rates of deforestation and spatial patterns of native forest fragmentation, few have focused on the role of natural forest regeneration and exotic tree plantations on landscape dynamics. The objective of this study was to analyze the dynamics of land cover change in order to test the hypothesis that exotic tree plantations have caused a major transformation of temperate forest cover in southern Chile during the last three decades. We used three Landsat satellite images taken in 1985 (TM), 1999 (ETM+), and 2011 (TM) to quantify land cover change, together with a set of landscape indicators to describe the spatial configuration of land cover. Our results showed that the major changes were dynamic conversion among forest, exotic tree plantation and shrubland. During the study period, the area covered by exotic tree plantations increased by 168% (20,896–56,010 ha), at an annual rate of 3.8%, mostly at the expense of native forest and shrubland. There was a total gross loss of native forest of 30% (54,304 ha), but a net loss of initial cover of only 5.1% (9130 ha), at an annual net deforestation rate of 0.2%. The difference between gross and net loss of native forest was mostly the result of conversion of shrubland and agricultural and pasture land to secondary forest following natural regeneration. Over the course of the study period, exotic tree plantations showed a constant increase in patch density, total edge length, nearest-neighbor distance, and largest patch index; maximum mean patch size occurred in the middle of the study period. Native forest exhibited an increase and then a decrease in patch density and total edge length, whereas mean patch size and largest patch index were lowest in the middle of the period. Overall, the observed trends indicate expansion of exotic tree plantations and increase in native forest loss and fragmentation, particularly between 1985 and 1999. Forest loss included both old-growth and secondary forests, while native forest established after secondary succession differed in diversity, structure, and functionality from old-growth and old growth/secondary forests. Since different successional stages influence the provision of ecosystem services, the changes observed in our study are likely to have consequences for humans that extend beyond immediate changes in land use patterns.

1. Introduction

Humans have changed land use and land cover for millenia, resulting in significant impacts on the environment (e.g. Klein Goldewijk et al., 2011). Human activities and demands are rapidly changing ecosystems and landscapes, and only small or remote areas of the globe show no evidence of human intervention (Lambin and Meyfroidt, 2011). Transformation of natural landscapes has eroded ecosystem functions, and habitat loss and fragmentation have increased vulnerability to edge effects and biodiversity loss (Laurance et al., 2006). Acting in the opposite direction is passive regeneration, which may counteract the effects of habitat loss and fragmentation (Morrison and Lindell, 2010; FAO, 2011), especially for areas where natural recolonization is fast due to seed availability, extensive residual cover of natural habitat, and conserved soil (Prach et al., 2007; Chazdon, 2008). Given their complexity, the processes involved in land cover change are the focus of research programs and strategies for sustainable management (Vitousek, 1994). Although important advances have been made, significant gaps remain in our understanding of the spatial ecology of these changes (Iverson et al., 2014).

Among the drivers of land cover change, tree plantations play an important role in many parts of the world. Tree plantations

* Corresponding author. Tel.: +34 91 8854987.
E-mail address: carlos.zamorano@edu.uah.es (C. Zamorano-Elgueta).

http://dx.doi.org/10.1016/j.foreco.2015.02.025
0378-1127/

are typically established on cleared agricultural land, but they also expand at the expense of native forest, which is an emerging cause of forest loss and fragmentation worldwide (Foley et al., 2005). Three factors have caused the expansion of tree plantations towards increasingly difficult-to-reach areas: depletion of finite resources, particularly timber; natural limits to increasing yield on high-quality land; and development of tree plantation technology feasible on cheaper marginal lands (Kröger, 2013). As a result, planted forests are rapidly expanding worldwide and they currently account for ca. 7% of the total forest area, whereas the area covered by native forests declined by 5.2 million ha annually between 2000 and 2010 (FAO, 2011; Kröger, 2013). The two main areas where plantation expansion has been particularly dramatic are South America, where area increased by 67% between 1990 and 2010, and the Asia–Pacific region, where area increased by 61.6% (Kröger, 2013).

Some tree plantations are intended to provide chiefly environmental benefits, including those fostered by the European Community Agrarian Policy (European Commission, 2013) and the Chinese Grain-to-Green project (Song et al., 2014). However, most tree plantations are grown primarily for producing wood efficiently and for contributing significantly to economic growth; these activities may produce substantial changes in natural ecosystems, with impacts on biodiversity and ecosystem services (Hartley, 2002). Furthermore, management practices such as periodic clearing of understory vegetation can have more drastic effects than any competitive or allopathic effects due to the planted trees (Atauri et al., 2004). The global trend of tree plantation expansion is likely to continue, especially for the production of biofuels (Kole et al., 2012) and carbon storage (Lindenmayer, 2009), while natural forests are in decline and increasingly fragmented (FAO, 2010).

In Chile, tree plantation establishment began in the 1940s (Toro and Gessel, 1999), and in the 1970s the country showed the highest annual rates of plantation increase in South America, especially between 1995 and 2009, due to both afforestation (49,020 ha) and reforestation (53,610 ha) (FAO, 2010; INFOR, 2010). At present, forest plantations are dominated by *Pinus radiata* (D. Don) and *Eucalyptus* spp., which account for 2.3 million ha (INFOR, 2013), an area increasing by 37,000 ha annually (CONAF, 2014). The geographic range of southern temperate forest has declined considerably during the last century (Smith-Ramírez, 2004), partly as a result of conversion of native forest to other land cover types. These processes, together with fragmentation of remnant habitats, threaten native forest in southern Chile (Echeverría et al., 2006; Lara et al., 2011; Nahuelhual et al., 2012). These temperate rainforests are globally important ecoregions because of their biodiversity (Myers et al., 2000; Smith-Ramírez, 2004; Smith-Ramírez et al., 2007), and they have been targeted for urgent conservation by the World Bank, the World Wildlife Fund and other organizations (Dinerstein et al., 1995). In Chile, the last remnants of temperate forest are restricted to upper elevations in the Andean mountains and the southern section of the Coastal Range, where continuous tracts of forest still exist (Smith-Ramírez, 2004).

Studying land cover change has always been limited by data availability. The development of Geographical Information Systems (GIS) has offered a variety of tools for analyzing landscape spatial patterns (Franklin, 2001). The evaluation of temporal forest change based on satellite imagery can then be linked to fragmentation analysis, representing a valuable set of techniques for assessing the severity of threats to ecosystems (Dávalos et al., 2014; Kumar et al., 2014). Many indices have been developed to quantify patterns at the landscape scale, including area (Armenteras et al., 2003), edge (Franklin, 2001; McGarigal et al., 2012), shape (Franklin, 2001; Mcgarigal et al., 2012), distance (Mcgarigal et al., 2012), and connectivity metrics (Franklin, 2001; Mcgarigal et al., 2012). The use of these metrics in deforestation and fragmentation studies has increased exponentially around the world in recent decades (Willson et al., 1994; Armenteras et al., 2003; Cayuela et al., 2006a,b; Dávalos et al., 2014), probably motivated by increasing accessibility to remote sensing data and powerful computers (Newton et al., 2009).

Relatively few studies have analyzed land cover change and forest fragmentation in Chile (Echeverría et al., 2006; Schulz et al., 2010; Nahuelhual et al., 2012; Altamirano et al., 2013). Echeverría et al. (2006) assessed the patterns of deforestation and forest fragmentation in the Coastal Range of south-central Chile over a 25-year period using data from 1975, 1990 and 2000. Schulz et al. (2010) investigated land cover changes and major trends in landscape dynamics in central Chile, including regeneration, using multi-temporal satellite images taken in 1975, 1985, 1999 and 2008. Nahuelhual et al. (2012) analyzed the drivers of plantation expansion in south-central Chile for the periods 1975–1990 and 1990–2007. Finally, Altamirano et al. (2013) analyzed patterns of deforestation and fragmentation in south-central Chile using fine-resolution (0.0225 ha) classified maps from satellite images taken in 1986, 1999 and 2008.

Notwithstanding the growing literature on land cover change, few studies have investigated simultaneously how landscape dynamics are affected by natural forest regeneration (e.g. Pütz et al., 2011; Schulz et al., 2010) and exotic tree plantations (e.g. Nahuelhual et al., 2012). Improving our understanding of such dynamics may help mitigate or reverse their impact on forest ecosystems, contribute to land use planning, and guide the design and implementation of conservation and restoration programs at the landscape scale. The objective of this study was to analyze the dynamics of land cover change in order to test the hypothesis that exotic tree plantations have caused a major transformation of temperate forest cover in southern Chile in a recent time period spanning 26 years. To achieve this goal, our study attempted to (1) determine the rates and amount of land cover change, (2) measure the spatial distribution of forest loss and expansion of plantations, and (3) examine whether natural regeneration has compensated for forest loss at the landscape scale.

2. Methods

2.1. Study area

The study area covers ca. 2700 km^2 of the Chilean Coastal Range (Fig. 1), including rivers and wetlands, and elevation ranges from 4 to 684 m. It has abundant endemic flora and fauna, which reflect the location of vegetation refuges during the last glacial period (Armesto et al., 1995). Evergreen forests are the dominant vegetation type, occupying 79% of the total forest cover in the study area (CONAF-CONAMA-BIRF, 1999). The predominant climate is temperate with Mediterranean influence, a mean annual temperature of 11 °C and a mean annual precipitation of 2500 mm. Soils are derived from metamorphic material and granitic rocks (IREN-CORFO, 1964).

Land tenure is characterized by a mosaic of different land cover types, productive activities, and local stakeholders. The dominant types of land tenure correspond to properties owned by forest companies (81,100 ha, 30% of the study area) that concentrate the area covered by exotic tree plantations, private protected areas (52,000 ha, 19.3%), and small properties (46,827 ha, 17%) owned by "campesinos". This Spanish name refers to rural people in the subsistence economy who live on <200 ha, as defined in Chilean law. The other major types of land tenure are large properties, i.e. $\geqslant$200 ha (45,663 ha, 16.97%) and public protected areas (26,000 ha, 9.74%). Most campesino-owned small properties show frequent and intense alterations due to constant efforts to achieve