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From the Holocene to the Anthropocene: A historical framework for land cover change in southwestern South America in the past 15,000 years

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ABSTRACT

The main forest transitions that took place in south-central Chile from the end of the last glaciation to the present are reviewed here with the aim of identifying the main climatic and socio-economic drivers of land cover change. The first great transition, driven primarily by global warming, is the postglacial expansion of forests, with human populations from about 15,000 cal. yr. BP, restricted to coastlines and river basins and localized impact of forest fire. Charcoal evidence of fire increased in south-central Chile and in global records from about 12,000 to 6000 cal. yr. BP, which could be attributed at least partly to people. The subsequent expansion of agriculture led to much clearing of forests and the spread of weeds and other indicators of open habitats. The Spanish colonial period in America may have been followed by a transient expansion of forest cover into abandoned land, as indigenous population declined rapidly due to disease and slaughter. The 18th and 19th centuries brought about extensive loss of forests due to the massive impact of lumber extraction for mining operations both in central Chile and in western North America. Two centuries of intensive deforestation, coupled to grazing by cattle and extremely variable rainfall had long-lasting effects on forest cover in south-central Chile, which persist until today. The transition from a preindustrial to an industrial society brought about the "golden age" of timber harvest, assisted by mobile sawmills and railway transportation since the late 1800s. These advances led to the exhaustion of native commercial timber by the late 20th century in south-central Chile. In North America, harvestable stands were exhausted in New England and the Midwest around 1920. Settlement of the independent territories in the late 1800s and early 1900s implied vast burning and clearing of land and mounting soil erosion. Industrial forestry, based on government-subsidized massive plantations of short-rotation exotic trees, developed in the late 20th century, in connection with postindustrial displacement of exploitative activities from developed to third-world nations. In the last two decades, economic globalization and free trade promoted the expansion of new crops and further decline of woodlands, despite modest increases in forest cover. These patterns are repeated in many Latin American countries. To prevent further depletion of native forest resources and to provide an insurance against climate change, in the 21st century developing nations should aim at: (1) relocating subsidies from fiber farms to restoring diverse forest cover, (2) promoting ecosystem management of diverse forest and crops within landscapes, and (3) fostering diverse cultural relationships between people and their land.

Introduction

Today, anthropogenic land cover change (Houghton, 1994; Vitousek, 1994) is arguably the main driver of future biodiversity loss (Sala et al., 2000), disruption of ecosystem services, spread of exotic species, and pollution of land and water (Tilman, 1999; Millennium Ecosystem Assessment, 2003). Since the onset of the human enterprise, growing demands for food, timber and water drove changes in the extent, structure, and diversity of wild

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habitats. Yet for the most part of human history such impacts were unplanned, local and transient, and therefore rapidly reversed by ecological succession. It is only during the past few centuries that industrialized agriculture, forestry, and rapid urban and rural population growth has led to global homogenization of landscapes (Turner, 1990; Houghton, 1994; Mather et al., 1998). Because continental-scale land cover transitions occurred largely in the past two centuries, climatic, social and ecological modulators of such changes are only beginning to be understood (e.g., Mather et al., 1998; McKinney and Lockwood, 1999; Millennium Ecosystem Assessment, 2003). It seems relevant therefore to evaluate, as a case study, the relative importance of physical versus anthropogenic drivers of land transitions during the Holocene in southern South America, and discuss how can we anticipate or modify the impending outcomes of land cover trends. Such analysis is a complex challenge because of the trans-disciplinary nature of factors involved. Only through integrated social and ecological understanding, we shall develop better explanatory models to guide sensible land use policies. This integration is even more urgent in Latin America, where the fast pace of land cover change threatens one of the richest biocultural landscapes in the world (Primack et al., 2001; Rozzi et al., 2000). This biocultural diversity underlies large differences in land use patterns and modes of living.

In the developed world, forest loss has been moderated by the concentration and intensification of agricultural production and by a broader social recognition of the environmental values of forest ecosystems beyond timber production. This has led to postindustrial recovery of forest cover, reversing the trend towards deforestation that dominated through the industrial age (Mather et al., 1998, 2006). However, this northern hemisphere transition is coupled to increasing deforestation in many developing nations, which are now the suppliers of timber and other natural capital needed to sustain the economic growth of developed countries (Siebert, 2003). In this context, land use trends in most developing countries in the beginning of the 21st century are ultimately driven by the demands of global economy (Siebert, 2003; Liverman and Vilas, 2006). Current ecological and social effects of land cover change in the developing world can be best viewed as externalities of the prevailing global free-market economy.

Analyses of forest transitions in Chile have generally spanned only a few decades (Fuentes and Hajek, 1979; Achard et al., 2002; Echeverria et al., 2006). Here, we review the history of land cover change in south-central Chile, from the first records of human habitation, at the end of the Last Glacial Age about 15,000 calendar years before the present (cal. yr. BP) (Dillehay et al., 2008) to the present (Lara and Veblen, 1993; Donoso and Lara, 1996; Claude, 1997; Armesto et al., 1994, 2001a), with the aim of identifying major transitions and their underlying climatic and socio-economic drivers. We start this review by analyzing the transition from the last glacial to the present interglacial in the mid-latitudes of western South America, which was primarily associated with global warming, forest expansion, and sparse indigenous populations of hunting-gatherers living in river basins (Dillehay et al., 2008). We show that postglacial events bear important consequences for the present latitudinal distribution of biodiversity in Chile and are relevant to assess the impacts of preindustrial and industrial land use change. Secondly, we examine pre-Hispanic forest cover transitions in south-central Chile, as human populations grew in number and diversified their agricultural and land use practices. Thirdly, we analyze the massive land transformations and deforestation beginning with the arrival of Europeans and culminating with the transition from industrial to postindustrial society. From this analysis, we propose a general framework for forest transitions in mid-latitude ecosystems of southern South America that encompasses the interval that begins in the Holocene and ends in the Anthropocene, defined by escalating human domination of global ecosystems starting in the late 19th century (Vitousek et al., 1997; Crutzen, 2002; Sanderson et al., 2002).

For the longest temporal scale, we focus on the western margin of South America, from Mediterranean to sub-Antarctic latitudes (Fig. 1A). When looking at the more recent transformations that took place from the arrival of Europeans through the mid-20th century, we focus on a more restricted area in south-central Chile, from the Mediterranean region to Chiloé Island (Fig. 1A). Our analysis of

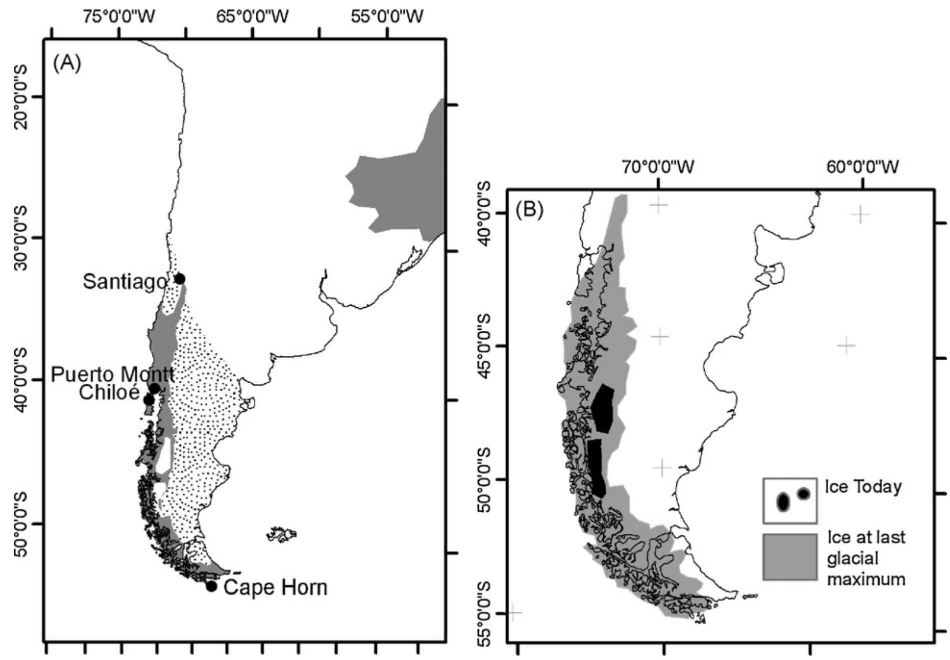

Fig. 1. (A) Study area. Temperate forests (33–56°S) are shown in dark color; stippled areas are semiarid scrublands and steppe. White spots in the forested area indicate extent of modern ice sheets. (B) Maximum extension of continental ice during the last glacial maximum (LGM), about 18,000 cal. yr. BP. Temperate forest cover was reduced by about two thirds of the present latitudinal extent (Fig. 1A).

contemporary changes focuses mainly on two areas where agriculture and forestry impacts can be more precisely assessed. We rely on paleoecological data for the prehistorical events (Latorre et al., 2007) and on historical accounts for the period starting with the European settlement (Otero, 2006; Camus, 2006; Castro-Lobos, 2002; Molina et al., 2006). Recent trends over the last decades are documented by available land cover statistics (INFOR, 2005; CONAF-CONAMA-BIRF, 1999; Instituto de Estudios Públicos, 2002) and by the examination of aerial photos and satellite images. Finally, we discuss the regional and global policy implications of our analysis in the face of rapidly changing climate and socio-economic drivers.

Postglacial forest recovery and the pattern of tree species richness

Chilean forests presently occupy about 13.5 million hectares (CONAF-CONAMA-BIRF, 1999), along the western margin of southern South America (Fig. 1A), representing the most extensive, continuous climatic gradient from mid to high latitudes in the southern hemisphere. Vegetation records based on fossil pollen in sediments (e.g., Heusser, 1983; Villagrán, 1988, 1991; Villagrán et al., 1996; Moreno and Leon, 2003; Heusser et al., 2000) show that the latitudinal range of forests was severely contracted in south-central Chile due to the expansion of continental ice sheets in the last glacial maximum (LGM), i.e. about 18,000 cal. yr. BP (Fig. 1B), along with concomitant proliferation of moorland and steppe vegetation. Because South American temperate and sub-Antarctic forests are restricted to a narrow latitudinal strip (Fig. 1A), bordered by the hyperarid Atacama Desert on the north and by the high Andean Mountain Range rising to above 3000 m on the east, potential latitudinal displacements of the forest biota as a consequence of global cooling were spatially constrained. Continuous forest cover was restricted to coastal ranges, unglaciated valleys and lowlands, at latitudes between 30°S (semi-arid Chile) and 38°S (Villagrán, 2001), wherever low temperatures were moderated by the oceanic influence. Since 38°S was the approximate northern limit of mountain glacier incursions onto lowland valleys (Fig. 1B), we estimate that in the LGM forest cover declined by at least two thirds of its present extent in south-central Chile. For instance, Chiloé Island, at latitude 42°S (Fig. 1A), where species-rich temperate rainforests, including high-diversity vine and vascular epiphyte assemblages, dominate today (Muñoz et al., 2003; Aravena et al., 2002), was largely occupied by moorlands prior to ~16,000 cal. yr. BP (Fig. 1B), as revealed by glacial pollen records (Villagrán, 1988, 1985; Villagrán et al., 1996; Abarzúa et al., 2004; Heusser and Heusser, 2006). As a consequence of glacial events, maximum woody species richness is presently confined to the areas that remained unglaciated, especially on the coastal range of south-central Chile (Villagrán and Hinojosa, 1997; Villagrán, 2001), between latitudes 37 and 39°S (Fig. 2). Woody species richness declines sharply both towards the arid north and towards the Patagonian fjords and archipelago region, where continental ice sheets extended to the sea level (Fig. 1B). This pattern of distribution of species richness (Fig. 2) must be taken into account when assessing the impact of more recent deforestation trends (Armesto et al., 1998, 2001a).

Accordingly, the forested landscapes where people settled, starting between 12,500 and 14,500 cal. yr. BP based on the evidence from Monte Verde and other archeological sites in the Americas (Dillehay et al., 2008; Meltzer, 2009), originated at mid-latitudes from rapid postglacial woodland expansion from small and restricted glacial refuges and sparse *Nothofagus* forests in the neighborhood of glaciated territories (Heusser and Heusser, 2006; Markgraf et al., 2009). Although the structure and composition of forests today is a consequence of the warmer climate developed during the current interglacial, the latitudinal distribution of tree species richness, as well as vertebrates and invertebrates (Samaniego and Marquet, 2009) still bears the imprint of glacial impacts on vegetation cover, as the biologically richest forests are found in the transition between temperate and Mediterranean-climate regions (Fig. 2).

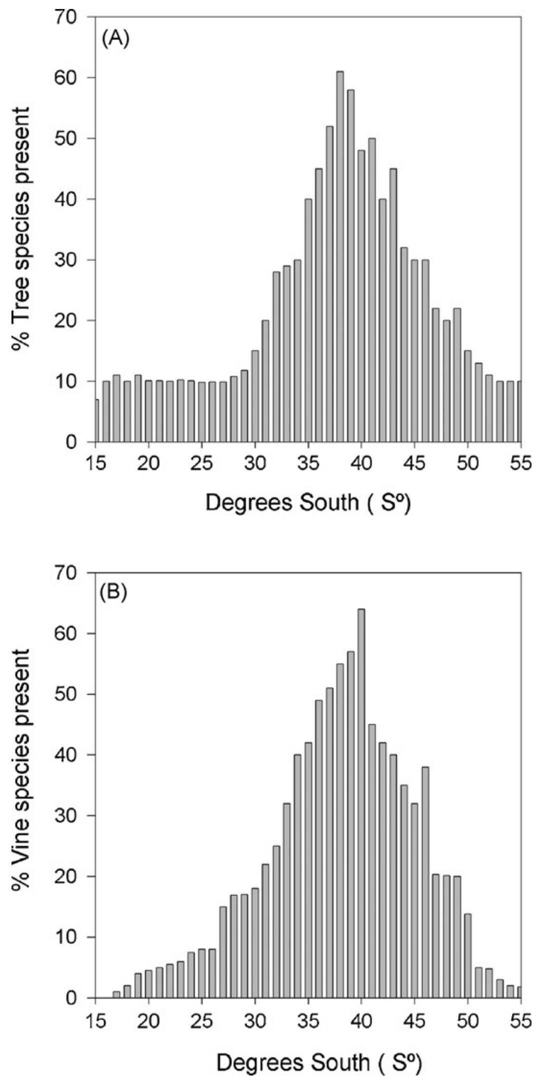

Fig. 2. Percent of woody species by degree of latitude (*Y*-axis) occurring at different latitudes along the western margin of South America, from 18°S (Chilean-Peruvian border) to 56°S (Cape Horn). (A) Trees, *N* = 133 species; (B) Epiphytes and vines, *N* = 65 species. Mediterranean and temperate forests extend from 30 to 47°S. Woody plant diversity decreases in sub-Antarctic forests from 30 to 56°S and in arid and hyperarid ecosystems from 18 to 30°S. Redrawn with permission from Villagrán (1995).

Holocene fire history

Global paleoecological studies show that in the past 20,000 years fire activity has been controlled primarily by climate and fuel load (Power et al., 2008). Records for southern South America suggest a low incidence of fire prior to the end of the last glacial period, which increased significantly during the interval between 12,000–6000 cal. yr. BP (Huber et al., 2004; Whitlock et al., 2007; Power et al., 2008; Abarzúa and Moreno, 2008; Abarzúa, 2009).

Humans inhabited this region concurrently with the onset of climate warming and the period of maximum fire activity in the past 15,000 years (Dillehay, 1997; Goebel et al., 2008). Although little is known about prehistoric woodland burning, it is likely that the inhabitants of temperate South America had a strong influence on fire activity, mainly through increasing rates of vegetation burning and localized forest clearing over several millennia (Veblen and Lorenz, 1988; Heusser, 1994; Markgraf and Anderson, 1994; Moreno, 2000; Villa-Martínez and Moreno, 2007; Abarzúa and Moreno, 2008). Patagonian natives traditionally used fire to hunt for guanacos and rheas at the eastern forest–steppe transition (Veblen and Lorenz, 1988). Charcoal records found in sediments and fire scars in trees document recurrent fire activity in the temperate and Patagonian forest region over several millennia (Veblen and Alaback, 1996). Fire scars of the long-lived southern conifer *Fitzroya cupressoides* have been dated in the pre-Hispanic period (Lara et al., 1999; Urrutia, 2002) and evidence of fire in the lowlands of Araucanian region (38°S) indicated a peak between 12,000 and 6000 cal. yr. BP (Abarzúa, 2009). It is difficult, however, to discriminate between forest burning by aboriginals and lightning-caused fire associated with droughts and fuel buildup. Pollen and charcoal records and dendrochronological studies suggest that strong climatic variability, driven by alternating dry and wet episodes, characterized the last millennia of the interglacial period. Prehistoric evidence of widespread forest fire in temperate latitudes of western South America often coincides with the negative phase of El Niño Southern Oscillation (ENSO), which is associated with southward displacement of the eastern Pacific anticyclone, causing the interruption of the westerly flow of humid air and consequently increased summer drought (Kitzberger et al., 1997).

Between 300 thousand and one million people of various ethnic groups may have inhabited southwestern South America in the pre-Hispanic period (Rozzi et al., 2000; Armesto et al., 2001b). Aboriginal populations used forests as hunting grounds, a source of construction materials, and sites for slush-and-burn agriculture, especially along the main river basins (Dillehay, 1997). Such influences may have generated extensive clearings and agricultural fields, as reported by Spanish chronicles (Camus, 2006) and shown by postglacial to Holocene pollen records from the Araucanian region (Abarzúa, 2009). Following the decline of indigenous populations brought about by the Spanish settlers, through direct slaughtering and disease, *Nothofagus* forests appear to have reinvaded open areas in south-central Chile (Donoso, 1983). The dominance of deciduous *Nothofagus* forests over evergreen trees, which occupy the understory, especially in the cultivated valleys in south-central Chile, has been attributed to the frequent disruption of succession presumably by fire since the prehistoric period (D. Frank, M. Finck, personal communication). Evergreen tree species dominate the forests in the neighboring coastal range (Armesto et al., 1996a).

Fire incidence, both anthropogenic and climate-related, may have shaped forest composition and structure during the Holocene between 11,500 to 6000 cal. yr. BP at different latitudes (e.g., Markgraf and Anderson, 1994; Power et al., 2008; Markgraf et al., 2009; Abarzúa, 2009), when higher temperatures and drier climate compared to today, expanded southward along the central valley (Villagrán, 2001; Abarzúa and Moreno, 2008). Warmer and drier conditions may have affected more intensely forests on the eastern Andean slopes and on lowlands east of the Coastal Range, where the rain shadow effect of the coastal mountains was presumably greater than today. In the forest–steppe transition east of the Andes fire seems to have been intense in association with the warm and dry early Holocene period (e.g., Markgraf et al., 2009).

Fig. 3. Old tree of *Fitzroya cupressoides*, one of the longest-lived tree species in the world, surviving in a small remnant patch of lowland forest, at Lauenñadi National Park, Chile. Thousands of hectares of *Fitzroya* forests were burned and logged in the Lake District in the 18th and 19th centuries leading to the nearly extirpation of stands in accessible lowland areas.

The Holocene–Anthropocene transition

The fuel wood catastrophe

With the arrival of Europeans, begins a period characterized by increasing rates of wood extraction from native ecosystems, mainly for the construction of villages, boats, fence posts, etc. In the following centuries, large volumes of timber were exported to the nearest and richer colonies in Peru (Camus, 2006). In addition, woodlands were cleared to open land for agriculture and livestock grazing, and intensely logged to supply fuel for domestic use and mining operations. It is estimated that during the 19th-century hundreds of furnaces for smelting copper ore entered in operation, leading to rapid devastation of surrounding woodlands (Bahre, 1979). Wood-burning smelters led to massive cover loss especially in north-central Chile (30–35°S). Because of the slow recovery of tree and shrub cover in the Mediterranean-climate region (Armesto et al., 2009), it is likely that open vegetation prevailed through the next century due to the continuous use of fuelwood, widespread fire and livestock grazing, despite the fact that the number of wood-burning furnaces in operation declined during the 20th century.

It must be noted that since the Spanish colonial period and well into these days, mining operations were highly prioritized over other land uses by the Chilean governments. Consequently, mine operators were granted extensive rights over the land, water and vegetation surrounding their exploitations (Bahre, 1979; Castro-Lobos, 2002). Such privileges prevailed well into the 20th century, for instance with regard to water use (D. Guzman et al., manuscript). Since the 17th century, cattle were massively introduced to provide food for mine workers and apparently did not in itself constitute an economically sustainable activity (Bahre, 1979). At the landscape scale, firewood extraction, followed by grazing by cattle and introduced rabbits in combination with irregular rainfall, undoubtedly had strong and long-lasting effects on the resilience of vegetation cover in central Chile, preventing woodland recovery (Holmgren et al., 2001) and maintaining a patchy cover until the present.

The golden age of "timber"

For more than a century, from the mid, 1800s through the first half of the 20th century, timber was extracted from forests without any concern for the renewal of the resource (Donoso and Lara, 1996). Widespread logging of the best trees in old forests led to rapid depletion of the most valuable timber species in south-central Chile and the exhaustion of forests of commercial age. A striking example was the non-sustainable logging of lowland stands of the giant and long-lived conifer *F. cupressoides* (Alerce) in the Chilean Lake District (Fig. 3). Logging of Alerce trees, which started soon after the arrival of Europeans in the 16th century, continued at increasing rates until the mid-20th century (Veblen and Ashton, 1982; Fraver et al., 1999; Molina et al., 2006). Unknown volumes of Alerce timber were shipped to the Spanish colonies and Europe in the 17th and 18th centuries. Nearly all stands at low elevations were exterminated by the 1950s (Fraver et al., 1999) where regeneration was absent. Because of the depletion of accessible harvestable stands during the 19th and 20th century, along with widespread burning (Donoso and Lara, 1996), logging and international trade of *Fitzroya* timber was banned in 1976. This long-lived conifer is probably the most valuable timber species in Chile today because its high-quality and durable wood, yet it has never been managed silviculturally (Donoso et al., 1990) despite that profuse regeneration after logging and fire was recorded in some sites in both the Andes and coastal range (Donoso et al., 1990; Smith-Ramirez, 2007).

Other valuable and now threatened timber species of Chilean forests are *Nothofagus obliqua*, *Nothofagus alpina*, *Persea lingue*, *Laurelopsis philippiana*, and *Laurelia sempervirens*. They continue to be harvested despite the fact that most commercial stocks have dropped to nearly zero (Fig. 4). Harvestable forests containing these species have disappeared from all but the less accessible sites in the Andes of south-central Chile. Other stands have been burned and converted to agriculture or other uses. Paradoxically, these trees are among the fastest growing timber species in Chilean forests, according to results of small-scale silvicultural assays (Donoso and Lara, 1999). Presently, stands of commercial age have been exhausted, while few remnants of second-growth stands, are under increasing pressure from cattle grazing, anthropogenic fire, and danger of conversion to other land uses (Echeverria et al., 2008; Wilson et al., 2005).

Technological advances, brought about by the introduction of steam-powered, mobile sawmills and the first railway of South America, facilitated the extraction and transportation of wood products from southern forests during the "golden age" of timber. Sawmills moved from place to place as timber stocks declined, in the same way as miners look for new veins. Hundreds of sawmills operated in the south-central Chile in the late 1800s, leading to the progressive demise of accessible forests of exploitable age.

Table 1
Regression coefficients (r^2) for linear and polynomial regression equations representing 50-year trends in sawn wood volume traded for six temperate tree species from Chilean temperate forests. The "years to zero" column is the estimated number of years before production declines to zero for those timber species with a negative trend, under the assumption that extraction rates will not change greatly. Based on data from INFOR (2005).

Tree species	Linear regression equation for sawn volume as a function of year	r^2	Years to zero
Laurelia sempervirens	$Y = -0.54X + 1090$	0.55	0
Nothofagus dombeyi	Polynomial, order 6	0.76	<10[a]
Nothofagus alpina	$Y = -0.82X + 1648$	0.39	11
Nothofagus obliqua	Polynomial, order 6	0.66	<10[a]
Laureliopsis philippiana	Polynomial, order 6	0.52	<20[a]
Nothofagus pumilio	$Y = 1.30X + 2543$	0.61	NA

[a] Visual estimate from plot.

In the late 1800s, timber sales represented up to 15% of Chile's national income from foreign trade (Camus, 2006). "Mining" of timber resources prevailed beyond the mid-1900s, as oil-powered sawmills operated until today in new roads through remote forests. It is remarkable that such unsustainable timber harvesting lasted well beyond the establishment of professional forestry schools in the country and continued under the regulating role of the Chilean Forest Service (CONAF) in the second half of the 20th century (Donoso and Lara, 1996). In the 1940s, the Chilean Government commissioned a group of international experts, the Haig's mission, to assess the status of forest resources in the country. The Haig's mission reported on the large-scale loss of forest cover and their degraded condition, estimating at the time the existence of more than one million hectares of heavily degraded secondary forest and about eight million hectares of remaining commercial forests (Castro-Lobos, 2002; Otero, 2006).

The "mining" of forest resources during the past 50 years is documented by the persistent decline of sawn wood volumes of the main timber trees in south-central Chile (Fig. 4). For some species, such as *Nothofagus dombeyi* and *L. philippiana*, the declining trend shows a break where wood production rose temporarily and then continued to drop. Negative slopes are statistically significant for five out of six tree species (Table 1). Based on regression models, we can predict that, in the absence of management, timber stocks for these species should collapse within one or two decades (Table 1). Recovering commercial stocks will require especial efforts to foster the regeneration of degraded stands and restore forests in areas where they have been degraded or substituted by other land uses. Silvicultural methods could improve the growth of young stands, following experiences underway (Donoso and Lara, 1999), and such practices should be a priority of the new Chilean forestry law.

The transient interruption of the overall declining trends (Fig. 4) are best explained by the opening out of new access routes to untapped timber sources during the second half of the 20th century. New roads allowed extraction of timber from remote sites, rather than investing on managing the already depleted stands. For instance, the opening of the austral highway ("ruta austral") south of Puerto Montt (Fig. 1A) in the 1980s allowed harvesting of *N. dombeyi* and *L. philippiana* from previously inaccessible old-growth forests on Andean foothills. The effect of the road network on the loss of forest cover is evident from the analysis of commercial forestry expansion (see below), as exotic plantations spread gradually from central to southern Chile along the main highway. Indeed, 90% of the area of existing forestry plantations in south-central Chile is within 2.5 km of roads (Wilson et al., 2005).

One exception to the decline of sawn wood volumes is the Sub-Antarctic beech, *Nothofagus pumilio* (Fig. 4). Slow-growing stands of *N. pumilio* in Magallanes (Chile) and the Argentinean Patago-

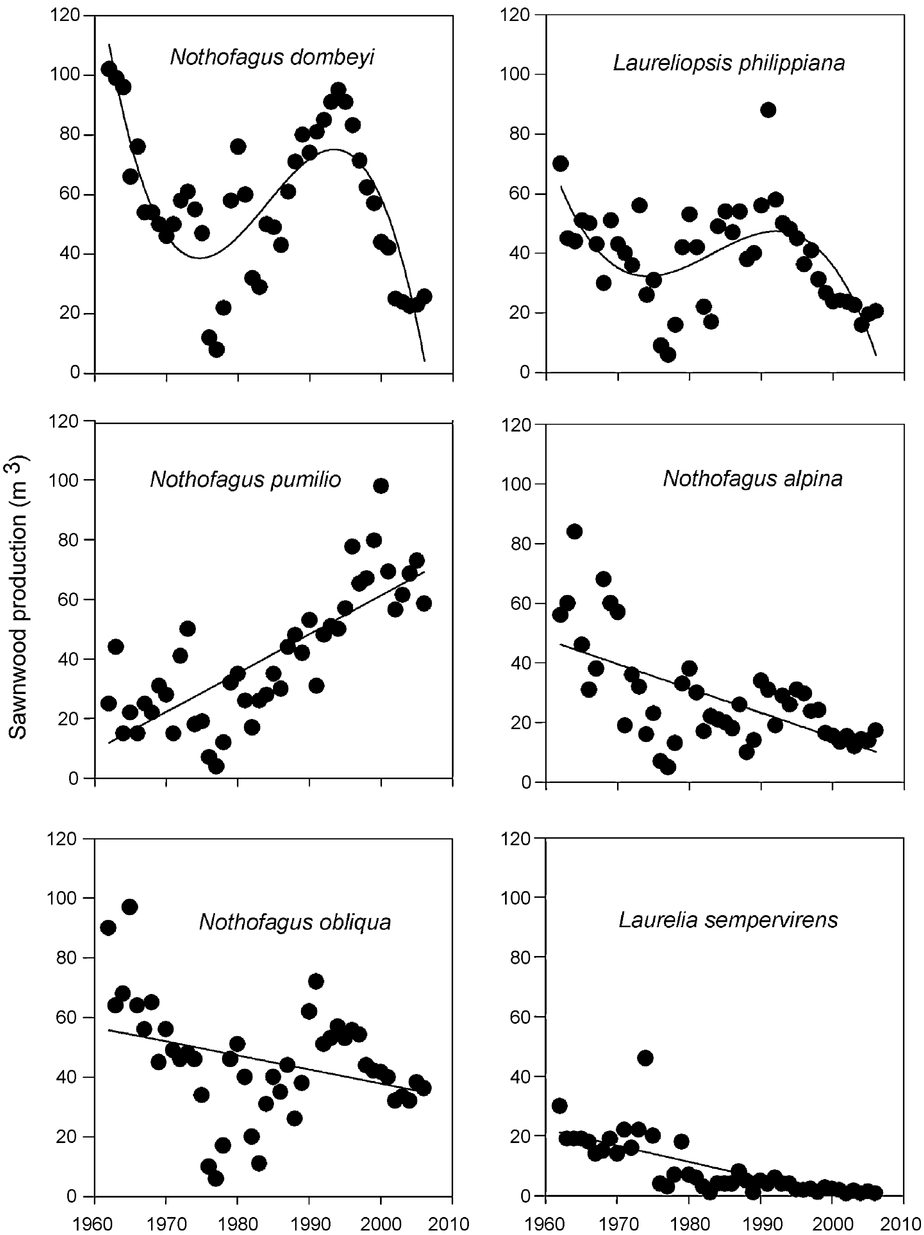

Fig. 4. Trends of sawn wood production for the main native timber trees in Chile during the past 50 years. The vertical axis is the sawn wood volume in thousands of cubic meters. Regression equations are given in Table 1. Data from INFOR (2005).

nia were commercially exploited just in recent decades (Arroyo et al., 1996), facilitated by new roads and improved infrastructure for timber transportation from such remote locations. A shelter-wood cutting system, which enhances the growth rates of remaining trees in the stands and protects regeneration, is commonly used (Donoso and Lara, 1999). The sustainability of this logging practice in Patagonian forests will depend on the rates of extraction versus recovery of logged stands to the commercial age (Armesto et al., 1996b) and remains to be demonstrated.

The onset of fiber farms

Widespread loss of forest cover stirred increasing public and political concern towards the end of the 19th century (Otero, 2006; Camus, 2006). Large-scale deforestation in south-central Chile was associated with the expansion of wheat farming the mid-1800s, a trend driven by the gold rush in California and Australia (Aschmann, 1991). Wheat exports represented about 60% of the revenues of the country during the mid-1800s (Camus, 2006), when South America shipped large volumes of food and timber to the growing population of western North America. Because during most of the 19th century goods were shipped from the Atlantic to Pacific North America mainly via the Strait of Magellan, at the southern tip of the Americas, it was considerably cheaper to provision the colonies directly from western South America. The opening of a new route through the Isthmus of Panama in the late 1800s caused the collapse of Chilean agriculture, as vast areas of farmland were abandoned and later subjected to intense soil erosion (Castro-Lobos, 2002).

At the beginning of the 20th century, because of mounting rates of soil erosion and sedimentation of rivers and estuaries, land cover loss became a serious national problem (Castro-Lobos, 2002; Camus, 2006). To mitigate this ecological collapse, the Chilean Government proposed the first environmental policies to promote the protection of severely eroded land and critical ecosystems and

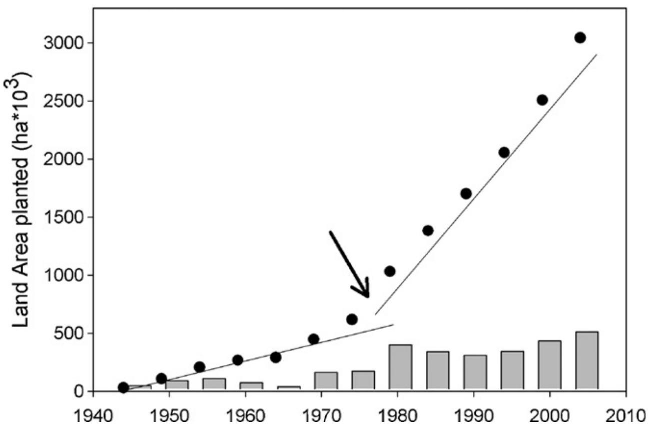

Fig. 5. Expansion of commercial forestry plantations (mostly *Pinus radiata* and *Eucalyptus globulus*) in Chile. Points are accumulated area planted; bars are the area planted per year. The arrow indicates the year (1974) when a Government Law (701) began to subsidize the cost of planting. The slope of the regression line for the period from 1944 to 1973 is 18, after 1974 the regression slope increased to 80 showing the accelerating effect of the subsidy. Both regressions are statistically significant ($p < 0.01$).

water sources. Indeed, by 1910; Federico Albert, a German forester hired by the Chilean government to assess the extent of soil loss and provide advice on how control the problem, introduced the planting of fast-growing tree species, most prominently two exotic trees, *Pinus radiata* and *Eucalyptus* spp. to restore vegetation cover and prevent soil erosion. These successful pilot experiences prompted the Chilean Forest Service to start large-scale plantations in public lands with the aim of controlling erosion.

With the introduction of fast-growing timber species originated from North America and Australia and the establishment of professional forestry schools, we entered the industrial age. During the second half of the 20th century, the Chilean timber industry shifted gradually away from harvesting native trees to concentrate on commercial plantations of *P. radiata* and *Eucalyptus*. Plantations began on public land in the early 1940s at a rate of 3000 ha per year (Toro and Gessel, 1999), and continued through the 1960s. Since the early 1970s, a State subsidy covered up to 75% of the costs of clearing, planting and thinning promoted plantations by private landowners. This subsidy, along with trade liberalization policies (such as the removal of the log export ban, Niklitschek, 2006), provided the incentive to develop a powerful forest industry, followed by the expansion of plantations by private corporations. Overall, subsidized plantation rates quadrupled (Fig. 5), spreading rapidly from central to southern Chile. With the aid of satellite images, Echeverria et al. (2006) estimated that native forest cover was lost at a rate of 4.5% per year in the area of Rio Maule-Cobquecura (36°S), due mostly to the expansion of exotic tree plantations. Native forest cover declined from 21% in 1975 to 7% in 2000. Similarly, Cisternas et al. (2001) provided a landscape analysis for the San Pedro watershed (36°51′S), based on aerial photographs, that yielded a forest loss rate of 3.4% per year, with a decline in native forest cover from 70.1% in 1943 to 12.6% in 1994. Plantations substituted extensive areas of second-growth native forests, as the subsidy did not discriminate between plantations established on abandoned farmland and those replacing degraded forest cover (Lara and Veblen, 1993). In four provinces of central Chile (Fig. 6) commercial plantations of exotic pines and eucalypts became the main land cover type, covering nearly 2.5 million hectares. Remaining native forests in these regions are represented mainly by degraded second growth stands (Fig. 6). Analysis of satellite images from the central valley around Valdivia (40°S) showed that 75% of farmland was substituted by plantations in the recent decades (Hernández et al., in preparation), which indicates that these trends were driven by the high value of plantation forestry in relation to traditional agriculture. Plantations are now the main source of fiber for a strong paper-mill industry, with pulp and cellulose becoming major export products of Chilean industrial forestry (INFOR, 2005).

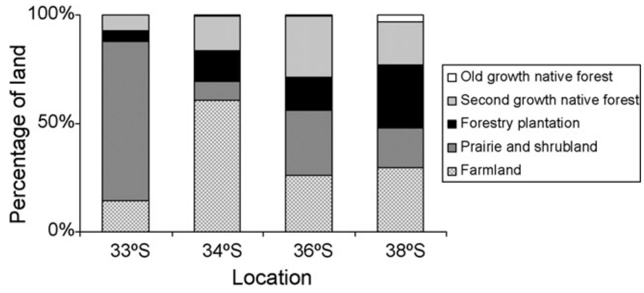

Fig. 6. Current vegetation-cover types in four central Chilean provinces, representing the climatic transition from Mediterranean to temperate forests. Data from CONAF-CONAMA-BIRF (1999). White shading = farmland (14–30%); stippled = shrublands (8–74%); light gray = industrial plantations of exotic trees (5–29%); dark gray = second-grow or degraded native forest (7–28%); black = old-grow or late successional native forest (0–3%).

New drivers of land use change

Plantation forestry is presently the second most important industry in Chile, at the same time that Chile has become the sixth major exporter of cellulose and the third major exporter of wood chips worldwide (CEPAL, 2005). Consequently, large volumes of lumber are required to meet the annual targets for woodchip export and to feed local pulp mills. These market forces are a powerful current driver of the southward spread of eucalypt plantations. Thus, the area planted each year continues to expand (Fig. 7). This trend contradicts the argument that "fiber farms", as these fast-growing plantations have become known, can "relieve" the extractive pressure on native forests. It is true that forest industry in Chile has largely given up the exploitation of native forests to concentrate on plantations of exotic trees, and moderate increases in vegetation cover can be inferred from recent national inventories (CONAF-CONAMA-BIRF, 1999). This inference is born from evidence that remaining native forests are predominantly restricted to parks and protected land (steep slopes, riparian habitats) and the substitution of native forests by plantations is presently unacceptable under

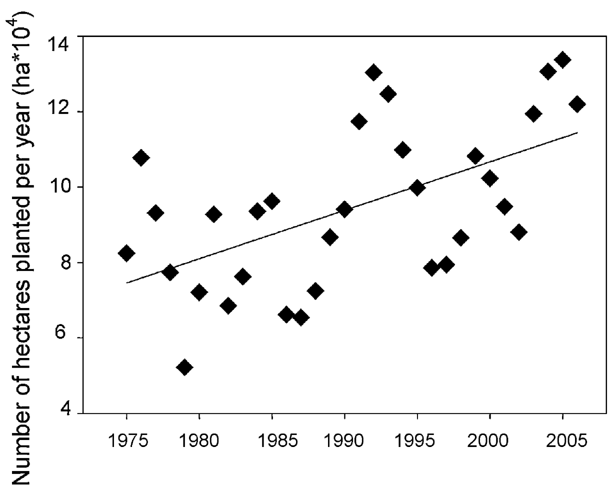

Fig. 7. The number of hectares of *Pinus radiata* plus *Eucalyptus globulus* planted per year during the past 30 years in south-central Chile. The increasing trend is statistically significant ($r^2 = 0.317$, $p < 0.01$). *Source*: INFOR, 2005.

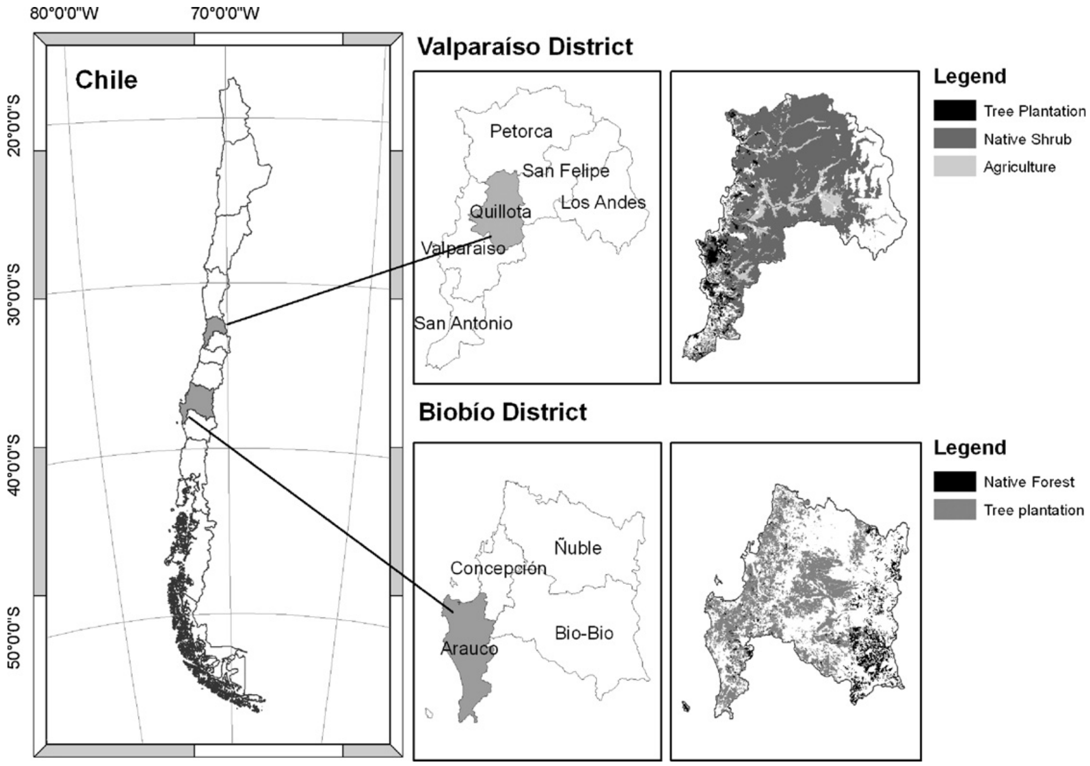

Fig. 8. Two areas illustrating recent trends in land cover change in south-central Chile. Above, the Province of Quillota, which is one of the targets of expanding new crops. Below, the Province of Arauco, located at the heart of the plantation forestry industry. The cover maps on the right hand show the main land cover types in each region. In each of these two Provinces, estimated changes in cover for the past 15 years show expansion of crops and monocultures of fiber-producing exotic trees (see text).

most international trade standards. However, expanding woodland cover in the Chilean central provinces is primarily the result of plantations of fiber-producing trees. We estimated that in the province of Arauco (37°S; Fig. 8), at the heart of the plantation industry, where sparse cover of native forest remains, native forest cover further declined, while the area of monocultures increased from 43 to 53% during the period from 1983 to 1998 (Mora et al., in preparation). In the vicinity of Puerto Montt and Chiloé Island (Fig. 1A), presently the southern frontier of plantation forestry, wetlands and moorlands have become sensible targets for the next generation of eucalypt plantations, still taking advantage of public subsidies. Degraded and burned stands of the valuable conifer *Pilgerodendron uviferum* and relict lowland populations of *Nothofagus antarctica*, on poorly drained soils (Armesto et al., 1995) are also being eradicated by expanding Eucalypt monocultures, thus reducing the chances for recovery or restoration. These plantations are expected to accrue large externalities because of disruption of hydrologic cycles and water supplies to rural areas, which are regulated by the water storage capacity of *Sphagnum* moorlands (F. Díaz, personal communication), where most plantations are now located.

In central Chile, in the Mediterranean sclerophilous forest region, new crops have become the main drivers of land cover change in the past 30 years. In the province of Quillota (33°S; Fig. 8), one of the target areas for the expanding wine and avocado (*Persea americana*) industries, the analysis of aerial photos shows an increase in the cultivated area from 32 to 42% in the period from 1983 to 2001 (Mora et al., in preparation). In the past 20 years, avocado plantations have tripled and the area of vineyards has nearly doubled at the expense of native vegetation on steep hillsides (Figs. 9 and 10). Such trends are coincident in time with the signature of Chilean free-trade agreements with the US and the European Union. New technologies for site preparation and planting on steep hillsides have severely depressed scrublands cover from previously inaccessible sites. Because <1.5% of the land in central Chile is currently protected (Armesto et al., 1998; Arroyo et al., 1999; Tognelli et al., 2008), the impact of such practices on the rich and endemic biodiversity of the region must be carefully evaluated. Parallel trends are followed in other biodiversity-rich Latin American countries by the expansion of sugar cane, soja, olives and other crops (Fearnside, 2001; Pengue, 2005).

A historical framework for forest transitions

We summarized the history of land cover transitions in southwestern South America in the past 18,000 years since the LGM and examined the main climatic and human-population drivers

Fig. 9. The recent expansion of avocado tree plantations onto hillsides previously covered by native shrublands in central Chile. Photo taken in 2007 (by JJA).

Table 2
A framework for climatic and human-driven land cover changes during the last 16,000 years in southern South America, with parallel changes in other temperate regions of the world. Based on literature cited in the text. Knowledge of climatic and socio-economic drivers of human behavior and policy decisions in response to environmental change can be actually or potentially applicable to understand, anticipate, and prevent future land use trends.

Chronology for southern South America	Main land cover transition	Main climatic or socio-economic driver	Policy decisions and/or human behavioral patterns	Main transitions and drivers in other regions of the world
Postglacial (16,000-12,000) and early Holocene (12,000–6000 BP)	Rapid forest expansion from glacial refugia.	Climate warming, hunting of megafauna, peak in fire incidence.	None.	Similar trends of forest recovery at mid and high latitudes worldwide.
Agricultural expansion (5000 BP to 1500 AD)	Decline of forests and local increase of open areas.	Farming and land clearing by aboriginal people in river basins.	Shift from nomadic to sedentary communities with stronger links to the land and social organization.	Slush and burn agriculture, spreading of weeds in North America, Europe and Asia.
Colonial period (1500 to 1800s)	Large-scale deforestation, timber exports to colonies, maximum expansion of open land.	Food demands from North America and Europe, wheat crops. Miners' rush, fuel wood supply energy to mines, cattle introduced.	Protection of areas around villages and water sources.	Growing deforestation and soil erosion globally. Gold rush in California and Australia.
Preindustrial–industrial (mid-19th century to mid-20th century)	Extreme deforestation, and vast soil erosion.	Burning by settlers, miners' rush continues, golden age of timber, fast rates of logging, sawmills, and railway.	First environmental regulations, first public parks.	Large-scale logging of forests in New England and Midwest US in late 1800s. Concentration of industrial activity in cities. First national parks.
Industrial–postindustrial (mid-20th century to present)	Fiber farms expand, homogenization of landscapes, limited forest recovery.	Public subsidy to plantation forestry, new roads, paper mill industry, free trade agreements signed, introduction of new intensive crops.	Management of semi-natural matrix, paying for externalities, need to diversify forest and crops, private conservation.	Conservation movements, private land protection, abandonment of farmland, forest recovery in Europe and North America. Consolidation of urban population, concentration of intensive agriculture, use of fossil fuels.

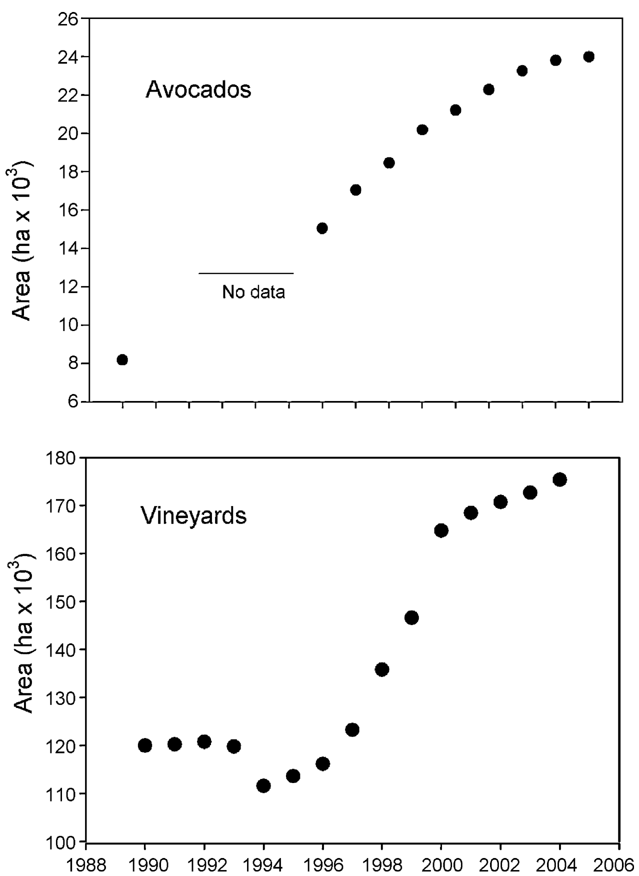

Fig. 10. Trends of increase in area of avocado plantations and vineyards at south-central Chile in the past two decades.

that led to either loss or gain of vegetation cover. We used the chronosequence of events effecting Chilean forests to illustrate these transitions. The main drivers of these land cover changes and their consequences, as discussed in this paper, are summarized in Table 2. This analysis offers a broad framework for understanding landscape change, which could be applied to other regions in Chile (Marquet et al., 1998; Nuñez and Grosjean, 2003). We offer comments about the application of this framework to Latin America and other regions of the world (Table 2).

The first great transition, from about 18,000 to 11,500 cal. yr. BP, entailed the fast recovery of forests from small and sparse glacial refugia to the present extent of 13 million hectares in southern South America (Villagrán, 1991, 2001). This trend that was nearly synchronous with paleoclimate changes recorded in the North Atlantic region and other southern hemisphere mid-latitude regions (Webb, 1981; Moreno et al., 2001). Human impact during this postglacial transition is globally perceived in the increased fire incidence, shown by charcoal remains in sediments from lakes in south-central Chile and Patagonia (Markgraf and Anderson, 1994; Moreno, 2000; Heusser et al., 2000; Abarzúa and Moreno, 2008) and reconstructions of fire history from many sites in North America (Russell, 1997; Power et al., 2008). The dramatic decline of elm in northern Europe starting about 5400 to 4500 cal. yr. BP has been attributed to the use of fire to open land for grazing (Williams, 2008). In southern South America, the fire peak coincides with the warmest and driest period of the entire Holocene (~12,000 to 6000 cal. yr. BP) representing the second major change in land cover since the postglacial recovery of mid-latitude forests. The last 5000 years of the Holocene are characterized by a gradual trend towards diversifying crops and significant land clearing, especially in the major river basins (Dillehay et al., 2008; Abarzúa, 2009). Trading of goods (e.g., fish, crops) among different ethnic groups provided access to new foods and may have reduced the pressure on the land (Camus, 2006). The worldwide process of land cover change largely associated with the clearing of land for farming seems to have been slow at first, but it became accelerated in the past 2000 years, as evidenced by the shift in vegetation from closed to open cover and the expansion of weeds, detected in pollen records from Great Britain, Europe and North America during this period (Niinemets and Saarse, 2007; Williams, 2008; Coombes et al., 2009). A similar shift in vegetation from closed to open conditions in China in the past 2000 years is coincident with the evidence of increased soil erosion (Dearing et al., 2008).

The Spanish conquest brought about the miners rush in the new world during the 18th and 19th centuries. This may have represented the following major land use transition in southern South America since the onset of agriculture, resulting in massive clearing of woodlands, as a consequence of the nearly uncontested miners' rights over the land. Large-scale lumber extraction for melting ores, together with the massive introduction of cattle and goats, led to the devastation of woody vegetation over much of central Chile (Bahre, 1979; Castro-Lobos, 2002). Similar and nearly simultaneous gold rushes in Australia and North America (Aronson et al., 1998) may have had similar impacts on land cover, through expansion of agriculture, livestock grazing and displacement of indigenous populations from their lands. Between 1850 and 1870, the first extensive cutting of the Sierra Nevada forests in the US was driven by the need of lumber for mining operations (Litman and Nakamura, 2007). In Chile, the vast destruction of vegetation recorded in this historical period led to pioneering environmental regulation efforts. Such regulations set the bases for gradually improving resource use practices during the 20th century.

The independence and instauration of the Chilean Republic period did not change the declining trends of forest cover, as deforestation by logging and fire extended from central to southern Chile. The "golden age" of timber exploitation dominated at the end of the 19th century and the beginning of the 20th century, intensified by the use of sawmills, railway transportation, and government incentives to European and Chilean settlers in the Lake District and further south. This logging rush led to the decline of most commercial stocks by the second half of the 20th century (Fig. 4). Similar large magnitudes of forest devastation by logging occurred in the New England region of North America at the end of the 19th century, with extraction of massive volumes of timber (Fuller et al., 2004), ending around 1920 due to the depletion of commercial stands. In the North American State of Indiana, clearing of forests for agriculture and timber extraction reduced forest cover from 85% of the land in the early 19th century to about 6% by 1920 (Evans and Kelley, 2008). In the Sierra Nevada, steam engines and railway increased the efficiency of logging in the late 1800s leading to vast deforestation by the early 20th century (Litman and Nakamura, 2007). Such processes of deforestation seem to have been replicated later by the trends in timber extraction observed in southern South America in the late 1800s and the first half of the 20th century, with several parallel drivers and outcomes.

Settlers of the frontier of the new Chilean republic brought about wide-ranging forest fires (Rozzi et al., 2000), as ownership of the land was gained by clearing forests. Such incentives operated throughout the Americas in the 19th century (Siebert, 2003). German immigrants, invited by Chilean minister Pérez-Rosales, burned large expanses of evergreen forest in Chile's Lake District (39°S–42°S) in the late 1800s. Many tree species that survived the glacial period in the lowlands were extirpated. Testimonies from that period are the remnant stumps of *F. cupressoides* – the longest-lived tree species of the southern hemisphere, with some individuals known to be 3600 years old (Lara and Villalba, 1993) – which are still found today between Valdivia and Puerto Montt. Following the same pattern, settlers of Aysen Province (45°S), south of Chiloé Island, burned about 300,000 ha of Patagonian forests between 1920s and 1950s, in one of the greatest devastations in Chilean environmental history (Otero, 2006). The area has remained largely deforested until the present due to the limiting conditions for tree establishment. Few improvements on environmental regulation were enforced in the early Republican period because of the need to settle the independent territories, a pattern which was repeated across the Americas (Siebert, 2003).

Chilean industrial forestry developed in the second half of the 20th century based on the spread of fast-growing exotic tree plantations. During this period, postindustrial societies in Europe and North America stimulated the development of extensive plantation forestry in third-world nations (Brechin and Kempton, 1994), because stronger environmental regulations and greater public appreciation of ecological benefits of forests limited the extent and rates of logging in the developed world. In Chile, short-rotation tree plantations started on previously cleared land, but soon expanded onto areas of second growth native forests (Lara and Veblen, 1993; Donoso and Lara, 1996; Armesto et al., 2001a). A similar proliferation of plantations occurred throughout Latin America. Intensely managed plantations of *P. radiata* and *Eucalyptus* species presently occupy 12.5 million hectares in the Latin American and Caribbean region as a whole and are expected to keep expanding in the coming decade (FAO, 2009). The economically 'successful' Chilean model of forestry development, based on large-scale pine and eucalypt plantations, has been replicated across the region without an analysis of its social and ecological impacts (Gwynne, 1993; Lara and Veblen, 1993). Developing countries became rapidly the hotspots of plantation forestry. Such rapid industrial growth was driven by their need to fulfill the demands of foreign markets, repay external debt (Siebert, 2003), and meet national development goals defined purely on economic terms. In the case of Chile, doubling the national per capita income in the next 20 years is an already established goal (Consejo Nacional para la Competitividad, Chile, 2008) that will be the main driver of land transformation in the decades to come.

In synthesis, forest cover change over the last millennia responded to variable climate and social drivers. Climate-related forcing and localized and transient human impacts during the early Holocene were replaced globally by persistent and massive human-driven land transformation, associated for several centuries with European settlement of new territories and unsustainable exploitation practices. In the late 20th century, increasing deforestation and loss of native forest in South America and other developing nations became linked to free-market economy and postindustrial improvement of environmental regulation in developed nations (Siebert, 2003; Mather et al., 2006). Technology and global markets greatly impacted local economies, homogenized landscapes, and endangered both biological and cultural diversity across the Americas. In our opinion, to slow down deforestation trends national development goals will need to be redefined, abandoning purely macro-economic targets, to integrate rather than exclude the vision of local economies, taking into account the externalities associated with current land use models, and eliminating all subsidies to unsustainable resource use (Table 2).

Land use policies for the 21st century

Table 2 suggests that environmental policies born from imminent threats to public good may promote human behavior and regulations that reduce the externalities of land use. Future land policy decisions should incorporate social values and ecological factors that are presently absent from predominantly economic reasoning. New land development policies should define socially acceptable targets considering non-instrumental values, different cultural relationships between people and the land, the intrinsic link between local cultures and biological diversity, the protection of local economies, and ethical concerns about the social and environmental consequences of free-market economy (Siebert, 2003; Primack et al., 2001; Rozzi et al., 2008a). Particularly positive developments regarding land use in the postindustrial age are large international investments on private conservation (Table 2). Such investments might become significant drivers of land cover change in Latin America and other developing countries in the next decades, supporting the preservation of global biodiversity. However, to be successful, international initiatives should make a conscious effort to link their agendas to the goals of local residents, scientists, policy-making institutions, and conservation practitioners (Rodríguez et al., 2007).

During the past 300 years forest cover was controlled primarily by human activities, and hence it seems reasonable to argue that policy changes, and socio-economic drivers will have strong effects in future land cover transitions. Currently heavily impacted landscapes are predominantly the product of recent industrial development facilitated by perverse government subsidies, excessive private rights on the land, and weak environmental regulation by the States. To modify these drivers key political changes will be necessary in developing countries. National land use policies for the future must go beyond setting aside land for preservation, at the same time disregarding the externalities of current land use outside parks. Future policy and conservation actions should shift to deliberately abating threats (Wilson et al., 2007) and directing public subsidies to sustainable ecosystem management of non-protected land, integrating humans (Armesto et al., 1998; Brown et al., 2003). Improving ecosystem management of productive landscapes is a critical priority given that an increasing amount of land will be under pressure in developing countries in the coming decades. Governments must reorient their land use policies accordingly. Substantial investment is needed to generate accurate databases for land use planning, which integrate economic needs, traditional land–people interactions, and ecological knowledge. Lack of planning is illustrated by the growing conflict between conservation of biodiversity and production in south-central Chile, where new crops, vineyard and forestry expansion endanger the last remnant habitats where floristic and faunal richness are concentrated (Fig. 2). In many areas, conservation and production aims broadly overlap, presenting a challenge for innovative science and policy, as well as for designing and implementing new economic activities based on sustainable uses of the native biota (Rozzi et al., 2003). Ecologists and other scientists can make valuable contribution to tourism, one of the fastest growing industries in Chile, by designing novel themes and activities that enhance public appreciation and conservation of the beauty and singularity of Chilean wildlife and ecosystems (Rozzi et al., 2006, 2008b).

Planning future land use is even more necessary because of the anticipated effects of global climate change (CONAMA, 2006). In central Chile, the frequency of droughts increased significantly over the last two centuries (LeQuesne et al., 2006). Such climate-change scenario calls for policies promoting (i) the diversification of regional land uses, using a broader range of forestry and crop species to buffer the effects of extreme climate, (ii) the protection of biocultural diversity and ecosystem management of productive land, and (iii) applying subsidies to the management and recovery of diverse vegetation cover, especially on mountain slopes, as an insurance against expected climatic extremes. A pressing task of governments will be to adapt the globally dominant economic model to these changing scenarios.

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