

RESEARCH ARTICLE

Using forest historical information to target landscape ecological restoration in Southwestern Patagonia

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Abstract Ecotonal zones between eastern semi-arid steppes and *Nothofagus* spp. forests in western Patagonia are the result of broad ecosystem changes, which have intensified in the last 140 years. Our objectives were to determine historical changes in land use, land cover, and forces driving such changes in *Nothofagus* ecosystems in the Río Verde district in southern Chile, to support future management recommendations. This interdisciplinary study used historical records including scientific and military expeditions, Landsat imagery, and other archival sources. Forest cover changed radically between the late nineteenth and mid-twentieth centuries, from subsistence use by indigenous peoples, to forestry and livestock industries. The main driving forces of landscape change have been anthropogenic forest fires, logging, exotic pasture establishment, and mining. Future perspectives suggest that conserving the cultural values and natural resources of this region will depend on ecologically sound landscape planning, reversing forest fragmentation, restoring riparian corridors, and preserving indigenous archaeological sites.

Keywords Ecological restoration · Forest history · Historical ecology · Land use change · *Nothofagus* forests · Patagonia

INTRODUCTION

Most forest ecosystems exhibit some degree of anthropogenic influence on the forest structure or on processes

occurring within the forest (Denevan 1992; Perlin 2005). However, the duration and intensity of the impacts of human land use vary widely (Bürgi et al. 2017). In the southernmost and northernmost parts of the world, as well as in some other seemingly ‘remote’ places, there remain areas that are often considered pristine and which have been much less, or only recently, influenced by modern intensive land use (Delcourt and Delcourt 2004; Rautio et al. 2016; Freschet et al. 2017). A common feature of such areas is that they have been inhabited by indigenous peoples, who have used their lands in traditional and mostly non-agrarian ways. The rapid transition from hunter–gatherer societies to industrial land use has put particular emphasis on today’s land tenure and how to protect both cultural values and natural resources in such ecosystems (Josefsson et al. 2009). For landscape planning and ecological restoration to have a positive and constructive future for native ecosystems and their human societies, we must understand, from a historical-ecological perspective, how these natural ecosystems have developed in the long term under changing patterns of use by humans (Szabó 2010).

Southern Patagonia’s sub-Antarctic temperate forest landscapes have undergone major changes in land use during the last c. 200 years (Martinic 1992). Since the early twentieth century, fragmentation of vast expanses of ‘lenga’ forests (*Nothofagus pumilio* [Poepp. and Endl.] Krasser) has created a mosaic-type landscape comprising patches of forest fragments and open grasslands (Veblen et al. 1996). This has caused drastic changes in land cover and landscape structure (Armesto et al. 2010; Gowda et al. 2011). Ecotonal or transitional landscapes, which are often characterized by high levels biodiversity, are often the most intensively used and disturbed ecosystems (Hansen and Castri 1992). Such landscapes are

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exemplified in the southern hemisphere by the ecotones from the steppes to the *Nothofagus* forest of southern Patagonia.

As well as understanding changes to the landscape per se, it is also important to understand the drivers of such change, i.e., influential processes in the historical trajectory of the landscape. This is best done through an integrated array of interdisciplinary methods (Bürge et al. 2004; Whitlock et al. 2018). A landscape's past conditions of use and cover can be determined, to a certain extent, from historical records i.e., historical maps or written records (Whitney 1994), which in combination with geographic information systems and a clear knowledge of their corresponding timescales (Gregory and Ell 2007) can provide information with high levels of temporal and spatial precision (Szabó and Hédli 2011). We currently need much more scientific data relating to large spatiotemporal landscape dynamics in southwestern Patagonia, especially in the steppe–forest transition zone, where environmental changes happen at some of the largest spatial scales in the region (Martinic et al. 2011). The Río Verde rural district, which includes both continental and insular land of Riesco Island along the Otway and Skyring sea inlets, is a good example of a place where major recent changes have occurred, and still are occurring in Patagonia. The area's early land use history is linked to indigenous *Kawésqar* and then Chilean/European settlers practicing animal husbandry, small-scale mining, and logging. The area is now experiencing radical changes related to the concentration of land ownership, open-cast coal mining, and rural depopulation (Martinic et al. 2011). In the present paper, we address the uncertain future of this landscape by reconstructing part of its natural and cultural history and thus contribute to the development of future forest management, conservation, and/or restoration strategies.

The overall aim of the present study was to characterize and analyze the land cover trajectory of the Río Verde south Patagonian forested landscape in Chile, in relation to human land use over the past c. 200 years. The specific questions we present are: (i) What were the main changes in land cover of *Nothofagus* spp. forest ecosystems during this period? (ii) What were the main drivers of change and when did they influence the transformation of the landscape during the studied period? We then discuss the future of local land use and of *Nothofagus* spp. forest recovery. Finally, we consider some of the potential management implications for landscape planning in this region in relation to both natural qualities and historical legacies of this landscape.

MATERIALS AND METHODS

Study area

The study area is located in the Río Verde municipality of the Magallanes Region in southernmost Chile (Fig. 1), between 52°20' and 53°35'S–71°25' and 73°20'W. The area covers 400 000 ha, of which 270 000 ha are inland and 130 000 ha are marine, including part of Riesco Island and the continental coast of the Skyring sound. The areas are separated by two oceanic inlets—the Otway and Skyring sounds—and the FitzRoy channel. It is an ecotonal zone between the eastern steppes and the western temperate forest.

Mean annual precipitation reaches levels above 1000 mm y^{−1} in the western evergreen forest zone, decreasing to 450–650 mm y^{−1} in the deciduous forest zone, to 350–500 mm y^{−1} at the steppe forest ecotone, and falling to below 300 mm y^{−1} in the eastern steppes. Mean annual temperature is ~ 6°C and mean temperatures for July (winter) and January (summer) are ~ − 2 °C and ~ + 10 °C, respectively (Schneider et al. 2003).

The soils are spodosols of glacial origin and formed relatively recently. They have light to medium texture, acid pH, and low organic matter content, which results in vegetation having a relatively shallow root system concentrated in the top 40 cm (Promis et al. 2010). Vegetation distribution and composition closely follows rainfall distribution. It varies from the western humid zone with evergreen mixed stands of *Nothofagus betuloides* (mirb.) Oerst., *Drymis winteri*, *Maytenus magellanica*, and *Pseudopanax laetvirens* (below 200 MAMSL), to deciduous *Nothofagus pumilio* (Poepp. et Endl.) Krasser, which becomes more dominant toward the east in either pure stands or mixed with *N. betuloides* in mesic zones, and *Nothofagus antartica* (G. Forst.) Oerst. under more xeric conditions. This latter species can grow as open forest or as shrublands closer to the forest-steppe ecotone zone, along with *Chilodendron diffusum*, *Berberis* spp. and *Empetrum rubrum* (Pisano 1997). Grasslands are present in both mesic and humid zones with exotic species such as *Holcus lanatus*, *Dactylis glomerata*, and *Trifolium repens*, associated with other native steppe species such as *Festuca* sp. under eastern xeric conditions.

General land use history

A more complete and fully referenced text is presented in the supplementary material (ESM).

After the last glaciation, natural grasslands and *Nothofagus* spp. extended throughout southern Patagonia

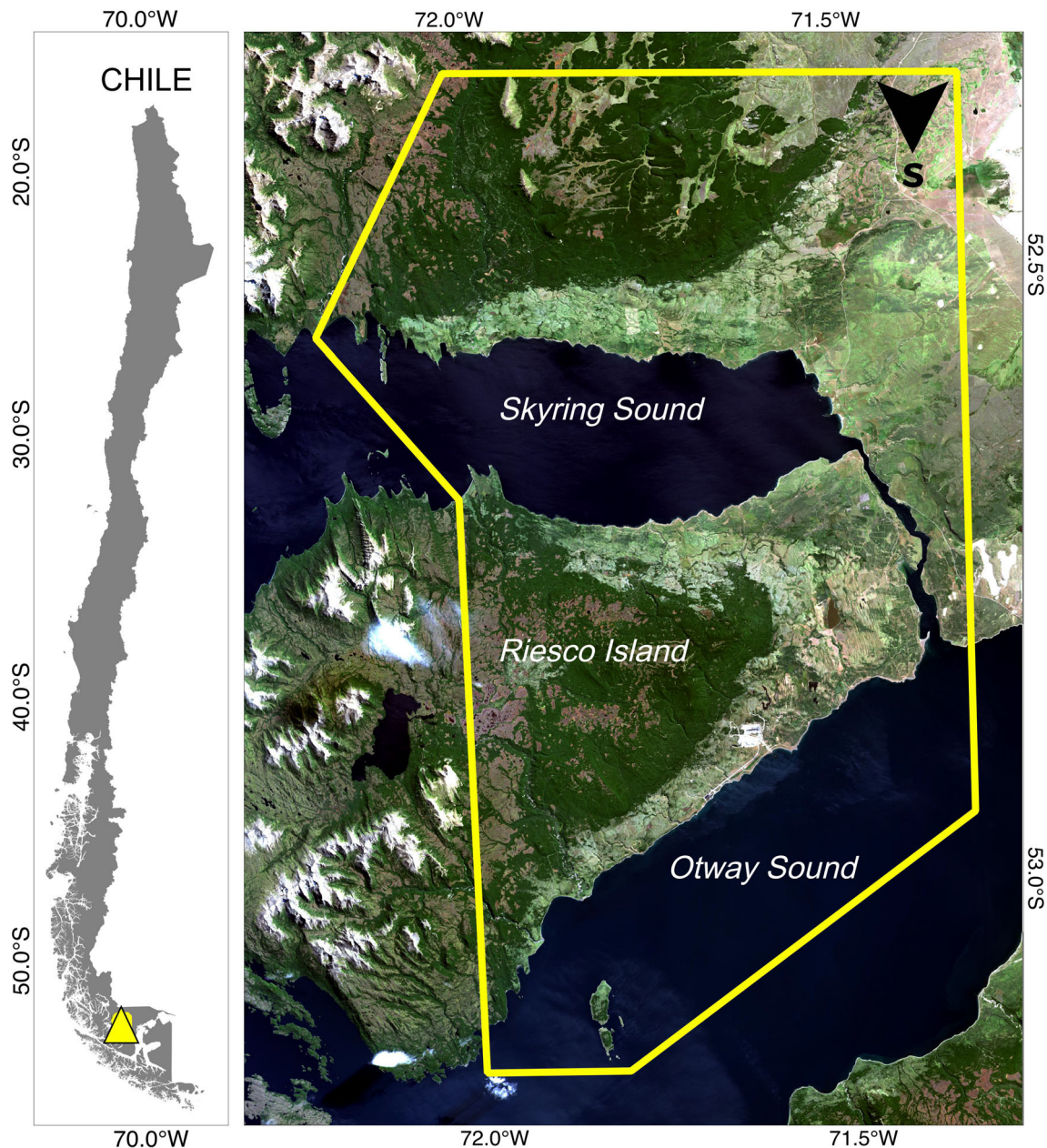


Fig. 1 Left—a map of Chile. The yellow triangle marks the location of the study area. Right, in the yellow frame—a 2014 Satellite image (Landsat 8) of the study area in true color

(Kilian and Lamy 2012). The earliest archaeological evidence of human habitation in the area goes back to 6663–7240 cal BP and it has been suggested that the area was a key point of origin for the onset of a marine hunter-gatherer navigation culture (Prieto et al. 2013). The land was home to both littoral *Kawésqar* people and the terrestrial *Aónikenk* people.

The first scientific European expedition reaching the Otway and Skyring inlets was commanded by Phillip Parker King and Robert FitzRoy from 1826 to 1830 AD, who collected detailed records of vegetation and landscape

patterns. The first Chilean-European settlements in the study area were established in the 1880s; settlers practiced small-scale farming, cattle ranching, and logging (Martinic et al. 2011). From 1911 to the 1950s, the ownership of land was concentrated in the hands of a few large financial groups that received large land concessions from the Chilean government. During this period, forced displacement of the *Kawésqar* people, along with diseases and famine, resulted in their ever diminishing and sporadic presence, which gradually ended in their eventual disappearance from this littoral landscape (Empeaire 1955; Martinic

et al. 2011). A crisis of the land colonization system in the region, along with the closing of coal mines in the territory, caused depopulation and land abandonment. This was later followed by the *national agrarian reform* (land property reform), which promoted land re-distribution into smaller-scale holdings and the development of incentives to promote the re-population of this region.

Finally, in recent times a new forced land concentration process occurred, with a few large mining and livestock companies becoming owners of most of Riesco Island's rural lands. In 2012, Chile's largest open-cast coalmine started operations on the island.

Analysis of historical maps and archival sources

The analysis of landscape change since the nineteenth century is based on available historical maps, aerial photographs, and Landsat images. The analysis of the changes and their driving forces is based on historical descriptions of the area and comprises an array of early explorers' notes (including those of Charles Darwin, Robert FitzRoy and Carl Skottsberg) and more detailed descriptions pertaining to the colonization period in the late nineteenth and early twentieth centuries. We also used oral sources as complementary data (see Table S1).

Land cover maps: 1885, 1944 and 2014

The earliest historical dataset was a land survey map created for the Chilean ministry of colonization by A. Bertrand in 1885 (published in 1886), containing the most accurate land cover and vegetation description of pre-colonization times for the continental part of the study area. The archive contains a 1:250 000 map (see Fig. S1) and a detailed written description of forest cover. Riesco Island was not surveyed by this expedition.

Historical records of the pre-colonization landscape, topography, and hydrographic maps, along with written descriptions of land cover structures in the past, were geo-referenced onto geographical points as a complementary database. These historical archives were contrasted with high-resolution LIDAR images for the delineation of pre-colonization land cover polygons, following the spatial extent of dead burned logs over present exotic grasslands at a 1:1500 spatial scale (see Fig. S2). This interpretation was confirmed with ground-truth validated GPS points across the study area, as illustrated in Fig. S3. A map was produced representing two classes of vegetation cover for the pre-colonization period: *forest* (dense and semi-dense *Nothofagus* spp. forest) and *non-forest* (shrublands and grasslands).

The second dataset comprised 1:20 000 aerial photographs of the national survey flight 'Trimetrogón' from 1944 (earliest official aerial records of the region). The

photographs were digitized and geo-referenced using the Georeferencing tool in QGIS 2.18 software. Vertical images were geo-referenced with visual interpretation over a DEM raster image. Only a part of the study area was covered by this data set, so a representative array of photographs was selected as a subset for further spatial analysis. Land cover classes were defined as *forest* and *non-forest* since it was impossible to differentiate between more specific classes at this spatial resolution.

The third dataset was the 2014 Landsat OLI satellite imagery; we used data captured during the vegetation growing season to ensure detection of deciduous *N. pumilio* and *N. antartica* forest. This was radiometrically corrected in ENVI raster analysis software using red, green, blue, near infrared and short-wave infrared. Atmospheric correction was applied using the dark object subtraction method as proposed by Chavez (1988). Ninety-three regions of interest (ROI) were created for each land cover class as a vector file, using both ground validation points taken in the field and high-resolution aerial photography (LIDAR images). Classes established were: *dense forest* (for *N. pumilio* and *N. betuloides*); *semi-dense forest* (for *N. antartica*—shrub species associations); *shrublands*; *grasslands*; and *peatlands* (Table 1). Supervised classification using maximum likelihood parameters was conducted on the images using 177 ground-truth validated GPS points and high-resolution aerial photographs as a reference. Post-classification analysis of the 2014 land cover map demonstrated acceptable accuracy, with a Kappa coefficient of 0.97.

Table 1 Description of land use classes for image classification

Land cover class	General description
Dense forest	Forest areas with canopy density estimated at 70% and above. The dominant species are: <i>Nothofagus pumilio</i> and <i>Nothofagus betuloides</i> with <i>N. antartica</i> present toward the east and <i>Drymis winteri</i> in humid, western littoral ecosystems. Range of height 12–20 m
Semi-dense forest	Forest areas with canopy density estimated between 40 and 70%. Dominant species are <i>N. antartica</i> in most of the transitional forest-steppe zone and <i>N. pumilio</i> toward the west, sometimes accompanied by <i>N. betuloides</i> along the edge of secondary forests. Range of height 4–8 m
Shrublands	Land covered by shrubs and bushes. Degraded forest areas with estimated canopy density below 40% are also included
Grasslands	Non-cultivated areas dominated by herbaceous vegetation. Including western humid pastures and eastern arid steppes
Peatlands	Land covered by mires or bogs

Historical records for land use change and driving forces analysis

The earliest historical sources date from 1826 to 1836 and comprise records made during Phillip Parker King and Robert FitzRoy's voyage on the *Beagle*, with precise records of landscape vegetation in several locations. Later expeditions by the Chilean navy in 1877 link precise data to certain locations on the Skyring and Otway sea coasts (Latorre 1878). Other primary references to the early Chilean-European settlers' landscape were recorded by Pacheco (1907) and Skottsberg (1911) (Swedish expedition to Patagonia in 1907–1909). They provide general vegetation descriptions of Riesco Island. Even though some of these sources originate from the time shortly after the onset of colonization, their records in certain geographical locations are extremely valuable for data-processing and delineating land cover maps of pre-colonization times.

We classified and analyzed land use according to general land use, social and ethnic changes, and specific technical and technological changes. Land division dynamics were evaluated with respect to the main environmental changes that affected forest cover (e.g., changes in public land concessions; property subdivision; forest fire suppression). Present and past land use dynamics in the Río Verde Community were obtained from eight semi-structured open interviews (Table S1), with key informants, all of them living in the study area for more than 40 years, and having traditional knowledge of their land and located in properties distributed across the study area. These data were classified for each farm visited (data not shown), and analyzed in relation to the land cover change map, to examine possible land use effects (e.g., cattle grazing over *Nothofagus* regeneration capacity) on natural forest regeneration. Land use change, together with the main ecological changes, was chronologically calibrated on a logarithmic scale as in Marcucci (2000).

RESULTS AND DISCUSSION

Interpretation of land cover and the changes 1885–2014

Pre-settlement land cover

The land cover map of 1885 refers to the period when a few pioneers established small-scale settlements within a landscape dominated by forests and very little open land. This is also confirmed by historical sources that show a clear dominance of *Nothofagus* spp. forest ecosystems in the study area, with dense littoral forest following the

coastline (Fig. 2) as far as the transitional zone of *N. antarctica*.

The southern coast of Riesco Island (northern Otway sea inlet) was, in Fitz Roy's (1839) words: "thickly-wooded with evergreens" and further east, covered with "stunted bushes and trees... trees were not evergreen, and at this time their leaves were withered and falling". This is consistent with observations made by the Swedish scientist Carl Skottsberg exploring the area almost 100 years later in 1907, who describes the southern coast of Riesco Island thus: "the slopes are clad with tall forest. In the south part it is covered by the evergreen trees that by-and-by are mingled with the light green Roble (*N. pumilio*), which reigns alone for a short stretch" (Skottsberg 1911). When Skottsberg refers to *evergreens*, he refers to *N. betuloides* forest. This was predominant on the western parts of the southern coast of the island, where rainfall and humidity are higher, whereas *N. pumilio* was more abundant toward the eastern side of the island's coastline.

Further north and east, along the FitzRoy channel connecting the Skyring and Otway Waters, FitzRoy (1839) describes its southern entrance as a "woody country, extending towards Tierra del Fuego (East)", and further north in the continental plains of the channel "No tree was seen; the soil seemed dry, rich, and light". "At the western end of the passage, which unites the waters, the shore is well clothed on the north side with luxuriant grass and trefoil, with here and there a sprinkling of brushwood, but is entirely destitute of trees". This last description proves that the north eastern corner of Riesco Island was covered with grasslands and shrublands as it is today. Skottsberg in 1907 saw a similar landscape, describing the area as follows: "Where the water narrows to Fitzroy Channel the country once more changes its nature, and we are on the edge of the Patagonian pampa, where groves of *N. antarctica* form a brushwood. Of course, these changes depend upon the climatic conditions, especially the decreasing rainfall". Both Bertrand's (1886) map and written records describe a very dense forest cover all along the northern Skyring coast, and from creek 'chorrillo la descarga' in the eastern coast, toward the north.

Pre-settlement forest covered 66% of the study area (178 480 ha) (Table 2). Non-forest vegetation (shrublands and grasslands) covered 20% of the total surface. Other land cover accounted for 14% of the study area (38 195 ha).

Land cover in 1944 and 2014

The land cover map from the Trimetrogon aerial dataset shows a spatial subset of 54 783 ha (approximately 20% of the total study area) (Fig. 3). To compare this map with that of 2014 and pre-settlement (1885) land cover maps, a spatial subset was extracted from both (Table 3). Forest

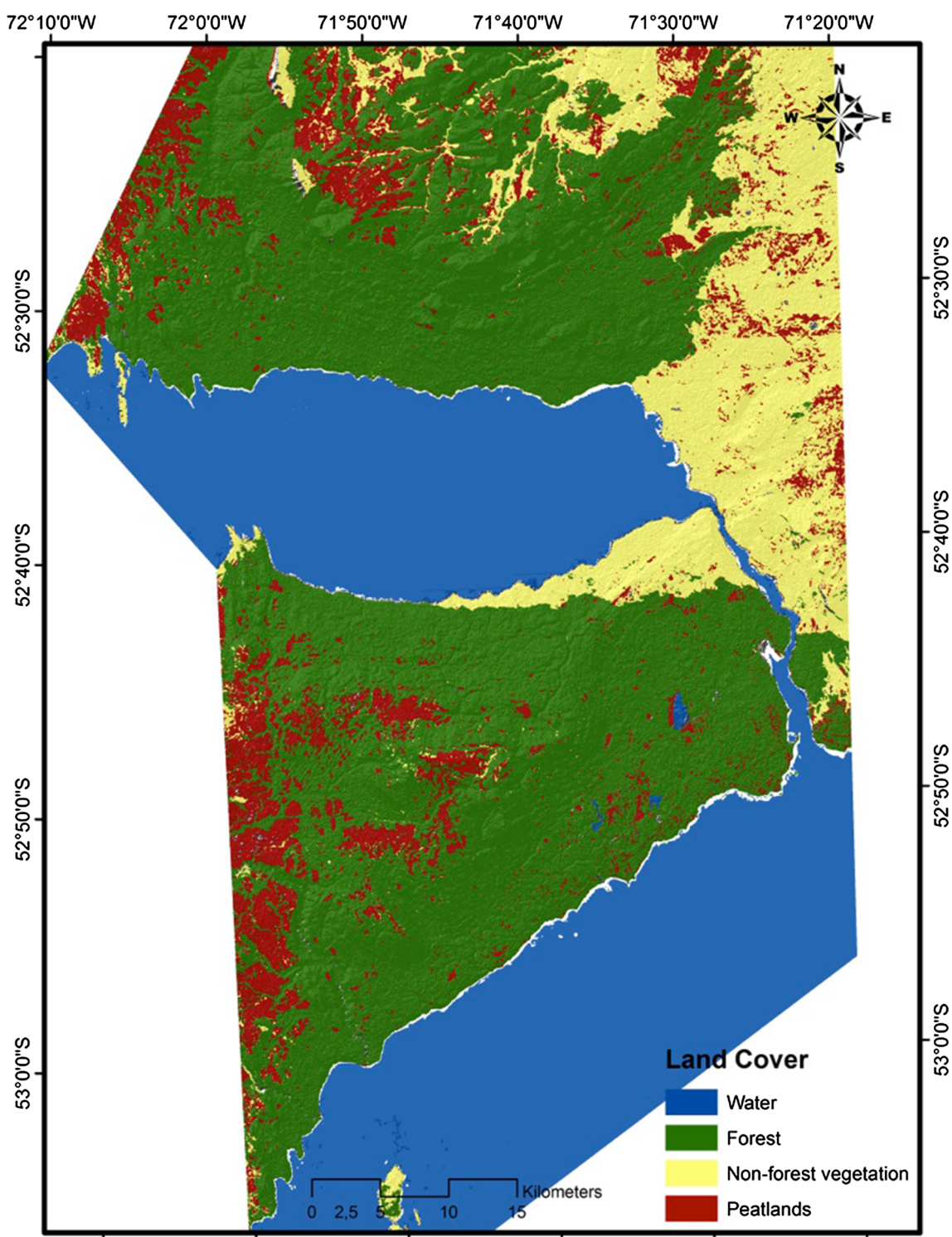


Fig. 2 Map of reconstructed land cover of the pre-settlement period showing the extension of forest cover (green) and non-forest vegetation (yellow) in the study area until the late nineteenth century

cover in 1944 was 60% (33 006 ha), 17% less than during pre-settlement times and 27% higher than in 2014. Non-forest vegetation accounted for 27% of the area (15 032 ha), 18% higher than in pre-settlement times, and 18%

less than in 2014. Other land cover (peatlands, bare land and snow) amounted to 12%, a minor variation in comparison with the pre-settlement map (13%) and 2014 (14%).

Table 2 Total land cover surface (hectares) and percentage (%) of each specific vegetation class (for 2014) and broad vegetation classes (for 1885)

Land use class 1885	Land use class 2014	1885		2014	
		Hectares	%	Hectares	%
Forest	Dense forest	178 479	66	96 494	36
	Semi-dense forest			12 763	5
Non-forest	Shrublands	53 407	20	23 341	9
	Grasslands			106 410	39
	Peatlands			28 748	11
Others	Bare lands	38 195	14	2127	1
	Snow			496	0.2
	Total	270 082		270 380	

In 2014 (Fig. 4), mixed *N. pumilio* and *N. betuloides*, represented by dense forest cover, accounted for 36% (96 494 ha) of the total surface area (Table 2), and semi-dense forest covered 5% of the study area (12 763 ha). Shrublands covered 9% of the study area (23 341 ha), and grasslands covered 39% (106 410 ha). Peatlands accounted for 11% (28 748 ha) of the study area; bare land and snow covered 1% (2127 ha).

Landscape change and driving forces

There is a clear relationship between land use in each historical period and major land cover patterns and processes. During the period of indigenous land use, there was little variation in forest cover. At a stand scale, changes in forest cover occurred due to local fires intended to create fuelwood and forest clearings for the establishment of settlements, as described by Empeaire (1955), by the *Kawésqar* people along the coast. Fires were also started by the *Aónikenk* during hunting activities; these extended to Río Verde's forests from the eastern *pampas* or steppe lands, as evidenced by pollen and charcoal records (Huber and Markgraf 2002). According to general land cover descriptions of early European and Chilean explorers in the region (i.e., FitzRoy, Bertrand and Skottsberg), the evidence of forest fires was only found at the small site-scale, as also indicated by the charcoal records (Huber and Markgraf 2002) from the area.

The pre-settlement land cover map (Fig. 2) shows the dominance of *Nothofagus* spp. forests over much of today's forest-steppe transition zone, indicating that most of the humid grasslands of the study area were then covered by a dense forest. This extended as far as the coast, suggesting the existence of an almost continuous forest landscape along the coast.

As in most of Patagonia, the colonization period in the late nineteenth century included a radical change in the techniques and technologies used for transforming the landscape, as well as in the socio-economic system inducing those transformations. At first, small-scale Chilean-European settlements practiced a subsistence economy, as well as local trade of wool and meat to supply incipient coal mining enterprises in the area (Fig. 6). We have no evidence of major land cover changes in this pioneer settlement period; these did not happen until the later period of large-scale ranching, mining and forestry estates. However, historical literature (Martinic et al. 2011), oral tradition, and the scientific records of Carl Skottsberg in the first decade of the twentieth century, suggest *Nothofagus* spp. cover in the area fluctuated, with local canopy openings and gaps occurring along the coast where pioneers established their settlements.

Both regional literature (Martinic 1992; Martinic et al. 2011) and oral information obtained in open interviews with the elders of Río Verde mention low-intensity forest management by early pioneers. Techniques employed included *high-grading forestry*, which allowed harvesting of the most valuable trees in wintertime, cutting timber for farm constructions and use in the mining developments; and *tree girdling*, which was an efficient technique for creating gaps of standing dead trees within the forest to encourage increased grass productivity for livestock, and dry fuelwood for the household. This was confirmed by our field observations during which we discovered, all over the open landscape, dead burned logs with girdle marks (Fig. 5). All these constitute key driving forces of landscape change occurring since the start of Chilean-European colonization (Fig. 6). Even though these techniques continued throughout the colonization process, their intensity and effects changed. The arrival of industrial technology, such as steam power and industrial sawmills, and the allocation of property to large estate companies (Martinic et al. 2011), turned these techniques into driving forces that had a far greater impact across the landscape (Fig. 6). During this early industrial period, the forest was logged, and any standing trees that remained were girdled to open the forest further and to produce dry fuelwood, or were burned; any clearings formed were sown with exotic pasture species. Despite the creation of the first forest protection law in 1931, which restricted the use of fire, oral sources confirm that illegal burning continued at least until the 1950s. By 1944 the forest cover was reduced from 77% in pre-settlement days to 60% (Table 3).

The latest large fire event, which took place in 1959, extended through most of Riesco Island's rural lands and parts of the continental Skyring coast; it reduced forest cover substantially. During this decade, there was regional land re-distribution to farmers and new settlers; a process

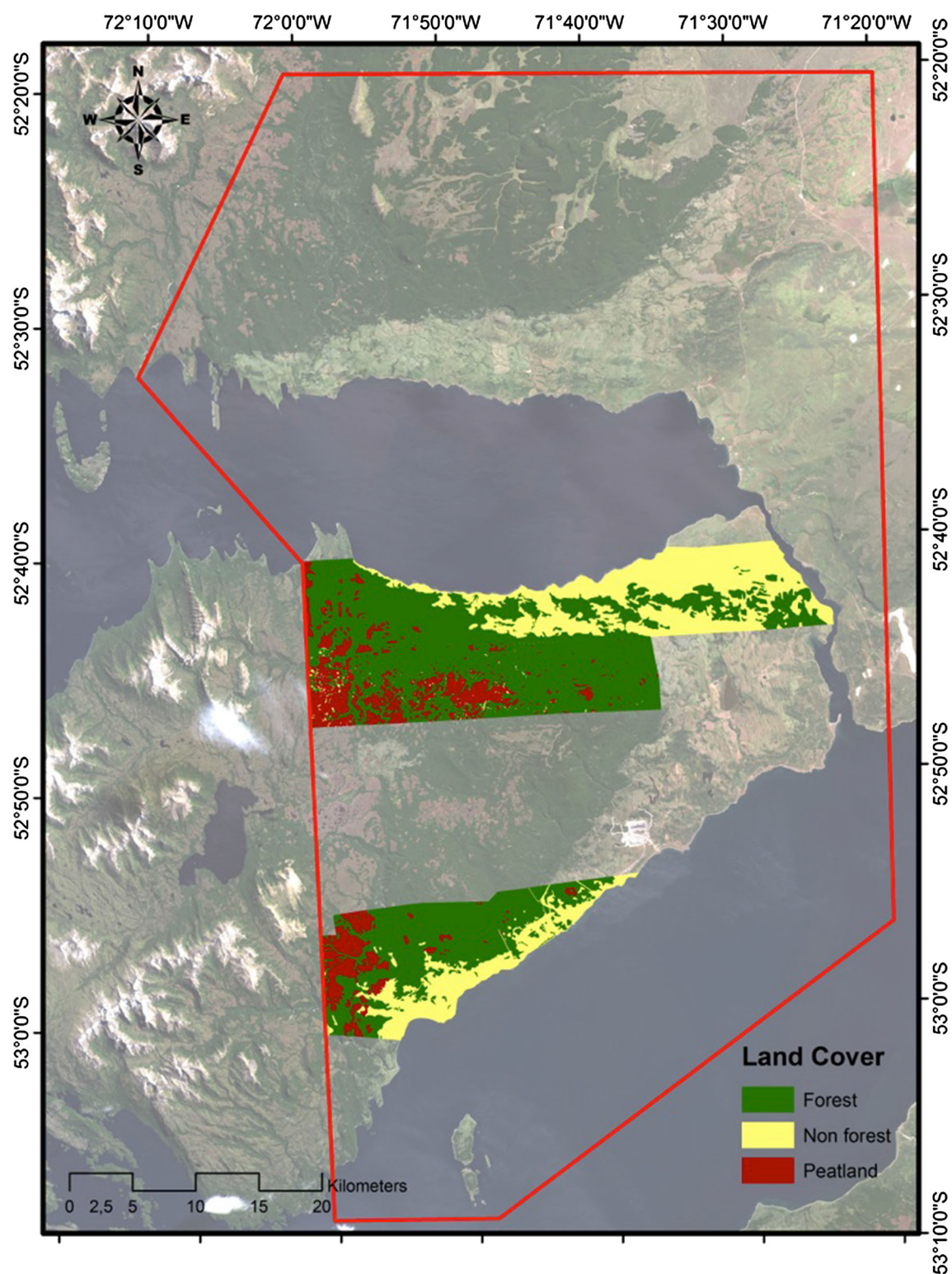


Fig. 3 Land cover subset map for the year 1944 during the peak time of colonization

intensified by the national agrarian reform in the 1970s. Forest fires for land clearing ceased, and modern silvicultural practices were introduced (Martinic et al. 2011). Coastal forests and a large amount of inland territory had

previously been converted into humid and semi-arid grazing grasslands. Oral sources and a visual interpretation of the landscape suggest that re-growth from burned *N. antarctica* transitional forest and arborescent shrublands was

Table 3 Land cover change between the years 1885, 1944, and 2014, within the spatial subset of the 1944 *Trimetrogon* aerial photography dataset

Land use class	1885		1944		2014	
	Hectares	%	Hectares	%	Hectares	%
Forest	42 297	77	33 006	60	22 707	41
Non-forest vegetation	5155	9	15 032	27	25 059	45
Others	7358	13	6744	12	7393	13
Total	54 810		54 783		55 159	

adapted into highly productive silvo-pastoral systems by the clearing of crisscrossed strips or ‘picadas’ within these forests, dividing them into small fragments with access for cattle and sheep to enter. These landscape elements were evident in the 2014 land cover map, in which they were classified as *semi-dense forest*; they are highly valued by local ranchers because they provide winter shelter for livestock and act as windbreaks, thus increasing grass productivity.

In the 1980s and 1990s the crisis in international wool markets, due to the wider use of synthetic fibers (Cibils and Borrelli 2005), was a significant driving force of landscape change. The local economy was severely affected and sheep stocking rates were significantly reduced, which in turn reduced grazing pressure on grasslands and forests, resulting in a denser *Nothofagus* spp. forest cover in certain areas (Zegers 2016). Further concentration of land into the hands of just a few owners changed the property structure of the whole landscape to one more similar to that during mid- and late colonization times. In the late 1970s, following the breakdown of the agrarian reform and land tenure re-distribution process, privatization of natural resources allowed private mining companies to acquire concession rights to some of Chile’s largest coal reserves. Open-cast coal mining operations have, since 2010, been a major driving force of land cover change, both because of the clear-cutting of forest stands and because yet more land has been bought from farmers for future mining extraction.

CONCLUSIONS AND FUTURE PERSPECTIVES

In the present study, we showed that *Nothofagus* spp forest cover and land use rapidly changed between the late nineteenth and mid-twentieth centuries, from subsistence use by indigenous peoples to forestry and livestock introduction by settlers during the region colonization. The main driving forces of landscape change have been anthropogenic forest fires and logging, exotic pasture establishment for livestock, and surface coal mining. We

have shown how processes involved in changing patterns of land use, from the indigenous *Kawésqar* era extending over millennia of low intensity land use, to today’s era of land ownership concentration, mining and rural depopulation, have acted to reshape the landscape in fundamental ways. The period of transformation is rather short when seen from a global perspective (Whitlock et al. 2018), but it is nevertheless very similar to what has occurred in other regions in both very southerly and very northerly locations (cf. Östlund et al. 1997; Delcourt and Delcourt 2004; Rautio et al. 2016). The range of historical influences that have affected this specific landscape, together with an understanding of natural processes within *Nothofagus* spp. forest ecosystems, can inform management strategies aimed at supporting critical ecosystem processes. These include forest restoration and conservation measures that take account of local culture and biodiversity. Such guidelines will be applicable to all of western Patagonia, since these problems have arisen across an area much larger than our study area, and have a common background and origin throughout the region.

Current rural depopulation processes, associated with industrial extraction of the territory’s natural resources through mining and logging, have serious consequences for the natural and cultural values of this rural landscape. Land abandonment could encourage the natural recovery of the forests (Zegers 2016). However, in natural forests, *Nothofagus* spp often survives and grows slowly in the understory (Veblen et al. 1996). Field evidence showed *N. pumilio* seedlings early mortality close to 70% when they were planted in open meadows with no protection (Valenzuela et al. 2018). Allowing the growth and development of such mix of forest and meadows, lacking in any systematic silvicultural (see López Bernal et al. 2012) or silvo-pastoral management, could lead to small fragments, irregularly distributed across the landscape and with limited value (Gea-Izquierdo et al. 2004). In addition, the threat of invasive species such as *Castor canadensis*, even though it has not yet affected this study area, is currently a major concern with respect to conservation and the success of natural forest regeneration. This has been the case in *Nothofagus* forest in Tierra del Fuego, and the species has also been recorded on the mainland of Patagonia in other areas (Pietrek et al. 2017). It is, therefore, essential that land management techniques should include ecological restoration methods that address the management of watersheds (Calle et al. 2012).

Today’s dominant ecosystems are open grazing pastures with introduced species, and with reduced opportunities for native species to recover. Active ecological restoration to an earlier forest structure would be costly and not necessarily viable due to livestock grazing impacts on regenerating *Nothofagus* spp. and soil degradation, competition

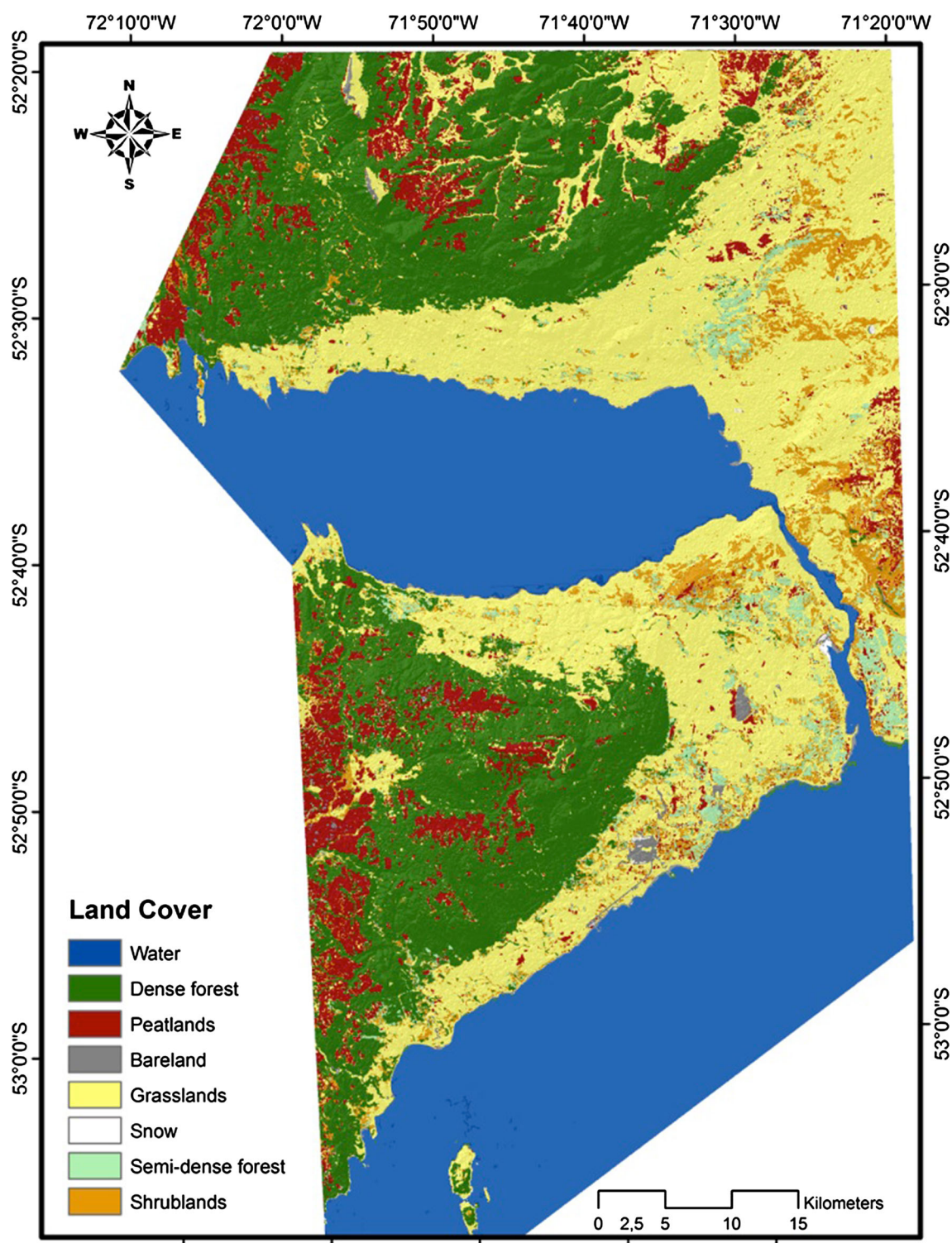


Fig. 4 Land cover map of the year 2014

with pasture grasses, and loss of vegetation structure (De Paz and Raffaele 2013; Paritsis et al. 2015; Gaitán et al. 2018). Nonetheless, combined passive and active, cost-effective restoration measures could be implemented to improve ecological connectivity between isolated forest

patches, along with restoring ecosystem services that were lost because of land clearance and habitat fragmentation. These measures could include, for example, fencing off exclusion zones in deforested riparian areas in order to allow long-term natural *Nothofagus* spp. regeneration to re-



Fig. 5 **a** Burned primary forest in an open grassland clearly showing the process of natural regeneration of mixed *Nothofagus betuloides* and *Nothofagus pumilio* forest. **b** Evidence of a girdled *Nothofagus* spp. that was later burned (photo by Gabriel Zegers)

establish the ecosystem functions of these biological corridors, and/or active reforestation of *Nothofagus* spp. and their accompanying herbaceous and shrub species such as *Berberis* spp. and *Chilodactylus* spp. Native species plantations should utilize natural defenses (e.g., shelter tubes and trees, using natural microtopography) against wind desiccation and herbivores, or more complex ecotechnologies as suggested by Valenzuela et al. (2016) and Valenzuela et al. (2018) for this study area.

Semi-dense *N. antarctica* and *N. pumilio* forests have a special silvo-pastoral value for local farmers, mostly because they are highly productive in terms of forage biomass with good nutritional value (Sánchez-Jardón et al. 2010). However, due to their slow regeneration capacity (Veblen 1992), overgrazing these ecosystems endangers their conservation and sustainability. We therefore recommend that local research should be conducted with the aim of restoring the structure and functions of these ecosystems, following technical guidelines as in Salinas et al. (2017) to ensure their future sustainability and economic potential for rural culture.

Coastal grassland ecosystems in areas that were originally covered by littoral forest should also be managed to recover key species and restore forest that bears a closer resemblance to its earlier structure. Both ecological and cultural values of these historical ecosystems are matters of

great concern. The few remnants of these forests within the Forest-Steppe transitional landscape and the presence of evergreen species such as *D. winteri*, *N. betuloides*, and *M. magellanica* within them make them a key biodiversity resource in southern Patagonia. We recommend that targeted restoration efforts should be concentrated in areas that still contain patches of remnant forest and indigenous archaeological sites, creating a mixture of natural and managed elements in the landscape, as achieved in southern Peru (Whaley et al. 2010).

Finally, we conclude that a detailed knowledge of past ecosystem properties, together with an understanding of the forces that have driven changes in the landscape, is absolutely necessary for the successful future management of this cultural landscape. However, it is imperative that further specific research is conducted with some urgency in the fields of natural forest regeneration, active restoration techniques, and cultural history, if we are to conserve these ecosystems, and preserve and fully appreciate their cultural value. We consider it particularly important to focus on and apply knowledge of the landscape structure prior to the European settlement period, since these elements are the ones that have been more widely lost, although they had the longest history. Future management, therefore, needs to be based on deep historical insights as well as a thorough understanding the effect of the introduction of exotic

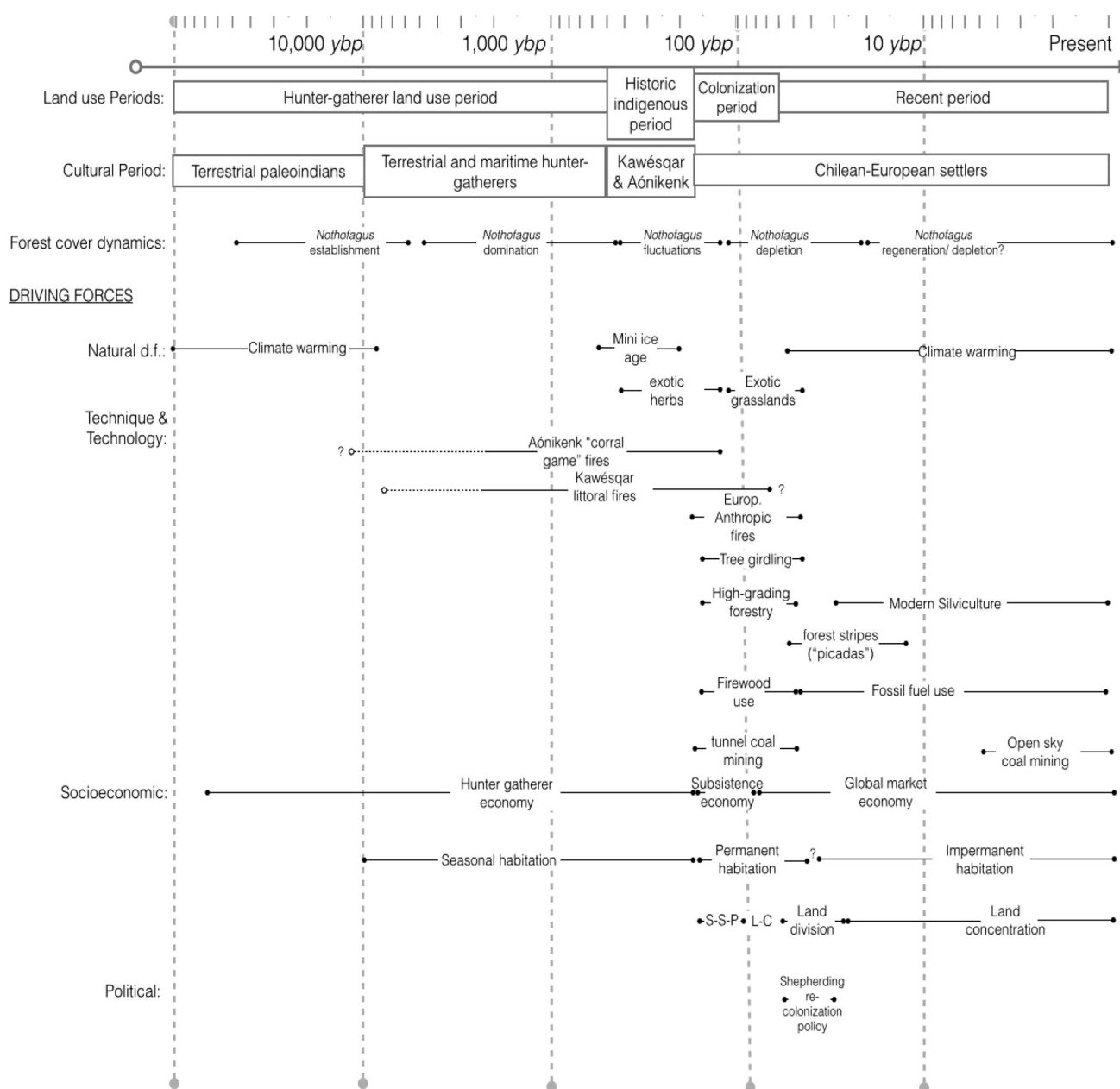


Fig. 6 Timeline in logarithmic scale of land use periods, cultural periods, forest cover dynamics, and the related driving forces of landscape change in the study area. *S-S-P* Small-scale properties, *L-C* land concentration, *ybp* years before present. See (Marcucci 2000)

grasses and animal farming; this would allow the cultural heritage and the biodiversity in these landscapes to be enhanced and protected.

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