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HISTORICAL DYNAMICS OF A PATAGONIAN LANDSCAPE: PATTERNS AND PROCESSES IN FOREST COVER AND USE SINCE LATE 19TH CENTURY IN CHILEAN SOUTHWESTERN PATAGONIA

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A mis padres y maestros

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HISTORICAL DYNAMICS OF A PATAGONIAN LANDSCAPE: PATTERNS AND PROCESSES IN FOREST COVER AND USE SINCE LATE 19TH CENTURY IN CHILEAN SOUTHWESTERN PATAGONIA.

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Abstract

At present, Landscapes in Southern Patagonian are the result of socioeconomic and ecological changes, intensified in the last 140 years. Ecotonal zones between eastern semi-arid steppes and western *Nothofagus sp.* forests and their remaining biological evidences of pre-European landscape, are clear examples of these changes. Our objectives are to (1) determine the historical changes in land use and land cover and their relationships to the driving forces associated to changes in *Nothofagus sp.* forest ecosystems; (2) and describe the recent trends of *Nothofagus sp.* forest cover and their potential management implications over landscape planning. The study area comprises 2700 Km^2 in the Rio Verde rural district (52°S – 71°W), where historical records from the 19th century including scientific and military expeditions, regional archives and bibliography, and oral tradition; all of which were integrated with photo interpretation of burned Wood's surface for constructing pre-settlement land cover maps. Trends in forest cover were observed with spatiotemporal analysis of classified Landsat imagery and field sampling, integrated in Geographic Information Systems. Overall forest cover change showed an average 25% reduction since late 19th century to mid 20th century, from a subsistence littoral forest indigenous use, to industrial forestry and livestock management. Natural forest regeneration was observed in the last two decades within forest-pasture border ecosystems, irregularly conditioned by changes in land use pressure and landscape resiliency; Forest to pasture change was associated to late silvicultural practices and livestock grazing; Forest to bareland change was associated to recent charcoal mining.

Key words: Patagonia; Forest history; Land-use change; Regeneration; Historical ecology; *Nothofagus* forests.

DINÁMICAS HISTÓRICAS DE UN PAISAJE PATAGÓNICO: PATRONES Y PROCESOS DE USO Y COBERTURA DE SUELOS DESDE FINES DEL SIGLO XIX EN LA PATAGONIA SUDORIENTAL CHILENA.

Resumen

Los paisajes de la Patagonia Sur, son el resultado de cambios socioeconómicos y ecológicos, intensificados durante los últimos 140 años. En ecotonos entre las estepas semi-áridas orientales y los bosques de *Nothofagus sp.* occidentales, las evidencias biológicas asociadas al paisaje previo al asentamiento Chileno-Europeo, constituyen claros ejemplos de esos cambios. Nuestros objetivos son (1) determinar los cambios históricos de uso y cobertura de suelos y su relación con las fuerzas de cambio del paisaje, asociadas a cambios en ecosistemas forestales de *Nothofagus sp.*; (2) describir la tendencia actual de cobertura del bosque de *Nothofagus sp.*, y sus posibles implicancias en el manejo y planificación del territorio. El área de estudio comprende 2700 Km^2 de la comuna de Río Verde (52°S – 71°O), Región de Magallanes, Chile. Se usaron registros históricos del S. XIX, incluyendo expediciones científicas y militares, archivos y bibliografía regional y tradición oral; integrada con la interpretación de fotografías aéreas con testigos de quemas forestales, para construir un mapa pre-asentamiento Chileno-Europeo de cobertura vegetacional de suelos. La tendencia reciente de cobertura forestal fue observada mediante análisis temporo-espacial de Imágenes Landsat clasificadas y muestreos en terreno, integradas en sistemas de información geográfica. Hubo una conversión del 25% de cobertura forestal a praderas, desde fines del S.XIX hasta mediados del XX, desde un uso indígena de subsistencia de los recursos de bosque litoral, a la explotación forestal, ganadera y minera industrial del territorio. En las últimas dos décadas, se observó regeneración natural del borde bosque-pradera asociado a la disminución en la presión de uso y resiliencia natural del paisaje; conversión de bosque a pradera asociada a explotaciones forestales y uso ganadero; y conversión de bosque a suelo desnudo por la apertura reciente de minería del carbón.

Palabras clave: Patagonia; historia forestal; Cambios de uso de suelo; Regeneración; Ecología histórica; Bosques de *Nothofagus*.

1. Introduction

Environmental change is one of the key issues in global resource management, especially today, when its impacts transcend individual, community and nation based scales (Vitousek, 1997). Ecosystems and the means of its human use are in nowadays a center issue in public and private decision-making, both because of the present evidence of species and habitat loss, but also its associated loss in cultural values (Drew and Henne, 2006; Rozzi *et al.*, 2006). Integrated ecosystems restoration and landscape planning constitute means to ensure the bio-cultural conservation and adaptation to these large-scale environmental changes and its correspondent impacts. Ecologically based Characterization of the landscape's properties, for both land use planning and ecosystem restoration is firmly rooted in present biotic conditions, lacking in many cases of a dynamic and long term perspective over natural and anthropogenic patterns and processes in socio-ecological systems (Marcucci, 2000; Metzger *et al.*, 2010). Understanding the long term development of natural systems under changing human use, from its earliest stage, to its present one, from a historical-ecological perspective (Bürgi and Gimmi, 2007) is proven to improve the efficiency of iterative landscape planning (Angelstam *et al.*, 2013; Marcucci, 2000); likewise, knowledge about early or pre-industrial ecosystem stages and their historical range of variability, is today an ineludible requirement for effective ecological restoration and ecosystem management (Szabó, 2010).

Southern Patagonia's sub-Antarctic template forest landscapes have been subject to major changes in land use during the last 140 years (Martinic, 1992). Since the early twentieth century, fragmentation of vast extensions of 'lenga' (*Nothofagus pumilio* [Poepp. and Endl.] Krasser) forests lead to a mosaic-type landscape with patches of forest fragments and open grasslands (Veblen *et al.*,1996). Causing drastic changes in land cover and landscape structure at a regional scale (Armesto *et al.*, 2010; Camus, 2006; Gowda *et al.*, 2011; Haig *et al.*,1946; Huber and Markgraf, 2003; Otero, 2006). Ecotonal or transitional zones, from the Patagonian steppes to the template forest, were the earliest forest dominated lands under human land use by indigenous groups in southern Patagonia since the deglaciation period (early Holocene); and were later, the first and more intensively used forest in the sub-Antarctic ecoregion, being mining, logging and cattle ranching the main exponents of land use during colonization stages and recent times (Martinic, 1992).

The ecological and cultural properties of the sub-Antarctic Magellanic ecoregion, have long been discussed and valued for its low world-scale representativeness, high non-vascular floristic richness (Armesto *et al.*, 2001; Rozzi *et al.*, 2008, 2012) and its close bio-cultural ties to ancient ethnic groups, highly threatened today in their cultures and language (Hidalgo, 1996). Changes in land use, from a low impact littoral human habitat by maritime (canoe) hunter gatherers in the transitional Patagonian landscape (from fiords to steppe), to early and late industrial European settlers land use, and present natural resources exploitation, may have (within a historical variability context) reshaped the landscape cover structure to a radically different one in nowadays, causing a partial loss of ecological and cultural diversity. Other than that, few evidence-based research has been made from a historical, ecological perspective at landscape ecological scales. Information is needed on the dynamic patterns and processes happening in past and present land-use environments and their main driving forces (i.e. influential processes in the evolutionary trajectory of the landscape (Bürgi et al., 2004)).

Understanding the long term temporal land use and cover changes requires an integrated array of interdisciplinary methods. Landscape's conditions of use and cover in the past can most certainly be determined with historical records (Whitney, 1994), but their lack in spatial precision mandates the use of field based ecological methods and its associated theoretical and empirically based analysis (Bürgi *et al.*, 2004), commonly supported by geographic information systems (Gregory and Ell, 2007) which gives, along with correspondent timescales, high temporal and spatial precision (Szabó and Hédl, 2011). Important pollen analysis records have been studied documenting vegetation changes with land use changes (Huber and Markgraf, 2002), and a vast literature supported by both archeological and historical records describes both general and local human land use history since early Holocene times. Nevertheless, more scientific evidence is needed for large spatiotemporal landscape dynamics in south-western Patagonia-in the Steppe-forest transition zone, where environmental changes are some of the largest in the region (Martinic *et al.*, 2011).

Earlier studies in Boreal and southern Sweden combine the use of historical records, cadastral maps, pollen analysis, field ecology, remote sensing and aerial photographs, in GIS tools, to successfully map past land vegetation cover, and the patterns and processes of its current development (Angelstam *et al.*, 2013; Axelsson and Östlund, 2001; Lindbladh *et al.*, 2000; Lindbladh *et al.*, 2011) Cases can be cited in

Romania (Pătru-Stupariu *et al.*, 2013) and North America. Furthermore Bürgi and Gimmi (2007) justifying the additional use of oral history interviews for conducting research in Landscape ecology. Improvements in ecosystem management could be reached by combining the mentioned methods for a southern Patagonian landscape's characterization in its past and present stages, and its related land use evolution process.

Overall objective

Characterize and analyze the land cover structure of a South Patagonian cultural landscape, based on its dynamic formation processes of land use, and their changing ecological effects over land cover. The selected area, corresponding to a rural area in southernmost Chile (52°S – 71°W), within the Otway-Skyring sea inlets is analyzed during a timeframe between pre-European settlement times (mid-XIX century) and present times.

Specific objectives:

(1) Determine the historical changes in land use and land cover and their relation to the Natural, technological, socioeconomic and political driving forces associated to changes in *Nothofagus sp.* forest ecosystems.

(2) Describe the recent trends of *Nothofagus sp.* forest cover and their potential management implications over landscape planning.

2. Materials and Methods

Study Area

The study area is located in the Río Verde municipality of the Magellan's Region in southernmost Chile (figure 1), Between 52° 20' and 53° 35' S – 71°25' and 73°20' W. The total area ranges for 400,000 ha, of which 270,000 ha are inland and 130,000 ha of water (sea), comprising the total rural and populated surface, including part of the Riesco Island and the continent in the northern zone, being both lands separated by two oceanic inlets (Otway and Skyring sounds) and the Fitz-Roy channel. It is a transitional or ecotonal zone between the eastern steppes and the temperate forest biome towards the pacific channels, accounting for some of the most favorable climatic conditions for animal grazing, forestry and human living in southern Patagonia (Martinic *et al.*, 2011). Besides livestock farming (mainly sheep, cattle and horse husbandry) new economic activities have established in the last decade, such as large-scale coal mining (Riesco Island) and salmon farming in the littoral border. Tourism accounts as a growing activity mainly for rural tourism, and lately for its proximity with the *Alacalufes National Reserve*, a vast national conservation reservoir extending through the Pacific fiords.

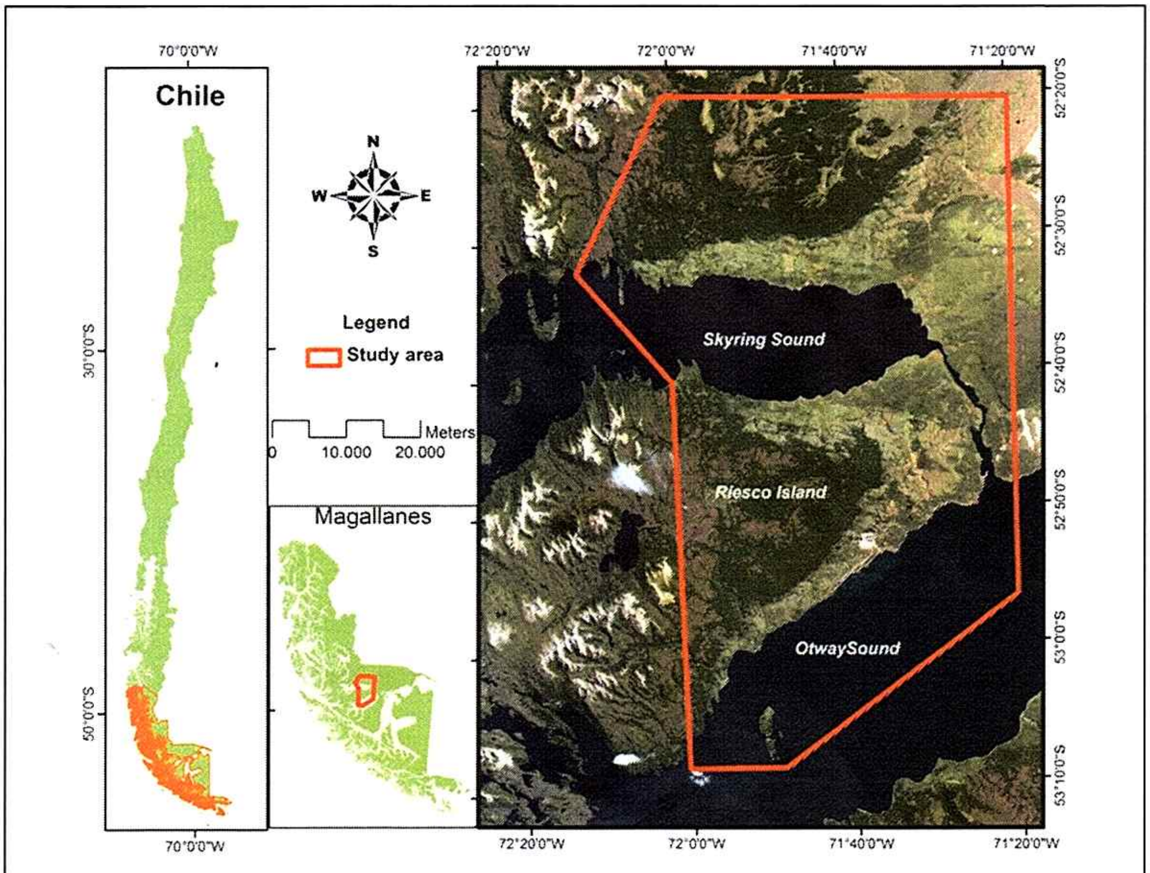

Figure 1. Map of Chile with Magellan's region outlined in red (left); Magellan's region with the study area in red polygon within the Rio Verde municipality (center); 2014 Satellite image in true color of the Rio Verde municipality and the study area in red comprising the rural portion of de district (right).

The mean annual precipitation reaches levels above 1000 mm yr^{-1} in the western evergreen forest zone, decreasing to 450–650 mm yr^{-1} in the deciduous forest zone, to 350-500 mm yr^{-1} at the steppe forest ecotone, decreasing below the 300 mm yr^{-1} at the eastern steppes. Rainfall variation also occurs (in a lower degree) from N to S from the littoral border (0 m.a.s.l.) to the higher altitude zones (1200 m.a.s.l. approx.) (Appendix 3). Mean annual temperature is ~6°C and means temperatures for July (winter) and January (summer) are ~–2 and 10°C, respectively. Mean wind speed is ~3.7 m/s, and mean daily maximum wind speed is 8.8 m/s cal. for the Skyring coast; there is an all year round westerlies influence (Schneider *et al.*, 2003).

Soils are spodosols of glacial origin and relatively recent formation. They have light to medium texture, acid pH, low organic matter content, and a relatively shallow rooting system concentrated in the first 40 cm of depth (Promis *et al.*, 2010). Vegetation distribution and composition follows clear relations with rainfall distribution, from the western humid zone with both simple evergreen *Nothofagus betuloides* (mirb.) Oerst. and mixed with *Drymis winteri* and *Pseudopanax laetvirens* (below 200 m.a.s.l.), or deciduous *Nothofagus pumilio* (Poepp. et Endl.) Krasser, which becomes more dominant towards the East in either simple or mixed forest with *N. betuloides* in mesic zones, and *Nothofagus antartica* (G.Forst.) Oerst. under more xeric conditions. This late species can grow as an open forest or even shrublands closer to the forest-steppe ecotone zone, along with *Chiliotrichum diffusum*, *Berberis spp.* and *Empetrum rubrum*. Grasslands are present both in the mesic and humid zones with exotic species such as *Holcus lanatus, Dactylis glomerata* y *Trifolium repens,* introduced after forest fires; and *Festuca spp.* associated with other steppe native species in the more xeric conditions in the eastern limit of the study area.

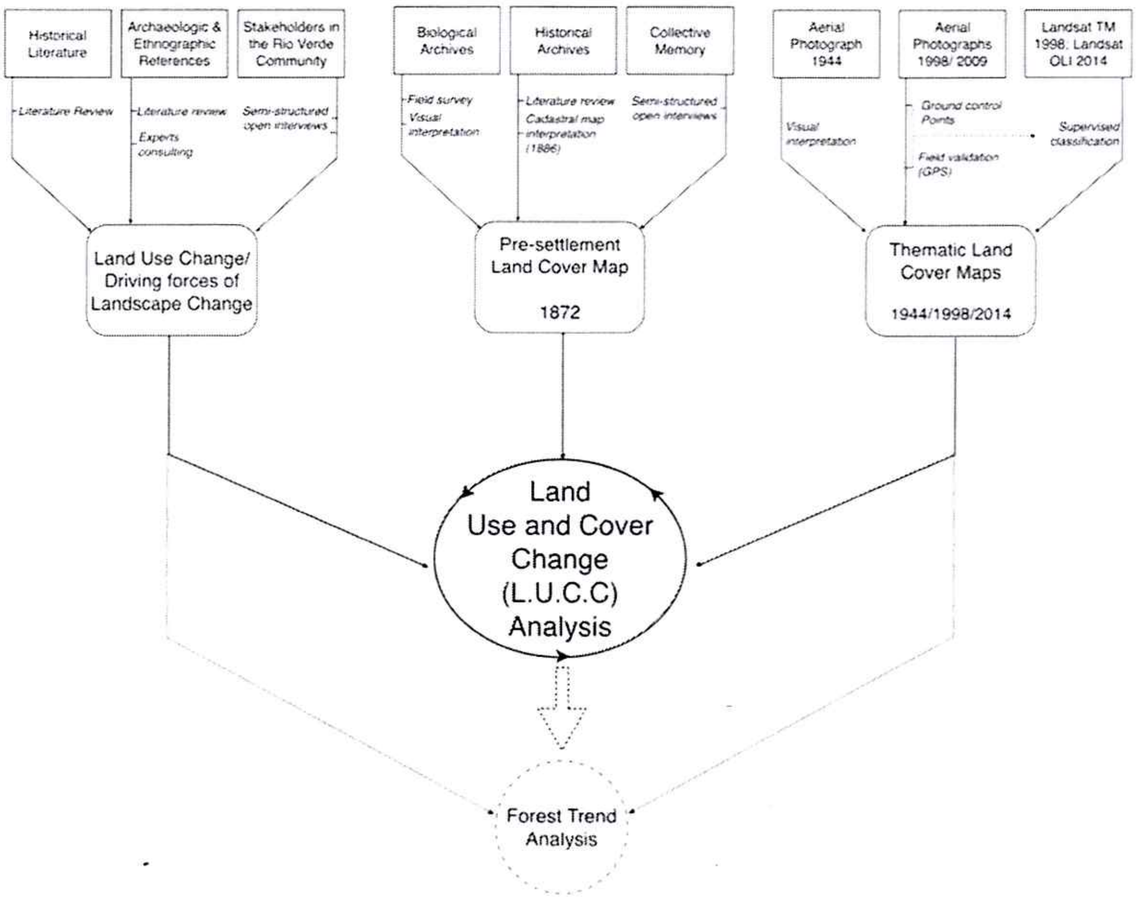

Figure 2. General methodology of this study. Square boxes on the top comprise the different historical, ethnographical, archaeological, biological and aerial (imagery) data used. Arrows show the method used for processing and analysis. Round edged boxes represent the resulting land cover maps and driving forces of landscape change identification. Finally the two spheres represent the analysis and discussion of land use and cover changes, the influential processes in the evolutionary trajectory of the landscape (Bürgi *et al.*, 2004) and the contemporary trends in *Nothofagus sp.* land cover.

General land use history

Terrestrial and maritime hunter-gatherer period

Continental Patagonia was populated by terrestrial hunter-gatherers around 12,000 BP (Borrero, 2008) during the late glacial period, as soon as biotic re-colonization gradually took place in the earlier deglaciated zones. Paleoecological records show that

Nothofagus species started covering western Patagonia and the archipelagos during late glacial period and even earlier (14 cal kys BP) (see regional review and "Río Rubens" bog by Kilian and Lamy (2012)) from glacial refugia close to the study area (Premoli et al., 2010). Charcoal levels evidence the early human use of fire during the late glacial in southern Patagonia (Whitlock et al., 2007), furthermore, pollen records analysis led by Heusser (2003) relates hunter-gatherer activities with vegetation modification by setting intentional fires.. The earliest archaeological evidence of human habitation within the study area corresponds to the Ponsonby site, located in the eastern extremity of the Riesco Island. It was shown by Legoupil (2003) to be occupied by terrestrial hunter gatherers when the separation with the continent did not exist (Fitz-Roy channel) in 8,275–7,570 cal BP. The layer shows evidence of an intensive use of guanaco (*Lama guanicoe*), typical of terrestrial hunter–gatherers, with only occasional exploitation of pinnipeds and cetaceans (Prieto *et al.,* 2013). Littoral adaptation and marine resource occupation arouses as a key process of land use change, as navigation allows for penetration in the Patagonian channels and its littoral forest utilization. Early marine occupation in the area was first proved by the discovery of the Englefield Island archaeological site in the Otway Sound (figure 1) by (Emperaire and Laming, 1961), later dated to at least 6000 yrs BP (Legoupil, 1988). The apparition of tree bark peeling artifacts, used for bark canoes or storage construction evidences the clear shift towards the littoral forest resources utilization (Martinic *et al.*, 2011); so does the numerous bone traces of the local deer *Hippocamelus bisculus* (a forest habitat specie) in the close Ponsonby site, a seldom regular food source for the navigators culture until historic times. The importance of the study area as a key origin point for the onset of navigation culture and costal border habitation in southern Patagonia has been widely proposed by Legoupil and Fontugne (1997) and by Prieto *et al.* (2013). Its nonrocky coast, open spaces and long beaches with cobbles and sometimes sand, with the almost continuous protection of littoral forest, suggests that the topography was favorable for their establishment (Orquera *et al.*, 2011).

Historic indigenous period

Technological continuity between the ethnographic or historic navigators (*Kawésqar* people) in the study area has been registered with archaeological records in the Otway and Skyring Sounds (Orquera *et al.*, 2011). Important ethnographic work was done during the first half of the XX C by the French Anthropologist Joseph Emperaire

(Emperaire 1955), describing land use and forest resources use by *Kawésqar* people. Other remarkable records exist thanks to other European explorers, such as Ferdinand Magellan, Pedro Sarmiento de Gamboa, Robert Fitz-Roy, Charles Darwin, and Carl Skottberg, among others.

There are evidences of a strong dependence of *Kawésqar* hunter gatherers with the marine and forest resources found in the littoral: constant firewood, huts for sheltering, canoes for transportation, baskets, and some weapons were proficiently fabricated using forest wood. Other artifacts such as bows and arrows were done with specially treated shrubs wood (Emperaire, 1955). According to Emperaire, Keeping fire alive was a permanent task. They would carry with them and inside their canoes a constantly ignited log, which was used for cooking as well as shaping and constructing canoes. Forest fires, even though infrequent were caused intentionally and at small scales during dry years in the littoral borders in order to keep dry fuelwood supply for future ventures (Emperaire, 1955). It is debated in nowadays if this study area was a permanently populated landscape or more like a key trading point between the *Kawésqar* from the archipelagos and the terrestrial hunter-gatherers from the Steppe. This later group, named *Aónikenk* visited the forest-steppe ecotone in the eastern zone of the study area, for either hunting Guanaco herds, or trading goods with the other group. The *Aónikenk*s were mainly habiting the Patagonian steppes, and their use of forest has been scarcely documented. Despite this, It is known both by ethnographic records and with a pollen analysis study done only 40 kilometers from the study area in a limiting forest, that their intentional fires for grouping and hunting the guanaco herds ("*corral games*"), would sometimes reach the ecotonal forests (Veblen and Lorenz, 1988; Huber and Markgraf, 2002).

Colonization period

Following the discovery of the Magellan Strait by Ferdinand Magellan and a series of military and scientific expeditions along with a failed intent to establish a Spanish colony in southern Patagonia, first economic relations with the territory started with the growing interest of European whalers and sealer ships in the archipelagos. Although no land based colony was established until the mid XIX century in the region, European contact already had impacted the species composition of the vegetation (Huber and Markgraf, 2002) along with the aboriginal population (Emperaire, 1955), who's numbers started reducing due to food scarcity (competition with European sealers) and European-introduced diseases. The first European expedition that reach the Otway and Skyring Waters was commanded by Phillip Parker King and Robert Fitz-Roy from 1826 to 1830 AD. They took detailed records on the landscape and land cover state, and the existence of numerous *kawésqar* families established along the study area. Later contact was established after the foundation of Punta Arenas in 1843 in the Magellan Strait (96 km from the study area), when first coal mines established with little success and in specific places of the Skyring costal borders between the 1880 and 90'. The incipient mining activities along with first settlers arriving in that district accelerated the establishment of small-scale farms, cattle herding, and logging. The process historically known as "*apertura de campos*" consisted in high grading logging for sawing and generating canopy gaps in the forest so that grass (sowed pasture species) could grow for feeding the animals. The Fire was used after logging at a small-scale for localized pasture establishment. Carl Skottsberg (1911) found material remnants of indigenous groups in 1909 along the study area, suggesting still the sporadic presence of these groups. By 1910, most of the Skyring costal zones (both in Riesco Island and Continent) were under European use, and sheep introduction, along with larger sawmills started operating in the area. Coal mining continued as an important activity, with documented impacts over the island's forest cover depletion, until 1950' when coal business collapsed. From 1911 to the 1950' the property of land was concentrated in few large financial capital groups, such as the *Sociedad Explotadora de Tierra del Fuego.* They received large land concessions from the Chilean government, displacing many of the previous small farmers. Large scale forest logging and burning of the remaining useless wood, set the startup for what is close to the present landscape: Large grazing pastures over the dead remnants of the old growth forest. Last *kawésqar* families were seen in the Skyring coast of the Riesco Island in 1944-45. During all this time, and according to ethnographical testimonies, some of the last nomadic *Kawésqar* people, gradually disappeared along with their littoral habitat. The last *Kawésqar* died in 2003 (Martinic *et al.*, 2011).

Recent Period (1950 – 2014)

A crisis of the traditional colonization system in the region along with the closing of coal mines in the territory, caused depopulation and land abandonment. Since 1953 up to 1970' A new land re-distribution process named by Martinic *et al.* (2011) as "shepherding recolonization" began by the re-concession of large estates still belonging to the state; divided into smaller family owned farms. This was later followed by the *national agrarian reform* (land property reform), which promoted land re-distribution of the land into smaller scale properties and the development of incentives in order to promote a re-population of the territory. The use of fire to clear forest was banned, which significantly decreased the rate of forest depletion. This was also associated with. silvicultural activity, which in 1970 took place in localized areas of the Skyring continental coast and in the Riesco Island.

Modern forest management continued through the next 2 decades by clear-cutting and more recently by "variable retention" silvicultural systems. A worldwide crisis of the wool industry during 1980' generated a change in the productive activities of the territory, decreasing the overall sheep population and increasing cattle raised as livestock for meat (INE, 2007), changing the whole grazing regime in Rio Verde. During this time, economic slowdown forced a partial depopulation of the land. Parallel, During late 1970' and mid 1980' during Chile's military regime, the state gave in concession to private mining companies a vast amount of the recently discovered subsoil Coal reservoirs for its exploitation (Martinic, 2004), whose operations started in 2010 along the southern coast of the Riesco Island; and because of the nature of open-sky mining, there was again vast exploitation of natural forests and pastures. Currently, property distribution is vastly concentrated in comparison to the situation of the "shepherding recolonization" period, with few mining and livestock companies owning much of the rural territory. At the same time, a contrasting array of interests in the use of Rio Verde's natural resources are faced between ranching, tourism, coal mining and wildlife conservation.

Data sources

Historical archives

The earliest primary historical sources used are land survey records from naval scientific and hydrographic expeditions, the first one dating between the years 1826 and 1836 by Phillip Parker King and Robert Fitz-Roy voyage on *the Beagle*, and who's records on landscape description on vegetation are precise in certain geographical locations. Later expeditions commanded by the Chilean navy in 1877 contain precise data to certain locations of the coastal border of the Skyring and Otway waters, both sea inlets in the study area (Latorre, 1878). A land survey map created by the topographer Alejandro Bertrand in 1885 for the ministry o colonization contains the most accurate land cover and vegetation structure of pre colonization times for most of the continental surface of the study area. The early limits of forest cover are described in this archive during the onset of the start of the colonial process (Bertrand, 1886), and represented in a topographic map at a scale of 1:250.000. The insular surface (*Riesco Island*) was not surveyed by this expedition. Other primary references to the pre-colonization landscape were found in Pacheco (1908) and Skottsberg (1911) during the Swedish expedition to Patagonia during 1907-1909, providing relevant records of land cover of the insular surface (*Riesco Island*). Even though some of these sources were produced shortly after the onset of colonization, their records in certain geographical locations are considered to be valuable for the data processing and land cover map delineation for pre-colonization times.

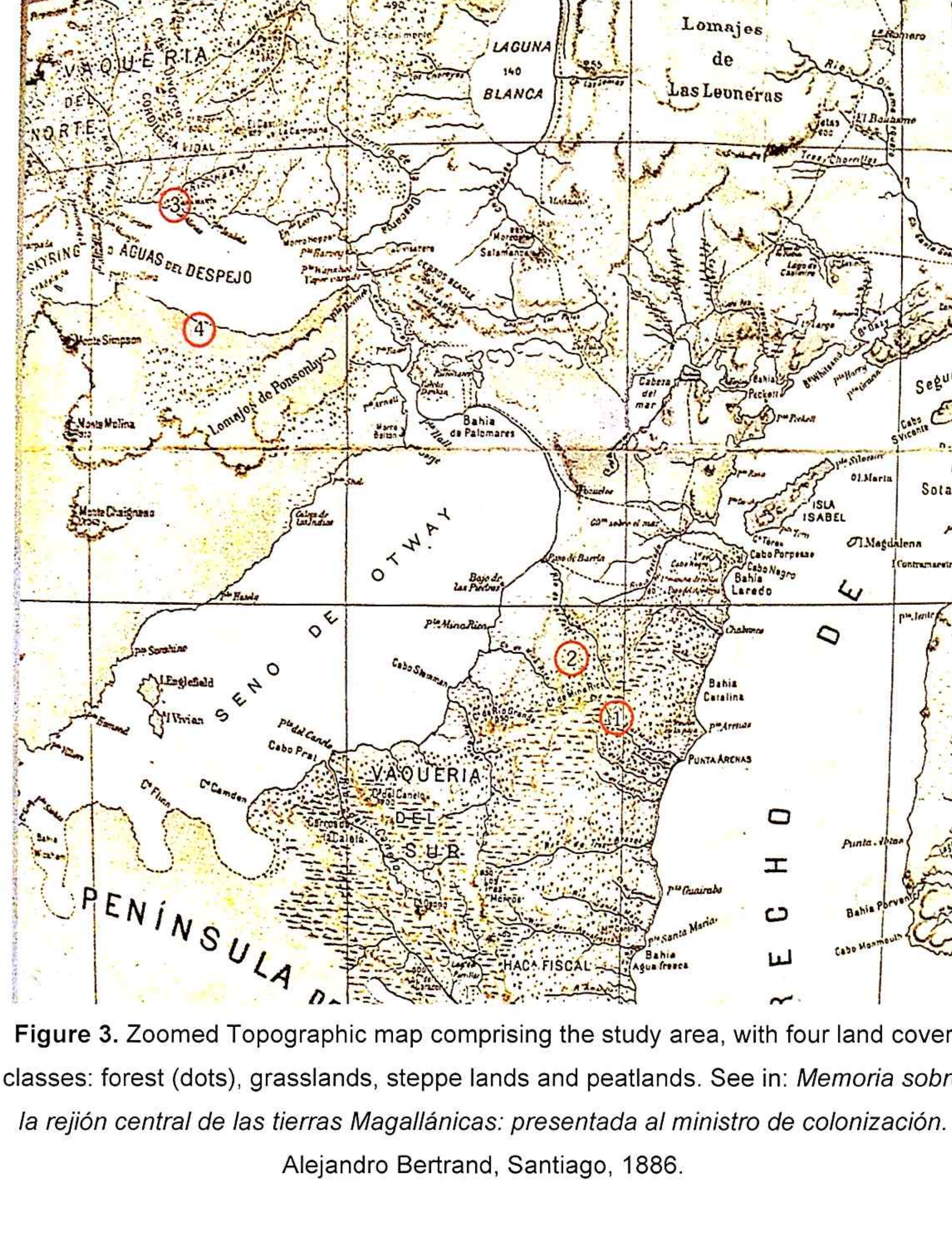

Figure 3. Zoomed Topographic map comprising the study area, with four land cover classes: forest (dots), grasslands, steppe lands and peatlands. See in: *Memoria sobre la rejión central de las tierras Magallánicas: presentada al ministro de colonización.* Alejandro Bertrand, Santiago, 1886.

Oral information

Semi-structured open interviews were applied to 10 key stakeholders in the study area, which together are land-use decision makers over 44% of the study area surface, including land owners, farm workers, and communal administration personnel, for documenting both general and particular changes in land use over history, and for recent trends in forest cover under present environmental and land use conditions. Interviews were recorded and later analyzed as a complementary source of land cover maps (Newing *et al.*, 2011).

Biological Archives

Transects all along the main coastal roads of the study area were made, geographically registering in GPS the different land cover classes, both as ground truth points for later image classification, and for the detection of burned wood. Burned logs and stumps served as material proof of earlier forest cover. Field validation along with the high-resolution 2009 aerial photograph was used to interpret visually the burned logs and stumps covering the land.

50 m transect were made within forest-pasture borders in the selected farms as ground truth validation for the recent (1998-2014) natural afforestation; vegetation structure, high and average DAP were registered; the presence of animal grazing over forest regeneration was also registered.

Aerial photography and satellite imagery

Aerial photographs of the national survey flight "Trimetrogón" of the year 1944 (the earliest official aerial records of the region) were used when available for some parts of the study area as a 1:20.000 reference state of the vegetation cover during the colonization period. For recent times mapping, one 1998 Landsat TM and one 2014 Landsat OLI satellite images were used. Both selected images were captured during the vegetation growth season to ensure the detection of deciduous *N. pumilio* and *N. antartica* forest, selecting the ones with better quality and less cloud cover. Even though the Landsat TM records go back to the year 1984 in the study area, the constant cloud cover and poor quality of images did not allow the use of older, nor more frequent landscape image analysis. As a source of control points of Landsat imagery classification, two sets of aerial photographs were used through simple visual interpretation, one from 1998, for the 1998 TM image and one from 2009 for the 2014 OLI image. Information about the processing process can be seen in the *Data Processing* chapter.

Data Processing

The 1998 and 2014 Landsat images were radiometrically corrected in a raster analysis software using the red, green, blue, near infra red and short wave infrared, to reflectance. Atmospheric correction was applied to both using the dark object subtraction method as used by Chavez (1988), and recommended by Song *et al.* (2001). 93 Regions of interest (ROI) were created for each land cover class as a vector file for both images using both the ground validation points taken in the field and high-resolution aerial photography. Classes established were; *dense forest* (for the *N. pumilio* and *N. betuloides* forests); *semi-dense forest* (for *N. antartica* – shrub species associations); *shrublands*; *grasslands*; and *peatlands* (Table 1). Supervised classification using maximum likelihood parameters was conducted over both 1998 and 2014 images using 177 ground-truth validated GPS points and the high-resolution aerial photographs as validation reference. Post classification analysis was conducted obtaining Kappa values of 0.97 and 0.98 for 2014 and 1998 images, respectively (Table 2). The good quality classification was overall demonstrated.

Table 1. Land use classes description for image classification.

Land cover class	General description
Dense forest	Forest areas with estimated 70% and above of canopy density. The predominant species are: *Nothofagus pumilio* And *Nothofagus betuloides* with presence of *N. antartica* towards the East and *Drymis winteri* in humid, western littoral ecosystems. Range of height between 12-20 meters.
Semi-dense forest	Forest areas with estimated canopy density between 40 to 70%. Predominant species are *N. antartica* in most of the transitional forest-steppe zone and *N. pumilio* towards the west, sometimes accompanied by *N. betuloides* along the edge effect of secondary forests. Range of height between 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.

Table 2. Accuracy assessment of supervised classification of the two Landsat Images.

Year	Overall classification Accuracy	Overall Kappa Statistics
1998	99.1 %	0.91
2014	99.6 %	0.97

An ASTER digital elevation model (DEM) was obtained from the USGS (ASTER GDEM is a product of METI and NASA) with a 1-meter resolution to improve the image and thematic map visualization and for further data analysis. Hydrographic system, Isohyetal lines (precipitation), land tenure structure, roads and main geographical attributes of the study area were collected from the regional government (Gobierno Regional de Magallanes) and systematized in a common geographic database for further analysis.

1944 aerial photographs were digitalized and georeferenced in a GIS software, using the Georeferencing tool. Vertical images were georeferenced with visual interpretation over a DEM raster image and 2014 Landsat Image. Even though 1944 flight lines and images do not cover the whole of the study area and there is a lack of image availability, a representative array of subset photographs was selected for further spatial analysis. Land cover classes were defined as *forest* and *non-forest* since it was not possible to differentiate between more specific classes. *Non-forest* comprised what in the 1998 and 2014 maps were the *shrubland*, *grassland*, *peatland and bareland* classes; and 1944 *forest* class comprised the *dense* and *semi-dense forest* classes.

Historical records of the pre-colonization landscape, topography, and hydrographic maps, along with the written descriptions of the past land cover structure previously mentioned, were georeferenced in geographical points as a database for the delineation of land cover polygons of the time. A new map was produced bases on the combination and analysis of the mentioned records, representing two classes of vegetation cover: *forest* and *non-forest* vegetation for the pre-colonization period. The 2014 land cover map was used as a spatial basis for the construction of the pre-colonization land cover map. The spatial extent of the 2014 forest cover was "expanded" to the limits of the pre-colonization forest cover with both visual interpretation of the burned stumps and logs cover in the high-resolution LIDAR 2009 aerial photography (figure 4). The shrub lands and pastures were grouped under the "*non forest*" class because of the lack of precise data for their differentiation in the selected time period. The peat lands were represented in this map with the same spatial distribution as in the 2014 land cover map since insignificant spatial variation is expected in such a time frame for this vegetation communities. Visual interpretation of burned wood was supported with historical data and observations.

Figure 4. LIDAR photograph example from the study area clearly showing the remnant dead logs in cream coloration.

Data Analysis

Land cover change detection

Thematic land cover maps were analyzed in ArcGIS software for the class statistics calculation. 2014 and 1998 land cover maps (Landsat-based) were analyzed in a raster format; the 1944 subset land cover maps and the pre-settlement map were analyzed in a vector format. Class statistics were calculated in hectares and percentage. For describing and analyzing the recent trends in afforestation/deforestation of the forest cover in the present land use context, a land cover change analysis was performed between 1998 and 2014 land cover maps. Using the Change detection difference map tool from ENVI software (version 5.0), we constructed a land cover change map, which spatially locates in classes the pixels, which experienced vegetation change between both dates. Each class represents an ecological process associated with afforestation/deforestation dynamics, showing in green color, those pixels that experienced a change from non-forest (shrublands, grasslands, peatlands and barelands) to *dense forest* class; in blue, those pixels that experienced a change from *semi-dense* to *dense forest*, representing an increase in canopy density; in yellow those pixels changing from *dense forest* to *semi-dense forest*, indicating possible forest degradation or simple canopy opening; in red the change from any of the forest classes to a non-forest cover class (deforestation process). This analysis compliments the general class statistics analysis by putting into a geographical location each of the mentioned changes.

Land Use change analysis

Collected and classified land use historical and contemporary data was analyzed considering both general land use changes and more specific human use dynamics over forest resources as requires the focus of this study. Main Social and ethnic changes were recorded and classified within certain time periods. The economical, political and demographic context was also taken into account when describing and discussing ecological changes. Land division dynamics was evaluated over main environmental changes that affected forest cover (e.g. changes in public land concessions; Property subdivision; forest fire banning). Present land use dynamics in the Río Verde Community, obtained from the semi-structured open interviews were classified for each visited farm, and analyzed about the land cover change map, for the discussion about possible land use effects (e.g. cattle grazing over *Nothofagus* regeneration capacity) over natural forest regeneration. Land use change was chronologically calibrated on a logarithmic scale, with main ecological changes in figure 5 as in Marcucci (2000).

3. Results

Thematic land cover maps

Three land vegetation cover maps were obtained for years 2014, 1998 and 1944 and one was obtained for the pre-settlement period (before year 1872) (figure 2). General land cover surface was expressed for each class in table 2, both in surface (hectares) and percentage of cover. Water surface was not considered in the study area's surface.

Difference in total study area surface was found between each of the three maps, probably due to an error in the automated area calculation process in GIS software, or due to differences of classification over the costal border, on which exact classification is hardly exact between bare soil and seawater. This difference was considered insignificant due to the study area magnitude and the lack of importance of these two classes in this study. Each map is chronologically presented as follows:

Pre-settlement land cover map

One land cover map was created for the time previous to European and Chilean settlement in the area (1872), being this, the reference state of the landscape and its ecosystems. Previously mentioned historical sources such as cadastral maps, land tenure archives, scientific and hydrographic expeditions records and biological archives (e.g. remaining dead wood and burned stumps), show a clear domination of *Nothofagus sp.* forest ecosystems from the onset of the western channels to the west in the Skyring and Otway sea inlets, following the coast line with a dense littoral forest.

The southern coast of the Riesco Island (northern *Otway* sea inlet) was in its western side, in Robert Fitz Roy's words (1839): *"thickly-wooded with evergreens"* (p.224) and further east, covered with *"stunted bushes and trees... trees were not evergreen, and at this time their leaves were withered and falling"* (p.226) which is coincident with Swedish scientist exploring the area, Carl Skottsberg (1911), who describes the southern coast of the Riesco island: *"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 (Nothofagus pumilio), which reigns alone for a short stretch" (p. 64).* When Skottsberg refers to *evergreens,* he refers to *N. betuloides* forest, which distribution was confirmed in terrain towards the western side of the southern coast of the Island, where rainfall availability and humidity are higher, whereas *N. pumilio* has higher presence towards the eastern side of the island, later mixed with *N. antartica.* This descriptions are reflected in figure 5 contrasting with the landscape's present condition, where forest cover is no longer present at the coast line, but only further inland.

Further North and East, along the Fitz Roy channel which connects the *Skyring* and *Otway* Waters, Fitz Roy (1839) describes its southern entrance as a *"woody country, extending towards Tierra del Fuego (East)"* (p.228), and further north in the continental plains of the channel *"No tree was seen; the soil seemed dry, rich ,and light"*

(p. 229) *"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"* (p. 571). This last description proves that the North Eastern corner of the Riesco Island was in the past naturally covered by grasslands and shrublands as it is today. Skottsberg (1911) saw at his time 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. antartica form a brushwood. Of course these changes depend upon the climatic conditions, especially the decreasing rainfall"* (p. 65). A very similar vegetation distribution was seen during field validation in this study, *N. antartica* forest presents lower canopy density and more sparse distribution due to fire and anthropic degradation (figure 8).

The Eastern coast of the Skyring water was covered by grasslands and shrublands until *chorrillo la descarga* (in eng.: la descarga stream), where according to the Chilean topographer Alejandro Bertrand (1886) *"arboreal vegetation distinctively increases; first small sparse Robles (N. antartica) appear, increasing little by little and forming compact woods to the North"* (p. 22), adding that *"the land covers completely with forest from the Ensenada cove"*. This record, along with most of Bertrand's notes over all of the Northern Skyring coast and inland are specially precise for the date, since not only he wrote description of general forest structure along his path, but also he took coordinates in many of his description locations, in addition to his cadastral map (figure 3) showing a forest cover thematic class. Further West and all along the Northern Skyring coast, Bertrand describes a very dense forest cover, a description that is also validated through our field campaign and through visual interpretation in high resolution aerial photographs, with remnants of burned wood, logs and stumps all along the coast and inland country.

Before European and Chilean settlement, the Northern coast of the Riesco Island was covered by dense *Nothofagus sp.* forest, although littoral forest along the coast line was, in this study, only proven to be present from 71°46'56"W & 52°42'7"S to the west, since no burned wood remnants or stumps were found along the coast to the East of the island, suggesting that natural steppe grasslands and shrublands prolonged from East to West in a narrowing stripe in between 50 to 100 m.a.s.l. No historical records were found for this part of the study area.

Total pre-settlement *forest* cover accounts for 66% of the study area (178,480 ha) (Table 4). *Non-forest* vegetation (shrublands and grasslands) covered 20% of the total surface, 25% less than in present times (2014). *Other* land cover accounted 14% of the study area (38,195 ha).

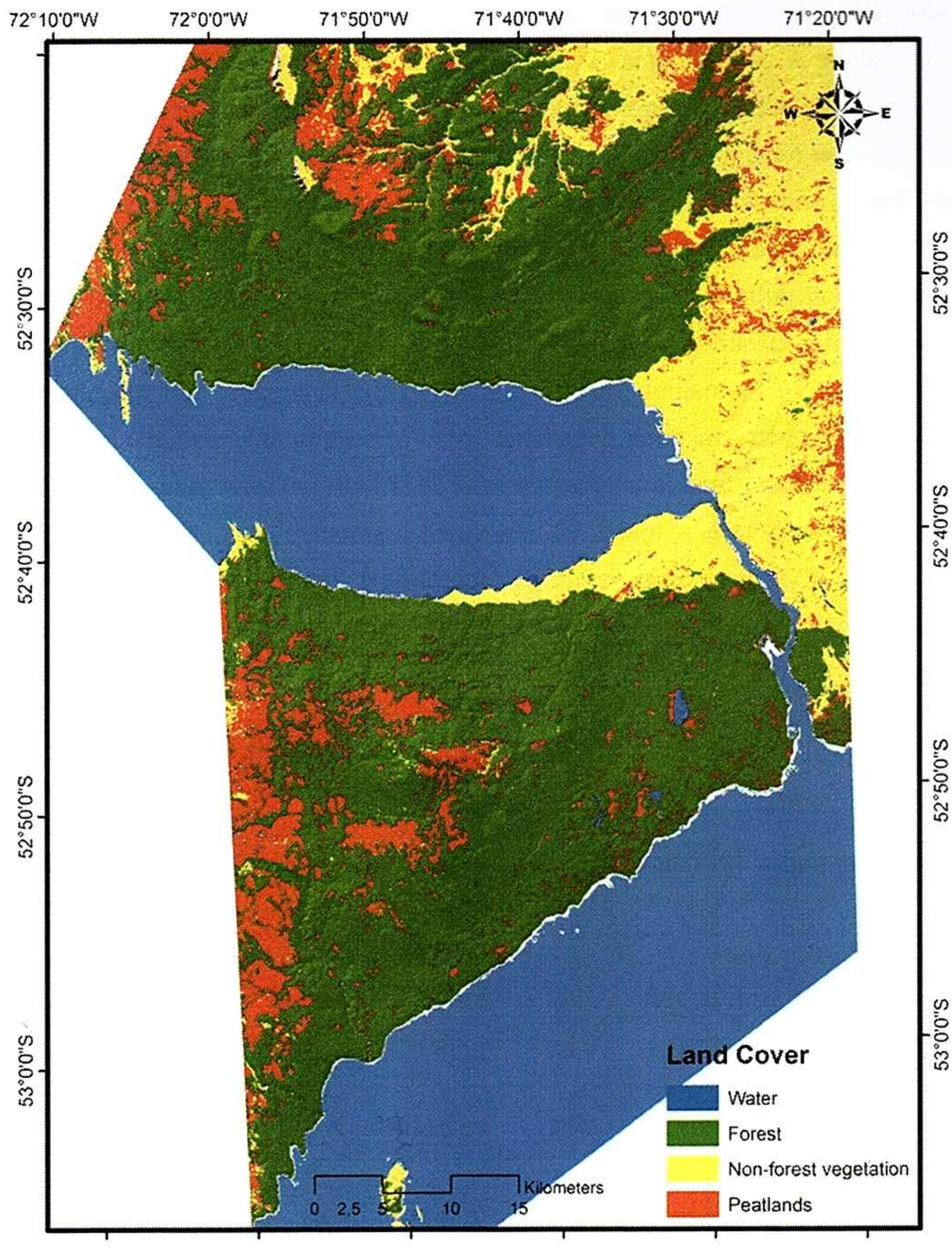

Figure 5. Pre-settlement land cover map showing the extension of forest cover (green) and non-forest vegetation (yellow) in the study area until late XIX century.

Land cover subset map 1944

One land cover map from year 1944 *Trimetrogon* aerial photographs was obtained according to the procedure detailed in the data processing chapter. A spatial subset of 54,783 ha (approximately 20% of the total study area), represented in vectors the space covered by the aerial photographs set (figure 6). Since no distinction was possible via visual interpretation between dense and semi-dense forest, only one forest class is visible. Shrublands were not distinguishable with grasslands in visual interpretation, so they were grouped under the *non-forest* class. Peatlands and other cover classes as bareland and snow were classified as *other* land cover. In order to compare this land cover map with the present (1998-2014) and the pre-settlement (≈1872) land cover maps, a spatial subset was applied to both, calculating each land cover class area as in table 3. Forest cover was by 1944 a 60% of the spatial subset (33,006 ha), 17% less than during pre European settlement times and 27% higher than present times (1998 land cover spatial subset map). Non-forest vegetation accounted 27% (15,032 ha) of the spatial subset, 18% higher than in the pre-settlement subset land cover map, and 18% less than in present times (1998). Other land cover (peatlands, bareland and snow) added 12% of the spatial subset, little variation in comparison to pre-settlement map (13%) and 1998 map (14%).

Table 3. Land cover change between years 1880, 1944 and 1998 within the 1944 *Trimetrogon* aerial photographs spatial subset.

Land Use	1880		1944		1998	
Class	hectares	%	hectares	%	hectares	%
Forest	42297	77.2	33006	60.2	22707	41.2
Non-forest vegetation	5155	9.4	15032	27.4	25059	45.4
Other	7358	13.4	6744	12.3	7393	13.4
Total	54810		54783		55159	

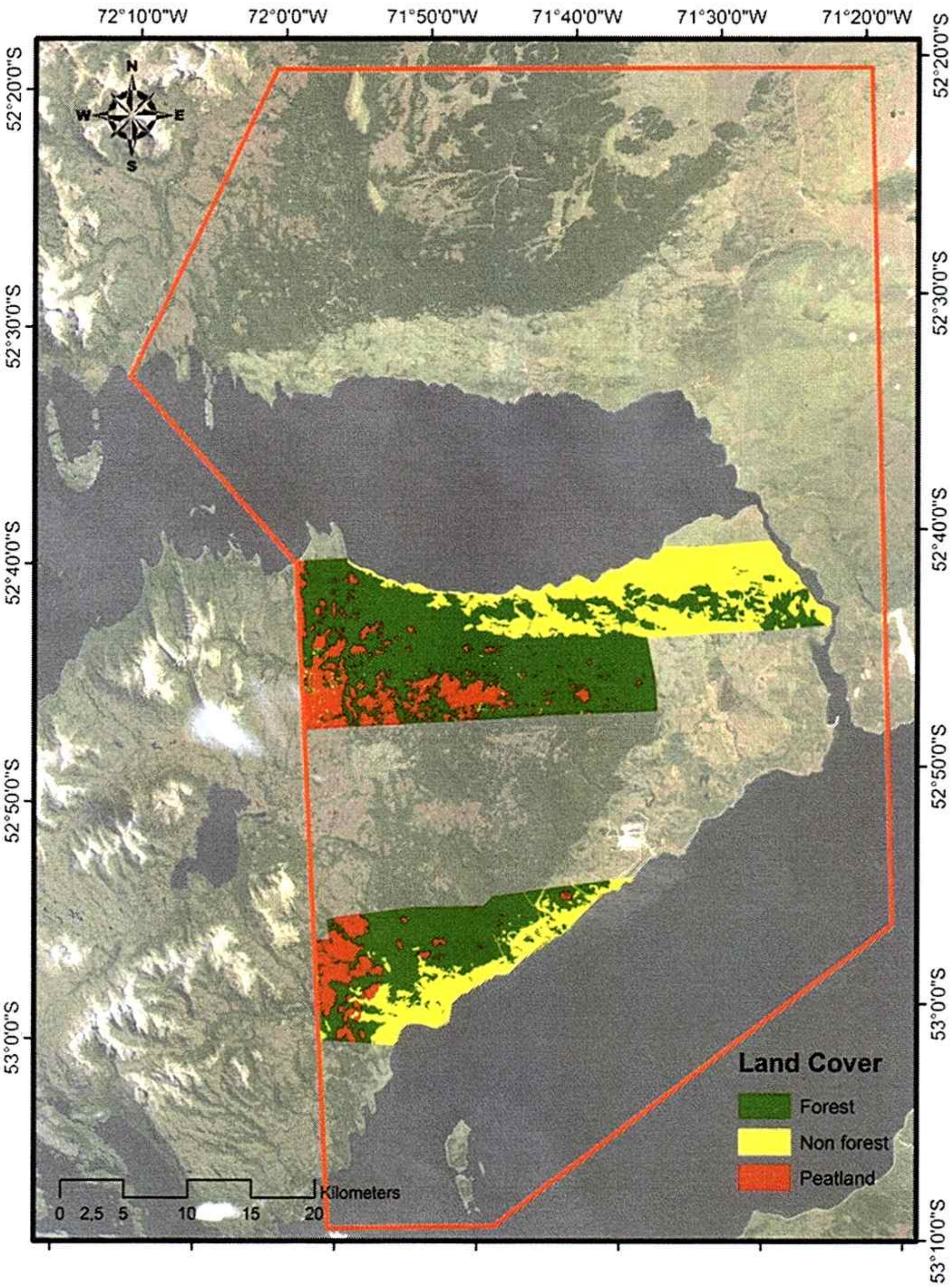

Figure 6. Land cover subset map for year 1944 during the peak time of colonization.

Land cover map 1998

Obtained from the supervised classification applied to the 1998 Landsat TM image as described in the *data processing* chapter, this map accurately represents each of the classes within the selected study area (figure 7). Dense forest accounts for 34% cover (92,364 ha) of the total surface (table 4); Semi-dense forest has a cover of 6% of the study area (17,465 ha), mainly present in the eastern coast of the Riesco Island and eastern inland country of the northern Skyring inlet coast, both places within the most abrupt climatic transition zone from the eastern steppes to the western channels, a zone precisely described as a transitional shrub land and *Nothofagus antartica* semi-dense forest. Shrublands cover a 12% of the study area (31,781 ha), mainly located within the northeastern part of the Riesco Island, and further east in the continent, mixed in many cases with *N. antartica* cover. Grasslands cover the biggest portion of the study area with a 35% (93,707 ha). Peatlands cover a 12% (32,377 ha); Areas with no vegetation cover are represented as bareland with a 1% (2,458 ha) and snow cover with less than 1% (353 ha).

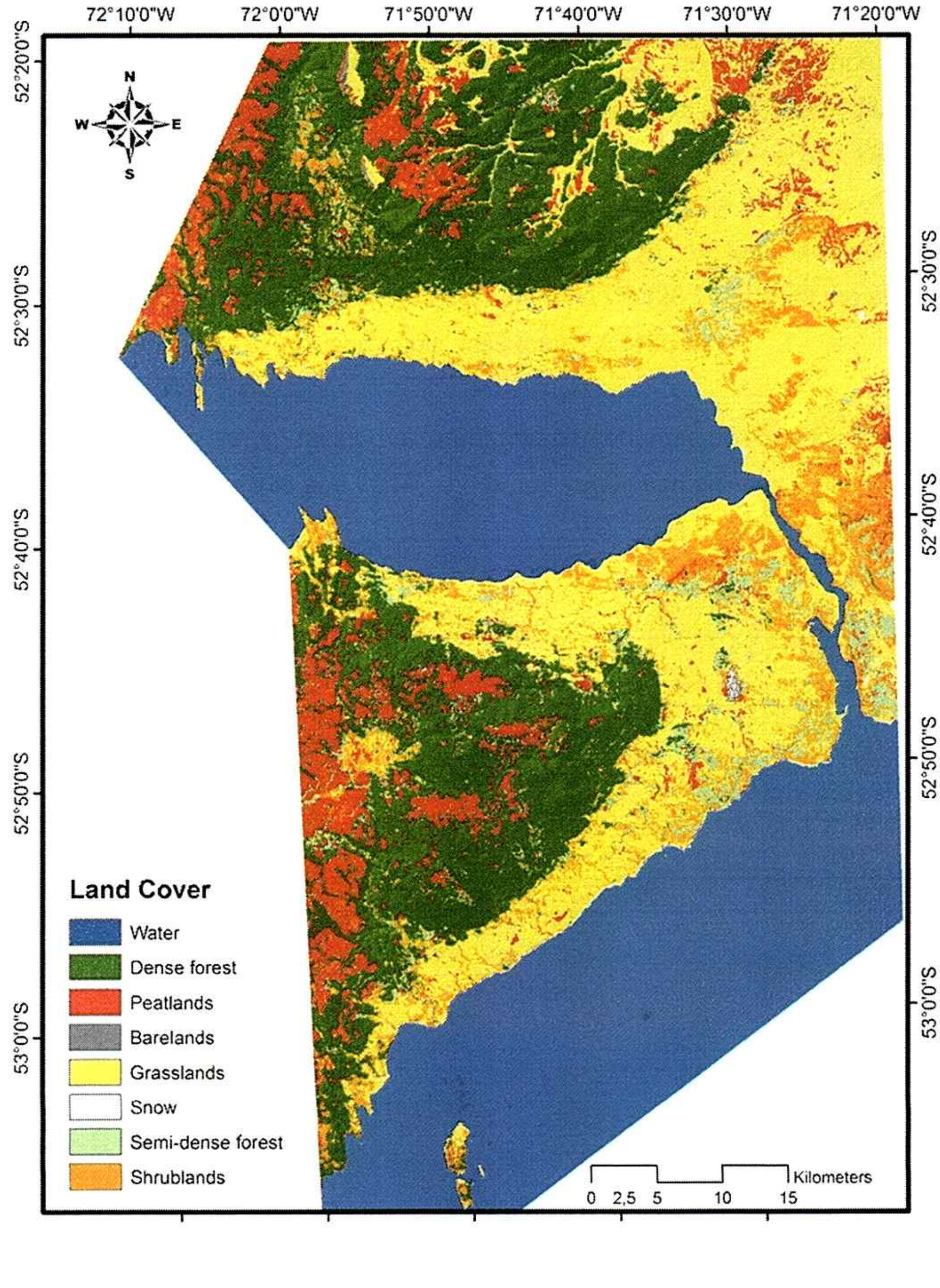

Figure 7. Land cover map for the year 1998

Land cover map 2014

In year 2014 (Figure 8), mixed *N. pumilio* and *N. betuloides*, represented as dense forest cover, accounted for 36% (96,494 ha) of the total surface (table 4), showing an overall increase of 2% between year 1998 and 2014. Semi-dense forest covered 5% of the study area (12,763 ha), 0.1% less than earlier 1998 cover. Shrublands covered 9% of the study area (23,341 ha), showing a decrease of 3% cover by year 2014. Grasslands covered 39% (106,410 ha) of the total land surface, 4% higher than earlier 1998 map. Peatlands account for 11% (28,748 ha) of the study area; barelands cover 1% (2,127 ha) and snow, less than 1% (496 ha).

Table 4. Total land cover surfaces (hectares) and percentages (%) of each specific vegetation class (years 1998 and 2014) and broad vegetation classes (year 1880).

Land Use Class (1880-1944)	Land Use Class (1998-2014)	1880		1998		2014	
		hectares	%	hectares	%	hectares	%
Forest	Dense forest	178480	66.1	92364	34.1	96494	35.7
	Semi-dense forest			17465	6.5	12763	4.7
Non-forest	Shrublands	53407	19.8	31781	11.7	23341	8.6
	Grasslands			93707	34.6	106410	39.4
Other	Peatlands	38195	14.1	32377	12.0	28748	10.6
	Bareland			2458	0.9	2127	0.8
	Snow			353	0.1	496	0.2
	Total	270082		270505		270380	

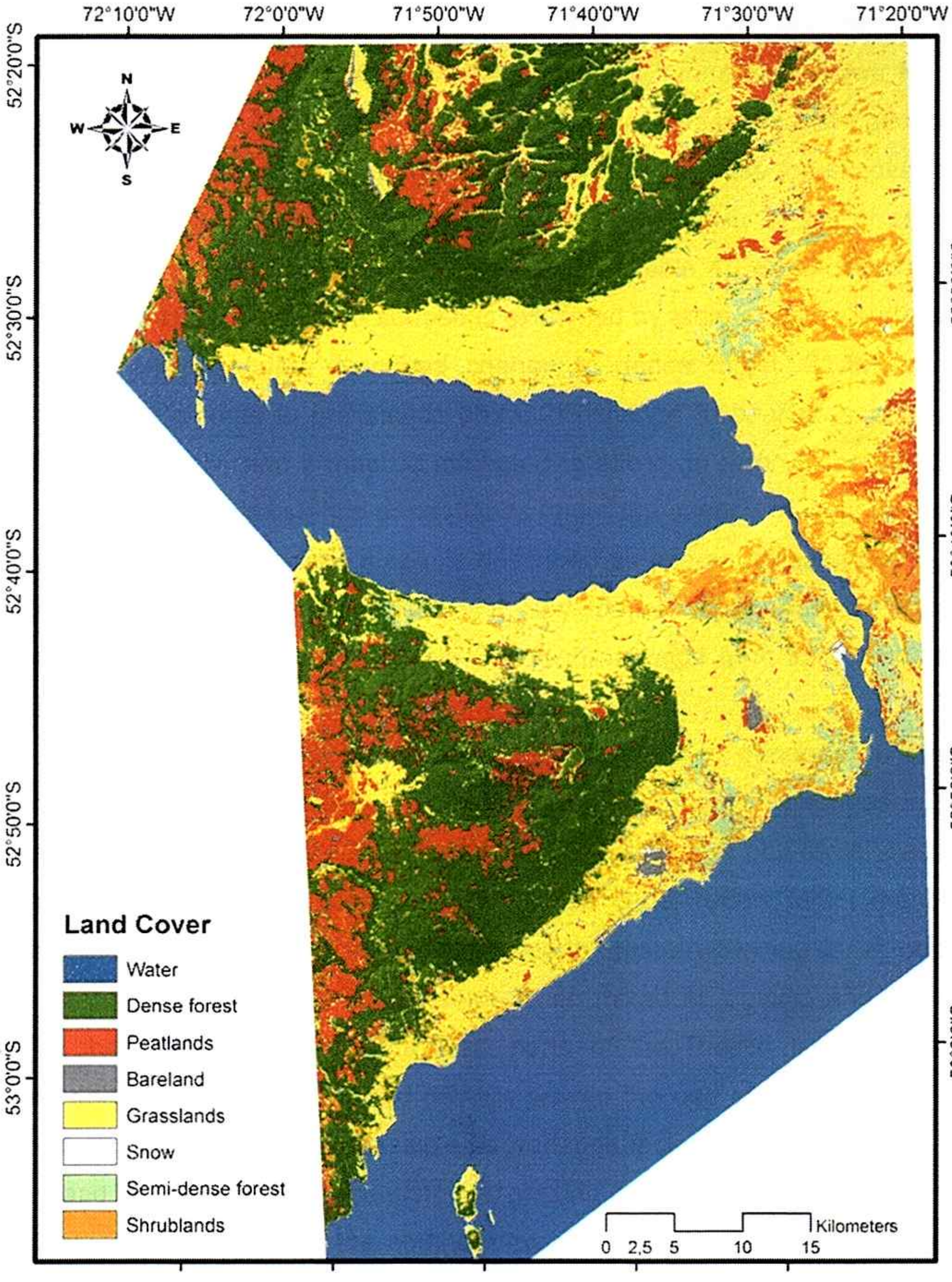

Figure 8. Land cover map of the year 2014

Nothofagus sp. forest land cover trends

Land cover change detection between years 1998 and 2014 was obtained for each of the classes changing into other classes (table 5). This information allows for a more complex analysis of recent vegetation trends in this time series than mere general gains and losses of each class. Therefore, the 2% net increase of *dense forest* cover over the total surface (table 2) is majorly explained by the reduction in 27.2% of *semi-dense forest*, 7.4% of *Shrublands* and 0.3% of *Grasslands* (Table 4). *Semi-dense forest* net decrease of 1% of total study area surface is explained by table 4, where surface losses are explained by previously described change to dense forest, 21.5% change to *shrublands*, 8.9% change to grasslands and 6.2% change to *peatlands*, although this last change is unlikely, and it may be attributed to either an error in the classification process or to the actual existence of peatlands under the canopy of semi-dense forest, often composed by *N. antartica*, a specie described as tolerant to saturated soils. Not only negative change was observed over *semi-dense forest* surface, but partial increase (not net increase) was possible due to the change from *shrublands* (11.2%) and *grasslands* (0.7%) (Table 5).

In order to identify the spatial location of land cover changes, a land cover change map was obtained between 1998 and 2014, aggregating changes in the four classes of figure 9. Land cover change from a forest class to a non-forest class (figure 9) as concentrated either in zones validated to be under recent forest management (harvest) (central part of the Riesco Island; North western Skyring inner coast; and North east corner of the study area); semi-dense mixed *N. pumilio and N. antartica* forests in the South-East and North-East parts of the Riesco Island, where field validation and oral interviews to land owners proved the use of this forest as grazing lands for livestock, suggesting a possible degradation factor, confirmed in one farm by its owner and by the high presence of animal grazing over forest sprouts. A more recent deforestation factor is seen in the southern coast of the Riesco Island, where a coal mine started functioning in year 2010, clear cutting dense and semi-dense forest patches and converting it in to *bareland* class (figure 10).

Changes from *semi-dense forest* to *dense forest* (27.2% of the first class area) occurred mostly along major forest borders (colored in blue in figure 9), or along "gaps" within these major size forests, like as occurring in the Northwestern part of the Skyring Northern coast (figure 9), within a former forest management area during 1980 and

1990 decades. This land cover class change rarely occurs in isolated as seen in figure 9. A similar pattern is observed in the change from non-forest classes to any of the forest classes, colored in green in figure 9, which occurs along major forest borders (with grasslands or shrublands), or inside gaps where managed areas (clear cuts) were field validated during the campaign. Changes from non-forest to forest classes are also observed in the eastern portion of the study area within former semi-dense forest patches. Further analysis of these *Nothofagus sp.* land cover trends will be discussed in the discussion chapter.

Table 5. Percent of land cover that was converted from each of the classes into the rest between 1998 and 2014.

Changed from	Changed to	Area change (ha) 1998–2014	Percent change 1998–2014
Dense forest	Semi-dense forest	1101.3	1.2
	Shrublands	1008.8	1.1
	Grasslands	1435.8	1.6
	Peatlands	438.6	0.5
	Bareland	27.3	0.0
Semi-dense forest	Dense forest	4747.3	27.2
	Shrublands	3750.8	21.5
	Grasslands	1555.9	8.9
	Peatlands	1082.9	6.2
	Bareland	55.4	0.3
Shrublands	Dense forest	2337.8	7.4
	Semi-dense forest	3549.3	11.2
	Grasslands	10603.1	33.4
	Peatlands	4098.5	12.9
	Bareland	137.9	0.4
Grasslands	Dense forest	241.9	0.3
	Semi-dense forest	660.3	0.7
	Shrublands	3556.4	3.8
	Peatlands	2753.1	2.9
	Bareland	444.6	0.5
Peatlands	Dense forest	878.8	2.7
	Semi-dense forest	1167.6	3.6
	Shrublands	3888.1	12.0
	Grasslands	6191.7	19.1
	Bareland	55.8	0.2
Bareland	Dense forest	43.2	1.8
	Semi-dense forest	8.3	0.3
	Shrublands	61.3	2.5
	Grasslands	598.6	24.4
	Peatlands	173.6	7.1

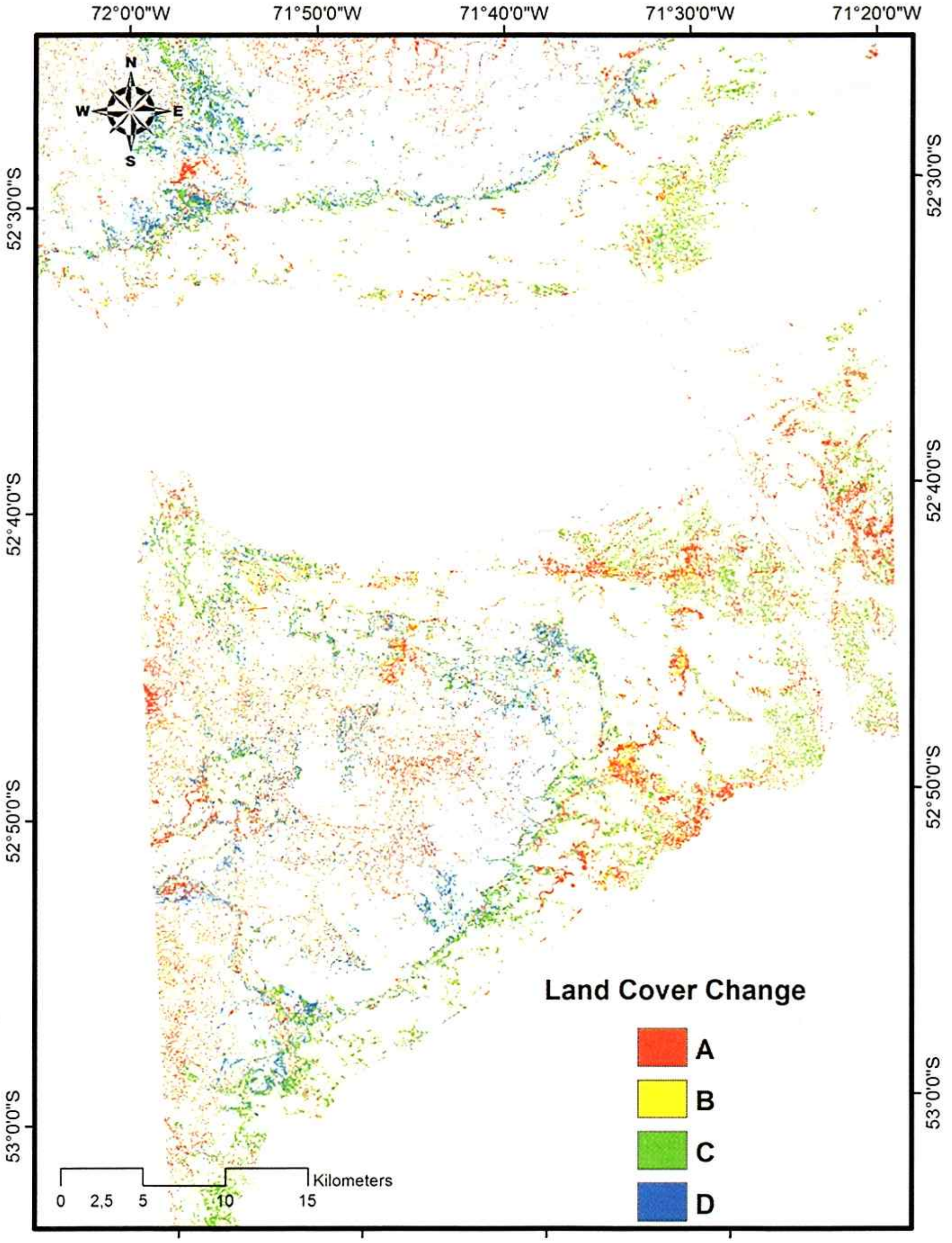

Figure 9. Land cover vegetation change map from year 1998 to 2014. (a) Surface changing from a forested to a non forested land cover class; (b) change from *dense forest* to *semi-dense forest*; (c) change from a non forested to a forested land; (d) change from *semi-dense forest* to *dense forest.*

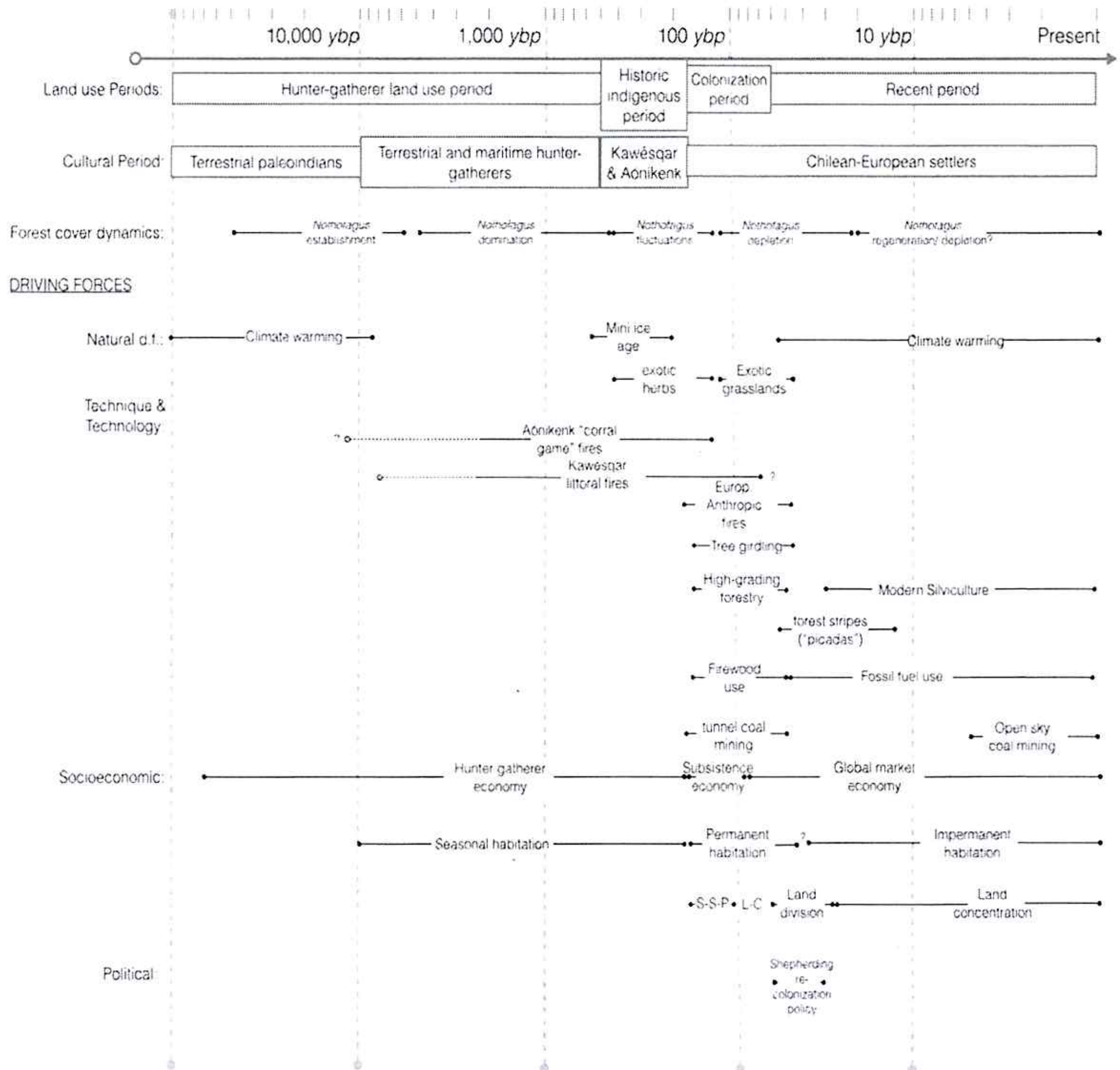

Figure 10. Timeline in logarithmic scale of land use periods, cultural periods, forest cover dynamics and their related driving forces of landscape change at the Río Verde municipality. S-S-P: Small-scale properties; L-C: Land concentration; ybp: years before present.

4. Discussion

Landscape change and driving forces

Our results show a clear relationship between the general land use historical periods and land cover patterns evaluated during the time lags we used in our maps. Hence, during indigenous land use, the effects of anthropic transformations over the natural system were low regarding variations in forest cover. At an ecosystem or stand scale, changes in forest cover occurred due to local fires with the intention of drying fuel wood, canopy openings for various uses and the establishment of settlements as described by Emperaire (1955) for the *Kawésqar* people in the coastal border. Also, forest fires extending to our study area from the *pampas* or steppe eastern grasslands were triggered by the *Aónikenk* during hunting activities (Huber and Markgraf, 2002). These changes were described by first European and Chilean explorers, as generating little effect to the forest cover at a landscape spatial scale, probably due to the low intensity in forest resources use at that time.

Our pre-settlement land cover map (figure 8) shows the domination of *Nothofagus sp.* forests over much of today's Forest-steppes transition zone, proving that most of the humid grasslands of the Rio Verde Municipality were by then, covered by a dense forest cover. This earlier land cover structure is of no great surprise since it is part of the traditional knowledge of local inhabitants and scientists at present times. What we think of great importance are the boundaries of the forest cover during the Indigenous land use period, when this transitional or ecotonal zone had its coastal border mainly covered by littoral forest, suggesting a completely different marine-coastal seascape structure. This littoral forest ecosystems, standing since glacial retreat and home of the marine hunter-gatherers and later historical *Kawésqar*, barely exists in this area, nor in most of the Forest-Steppe transitional landscapes of marine influence in southern Patagonia, following a similar land use history.

The onset of the colonization period in late XIX century was, from a driving forces perspective, marked by a radical change in the techniques and technologies used in transforming the landscape, as in the socio-economic system inducing those transformations. Pioneer European and Chilean settlements in the area were as described in the beginning of this study, at a small scale and within an economy based on subsistence, as well as local trade of wool and meat for supplying the incipient coal mining business in the area (figure 10). Although we have no evidence of land cover changes between this pioneer settlement period, and later period of large ranching, mining and forestry estates, run both by national and international mercantile companies; historical literature (Martinic *et al.*, 2011), oral tradition trespassed by local inhabitants in open semi-structured interviews and scientific records by Carl Skottsberg in the first decade of the XX century (Skottsberg, 1911), suggest only a fluctuation of the *Nothofagus sp.* cover in the area, with local canopy openings and gaps along the coast line where pioneer settlers established.

Forest management techniques, such as *high-grading forestry*, which allowed harvesting the most valuable trees in wintertime, sawing them for farm constructions or tunnel coal mining development; and *tree girdling*, which was an efficient and effective technique for creating gaps of standing dead trees within the forest, allowing the entry of light at soil level for increasing grass productivity for livestock and at the same time drying fuelwood for the household. All these constituted a key driving force of landscape change since the beginning of colonization (figure 10). Even though these techniques continued through the colonization process, their intensity and effects changed. The arrival of industrial technology, such as steam power and industrial sawmills (figure 10), and the allocation of property to large estate companies, turned these techniques into driving forces generating a far greater impact over the landscape. The large extent of the forest cover was now reached for selective logging, and leftover trees were girdled extensively for drying, burning and sowing of exotic grazing pastures. Therefore, 77% of pre-settlement (and possibly early pioneer settlement) forest cover was reduced to 60% to 1944 in our sub-set area for 1944 aerial photographs (table 3).

According to oral tradition recorded in interviews, the last large fire event, which took place in 1958, included most of the Riesco Island rural lands and parts of the continental Skyring sea coast, producing much of the land cover structure existing today, ending with the frontier colonization expansion over the forest.

During this decade, regional land re-distribution to a vast number of farmers and new settlers occurred and the national agrarian reform in the 1970s continued this process. Forest fires for land clearing were banned, and modern silvicultural practices were introduced for forest management in the 1980s, both in the central forests of the Riesco Island, and forests in higher altitudes of the mainland. The costal forests and a large amount of inland territory had previously been converted into humid grazing grasslands, regionally known for their high grass productivity (SAG, 2004).

Re-growth from burned *N. antartinca* transitional forest and arborescent shrublands was adapted into highly productive silvo-pastoral systems by the clearing of crossed stripes or "picadas" within this forests, dividing them into small fragments, allowing cattle and sheep to enter in the forest, being these, most of what in 1998 and 2014 land cover maps was classified as *semi-dense forest*, highly valued for their winter shelter to livestock and as windbreaks for increasing grass productivity.

In the 1980 and 1990, the crisis of the wool international markets (Cibils and Borrelli, 2005) due to the substitution with synthetic fibers (amongst other factors), was a significant driving force of landscape change. Local economy was heavily affected and subsequently sheep livestock was significantly reduced, therefore reducing the grazing pressure on grasslands and forests, a very possible explanation for dense *Nothofagus sp.* forest cover afforestation patterns due to natural regeneration over grasslands (table 2; figure 9). Land abandonment and depopulation were significant, reducing the anthropic pressure over the land. Land concentration in few owners changed the property structure of the whole landscape to one more similar to mid and late colonization times. In late 1970', following the breakdown of the agrarian reform and land tenure redistribution process, privatization of natural resources, allowed for the concession to private mining companies of some of Chile's largest coal reservoirs. Large-scale "open sky" coal mining operations since 2010 are today a driving force of land cover change, both for present forest clear-cuts and for owning much of the Riesco Island farms for future extractive operations, most of them comprising large surfaces of dense forest cover.

Forest trend analysis

As described under results, the overall increase in dense forest cover occurred mostly along the border of primary, old-growth forest patches. This natural regeneration of secondary *Nothofagus* forest corresponding to the change of grassland, shrublands and semi-dense forest into dense forest, could be partly explained by the microenvironmental conditions occurring in localized parts of forest edges, which could be to some extent similar to the ones occurring under gap dynamics, the main natural regeneration strategy of *Nothofagus pumilio* and *Nothofagus betuloides* forests (Heinemann *et al.*, 2000; Martínez Pastur *et al.*, 2011; Promis *et al.*, 2010). This can be also sustained by the fact that increase in semi-dense forest cover along these same edges (figure 9), corresponds mostly to a state similar to an "arborescent shrubland", possibly due to a facilitation effect of understory vegetation over seedling survival as described by Heinemann and Kitzberger (2006), or thanks to a possible nurse effect as occurring with the shrub *empretrum rubrum* and *N. antartica* (Henriquez and Lusk, 2005), although this last example requires to be validated under local conditions.

Although the general tendency of forest natural regeneration is positive along most of the study area's old growth forest edges, a contrasting process of no-change or little change was observed in some locations. Time and resource limitations did not allow for an experimental study to explain the absence of natural regeneration, nevertheless, qualitative land management data was obtained from two land owners in contrasting farms, with abundant natural regeneration and afforestation processes (North-West inland along the Skyring Sound) seen in green and blue colors of figure 9 and with little or no afforestation processes along old growth forest edges (South –West inland of the Riesco Island).

In spite of the wide range of micro environmental, climatic and topographic differences that influence natural regeneration, contrasting situations like these, can be explained by the differences in domestic herbivore grazing pressure. There is a widespread belief that selective grazing by herbivores would first consume grass biomass, later including more woody plants in their diet, as Soler *et al.* (2011) suggests for the case of higher *Nothofagus* forage consumption during winter season in southern Patagonia by domestic herbivores. This suggest the possibility that differences in land cover from both sites could have a strong relation to the seasonal management of domestic herbivores in forest edges in order to favor or reduce natural regeneration.

Another factor that can explain the absence or presence of local regeneration dynamics are the strong interactions between seedling survival and growth and herbaceous vegetation in the border patches and grasslands. Previous studies in similar ecosystems of North-western Patagonia, suggest that understory herbaceous vegetation, with higher abundance of non-native species in open landscapes can inhibit regeneration by competing for light, growing space, or other resources, or by allelopathic interactions. Although the same author confirms that the cover of herbaceous vegetation had a facilitative effect on the survival of N. pumilio seedlings on microsites with high level of solar radiation (open sites). The opposite happens with seedling shoot growth where it has an inhibition effect (Heinemann et al., 2000; Heinemann and Kitzberger, 2006)

On the other hand the sites where successful natural spontaneous regeneration in forest edges took place from year 1998 to 2014, had a higher abundance of *N. betuloides,* commonly described as a species less affected by grazing, forming even-aged, post-fire stands with dense canopies and little understory development to attract livestock (Veblen *et al.*, 2004). From a silvo-pastoral point of view, little silvicultural or grazing use can be bound to these systems, which can –according to present general land owner perception- lead to a negative valorization of natural regeneration. Further experimental research should take in account the grazing species selection and land sustaining capacity to better manage forest regeneration in this forest-grassland ecotonal environment in southern Patagonia. Silvo-pastoral use of *Nothofagus* forest, mostly represented in the semi-dense forest class in our study area should, in a southern Patagonian context, have greater concern about the sustaining capacity of these forests to maintain the natural regeneration dynamics, specially affected in *N. antartica* grazing forests. There is an existing relationship between overgrazing of these forests and their degradation into shrublands or grasslands for a lack or regeneration. The high biodiversity value of these transitional ecosystems, along with their high economic value for their higher grassland productivity and herbage nutritive value in comparison with open grasslands (Sánchez-Jardón *et al.*, 2010; Sánchez-Jardón *et al.*, 2014), are key reasons to better understand, care and restore these environments.

Implications for future Landscape/forest management

Both natural regeneration and deforestation dynamics and the different driving forces historically conducting those processes, should according to our results for this study area, from a landscape planning and/or ecological restoration perspective, have special awareness on the state and trajectory of the different ecosystems that should be conserved, transformed or restored within the landscape (Hulvey *et al.*, 2013). For this purposes, the comparison or change analysis between pre-settlement and present landscape structure, gives us in terms of land cover, the present distribution of what Hobbs *et al.* (2014) describes as ecosystems which lie within their known or assumed historical range of variability, for example, those old growth primary dense forests existing above the 150 to 200 m.a.s.l., which were not burned during the colonization period because of a lack of ignition conditions, mainly due to higher humidity than below that altitudinal range. These remaining ecosystems can be considered today of great bio-cultural value, a part of this landscape which is as well a key regional remnant of transitional *Nothofagus* forest in-between the arid steppes and the humid template forests of the western channels.

In semi-dense forest ecosystems, comprising both *N. antartica* and *N. pumilio* forests, both historic and present silvo-pastoral use prove superior ranching value for its higher forage biomass production and nutritional value (Sánchez-Jardón *et al.*, 2010), which at the same time puts them in a more endangered conservation situation (Veblen, 1992). This land use reality could suggest a more realistic recognition of these ecosystems regarding ecological restoration, as what Hobbs *et al.* (2014) framework calls Hybrid ecosystems (i.e. ecosystems that have moved out of the historical range of variation because of the arrive of novel elements). Their hybrid reality in southern Patagonia, characterized by high degradation of these vegetation communities due to wild-fires and overgrazing, and the particular chance in our study area that they are to some extent cleared for mining large coal reservoirs beneath them in the future, should recall decision makers to invest in generating the proper knowledge on how to practice a more sustainable regeneration-oriented grazing management in order to ensure their pastoral value as well as the array of ecosystem services they provide.

Grassland ecosystems, comprised mostly of humid grazing pastures that were in pre-settlement times covered by dense forest cover, can be categorized today as novel-type ecosystems from a historical variability perspective. Ecological restoration to its early forest structure would be highly inefficient and costly due to natural variables such as exotic weed competition for water and nutrients and wind desiccation. Other than that, these are highly valued for livestock grazing and are a key resource for maintaining settler's cultural aspects. Nonetheless, simple passive –cost effective- restoration measures could be implemented for improving ecological connectivity between isolated forest patches, restoring particular ecosystem functions and services that were lost because of land clearing, such as shelter for livestock, biological pest control and the aesthetic value of the landscape, ever more important for the growing tourism in the region. Some of these measures could be as simple as fencing exclusion zones in deforested water streams allowing for long-term natural regeneration.

At last, coastal grassland ecosystems, earlier covered by coastal or "littoral" forest, could be, to some extent restored to a reference ecosystem closer to their historical structure. Both biological and cultural singularity of these historical ecosystems is as we have described in this work, of great value. Species composition is different in these littoral ecosystems, the presence of evergreen species such as *D. winteri* and the few remains of these forests within the Forest-steppe transitional landscape turns them today into a key biodiversity issue in Southern Patagonia. The scientific community, Landowners and decision makers cannot forget these marine-terrestrial ecotones. These were the substrate for the onset and evolution of native American navigator cultures, and a key ecological element for the entire region.

5. Conclusions

Our analysis of the changing patterns and processes in Rio Verde's Landscape in southwestern Patagonia, constitutes an empirical registry of the historical ecological changes after the onset of Chilean and European colonization. Land use and land cover dynamics can, according to our results be better understood by cross-dating them to the main driving forces of landscape change. This, as expected, leads to more complex interpretations and novel research questions. The interdisciplinary integration of historical, ecological and geographical materials and methods was necessary for this study as. In spite of the difficulty in finding accurate and systematic historical data over past landscape ecological structures (e.g. cadastral maps) in Chile; valuable data was found for our study area. allowing for more robust interpretation of driving forces leading to todays landscape. We had to integrate both precise and imprecise data in order to re-construct our study area's ecological history to the most reliable reality. Further historical research could focus in the techniques and technologies facilitating land cover changes, such as *tree girdling* and the introduction of steam power; as well as the relationship of national political and economical driving forces influencing those changes. Also we think further research should trespass the chronological limit of European settlement in order to study the use and transformation of forest and littoral resources by indigenous *Kawésqar* people in the past.

The outcomes regarding present land use and present trends in *Nothofagus sp.* forest cover are of value for future land management and ecosystem restoration plans, as it puts the present land cover dynamics into a historical range of variability, which allows to plan with a bigger understanding of local capability of natural regeneration and its timings in response to the different land use changes of each historical period mentioned (i.e. Landscape resilience). It can be a resource for complementing with spatial and chronological information and context, to models for predicting land use change. We hope this research will help present and future generations to understand the effect of human intervention in this extreme geographic area and also, to understand how time and chronology marks a context to the changes in the evolutionary trajectory of this southwestern Patagonian Landscape.

Abstract

At present, Landscapes in Southern Patagonian are the result of socioeconomic and ecological changes, intensified in the last 140 years. Ecotonal zones between eastern semi-arid steppes and western *Nothofagus sp.* forests towards the Pacific Ocean are clear examples of these changes, where biological evidences of a pre-European landscape are still visible. This zone concentrates some of the most productive pastures, forests and mining resources in the region. Our objectives are to (1) determine the historical changes in land use and land cover and their relationships to the driving forces associated to changes in *Nothofagus sp.* forest ecosystems; (2) and describe the recent trends of *Nothofagus sp.* forest cover and their potential management implications over landscape planning. A 3000 Km^2 surface was chosen in the Rio Verde rural district (52°S – 71°W), where historical records from the 19th century including scientific and military expeditions, regional archives and bibliography, and oral tradition; all of which were integrated with photo interpretation of burned Wood's surface for constructing pre-settlement land cover maps. Trends in forest cover were observed with spatiotemporal analysis of classified Landsat imagery and field sampling, integrated in Geographic Information Systems. Results show the process of forest cover changes since 140 years, from costal border and indigenous use, to its present limits in mid-altitude mountainous zones with an average 25% reduction. Overall, natural regeneration has had a positive trend in the forest patch-grazing pasture border zones, irregularly conditioned by changes in land use pressure, a determinant factor in *Nothofagus* regeneration dynamics.

Key words: Patagonia; Forest history; Land-use change; Regeneration; Historical ecology; *Nothofagus* forests.

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Appendices

Appendix 1. Map of the Koppen climatic classes of the Río Verde Municipality.

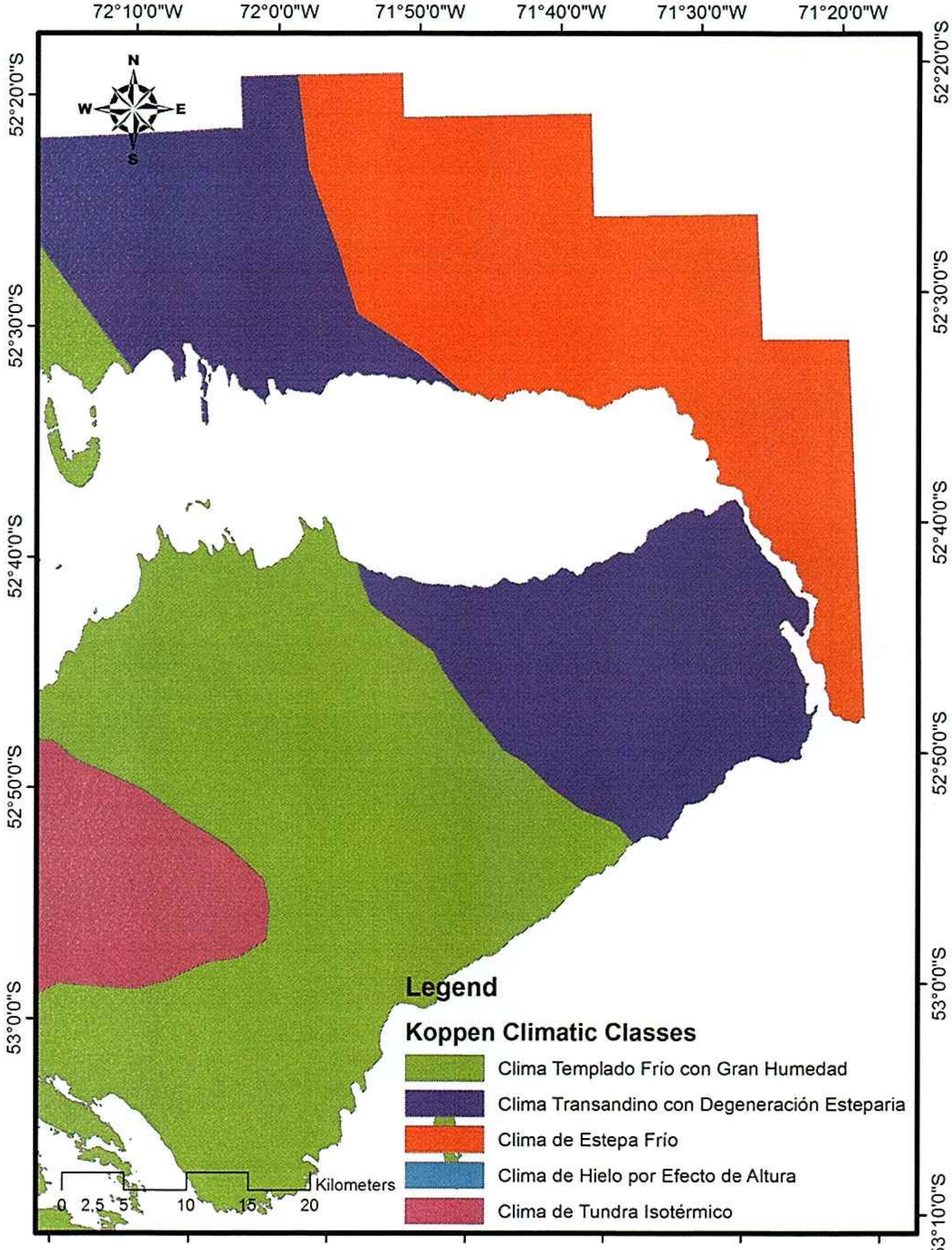

Figure A1: Koppen climatic classes of the Río Verde Municipality.

Appendix 2. Map of the rainfall spatial distribution of the study area.

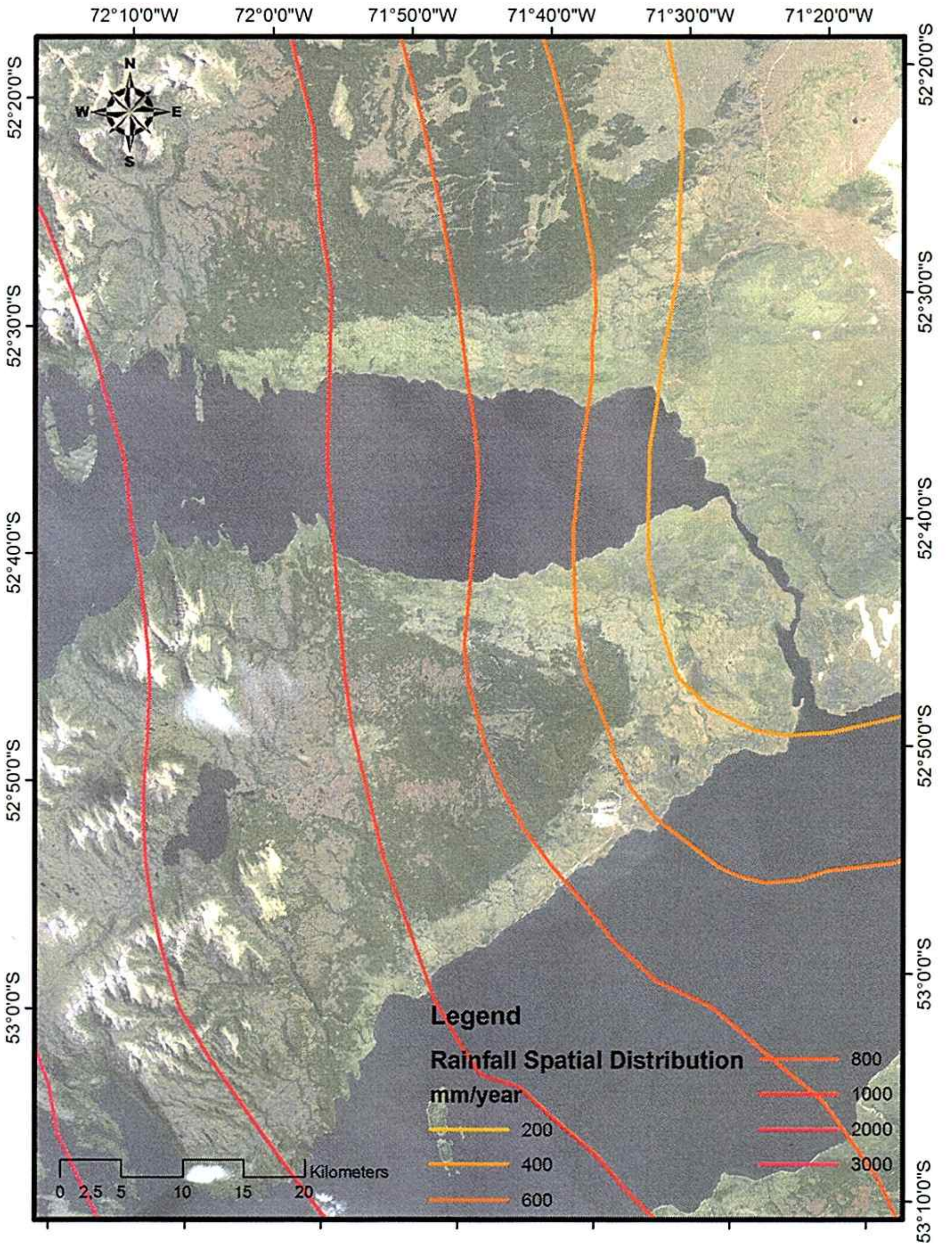

Figure A2. Rainfall spatial distribution (Isohyets) in millimeters per year, increase from East to West.

Appendix 3. Map of the elevation distribution of the study area.

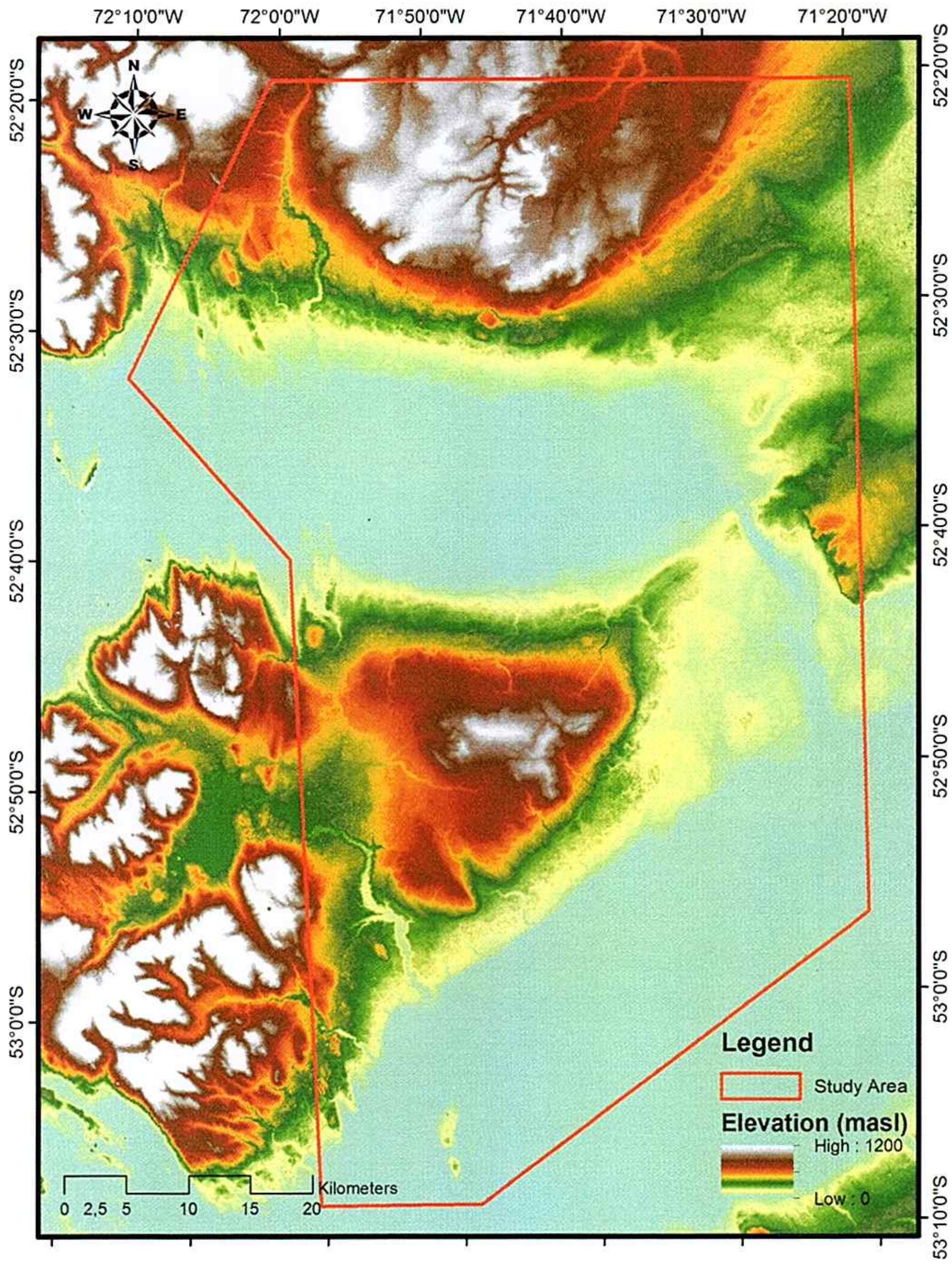

Figure A3. Digital elevation model of the study area in meters above sea level (m.a.s.l.).

Appendix 4. Map of the hydrographic network of the study area.

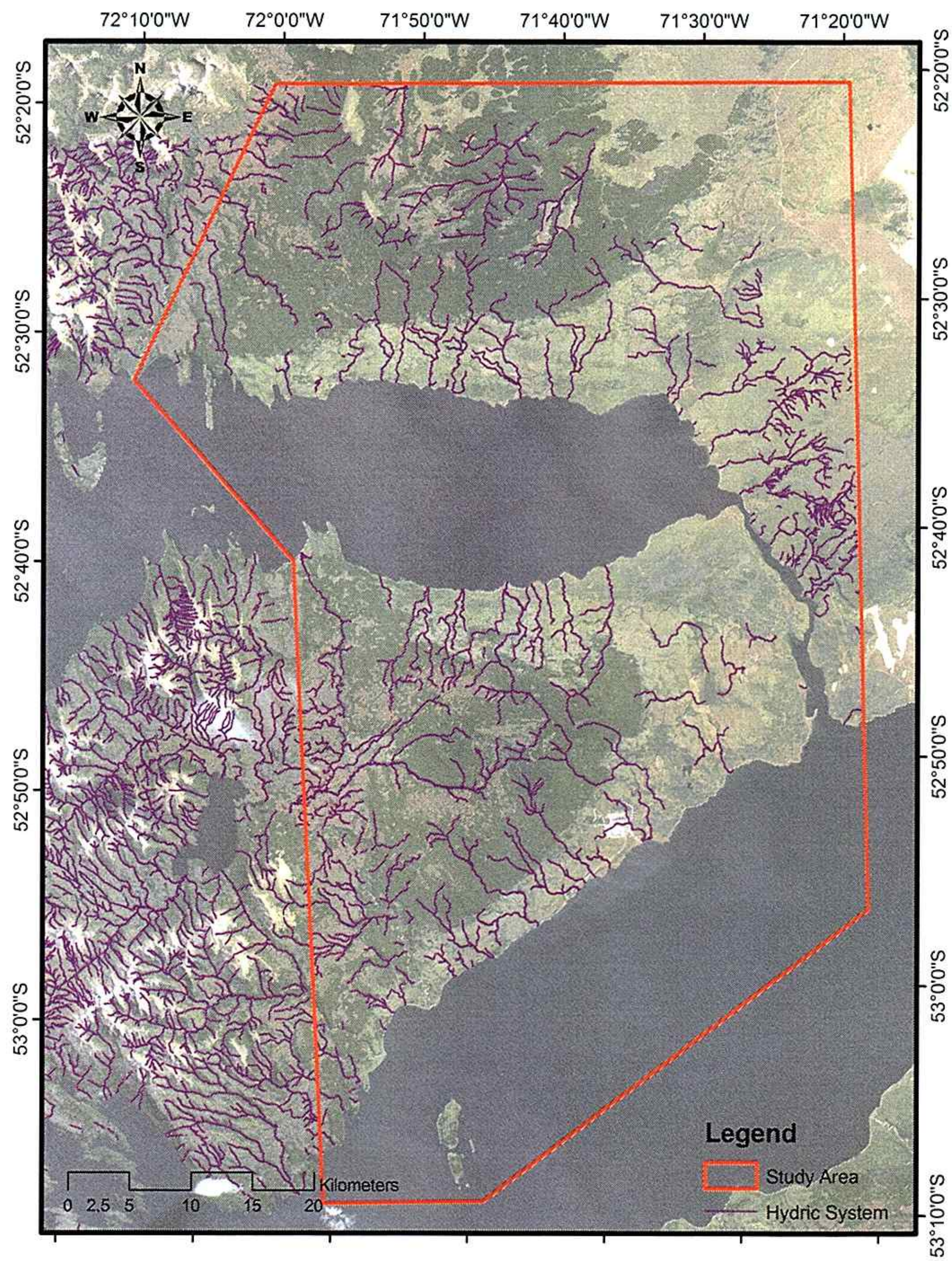

Figure A4. Hydrographic network of the study area, representing rivers and streams in purple color.

Appendix 5. Map of Land tenure or property structure of the study area.

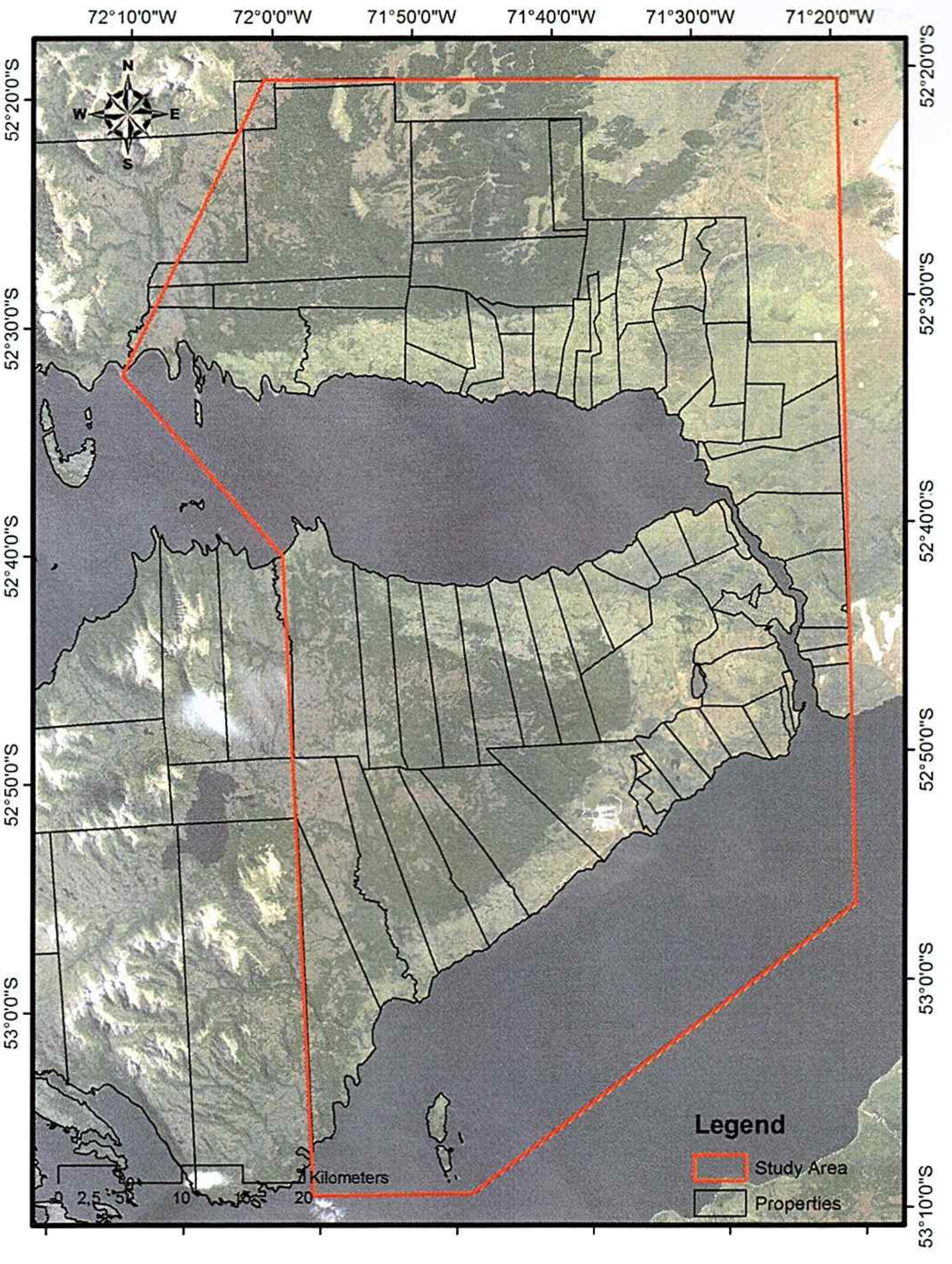

Figure A5. Land tenure structure of the study area. Black polygons represent the boundaries of each property.

Appendix 6. Map of the ground validation points in the study area.

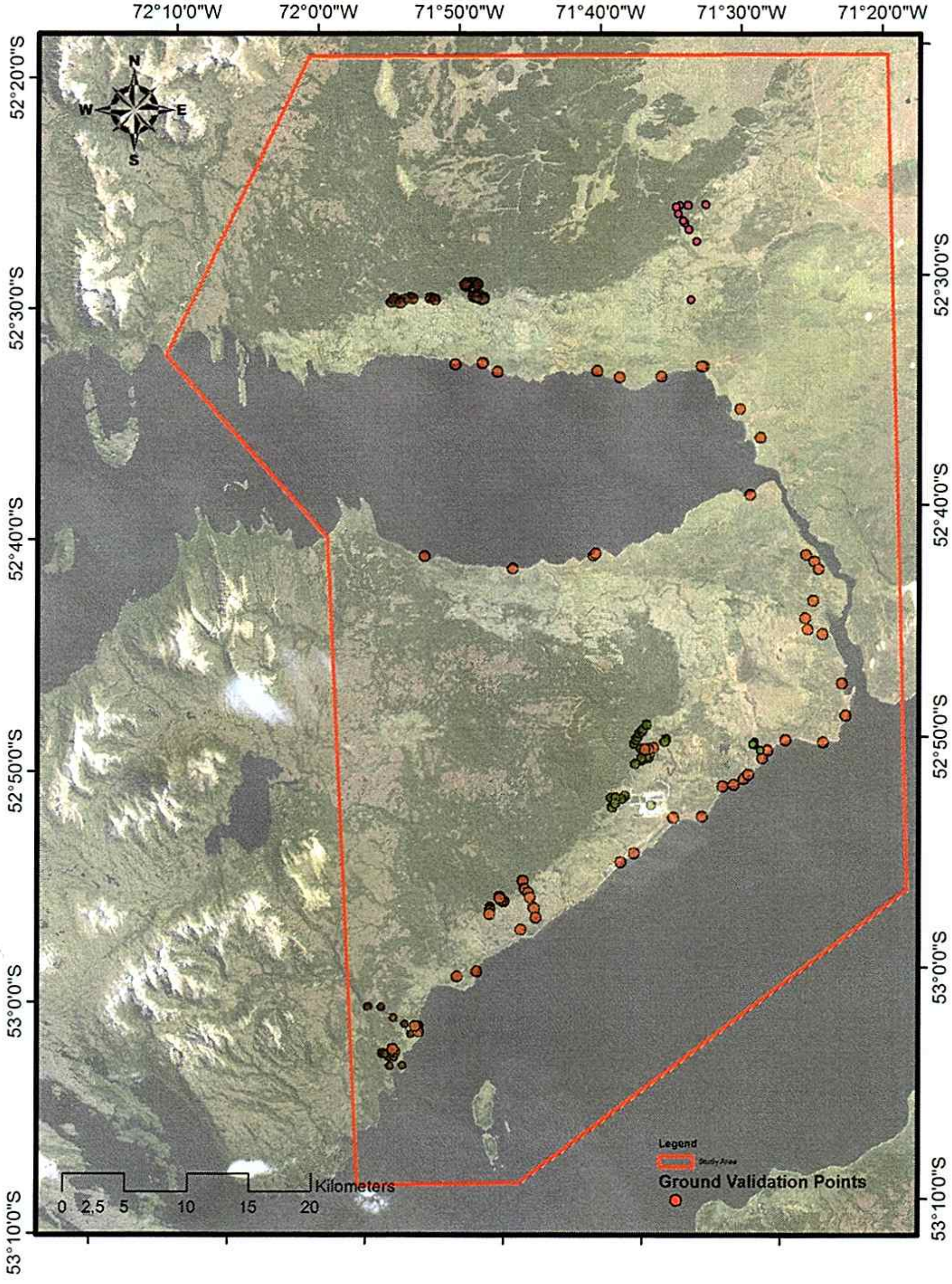

Figure A6. Spatial distributions of each ground validation point in the study area.

Appendix 7. Pictures of two contrasting conditions of forest.

Figure A7. Contrasting images of natural regeneration. Above image: Dense secondary mixed *Nothofagus betuloides* and *Nothofagus pumilio* forest regenerating over an open grassland, which was a former primary forest in the past (note the dead log remnants). Below image: Absence of natural regeneration from an old-growth forest (in the back) to the open grassland (a former old-growth forest which was burned).