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RESEARCH ARTICLE

Forest landscape dynamics after intentional large-scale fires in western Patagonia reveal unusual temperate forest recovery trends

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Abstract
Context Western Chilean Patagonia is an isolated temperate region with an important proportion of intact forest landscapes (IFL) that was subjected to large-scale fires over 60 years ago. However, there is no empirical evaluation of the land cover dynamics to establish the forest loss and recovery, and the effect on the landscape structure and function, and remnant IFL following the fires.
Objectives The present study addressed the following questions: (1) What have been the main trends of the land cover dynamics between 1984 and 2018 following earlier fires, and how have these trends shaped the spatial patterns and potential carbon stock of forests in western Patagonia? (2) What proportion of forest landscape remains intact following fires in this region?
Methods We selected the Coyhaique Province (1,231,910 ha) in western Chilean Patagonia as the study area. Land cover maps for three dates (1984, 2000, 2018) were used to evaluate landscape dynamics after fires. A map of persistence and change occurrence was made to estimate the IFL area over the 1984–2018 period. Landscape metrics were used to assess landscape structure change, and potential carbon stock was estimated based on a literature review.
Results Following fires, the main land cover changes between 1984 and 2018 were loss of ~ 32,600 ha of old-growth forest and a recovery of ~ 69,000 ha of second-growth forest. The increase in second-growth forest area mainly resulted from loss of agricultural cover (~ 41% of the area). Despite these changes, ~ 61% of the area could potentially remain as IFL after fires. Over the 1984–2018 period, a slight increase in fragmentation of old-growth forest, and a

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decline in second-growth forest were observed. Coyhaique Province experienced a slight increase (3.6%) in overall potential carbon stock, likely as a result of second-growth forest recovery.

Conclusions Our study provides the first evidence of the western Patagonia landscape state after more than six decades since the large-scale fires. The results provide baseline information on landscape structure and function that could help to make conservation and forest management decisions on specific territory areas.

Keywords Landscape metrics · Temperate ecosystem · Forest fragmentation · Forest regeneration

Introduction

Fire as a natural process plays a major role in shaping forest landscapes and maintaining biodiversity worldwide (Shlisky et al. 2009). However, human-induced changes in fires regime promote extensive terrestrial ecosystem degradation (Bowman et al. 2009). Forest losses due to intentional fire have been estimated at between 26 and 29% over recent decades (Tyukavina et al. 2022). At the landscape level the effects of fire can result in a range of land cover trajectories (Armenteras et al. 2021), changes in structure (e.g., spatial patterns), and ecosystem functions, such as the carbon stock (Peterson 2002; Latty et al. 2004; Turner et al. 2013). Therefore, an effective way of understanding fire effects on forest landscapes is to assess its dynamics through changes in structure and ecosystem functions (Forman 1995; Turner and Gardner 2015). Particularly, land cover change (LCC) analysis can reveal the transformation of spatial patterns and trajectories of land cover over time (i.e., structure change), and is the most efficient way to quantitatively assess, manage and understand spatiotemporal dynamics of landscape (Ellis and Ramankutty 2008; Tropek et al. 2013; Turner and Gardner 2015; Song et al. 2018; Radwan et al. 2021). Ecosystem functions usually refer to the combination of processes and structures of an ecosystem, which can be represented as the potential capacity to deliver ecosystem services (Costanza and Daly 1992; Müller et al. 2010). For example, carbon stock, as an ecosystem function, can be defined as the amount of carbon that has been sequestered from the atmosphere and stored within a pool from the landscape at a specified time (Mukul et al. 2020). Though, carbon stock is fact one of the most sensitive ecosystem functions at the landscape scale following fires (e.g., Huang et al. 2018) and LCC (e.g., Pellikka et al. 2018; Fryer and Williams 2021). Nevertheless, large-scale studies of the influence of fire on forest landscapes and post-fire recovery, which are still limited, are urgently required, especially given the widespread scale of threats associated with global change.

Forests provide a range of critical ecosystem services and functions (Miura et al. 2015), support a major proportion of terrestrial biodiversity (Gibson et al. 2011; Venier et al. 2014), and store large amounts of terrestrial carbon (Pan et al. 2011). However, global forests are being transformed by human activity at an unprecedented rate (FAO 2020), and it is generally accepted that forests altered by these anthropogenic disturbances are less effective at preserving ecosystem functions and biodiversity than old-growth forests (Gibson et al. 2011; Watson et al. 2018). Therefore, old-growth forest is valued more greatly in conservation terms (Watson et al. 2018). However, forest recovery following anthropogenic disturbances is an important process potentially leading to a return of some original functions (Chazdon et al. 2020; Soto and Puettmann 2020). Therefore, it is imperative to monitor both the stability and loss of primary or old-growth forests, as well as forest recovery following fires or LCC.

Given the current scenario of a warming and rapidly changing world, the landscape dynamics assessments post fires are especially important in regions where intact forest landscapes (IFL) remain (Potapov et al. 2017; Watson et al. 2018; IPCC 2021). IFLs are natural areas characterized by no (or minimal) remotly detected signs of human activity or habitat fragmentation in area of at least 500 km^2, which is considered a sufficient size to maintain all or most native biological diversity (Potapov et al. 2008, 2017). Although IFLs are a part of the global forest biome, some of them may contain extensive naturally treeless areas, such as grasslands, wetlands, lakes, alpine areas, and ice (Fa et al. 2020). Globally, IFL or those subject to low levels of anthropization are shrinking, following human activities that have extended to almost every location on earth (Ellis and Ramankutty 2008; Potapov et al. 2017). Considerable efforts of protection have been targeted at primary forests and large IFLs. Only about 32% (1.3 billion hectares) of the planet's current forest cover is primary forest, of which 23.5% corresponds to IFL (Potapov et al. 2008). Only 7.2% of global IFLs were found in temperate forest zones in 2000 (Potapov et al. 2008). Landscape monitoring efforts should therefore focus on forests within temperate ecosystems that may still maintain IFL and areas of old-growth or primary forest. This monitoring should also assess where intact conditions are being maintained or where they have become subjected to processes of anthropic transformation, either through LCC or as a result of new or altered regimes of disturbances such as fires or other stressors. Since most landscapes have been significantly affected by anthropogenic transformations, highlighting the location, surface area, and function of IFL may strengthen climate change mitigation and adaptation efforts. This, addition to biodiversity conservation strategies that could extend beyond their local relevance (Potapov et al. 2008, 2017).

South American temperate ecosystems still retain areas with IFLs subject to low human impacts (Potapov et al. 2017; Jacobson et al. 2019). Chilean Patagonia provides a good example of temperate forest landscapes with low population density, small urban areas, and little development of road networks (Hernández-Moreno et al. 2021). Particularly, western Patagonia is one of the most isolated temperate regions of the world, with considerable contemporary interest because contains a large area of old-growth forests (Watson et al. 2018) which are in near pristine condition (Astorga et al. 2018), with a 54% of the region under protection (Martínez-Harms et al. 2022). Therefore, western Patagonia has been categorized as one of the last remaining low anthropized landscapes (Jacobson et al. 2019; Hernández-Moreno et al. 2021) and also qualifies as an intact forest landscape (Potapov et al. 2017). Despite these characteristics, anthropogenic fires occurred in western Patagonia during the 1930s and 1950s opening up ca. 3 million hectares for agriculture and cattle (Otero 2006; Quintanilla 2008). Despite the extent and severity of these large fires, more than half a century has since passed with little empirical assessment of how the land cover dynamics and trajectories have shaped spatial patterns and changed functions within the landscape, and how much IFL remained in spite of these disturbances. Few studies in this region have focused on landscape dynamics after fires, but at the watershed scale, Bizama et al. (2011) found that old-growth forests appear to have become fragmented. Thus, we focused on a landscape in western Patagonia influenced by the fires that occurred approximately half a century ago, and addressed the following questions: (1) What have been the main trends of the land cover dynamics during the 1984–2018 period? (2) How much intact forest landscape remains, and where? (3) What are the changes in spatial patterns in forests after fires? (4) What are the changes in potential carbon stock?

Materials and methods

Study area

The study was conducted in the Coyhaique Province (44°S–45°S) that covers an area of 1,231,910 ha within the Aysén administrative region in western Chilean Patagonia (Fig. 1a). The Coyhaique Province is an intact forest landscape subject to low human influence according to global comparisons (Potapov et al. 2017; Jacobson et al. 2019). The main vegetational community corresponds to Andean-Patagonian forests, dominated by cold-dry deciduous *Nothofagus pumilio* (Poep. Et Endl Krasser, lenga), and the more mesic evergreen *Nothofagus dombeyi* (Mirb; coigüe) present in the northwestern part of the study area (Luebert and Pliscoff 2006). The eastern, most continental zone of Coyhaique Province is dominated by the Patagonian steppe (Luebert and Pliscoff 2006).

The study area was one of most affected by historical fires in western Patagonia associated with establishment of large cattle ranches (Osorio et al. 2007, 2014; Martinic 2014), and the settlement of the city of Coyhaique (name homonymous with the Province), which became the capital of the Aysén administrative region (Fig. 1). The city houses the largest population within Aysén (61,496, www.ine.cl), which concentrates pressures on land use, and firewood and timber extraction in the nearby forested areas, though exerting a relatively low and stable anthropization force during the last four decades (Hernández-Moreno et al. 2021). The study area has the lowest coverage of protected areas in western Patagonia (www.conaf.cl/conaf-en-regiones/aysen/) and is thus more exposed to landscape transformations.

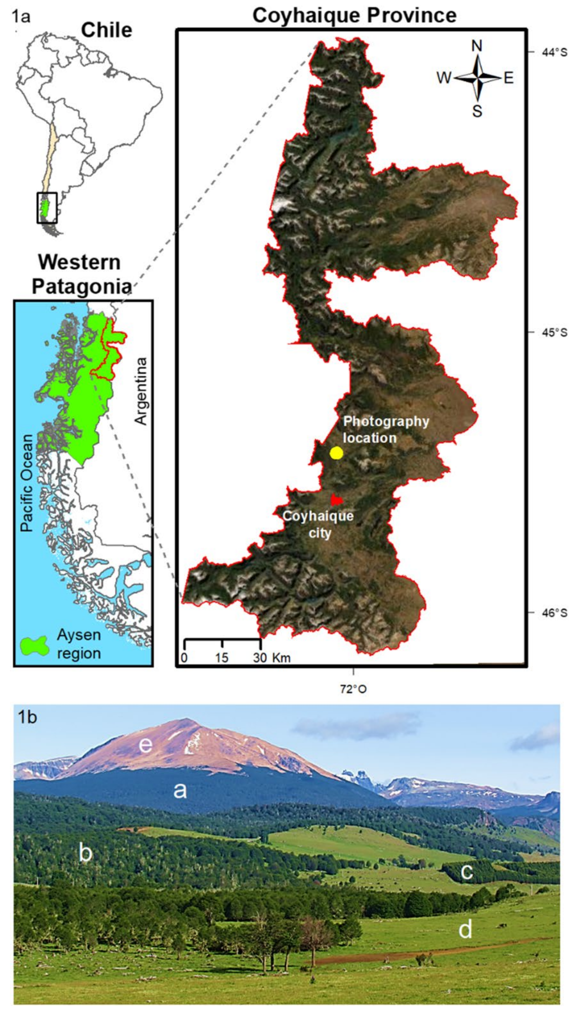

Fig. 1 Study area: 1**a** The location of Coyhaique Province in southern Chile using a base image from Google Earth, 1**b** Photograph showing a current landscape mosaic (2018) with the following land covers: (a) old-growth *Nothofagus pumilio* forests, (b) second-growth forest of *N. pumilio*, (c) exotic tree plantation, (d) agricultural land, and (e) land cover above the vegetation tree line, i.e., bare land and snow

Spatial data

Land cover change (LCC) was assessed for a 34-year period between 1984 and 2018. Land cover maps were derived from satellite images (30 m pixel resolution) for the years 1984, 2000, and 2018. For each date, imagery from the following satellite products were used: Landsat 5 Thematic Mapper (5TM) for 1984, Landsat 7 Enhanced Thematic Mapper Plus (7 ETM+) for 2000, and Landsat 8 Operational Land Imager (8 Oli) for 2018. A supervised maximum likelihood classification was conducted to identify 11 land covers on each image: (1) old-growth forest, (2) second-growth forest, (3) shrubland, (4) agricultural, (5) steppe, (6) exotic tree plantation, (7) water bodies, (8) bare soil, (9) urban, (10) glaciers/snow, and (11) highland vegetation (Details in Table S1). The classification was conducted using ENVI 5.3 software (Exelis Visual Information Solutions, Boulder, CO). The classification accuracy was evaluated using a confusion matrix between the reference data and the classified data from which it was evaluated the Kappa statistic, and the overall accuracy (Olofsson et al. 2014). Overall accuracy assessments of these maps were: 89% for 1984, 88.1% for 2000, and 87.8% for 2018, and were carried out in R software using the raster library (Hijmans et al. 2019). Image pre-processing and classification details are given by Hernández-Moreno et al. (2021).

Land cover change analysis

The land cover change was evaluated through changes in area of the land cover types between the 1984–2000 and 2000–2018 periods. To quantify the annual rate of change we used the equation developed by Puyravaud (2003), which has been widely adopted in landscape monitoring studies (e.g. Armenteras et al. 2013a, b; Beuchle et al. 2015; Miranda et al. 2017):

$$\mathrm{rt} = \frac{1}{(t_2 - t_1)} \times \mathrm{Ln}\left(\frac{A_2}{A_1}\right) \times 100$$

where, rt is the rate of change for each land cover within a certain period of time, t_1 is the initial year, t_2 is the final year, A_2 and A_1 are the areas (in ha).

Land cover dynamics were assessed with trajectory analysis using the transition matrices between the 1984–2000 and 2000–2018 periods through the IDRISI Selva software (Eastman 2012). This analysis was focused on trajectories of native forest covers (i.e., old-growth and second-growth forests), and included other land covers whose net changes represented more than 1% of the study area (i.e., agricultural and shrubland) according to Hernández et al. (2016). Therefore, the trajectories assessed were the following: (i) from old-growth forest to second-growth forest, to shrublands, or to agricultural, (ii) from second-growth forest to shrublands, or to agricultural, (iii) from shrublands to agricultural, iv) from shrublands to second-growth forest, and v) from agricultural to shrublands or to second-growth forest.

Quantification of intact forest landscape (IFL)

The Province of Coyhaique has been previously mapped as an IFL, located within a temperate ecosystem (Potapov et al. 2017). To quantify the changes in this IFL, we used the approach of Jacobson et al. (2019) using binary change/no change maps processed for each study period (1984–2000 and 2000–2018). The two resulting maps were added to produce a map of persistence and change occurrence (one, two, or unchanged) for the whole study period. From this map, the unchanged pixels were used as a proxy to estimate the IFL area between 1984 and 2018.

Assessment of spatial patterns in native forest

Landscape metrics were used to estimate the changes in spatial patterns of forests over the study period. The landscape metrics were analyzed for the same land covers used in the trajectory analysis (i.e., old-growth forest, second-growth forest, shrubland, and agricultural). The quantification and comparison of spatial patterns was conducted with five key landscape metrics widely used in studies on landscape fragmentation (e.g., Uuemaa et al. 2013, 2009; Zhao et al. 2016; Inkoom et al. 2018), these are: (i) mean patch area (ha), (ii) patch density (number of patches per 100 ha), (iii) largest patch index (% of landscape occupied by the largest patch), (iv) proximity index, which increases as the neighborhood (500 m radius) is increasingly occupied by patches of the same type, and as patches become closer and more contiguous (or less fragmented), and v) edge density (edge length per hectare). A detailed description of each metric can be found in McGarigal et al. (2012). These metrics were computed using FRAGSTATS Version 3.4 (McGarigal et al. 2012).

Potential carbon stock assessment

We mapped potential carbon stock for each land cover with aboveground biomass content (i.e., old-growth forest, second-growth forest, shrubland, agricultural, steppe, tree plantation, and highland vegetation) with data derived from a review of relevant literature (Table S2), following the method proposed by (Duarte et al. 2016). Specifically, we searched carbon stock values for each of the different land cover types within the same geographic area (i.e., Patagonian temperate *Nothofagus* forest) of the present study (Table 1). Since the present classification did not differentiate between deciduous and evergreen forests, we used the vegetation bioclimatic classification from Luebert and Pliscoff (2006) to differentiate these two forest types. The values of carbon stock for the different land covers were imputed at pixel level at different times (i.e., 1984, 2000, 2018 maps), but the resulting maps had discrete values of carbon stocks (i.e., not

Table 1 Area (ha) and annual change rate (%) of land cover classes for each year in Coyhaique Province

Land cover	1984		2000		2018		Annual change rate (%)		Net Change (ha)
	ha	%	ha	%	ha	%	1984–2000	2000–2018	1984–2018
Old-growth forest	392,567	31.29	373,087	29.74	360,259	28.71	−0.3	−0.2	−32,308
Second-growth forest	48,597	3.87	69,150	5.51	118,149	9.42	2.2	3.0	69,552
Shrubland	153,127	12.21	184,964	14.74	179,437	14.30	1.2	−0.2	26,310
Agricultural	193,637	15.43	160,360	12.78	114,407	9.12	−1.2	−1.9	−79,229
Exotic tree plantations	526	0.04	6,776	0.54	17,179	1.37	16.0	5.2	16,653
Steppe	137,049	10.92	139,063	11.08	144,981	11,56	0.1	0.2	7,932
Highland vegetation	57,641	4.59	59,304	4.73	54,323	4.33	0.2	−0.5	−3,317
Urban	532	0.04	895	0.07	1,252	0.10	3.2	1.9	719
Water bodies	20,360	1.62	18,860	1.50	19,772	1.58	−0.5	0.3	−588
Bare soil	203,151	16.19	205,013	16.34	214,359	17.09	0.1	0.2	11,208
Glaciers/Snow	24,723	1.97	14,439	1.15	7,791	0.62	−3.4	−3.4	−16,931

continuous). To give variability to the pixels of the different land covers, we converted the discrete maps into continuous ones. Since the normalized difference vegetation index (NDVI, Rouse et al. 1973) is a continuous variable and related to carbon stock (Myeong et al. 2006), we developed a new approach, where this variable was used as a weighting factor to give variability to the discrete values attributed to the maps for the different land covers. We built maps using a weighted NDVI ($NDVI_w$), which is the ratio between each $NDVI_{ij}$ pixel value for a given land cover (for each of the three dates analyzed) and the average NDVI ($NDVImean_{lc}$) of each land cover for the study area. The equation of the $NDVI_w$ is as follows:

$$NDVIw = \frac{NDVI_{ij}}{NDVImean_{lc}}$$

This model provides a factor, which varies between 0.1 and 1.9. When multiplying this $NDVI_w$ value by the discrete value of carbon stock normalized at pixel level, this allows us to give the inherent variability to carbon stock obtained from the literature review. Therefore, the new continuous value is called "potential carbon stock" imputed at the pixel level. Using this new methodology, we built three maps for different times to evaluate potential carbon dynamics at the landscape level. Lastly from these maps, we computed a difference of potential carbon stock between the period 2018–1984 to map gains and losses along the study period.

Results

Land cover dynamics

The land cover change analysis showed the dynamics in gains and losses in area several decades after the fires in Coyhaique Province (Table 1). The land covers with the greater losses were the old-growth forest and agricultural. The old-growth forest lost ~ 32,300 ha between 1984 and 2018 but maintained the largest area within the landscape with 29% in 2018 (Table 1; Fig. 2a, b). The agricultural land showed the greatest area reduction of 79,229 ha throughout the study period, with an annual change rate of − 1.2% and − 1.9% in the first (1984–2000) and second (2000–2018) periods, respectively (Table 1; Fig. 2b). The land covers showing greatest gains were second-growth forest, exotic tree plantations, and shrubland. The second-growth forest increased by 69,552 ha between 1984 and 2018, doubling its initial area, and increasing at an annual rate of 2.2% and 3% in the first (1984–2000) and second (2000–2018) periods, respectively (Table 1; Fig. 2a, b). Exotic tree plantation increased by 16,653 ha between 1984 and 2018, which represented 0.04% of total area in 1984 and 1.37% in 2018 (Table 1; Fig. 2a). Shrubland increased by 26,310 ha during the study period, increasing at an annual rate of 1.2% between 1984 and 2000 but decreasing at a rate of − 0.2% in the second period (2000–2018) (Table 1). Further detailed information is given in Table 2.

Landscape change trajectories

The change trajectories showed interactions between gains and losses in areas of old-growth forest, second-growth forests, shrubland, and agricultural. This analysis showed that old-growth forest cover has been highly stable with 95% and 96% of area stable during the first (1984–2000) and second (2000–2018) period, respectively (Fig. 3). Losses in the old-growth forest were mainly by trajectories towards shrubland by 3% and by 2% in the first and second periods, respectively (Fig. 3). The second-growth forest showed a similar stability in cover over time with 89% of area stable between 1984 and 2000, and 93% between 2000 and 2018. This apparent recovery in second-growth forest occurred principally by contribution of direct trajectories from shrublands by 12% in the first period, and by 19% in the second period (Fig. 3). The agricultural cover also showed large trajectories for forest recovery through indirect contributions towards shrubland, by 23% between 1984 and 2000, and by 21% between 2000 and 2018, and a direct contribution towards the second-growth forest in the second period by 7% (Fig. 3).

Intact forest landscape changes

Most of the Coyhaique Province landscape has remained stable (i.e., unchanged) over the 1984–2018 period with land cover changes occurring only in ~ 21% of the landscape (Fig. 4). The landscape was subject to one LCC change between 1984 and 2018 on 17.1% of the pixels and two changes in 3.9% of

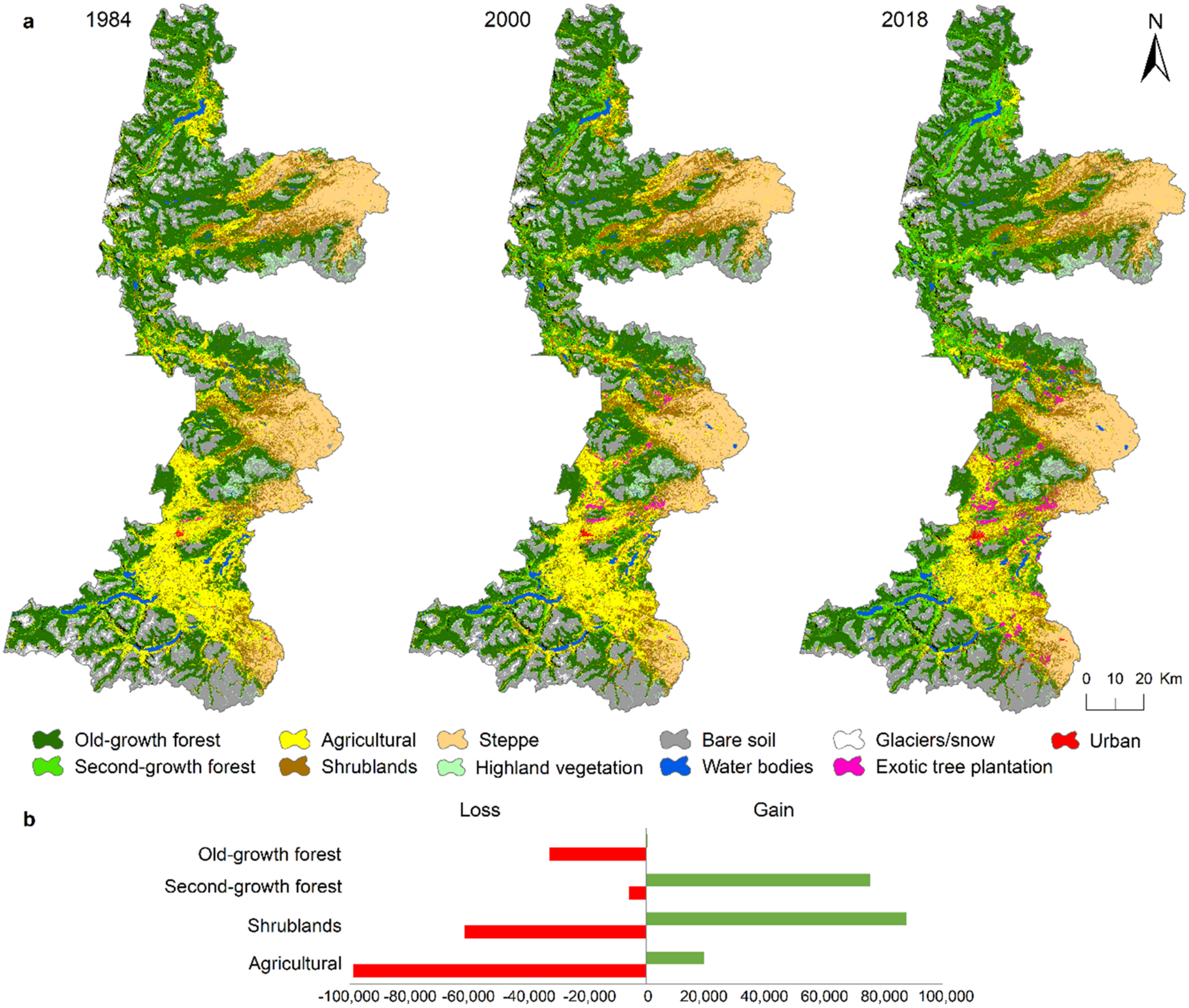

Fig. 2 Land cover change Coyhaique Province after historical fires: **a** land-cover maps for each study year, and **b** land covers with the higher net change in area between 1984 and 2018

the pixels, whereas 78.8% pixels were unchanged (Fig. 4a, b). Within these unchanged areas, 17.5% corresponded to non-IFL areas in 1984 (i.e., urban, exotic tree plantation, agriculture, shrublands, and second-growth forest). Therefore, ~61% of these unchanged pixels could be considered as remnants of intact forest landscape, consisting mostly of old-growth forest and glacier cover (Fig. 4b).

Spatial patterns of forest cover

The landscape metrics showed that the old-growth forest had a slight tendency towards increased fragmentation. However, the second-growth forest and shrublands showed a tendency toward decreased fragmentation (Table 2). In particular, the patch density showed a large increased in the second-growth forest by 71% over the study period (1984–2018), while in old-growth forest, shrubland, and agriculture, it decreased (Table 2). Regarding the patch area, old-growth forest showed larger patches in 2000, but reduced slightly by 5% over the entire period. Conversely, the second-growth forest presented smaller patches although with a constant size increase of 4% between 1984 and 2000, and 36% between 2000 and 2018. The patch area in shrubland also increased, but only in the first period by 55%, while agriculture decreased by 35% during the entire study period

(Table 2). Regarding the proximity index, the old-growth forest showed higher values, that is, patches are bigger and closer to each other (i.e., less fragmented), but despite this, the index decreased by 18% throughout the study period (1984–2018). The second-growth forest showed the lowest proximity values, although with a ~ tenfold increase in proximity between patches over the entire study period (i.e., fragmentation reduction). A similar trend showed an increase in proximity of shrublands of 330% between 1984 and 2018. In contrast, the proximity of agricultural patches was reduced by 61% throughout the study period (Table 2). Regarding the edge density, the second-growth forest showed the greatest increase by 90% throughout the study period (1984–2018), with shrubland increasing the edge density by 30%, and old-growth forest remaining practically stable. Lastly, the largest patch index reflected that the old-growth forest maintained the largest patches, although with a slight decrease of 12% between 1984 and 2018. Agriculture showed the second-largest patch value, but this also reduced by 42% over the study period. However, second-growth forest and shrubland showed an opposite trend, reflecting a persistent increase of the largest patches throughout the study (Table 2).

Potential carbon stock dynamics

Old-growth forest has the highest potential carbon stock capacity, although it showed a continuous reduction of ~ 7% over the study period (1984–2018) (Table 3). The second-growth forest showed the second highest potential carbon stock capacity (Table 3), which increased 43% between 1984 and 2000, 71% between 2000 and 2018, and 144% over the entire period. Exotic tree plantations showed the highest net change of carbon stock potential capacity by 1194% between 1984 and 2000, and by 154% between 2000 and 2018 (Table 3). The agricultural cover showed a decrease in potential carbon stock with a net change of − 34% between 1984 and 2018 (Table 3). Finally, the entire Coyhaique landscape showed a slight reduction in its capacity to store stock by 0.5% in the first period (1984–2000), and subsequently, an increase by 4% for the second period (2000–2018).

The gains and losses during the entire study period are shown spatially in Fig. 5a and b. The spatial

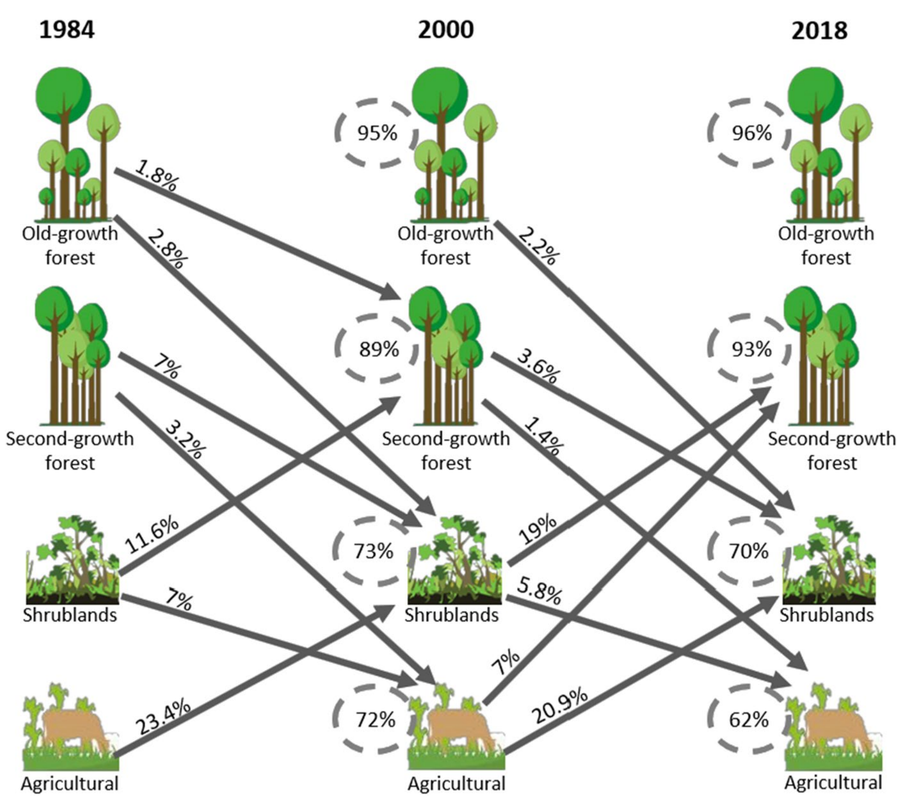

Fig. 3 The change trajectories in forest-related land covers during the 1984–2000 and 2000–2018 periods. Circles with a dashed gray line represent the proportion of a land cover that remained stable in the 1984–2000 (circles in the 2000 year), and 2000–2018 (circles in the 2018 year) periods. Net changes represented > 1% of the study area

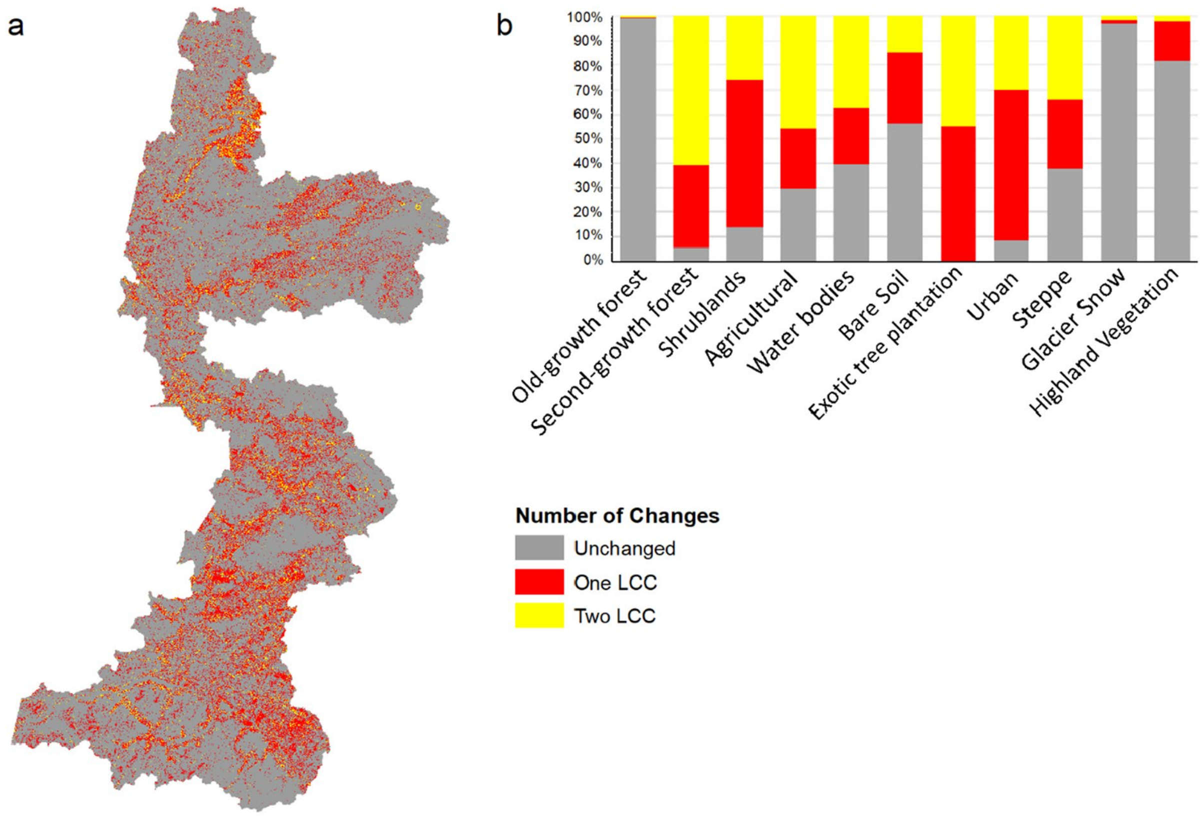

Fig. 4 Intensity and persistence of landscape changes showing pixels with one or two LCCs between 1984 and 2018, or those remaining unchanged. **a** spatial distribution of the number of changes, **b** proportion of changes for each type of land cover the during entire study period

change analysis showed that most were small changes in pixels around a mean of 0.7 tonC/pixel (Fig. 5c), i.e., with a slight trend towards small carbon stock gains over the entire study period (Fig. 5c). The 35.70% pixels (i.e., 447,956 ha) showed gains in the lower range of carbon stock (0.01 to 5 tonC/pixel), and just by 0.03% of pixels (i.e., 426 ha) showed gains in the higher range (25.01 to 37.8 tonC/pixel, Fig. 5). Regarding the losses, 33% of pixels (i.e., 413,622 ha) showed small losses in a low range between − 4.99 and − 0.01 tonC/pixel, and 1.6% of pixels (i.e., 20,052 ha) showed high losses in pixels with a range of − 37.6 to − 25 tonC/pixel (Fig. 5). Last, the spatial distribution of aboveground potential carbon stock for each time (1984, 2000, 2018) in Coyhaique Province is shown in Fig. S1.

Discussion

Our study has revealed that over the 1984–2018 period in Coyhaique Province, old-growth *Nothofagus* forests have experienced losses in cover, while second-growth forest cover has followed a process of recovery. Despite a large number of studies on land cover dynamics in Latin America (e.g., Kitzberger and Veblen 1999; Rodríguez Eraso et al. 2013; Lima et al. 2016; Armenteras et al. 2017) and on forest recovery in other regions (e.g., Smith Pinto et al. 2008; Dobor et al. 2018; Smale et al. 2018; Nanni et al. 2019), the present study provides the first empirical evidence on patterns of temperate forest recovery at the landscape level in western Patagonia after the large-scale anthropogenic fires during the 1930–1950s period. Despite the historical fire disturbances, we found that a relatively large proportion

Table 2 Landscape metrics for each analysis year and change rate for the entire study period (t1 = 1984 and t3 = 2018) in Coyhaique Province

	Year and change rate	Patch Density[a]	Mean Patch area (ha)	Large Patch Index (%)	Edge Density (ha)	Proximity Index[b]
Old-growth forest	1984	4.572	6.843	7.258	42.604	15,748.135
	2000	4.311	6.897	6.751	41.089	14,256.267
	2018	4.434	6.475	6.381	42.769	12,931.404
	Change t1–t3 (%)	−0.030	−0.054	−0.121	0.004	−0.179
Second-growth forest	1984	5.021	0.771	0.071	20.966	23.579
	2000	6.854	0.804	0.104	27.611	42.380
	2018	8.589	1.096	0.728	40.775	275.057
	Change t1–t3 (%)	**0.711**	0.421	**9.312**	**0.945**	**10.665**
Shrublands	1984	9.860	1.238	1.079	57.619	927.871
	2000	7.682	1.919	3.119	57.445	3,734.593
	2018	7.945	1.800	3.210	58.138	3,992.765
	Change t1–t3 (%)	−0.194	**0.454**	1.974	0.009	3.303
Agricultural	1984	5.368	2.875	5.471	36.038	5,530.393
	2000	4.814	2.655	7.074	29.566	10,122.056
	2018	4.896	1.863	3.173	25.852	2,184.380
	Change t1–t3 (%)	−0.088	−0.352	−0.420	−0.283	−0.605

Higher changes are highlighted in bold

[a]Number per 100 hectares

[b]increases as the neighborhood (500 m radius) is increasingly occupied by patches of the same type

Table 3 Potential carbon stock changes (megatonnes C) based on literature for each land cover (sum of all pixels of each land cover type) in the Coyhaique Province

Land cover	1984	2000	2018	Net change (%)		
	MgtonC			1984–2000	2000–2018	1984–2018
Old-growth forest	72.58	69.59	67.20	−4.1	−3.4	−7.4
Second-growth forest	4.81	6.86	11.71	42.7	70.8	143.6
Shrubland	0.62	0.77	0.99	25.2	28.8	61.2
Agricultural	0.33	0.30	0.22	−7.0	−28.9	−33.9
Wetland	0.02	0.01	0.01	−40.7	14.9	−31.9
Exotic tree plantations	0.03	0.42	1.07	1,194.1	153.5	3,180.9
Steppe	0.10	0.09	0.10	−2.8	2.5	−0.4
Highland vegetation	0.25	0.26	0.24	5.4	−8.4	−3.5
Total	78.73	78.31	81.54	−0.5	4.1	3.6

Relative net change is shown in the last three columns

of forest landscape remains that could be considered “intact” in the province of Coyhaique.

Land cover dynamics after past fires

Our results showed that old-growth forest represents the most extensive land cover in the landscape of Coyhaique Province. Maintaining a high proportion of old-growth forests can contribute to temperate ecosystem conservation, given that the area of these forests is decreasing across many regions of the world (Watson et al. 2018). Despite global relevance of this natural resource, many of the old-growth forests in Coyhaique Province are located outside of protected areas, although many of these they have some de facto protection in that they are located in inaccessible areas (i.e., topography barriers, and lack of road infrastructure).

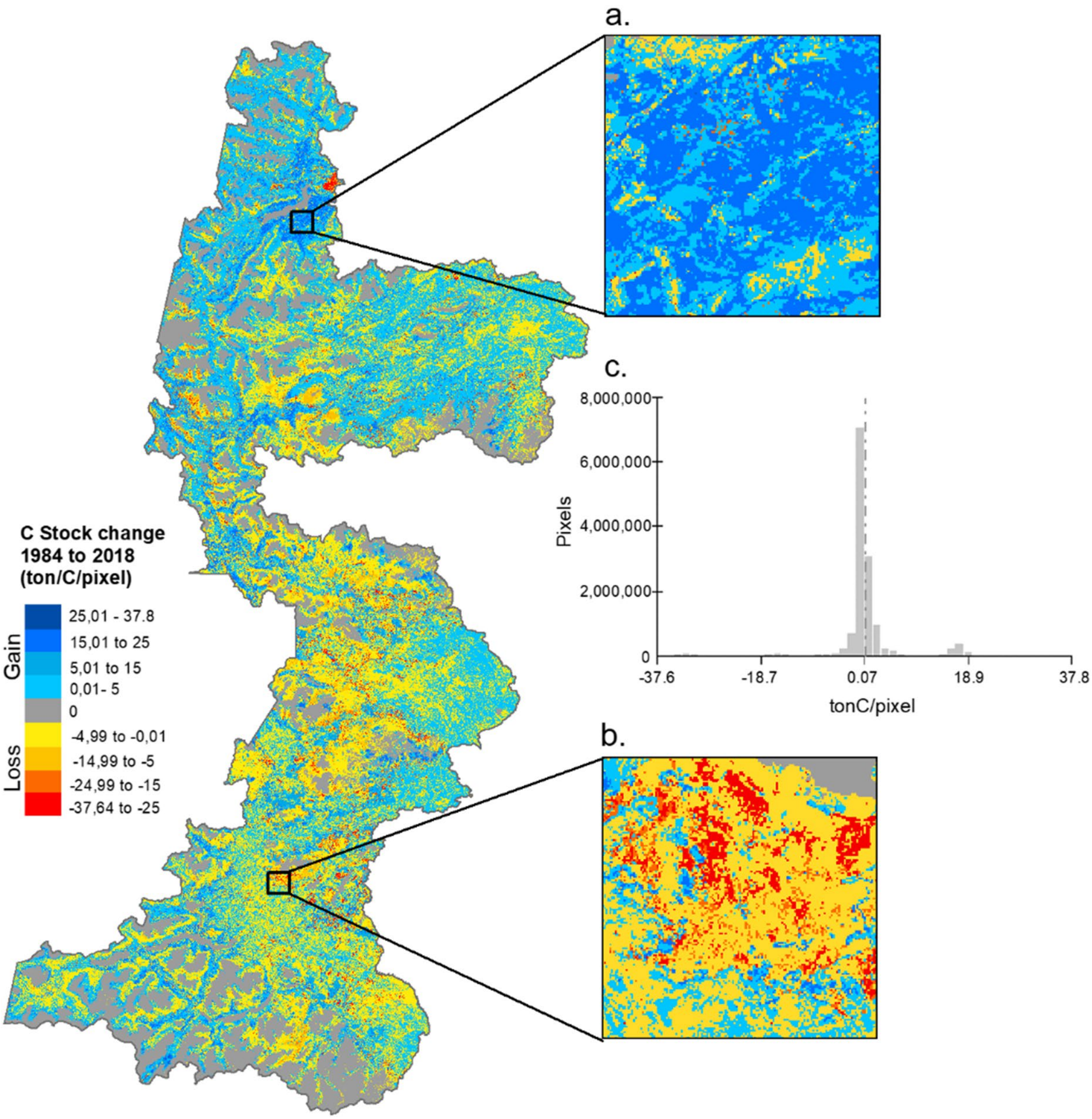

Fig. 5 Potential carbon stocks change map (1984–2018). Zoom boxes show examples of areas with gains (**a**) and losses (**b**). **c** frequency histogram shows pixel distribution according to potential carbon stock content over the entire study period

However, others are located in areas with new accessibility (e.g., new road infrastructure) rendering them vulnerable to anthropic disturbances such as illegal logging or the presence of livestock (Zamorano-Elgueta et al. 2012), which in the worst cases leads to land cover change (Bizama et al. 2011; Hernández-Moreno et al. 2021). This lack of legal protection could explain why between 1984 and 2018 more than ~ 32,000 ha of old-growth forest was lost in the Coyhaique Province (Fig. 2; Table 1), a concerning trend given that these areas represent some of the last remnants of temperate old-growth forest in the southern hemisphere (Astorga et al. 2018; Watson et al. 2018). In contrast, second-growth forests increased in area by ~ 70,000 ha over the same period (1984–2018). McIntire and Fajardo (2011) observed a similar pattern at the stand scale and showed that recovery of second-growth forest was generated in places close to old-growth forest patches where tree regeneration occurred through seed dispersal. Similar recovery trends at the stand level were found in Argentina (northeastern Patagonia), showing successful regeneration capacity of *Nothofagus pumilio* after fires (Kitzberger and Veblen 1999). Another type of forest regeneration that could have contributed to second-growth forest recovery is gap regeneration, in which seeds disperse into natural or man-made gaps according to Fajardo and de Graaf (2004). This process preserves the traits of temperate forests, such as an irregular forest structure or uneven-aged stand features, and creates a great similarity to old-growth forest attributes (Fajardo and de Graaf 2004; Soto et al. 2022). Additionally, landslides on hilly slopes in some parts of the Coyhaique Province landscape could have resulted in substantial secondary forest recovery (Veblen et al. 2004). Several studies demonstrate that forest recovery processes may occur when agricultural land or open lands after fires are abandoned, resulting in resilient forest ecosystems (Crouzeilles et al. 2017; Chazdon et al. 2020). This trend was observed in the present study area, where trajectories from agricultural cover contributed more significantly to second-growth forest recovery (Fig. 3). Our research is consistent with other studies in some temperate regions worldwide that have documented broad forest recovery, primarily owing to the abandonment of agricultural and livestock lands (Potapov et al. 2015; Song et al. 2018).

Our data also showed a constant and relatively high loss of agricultural land cover during the study (Table 1). This trend could be explained by the nature of the historical fires that occurred more than 60 years ago; these fires were often out of control and burned more forest area than expected by the settlers whose goal was to open up the land for agricultural and cattle grazing (Quintanilla 2005). Our observed pattern of agricultural loss and second-growth forest gain contrasts with most studies conducted in other parts of the world, where agricultural land generally tends to expand continually into areas covered by forests (Tropek et al. 2013; Song et al. 2018). The loss of agricultural cover in areas surrounding Coyhaique City is of particular interest; Coyhaique is experiencing a constant urban expansion (Hernández-Moreno and Reyes-Paecke 2018) which has begun to show changes in land cover principally from agricultural cover to housing (i.e., land ownership subdivision for peri-urban housing), a pattern also observed for other cities in southern Chile (e.g., Gálvez et al. 2021).

Although exotic tree plantations represent a low proportion of the Coyhaique Province landscape, they may be significant. Exotic tree plantations increased mainly during the first period but showed a slowdown in the second period (Table 1). This trend contrasts with that observed in the temperate region of south-central Chile, where expansion rates of tree plantations have increased constantly during the last four decades due to native forest conversion intensive to exotic tree plantations for timber and pulp-wood purposes (Echeverría et al. 2006; Miranda et al. 2017; Altamirano et al. 2020). However, in the Coyhaique Province, a large part of the increase in exotic tree plantation during the first period was in fact driven by policies to stop/prevent soil erosion following anthropic fires, not for commercial purposes (Fajardo and Gundale 2015). Exotic plantations were also planted for commercial purposes contributing to the increase during the study period, but this slowed down around the year 2012 because the tree growth trend was lower than expected (economic value), government subsidies for planting stopped, and infrastructure was lacking (e.g., roads) (Moreno Meynard and Obando Barría 2006). Despite this slowdown, an additional factor that contributes to the increase of surface has become relevant in recent years in the Coyhaique Province, that is, the biological invasion by exotic pine species, and in particular *Pinus contorta* (Langdon et al. 2010; Braun et al. 2017). Similar trends have been found in other temperate regions, such as New Zealand, Argentina, and the USA, where *P. contorta* has been identified as an invasive species (Richardson et al. 1994; Taylor et al. 2016). The highlighting of these trends provides an early warning that can help to establish measures to slow this invasive species in the Coyhaique Province.

Intact forest landscape trends and management

The results showed that majority of the monitored landscape (79%) showed no change during the entire study, and all of the land cover dynamics occurring just in 21% of the study area (Fig. 4). However, of this unchanged area (i.e., 79%), 61% could be classified as landscape having low anthropic influence, or could even be described as an IFL due most of the Coyhaique Province area is covered by old-growth forest (Fig. 3b). Land cover types such as bare soil, water bodies, and highland vegetation are also subject to low human influence, and these also contributed to the unchanged area. Astorga et al. (2018) found a similar trend in an analysis of intact forested watersheds from western Patagonia. This trend is confirmed by a study that adopted an anthropization index which highlighted the relatively low human pressure on the Coyhaique Province landscape during the last four decades (Hernández-Moreno et al. 2021). Despite the disturbances caused by historical fires, our study shows that this forest landscape could be considered mostly intact or with low anthropization, which is in agreement with global studies (Potapov et al. 2017; Jacobson et al. 2019). This is an important observation in the context of current trends in global change and the accelerated rates of land use and land cover change both locally in Chile (Hernández et al. 2016; Locher-Krause et al. 2017; Miranda et al. 2017; Otavo and Echeverría 2017; Altamirano et al. 2020) and global (Tropek et al. 2013; Venter et al. 2016; Allan et al. 2017; Song et al. 2018; Potapov et al. 2020). This suggests that for isolated landscapes such as Patagonia, it is still possible to maintain IFL proportions even in times of global change. Our findings reinforce recent initiatives that consider Chilean Patagonia as a Sub-Antarctic natural laboratory for science (http://www.nodosubantartico.cl/). However, in order to maintain this IFL trend, it is necessary that decision makers to define their interest in the protection of "intact" areas or those with low anthropization and manage territorial planning that promotes the landscape strategic use.

Spatial patterns after past fires: fragmentation trends

The dynamics of land cover described here is associated with changes in spatial patterns of native forest. In particular, the old-growth forest has shown a slight tendency towards fragmentation as monitored by landscape metrics. The reduction of the large patch index and the proximity index over the entire study period is highlighted (Table 2). The reduction of the large patch index indicates that the area with the greatest amount of continuous habitat in the landscape would be reduced. The proximity index indicates that between 1984 and 2018 the patches of old-growth forest became more distant from each other (taking into account the specified radius of 500 m), suggesting an increase in fragmentation. This is consistent with global trends generally showing habitat reduction resulting from the increase in forest fragmentation (Jacobson et al. 2019). This trend should be considered watched carefully as the increase in forest fragmentation can result in reduced ecosystem functions, including carbon stock (Islam et al. 2017). For example, Islam et al. (2017) found that carbon stock in a tropical ecosystem is lower in fragmented forests than in contiguous forests. Although the fragmentation trend in Coyhaique forests was relatively slight, these spatial patterns should be monitored periodically because short-term recovery of patches of old-growth forests is difficult.

In contrast, analysis of metrics of second-growth forests showed a trend of decreasing fragmentation. In particular, the large patch index and proximity index increased over the study period, indicating an increase in the continuous habitat area and a reduction in second-growth forest fragmentation. It should be emphasized that in Coyhaique Province the changes in spatial patterns were initially generated by the past fires. When fires influence spatial patterns, fragmentation is typically associated with landscape mosaics in extensive natural systems, with dynamics dominated by succession (Driscoll et al. 2021). The specific level of fragmentation is primarily determined by land-use change, and fragmentation dynamics are linked to the rate of land clearing and land abandonment (Driscoll et al. 2021). Jonson (2010) found that when the land is abandoned, the landscape may recover through revegetation, as was demonstrated in the present study by recovery of second-growth forest following the fires. This recovery dynamic could explain the trend of decreasing fragmentation in second-growth forest in Coyhaique Province. This decreasing trend in western Patagonia contrasts both with that found in temperate forests in south-central Chile where spatial patterns have shown an increase in fragmentation during the past few decades (Echeverría et al. 2006, 2008), and with the observed increase in tropical forest fragmentation resulting from fires (Armenteras et al. 2013a; Taubert et al. 2018). However, an increase in forest cover is not always associated with decrease in fragmentation (Kozak et al. 2018), and further research is clearly needed to empirically assess the quality and function of new patches of second-growth forest relative to those of old-growth forest.

Ecosystem function: potential carbon stock of landscape

The great gains and losses in the carbon potential stock may be the effect of main land cover changes in Coyhaique Province, such as the loss of old-growth forests mainly during the first period (1984–2000), and the recovery of second-growth forests over the second period (2000–2018). However, micro-scale changes in the carbon potential stock (i.e., small gains and losses) was more evident at the landscape level than large changes were unveiled by the results (Fig. 5). These micro-changes would indicate that much of the gains or losses in the potential carbon stock was not necessarily driven by land cover changes, but by alterations from climate or degradation in the forest (Zamorano-Elgueta et al. 2012) which could have an effect on primary productivity, which in turn is related to capture and carbon stock. Furthermore, it has been found that old-growth forests of *Nothofagus pumilio* in the Province of Coyhaique have reduced primary productivity due to cavitation disturbances in the upper level of the canopy (i.e., the section captured most readily by satellite image) due to climate change disturbances (Soto et al. 2022). Also, the structural alterations that the landscape metrics showed (Table 2, previous discussion) with slight old-growth forest fragmentation likely caused reduced carbon stock in fragmented forests (Islam et al. 2017). This trend of micro changes in carbon stock highlights the importance of landscape-scale management intervention in the forest.

The need for quantification of aboveground carbon stocks has been repeatedly emphasized (Rappaport et al. 2018; Noon et al. 2021). Here, we combined data for land cover changes with data taken from the literature both to estimate potential carbon stock, and to examine the effect of land cover change on aboveground carbon potential stock. Clearly, the total biomass of these forests cannot be directly measured, and the use of relevant data from the literature can help to extrapolate an initial approximation of general trends in carbon stocks at the landscape level. However, we acknowledge that these are broad approximations for estimating carbon potential stock, and key details of forest cover at different stages of growth can be oversimplified by this approach (Peri et al. 2010). For greater accuracy, future studies could improve estimates of total carbon storage using local field samples, with special emphasis on old-growth and second-growth forests.

Implications for landscape ordination and management

The general trends observed in our study, such as continuous old-growth forest loss and second-growth forest recovery, highlight the need for sustainable management for conservation programs in a region that still maintains a large proportion of intact forest landscape (sensu Potapov et al. 2008). In order to propose management and conservation plans, it is necessary to have baseline information as provided in this study, coupled with ecological and social knowledge to implement management strategies aimed to increase the adaptative capacity of these forests, even the old- and second-growth forests. In this sense, the new paradigm to see the forest as a complex adaptive system could provide novel insights to manage forests to increase their structural complexity (Puettmann et al. 2009; Messier et al. 2019). Theoretically, forests with high structural complexity (i.e., irregular tree-size distributions, high deadwood, and high species richness on the forest floor, such as old-growth forest stage) are more resilient and resistant to novel disturbances at stand and landscape levels (Soto and Puettmann 2020; Messier et al. 2019; Mina et al. 2021). On the contrary, second-growth forest recovery tends to be characterized by single tree-dominated forests (e.g., *Nothofagus pumilio*), that is, forests with low structural complexity, being more vulnerable to novel disturbances influenced by global change, such as severe droughts, outbreaks and fire. Under this context, the results of this study provide baseline information on structural (e.g., landscape metrics) and functional (e.g., carbon stock) characteristics that could help to make conservation and forest management plans on specific areas of the territory (Soto et al. 2022).

Conclusion

Western Patagonia in the southern Andes provides a unique opportunity to evaluate the effects of large-scale fires and resulting land cover change on the structure and functions of a landscape with low anthropization. This study presents the first evidence of the state of the forest area after more than six decades since the large-scale fires of temperate forests landscape for land clearing in western Patagonia ended. The results indicated that the old-growth forest area is still in decline, while second-growth forest recovery has been rapid. Interestingly, the rate of second-growth forest recovery at the landscape scale contradicts the high forest loss documented in the past decades in south-central Chile. These observations were not the result of land planning but a consequence of the abandonment of agricultural land due to lack of accessibility or topographic barriers. This study highlights the ability of southern temperate forests to recover after large-scale fires and the exceptional trend to still conserve a large tract of intact forest landscapes in the current global change context. Last, our data could lead to improved landscape development and/or management decisions, such as identifying and prioritizing conservation areas where old-growth forest has been lost and implementing programs for forest management in selected areas to enhance the potential capacity of carbon stock.

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Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interest The authors have not disclosed any competing interests.

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