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Rural Property Subdivision: Land Use Change Patterns and Water Rights Around Cerro Castillo National Park, Chilean Patagonia

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Abstract

Protected areas (PAs) are increasingly exposed to anthropogenic pressures under global change scenarios, with surrounding land subdivision and land use/land cover change (LULCC) dynamics often undermining their conservation goals and intensifying demand for basic services such as water availability. This study analyzed the buffer zone around Cerro Castillo National Park in Chilean Patagonia to assess the evolution of rural private properties, considering their subdivision, LULCC, and legal water demand dynamics. Using cadastral records, Landsat 8 imagery, and official water rights databases, we quantified property subdivision and analyzed LULCC and water rights distribution patterns through spatial overlap analysis. Results indicate a nearly fourfold increase in subdivisions between 2011 and 2023, with 304 properties divided into 3237 units occupying 43.7% of the private land area. LULCC analysis revealed a net recovery of native forest (+10%) alongside notable increases in urban coverage (+152%) and exotic plantations (+245%). Legal water demand almost doubled, with 68% of consumptive rights concentrated in subdivided properties. These findings highlight property subdivision as an important factor influencing socioecological change in the territories that surround PAs. We argue that subdivision dynamics can serve as an early indicator for anticipating land use pressures and can complement integrated landscape-scale planning, consistent with the transformative change approaches advocated by international biodiversity frameworks.

Keywords: protected areas; buffer zone; land use and land cover changes (LULCC); water availability; sustainable territorial transition; IPBES framework

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1. Introduction

Contemporary socioecological systems worldwide are undergoing global change, accelerating degradation, biodiversity loss, and limiting societal capacity to pursue sustainable development for future generations [1–4]. These challenges are so profound that they demand fundamental shifts in conservation and development approaches [5]. The

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) consequently advocates for transformative change in human–nature relationships to halt biodiversity decline and achieve the goals of the Kunming–Montreal Global Biodiversity Framework (GBF) [2].

Protected areas (PAs) have proven to be one of the most effective ways to protect biodiversity in the context of ecosystem degradation, as they play a key role in mitigating the loss of natural habitats and maintaining species populations, while also contributing to the economic development of surrounding communities [6,7]. Target 3 of the GBF proposes protecting 30% of the planet by 2030 as a path to sustainability. This effort emphasizes a comprehensive vision that frames PAs as part of larger landscapes to maintain ecological connectivity. Therefore, it must be accompanied by sustainable management of the remaining 70% of the territory, which involves aligning policies and engaging multiple actors [8].

However, the areas surrounding PAs, where public and private lands meet, are increasingly shaped by rural land subdivision, which drives housing and infrastructure development and intensifies demand for basic services such as water, access, energy, and sanitation systems [9–11]. These pressures, together with broader urbanization trends, compromise conservation as land use intensity emerges as a critical factor undermining landscape ecological resilience [12–14]. The situation is particularly pronounced in regions with conservation-based development models, where PAs act as economic catalysts: tourism revenues transform local communities, stimulate visitor expenditure, and attract new residents through gateway community formation and amenity migration [15–17]. While these dynamics risk accelerating land use/land cover change (LULCC), governments have actively promoted them to boost regional economies [15,18,19].

At the same time, global studies have shown that the zones surrounding PAs experience higher than average rates of LULCC, suggesting a boundary effect that compromises their environmental integrity [12,20,21]. One hundred and fourteen million hectares of PAs experienced habitat loss between 2003 and 2019 due to external pressures such as deforestation, agricultural conversion, and urban expansion [20]. De la Fuente et al. [13] calculated the percentage covered by built-up areas in and around PAs. The proportion of built-up area within 10 km surrounding PAs greatly exceeds that within the interior (2.71% vs. 0.12% in 2014) [13], confirming significant urbanization trajectories at the edge [9,10].

Anthropization processes are intensifying water scarcity in a global change context, disrupting ecological and human systems and underscoring the urgency of sustainable water use [22–25]. Rural areas face critical challenges in water supply and distribution, largely due to weak regulation of settlement patterns and water demand, compounded by climate change [26]. Empirical studies show that rural settlements cluster near roads and hydrographic networks, offering insights for integrated land and water management [27]. Álvarez-Garretón et al. [28] calculated water stress indices for 277 river basins in Chile. Their findings reveal that if consumptive water rights were fully exercised, 18% of river basins would surpass extreme risk thresholds, exceeding both legal and physical limits. These dynamics highlight the need to integrate social dimensions into hydrological frameworks [29,30], consistent with the principles of Integrated Water Resources Management (IWRM), which promotes the integration of cultural, ecological, and economic aspects with hydrological dimensions through participatory decision-making processes [31,32]. Considering the trends toward increased consumptive use and changes in water demand due to population growth, social needs, and productive activities [22], there is a need for better understanding of water rights allocation to improve legal management.

Thus, interface zones are essential for conservation and sustainable planning, as they mediate interactions between human activities and ecological processes, thereby mitigating the island effect that confines conservation within PA boundaries [11,12,33]. Research integrating ecological and social dimensions is needed to enhance sustainability pathways, particularly in diverse ecological, climatic, and developing country contexts [11,25].

Chile faces significant challenges in this regard, as nature-based tourism constitutes a major driver of national development, with PAs playing a central role in this process [34]. The subdivision of rural land around these areas and the arrival of new settlers are taking place amid long-standing deficiencies in Chilean rural planning frameworks [35,36]. Since the 1980s, the primary rural planning instrument has been Decree Law 3615, which allowed urban expansion without adequate planning oversight, fueling real estate speculation [37,38]. Chile's accession to the OECD in 2010 encouraged a shift from fragmented treatment of urban and rural spaces toward integrated territorial planning [37,39]. Subsequent policy developments include the National Urban Development Policy [40], the National Rural Development Policy [39], and the 2023 creation of the National Territorial Development Council, which merged prior urban and rural councils [41]. Despite these measures, unregulated rural subdivision persists, prompting the drafting of a 2024 bill on rural areas and rural life. This initiative highlights that subdivision now encompasses an area equivalent to all built-up land nationwide, yet continues with minimal regulation and oversight [42]. In parallel, Law 21,600, establishing the Chilean Biodiversity and Protected Areas Service, introduces buffer zone definitions for PAs based on scientific criteria but limits restrictions to territorial planning instruments, thereby reducing their regulatory effectiveness [43].

Research on rural subdivision in Chile has concentrated largely in central regions, especially Santiago and Valparaíso, where legal and institutional aspects of property rights and regulation dominate the debate [44,45]. More recent work has broadened this scope: Villavicencio-Pinto [46] conducted a historical, cartographic, and sociolegal study in central Chile, highlighting challenges associated with productivity, ecological thresholds, and climate change adaptation. In the Los Ríos and Los Lagos regions, territorial approaches combined land use photointerpretation with real estate market data [47] and advanced spatial methods such as kernel density analysis and machine learning [35]. Similar processes have been studied internationally, including second homes in rural Finland [48] and Italy [9], exurban growth in Puerto Rico [10] and the western United States [16], and amenity migration near PAs in Spain [49]. These dynamics consistently generate pressures on biodiversity, water security, and land governance. The Chilean government also recognizes the socioecological risks of uncontrolled subdivision, highlighting the need for stronger empirical evidence to inform sustainable development [36].

Despite its significance, the Aysén region in Chilean Patagonia—identified as both a subdivision hotspot [36] and an area of high conservation value [50]—remains understudied. Only two works have addressed this territory: one as part of a national policy framework discussion [36] and another focused on the Levicán Peninsula using qualitative methods [51]. Yet, Patagonia is globally distinctive for its high degree of naturalness [50,52,53], with more than half of its territory under formal protection [54]. It illustrates tensions between conservation-based development and global change [34,55–57], being highly vulnerable to climate variability. The 2016 mega-drought reduced precipitation and river flows by 50% [58], amplifying pressures on ecosystems. These climatic challenges intersect with socioeconomic transformations triggered by the Southern Highway (Carretera Austral) in the 1970s, which facilitated population growth, tourism, and amenity migration [15], resulting in nature-based tourism becoming one of the main economic drivers [59,60]. Although Chile has advanced Integrated Water Resource Management (IWRM) frameworks to address droughts and hydrological risks [61–63], their implementation remains hindered by governance and regulatory limitations [64], posing urgent challenges for sustainable regional planning [65]. Against this backdrop, Chilean Patagonia emerges as a critical setting for advancing research on rural subdivision around PAs.

Even though there is evidence that PA interface zones are undergoing an accelerated process of land subdivision, along with higher rates of LULCC, and water demand, no studies have addressed whether there are differences in these dynamics between properties that have been subdivided and those that have not. Our study analyzed the interface zone of Cerro Castillo National Park (CCNP), in the Aysén region (Chilean Patagonia), a well-connected PA prioritized by the Chilean government for tourism development, whose surroundings are experiencing socioecological changes and land subdivision [19,59,66]. The objective is to assess the evolution of rural private properties between 2011 and 2023, considering their subdivision, LULCC, and legal water demand dynamics. The following research questions guided this study: (1) To what extent have private rural land subdivisions increased in the study area from 2011 to 2023? (2) Do subdivided and undivided properties differ in terms of LULCC? (3) Do subdivided and undivided properties differ in terms of legal water demand?

This descriptive approach improves understanding of land subdivision patterns and provides baseline information for advancing land and water management, as well as for improving public policies in rural areas of Chile and other regions worldwide. The importance of this research is closely aligned with IPBES frameworks [1,2,11], which emphasize the use of scientific approaches to improve territorial planning through sustainable resource management and inclusive governance models aimed at collective well-being, thereby supporting pathways for transformative change [2].

2. Materials, Methods, and Analysis

2.1. Study Area

The park is situated on the watershed divide between two major river basins that extend across and beyond the study area (Figure 1). The northern section drains into the Aysén River basin through tributaries that traverse one of the region's most developed livestock areas. The southern section drains into the Baker River basin, which includes one of Chile's largest rivers. The nearest settlements to the park include Valle Simpson (336 inhabitants), Villa Frei (94 inhabitants), El Blanco (250 inhabitants), Balmaceda (405 inhabitants), Villa Cerro Castillo (376 inhabitants), and Puerto Ingeniero Ibáñez (764 inhabitants) [67].

Public/private land interface zones are crucial for extending healthy ecosystem benefits beyond PA boundaries [12,33]. However, globally, including in Chile, a gap remains in defining PA buffer zones and their functions [33]. In Chile, Law 21,600 proposes scientific and technical criteria for buffer zone delimitation [43], but does not specify a methodology or specific criteria to be considered. Thus, a 10 km buffer from the park boundary was chosen, as this is a useful distance for analyzing landscape dynamics around PAs [13,68,69]. Qualitatively, this distance provides adequate space to capture the relational dependencies of settlements near the park (e.g., water supply, tourism, views) and their development.

The main economic activities in the area surrounding CCNP are livestock farming, agriculture, forestry, and tourism, with the latter playing an increasingly important role due to CCNP's designation as a priority area for regional development [60]. In this context, CCNP represents an emblematic case due to several factors. It is among the most accessible parks, owing to its proximity to Balmaceda Airport (the main point of entry to the Aysén Region) and its connection to the Carretera Austral, which crosses the park for 25 km. In 2010, it was prioritized under Law 20.423 for sustainable tourism concession development [70], and in 2017 it became part of the "Route of Parks of Patagonia", an initiative of Tompkins Conservation and the Rewilding Chile Foundation promoting economic development based on conservation and nature tourism [71]. Additionally, the interface zone south of the park was designated a "Tourism Interest Zone" by the Chilean Undersecretary of Tourism, further promoting tourism industry development [19,59].

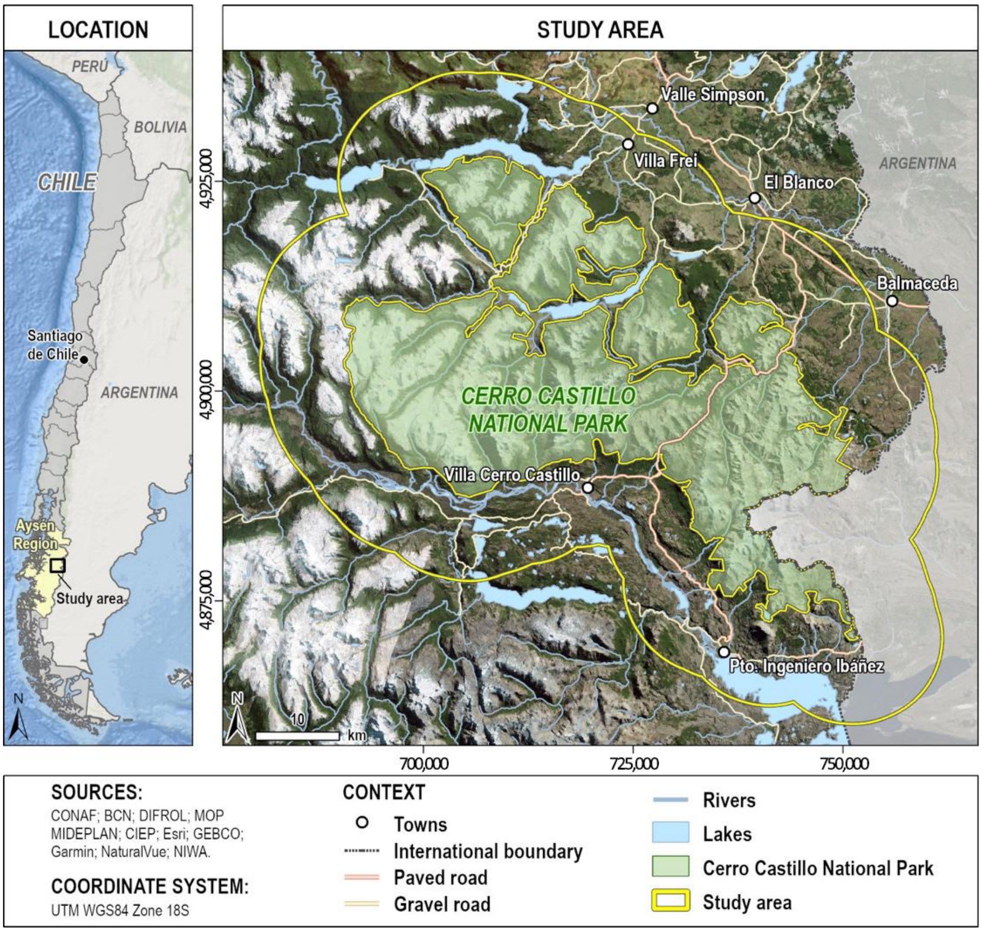

Figure 1. Study area.

As a result of these efforts, the area has experienced growth in tourism-related businesses and sales volumes [72], alongside a decline in traditional activities such as livestock farming and agriculture. However, some residents oppose these changes, leading to conflicts over imbalances between local interests, tourism development, and governance [19,59,73]. Simultaneously, national and international promotion of the park has attracted investors who purchase rural properties, subdivide them, and market them as recreational or residential plots, typically to foreign buyers. This process is compounded by automatic land subdivision upon an owner's death, which under Chilean inheritance law results in 50% of the land passing to the spouse and the remaining 50% being divided equally among children in the absence of a will [19]. Rural land subdivision and new home construction have increased demand for basic services, including electricity, sanitation, road infrastructure, and water, while altering land use patterns. In these areas, water supply is mainly organized through Rural Sanitation Services, managed by local communities with state support, which supply a large part of the rural population. At the same time, there are individual or informal supplies, where families depend on wells, springs, rivers, or water trucks in situations of scarcity.

2.2. Data Sources

The research used various data sources. The number of rural land subdivisions in the study area was quantified using a geographic layer of rural properties from 2011 [74] and rural property information from the Chilean Internal Revenue Service's digital map viewer from 2023 [75].

The spatio-temporal analysis of LULCC was conducted using two images from the Operational Land Imager (OLI) sensor on the Landsat 8 satellite [76] from 2014 and 2024, whose spectral information is suitable for land cover identification and well matched to the working scale of the study area (30 m pixel resolution). Fieldwork and images available in Google Earth Pro 7.3.6.10201 (64-bit) software [77] were used to complete supervised classification tasks for land cover identification.

To calculate legal water demand, an official database on consumptive water rights (CWR) from 1988 to 2023 was used, provided by the Chilean Water Authority [78]. CWR represent those rights that record total water consumption across all activities, including irrigation and human and animal consumption, among others. Subsequently, collaborative work with Chilean Water Authority officials enabled the acquisition of more accurate and refined information. Although CWR do not reflect actual water consumption, the flow rate recorded in the rights is a standard and comparable quantity, which makes it possible to construct water balances, assign priorities, and analyze the pressure on sources. They have been used in studies focused on assessing water stress in scenarios of legal water use [28]. Therefore, they are a good option for approximating the amount of water legally committed in the context of the study.

2.3. Methodology and Analysis

The 2011 rural properties layer was imported into ArcGIS Pro 3.5.2 software [79], and properties were identified through photointerpretation and their unique identifiers determined by comparing data and boundaries in the Chilean Internal Revenue Service's 2023 map viewer. Once parent properties were identified, subdivisions within each property were assessed, counted, and recorded, with data stored in the database associated with the rural property layer. This allowed us to identify subdivided and undivided properties as a basis for quantifying LULCC dynamics and CWR in each case.

For the LULCC process, we used a Landsat 8 image from 2014 and another from 2024, which we consider valid for detecting potential changes, given that recent studies report landscape stability in the area [53]. Both images were acquired in April and exhibit minimal cloud cover (2.05% for the 2014 image and 2.14% for the 2024 image). Both images are Level-2 products, which incorporate radiometric and atmospheric corrections. A supervised classification process was conducted for both images using the Support Vector Machine method [80,81]. Ten land cover types were identified, adapting the classification proposed by Hernández-Moreno et al. [53]: "native forest", "plantation" (exotic vegetation), "scrubland", "pastures", "bare soil", "water bodies", "snow", "urban", "other coverage", and "shadow" (Table 1).

A collection of ground control points and high-resolution images available through Google Earth Pro software [77] complemented the classification process. Each satellite image included at least 100 training samples. Classification accuracy was evaluated using ArcGIS Pro 3.5.2 software [79], through confusion matrices comparing reference data (139 points for each image) and the resulting classification. The Kappa index values obtained were 0.86 for the 2014 classification and 0.85 for the 2024 image. Finally, maps and transition matrices (two-dimensional tables) were generated to analyze land cover changes between 2014 and 2024 (Appendix A). Areas covered by shadows are included in the transition matrices to maintain the complete analysis area but were excluded when examining land cover dynamics.

Table 1. Description of land cover types.

Land Cover	Description	Source
Native forest	Forests composed mainly of *Nothofagus pumilio*, *Nothofagus antarctica*, *Nothofagus dombeyi*, and other native tree species.	[53]
Plantation	Exotic tree plantations, composed mainly of *Pinus ponderosa*, *Pinus contorta*, and other exotic tree species.	[53]
Scrubland	Shrubs, sparse vegetation (tree cover $\leq$ 50%) and small tree cover such as *Nothofagus* sp. or other native or introduced shrubs.	[53]
Pastures	Herbaceous vegetation cover.	[53]
Bare soil	Exposed rocks, sand dunes, and areas with minimal vegetation cover.	[53]
Water bodies	Rivers, lakes, and lagoons.	[53]
Snow	Seasonal snow cover.	[53]
Urban	Built-up areas containing villages and small clusters of rural buildings.	[53]
Other coverage	Land above the treeline (>1200 m above sea level).	[53]
Shadow	Areas obscured by shadows in satellite images.	[53]

The CWR are georeferenced, allowing for the generation of geographic layers and for relating them to land subdivision maps (Figure 2). For the analysis, intervals were established for average annual consumption, following guidelines applied by the Chilean Water Authority in the area [82]: very low flows (<10 L/s); low (≥10 and <50 L/s); medium (≥50 and <200 L/s); and high (≥200 L/s). Figure 2 shows the methodological process.

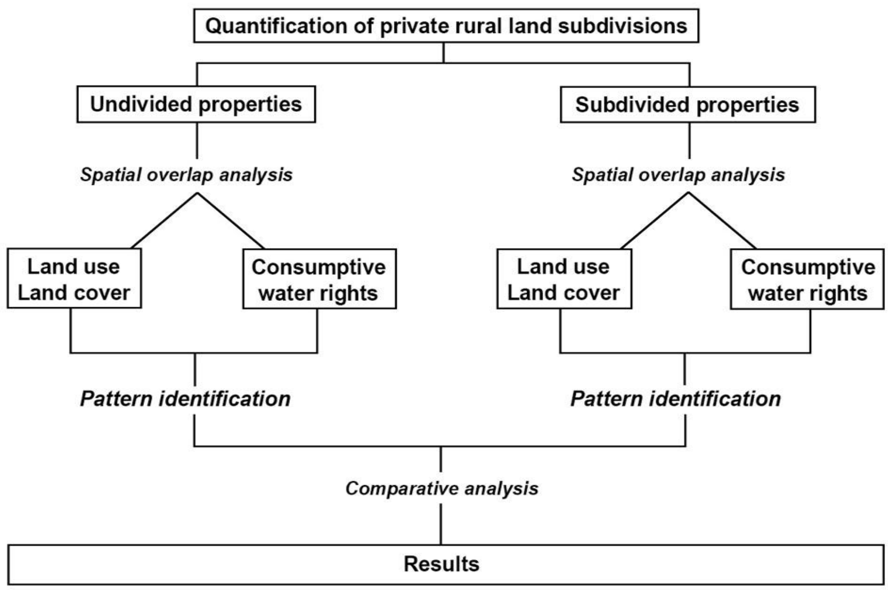

Figure 2. Methods diagram.

3. Results

3.1. Dynamics of Land Subdivision

In 2011, 810 private properties were identified within the study area (10 km radius around CCNP), occupying a total of 156,036.8 ha. By 2023, 304 properties were found to contain internal subdivisions, totaling 3237 subdivisions. The subdivided properties occupy 68,265.6 ha, representing 43.7% of the total private land area. The remaining 506 properties remained undivided and occupied 87,771.2 ha.

The number of property subdivisions quantified from 2011 to 2023 ranged from two to 207, with an average of 21.7 divisions per property. There were 270 properties with fewer than 20 subdivisions distributed throughout the study area, and 34 properties with 20 or more subdivisions located near population centers (Villa Frei, Villa Cerro Castillo, and Puerto Ingeniero Ibáñez), lakes (such as Monreal Lake and Las Ardillas Lake), and rivers (such as Paloma River and Ibáñez River). Undivided properties were distributed throughout the study area, with slight concentrations around the town of Balmaceda and in areas near Puerto Ingeniero Ibáñez (Figure 3).

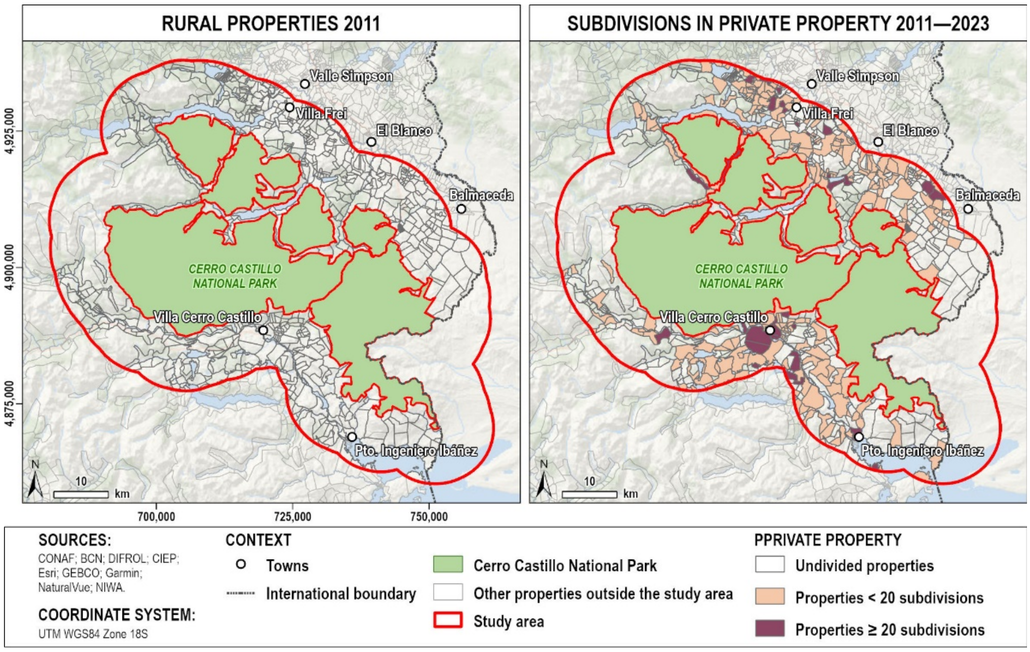

Figure 3. Distribution of rural properties in the study area in 2011, and quantification of subdivisions between 2011 and 2023.

3.2. Land Cover Changes

3.2.1. Area Occupied by Private Properties

The analysis of land cover changes reveals the evolution of cover types from 2014 to 2024. Overall, of the 156,036.8 ha occupied by private properties in the CCNP interface zone, 79.6% maintained their land cover while the remaining 20.4% underwent change (Table A1).

Regarding land cover dynamics, net area increases occurred in "native forest" (5160.8 ha) "plantation" (2392.7 ha), "bare soil" (727.9 ha), and "urban" (96.3 ha) categories. In relative terms, "plantation" showed the most dramatic growth, with an increase of 244.6%, followed by "urban" cover, which expanded by 152.2%. The land cover types that experienced area losses were "scrubland", "pasture", and "snow". "Scrubland" experienced the greatest net loss, declining from 29.6% of the area in 2014 to 25.1% in 2024. "Pasture" experienced a more modest reduction of 2.6% in its area (Table 2). Regarding "snow" cover, its seasonal nature should be noted (Table 1). At the time of image acquisition (April), snow was primarily located on mountain peaks, and areas above 1200 m above sea level were classified as "other coverages" in this study. Therefore, these data are not suitable for assessing "snow" cover dynamics.

Table 2. Area of land cover, percentage of land cover relative to total private property area, net change, and rate of change.

Land Cover	2014		2024		Net Change (ha)	Change Rate (%)
	ha	%	ha	%	2014–2024	2014–2024
Native forest	51,319.5	32.9	56,480.3	36.2	5160.8	10.1
Plantation	978.1	0.6	3370.8	2.2	2392.7	244.6
Scrubland	46,123.3	29.6	39,235.1	25.1	−6888.2	−14.9
Pastures	51,089.5	32.7	49,758.2	31.9	−1331.3	−2.6
Bare soil	1988.9	1.3	2716.8	1.7	727.9	36.6
Water bodies	1160.1	0.7	1161.3	0.7	1.2	0.1
Snow	180.8	0.1	19.6	0.0	−161.2	−89.1
Urban	63.3	0.0	159.6	0.1	96.3	152.2
Other coverages	3011.5	1.9	3013.8	1.9	2.3	0.1
Shadow	121.8	0.1	121.2	0.1	−0.5	−0.4
TOTAL	156,036.8	100.0	156,036.8	100.0	-	-

3.2.2. Differences Between Subdivided and Undivided Properties Regarding Land Cover

The area occupied by subdivided properties has been more dynamic than that occupied by undivided properties. Although the net area of change in undivided properties is 1218.8 ha greater than that in subdivided properties, it represents a smaller percentage of the total area (Table 3).

Table 3. Stable area and area of change in subdivided and undivided properties.

Property Type	Area that Maintained the Land Cover 2014–2024		Area that Changed Land Cover 2014–2024	
	ha	% of Total Area	ha	% of Total Area
Subdivided properties	52,955.7	77.6	15,309.9	22.4
Undivided properties	71,242.5	81.2	16,528.7	18.8
TOTAL	124,198.2	-	31,838.6	-

For both subdivided and undivided properties, a larger proportion of area maintained land cover without change (Figure 4).

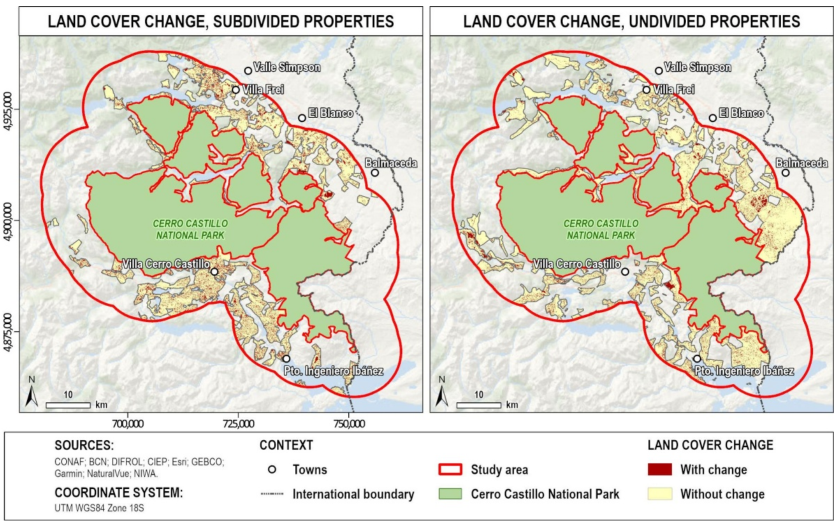

Figure 4. Land cover changes from 2014 to 2024 in subdivided and undivided properties.

Table 4 shows the evolution of land cover on subdivided properties. The most significant net gain occurred in "native forest", with more than 2500 ha. However, the most significant positive change rates occurred in "plantation" (129.5%), "urban" (115.5%), and "bare soil" (46.3%). The most significant loss, both in net area and percentage terms, occurred in "scrubland", which primarily benefited "native forest" (4894.0 ha), "pasture" (2655.2 ha), and "plantation" (421.3 ha) (Table A2).

Table 4. Area of land cover, percentage of land cover relative to the total subdivided property area, net change, and rate of change.

Land Cover	2014		2024		Net Change (ha)	Change Rate (%)
	ha	%	ha	%	2014–2024	2014–2024
Native forest	20,559.4	30.1	23,099.8	33.8	2540.3	12.4
Plantation	591.1	0.9	1356.8	2.0	765.7	129.5
Scrubland	21,440.7	31.4	18,565.8	27.2	−2874.9	−13.4
Pastures	24,030.2	35.2	23,266.8	34.1	−763.4	−3.2
Bare soil	617.8	0.9	904.0	1.3	286.2	46.3
Water bodies	655.8	1.0	657.5	1.0	1.6	0.2
Snow	24.1	0.0	0.0	0.0	−24.1	−100.0
Urban	59.7	0.1	128.6	0.2	68.9	115.5
Other coverages	199.9	0.3	200.0	0.3	0.1	0.0
Shadow	86.9	0.1	86.4	0.1	−0.5	−0.6
TOTAL	68,265.6	100.0	68,265.6	100.0	-	-

Undivided properties also experienced their most significant net gain in "native forest", with more than 2600 ha. Regarding the most significant positive change rates, "urban" (760.0%), "plantation" (420.4%), and "bare soil" (32.2%) were prominent. Notably, the sharp increase in "urban" cover results from the small baseline area of only 3.6 ha in 2014, which increased to 31 ha in 2024, representing a net gain of 27.4 ha. In contrast, "plantation" showed a substantial net increase of 1626.9 ha. As with subdivided properties, "scrubland" again experienced the highest losses, both in net area and percentage terms (Table 5). The main beneficiaries were "native forest" (5232.6 ha), "pasture" (2582.3 ha), and "plantation" (977.4 ha) (Table A3).

Table 5. Area of land cover, percentage of land cover relative to total undivided property area, net change, and rate of change.

Land Cover	2014		2024		Net Change (ha)	Change Rate (%)
	ha	%	ha	%	2014–2024	2014–2024
Native forest	30,760.1	35.0	33,380.6	38.0	2620.4	8.5
Plantation	387.0	0.4	2013.9	2.3	1626.9	420.4
Scrubland	24,682.6	28.1	20,669.3	23.5	−4013.3	−16.3
Pastures	27,059.3	30.8	26,491.4	30.2	−567.9	−2.1
Bare soil	1371.2	1.6	1812.9	2.1	441.7	32.2
Water bodies	504.3	0.6	503.8	0.6	−0.4	−0.1
Snow	156.7	0.2	19.6	0.0	−137.1	−87.5
Urban	3.6	0.0	31.0	0.0	27.4	760.0
Other coverages	2811.6	3.2	2813.9	3.2	2.3	0.1
Shadow	34.8	0.0	34.8	0.0	0.0	0.0
TOTAL	87,771.2	99.9 [1]	87,771.2	99.9 [1]	-	-

[1] Totals may not equal 100% due to rounding.

Figure 5 illustrates the evolution of land cover for both total private property area and subdivided versus undivided properties. This map series shows that the largest patches experiencing land cover changes (shown in Figure 4) correspond primarily to "plantation" areas.

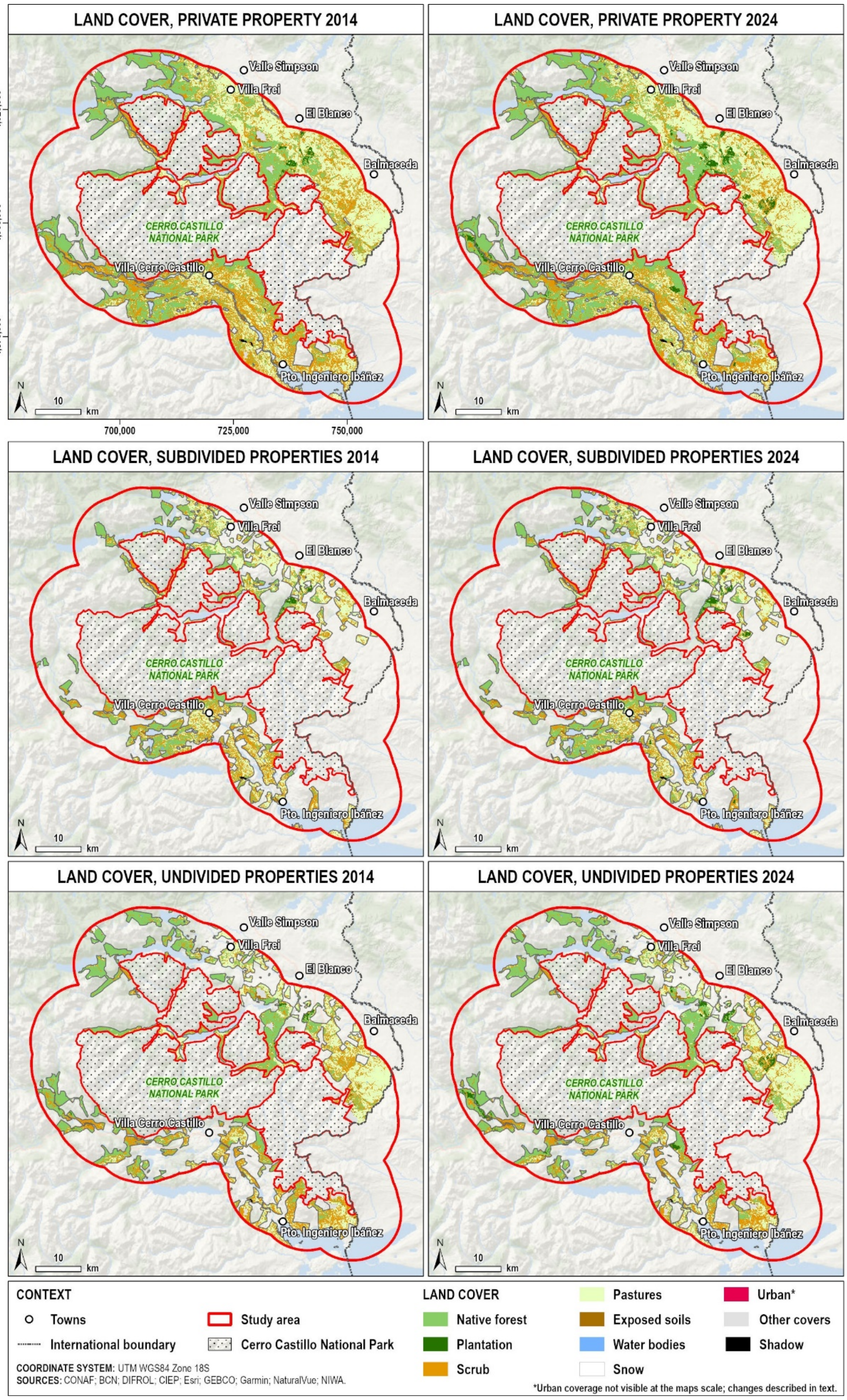

Figure 5. Evolution of land cover between 2014 and 2024 for total private properties and for subdivided and undivided properties.

3.3. Legal Water Demand

Legal water demand has experienced significant growth in recent years, as reflected in formal applications for water use rights. In the study area, the oldest CWR dates to 1988. From that date until 2011, 139 CWR were recorded in the area occupied by private properties, totaling an average annual consumption of 1736.0 L/s. By the end of 2023, 356 CWR were registered, yielding an average annual consumption of 3206.3 L/s, almost double that of 2011. The density of CWR per hectare in 2023 is 2.6 times higher than in 2011 (Table 6).

Table 6. Consumptive water rights (CWR) on private properties within the study area. The number of water rights for each flow interval is shown, with average annual flow in parentheses. The last column expresses the density of water rights per hectare.

Period	Consumptive Water Rights (CWR) and Average Annual Consumption (L/s)					Area (ha)	Density (rights/ha)
	<10 L/s	≥10 and <50 L/s	≥50 and <200 L/s	≥200 L/s	Total		
CWR 1988–2011	100 (205.0)	31 (579.8)	6 (494.0)	2 (457.2)	139 (1736.0)	156,036.78	0.0009
CWR 2012–2023	189 (331.4)	23 (452.9)	4 (466.4)	1 (219.6)	217 (1470.3)	156,036.78	0.0014
TOTAL	289 (536.4)	54 (1032.7)	10 (960.4)	3 (676.8)	356 (3206.3)	156,036.78	0.0023

Differences Between Subdivided and Undivided Properties Regarding Legal Water Demand

Figure 6 shows the spatial distribution of CWR and the associated demand. The left map reflects the situation in 2011, while the right map shows the situation in 2023. The size of each point is proportional to the average annual consumption based on assigned flow rates. In the 2023 map, CWR have clearly increased compared to 2011, particularly in areas near Villa Frei, El Blanco, and Villa Cerro Castillo.

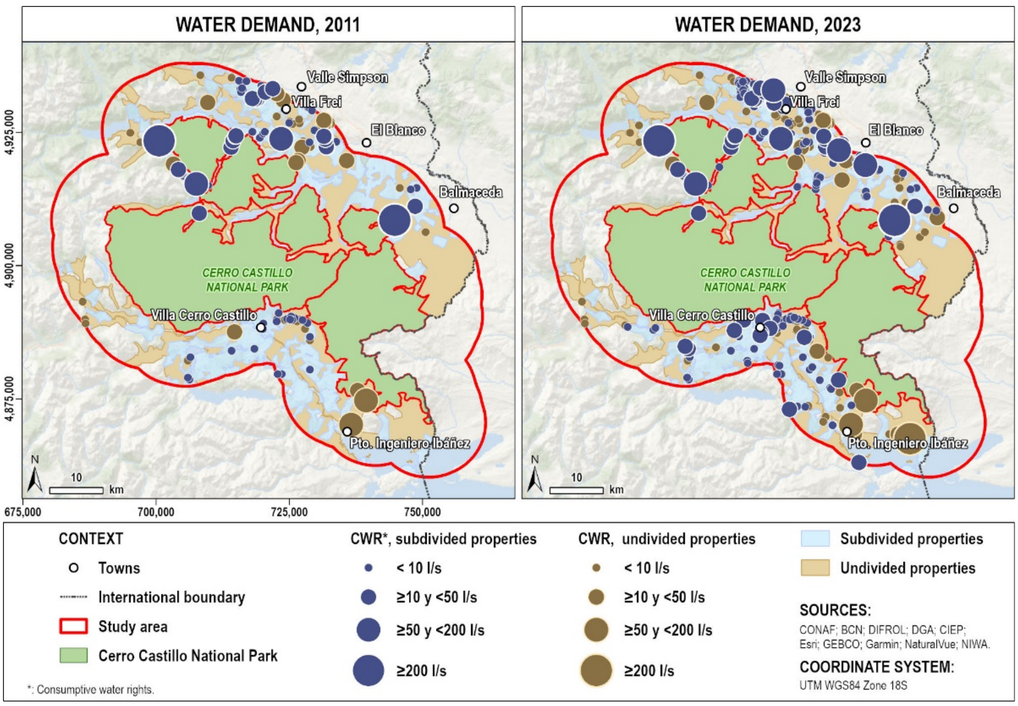

Figure 6. Spatial distribution of consumptive water rights (CWR) on private properties within the study area in 2011 (**left**) and 2023 (**right**).

Of the 356 CWR on private properties, 68.3% were located on subdivided properties. The flow range <10 L/s experienced the most pronounced growth, increasing from 63 CWR recorded through 2011 to 200 CWR recorded by 2023. The density of CWR per hectare in the 2012–2023 period reached 0.0023, nearly double that recorded in 1988–2011 (Table 7).

Table 7. Consumptive water rights (CWR) on subdivided properties within the study area.

Period	Consumptive Water Rights (CWR) and Average Annual Consumption (L/s)					Area (ha)	Density (rights/ha)
	<10 L/s	≥10 and <50 L/s	≥50 and <200 L/s	≥200 L/s	Total		
CWR 1988–2011	63 (138.5)	18 (278.0)	2 (100.0)	2 (457.2)	85 (973.7)	68,265.63	0.0012
CWR 2012–2023	137 (221.9)	18 (359.4)	3 (320.0)	0 (0.0)	158 (901.2)	68,265.63	0.0023
TOTAL	200 (360.4)	36 (637.4)	5 (420.0)	2 (457.2)	243 (1874.9)	68,265.63	0.0036

Undivided properties contain 31.7% of the 356 CWR on private properties. As with subdivided properties, the most notable increase occurred in the <10 L/s flow range, but with lower intensity. The density of CWR per hectare in the 2012–2023 period remained similar to the 1988–2011 period (Table 8).

Table 8. Consumptive water rights (CWR) on undivided properties within the study area.

Period	Consumptive Water Rights (CWR) and Average Annual Consumption (L/s)					Area (ha)	Density (rights/ha)
	<10 L/s	≥10 and <50 L/s	≥50 and <200 L/s	≥200 L/s	Total		
CWR 1988–2011	37 (66.4)	13 (301.8)	4 (394.0)	0 (0.0)	54 (762.3)	87,771.15	0.0006
CWR 2012–2023	52 (109.6)	5 (93.5)	1 (146.4)	1 (219.6)	59 (569.1)	87,771.15	0.0007
TOTAL	89 (176.0)	18 (395.3)	5 (540.4)	1 (219.6)	113 (1331.4)	87,771.15	0.0013

4. Discussion

This research examined the interface zone of CCNP (10 km radius) to study territorial dynamics specifically focused on rural land subdivision patterns, legal water demand requirements, and land cover changes. Important trends were identified regarding rural land subdivisions, anthropogenic land uses, and legal water demand, revealing the CCNP interface zone as a territory in transition. This contribution to understanding PA interface zone dynamics is expected to inform improved territorial planning of rural spaces in Chile and globally. In broader terms, it represents a contribution toward transformative change to address global change challenges, consistent with the GBF.

4.1. Private Properties and Land Cover Change

The results show that rural private land subdivisions increased nearly fourfold between 2011 and 2023. An increase in "native forest" was identified in both subdivided and undivided properties, which indicates that the subdivision itself does not entail a loss of native forest, which is consistent with previous research [53]. The recovery of "native forest" can result from both natural processes, such as seed dispersal, and anthropogenic causes, such as the abandonment of farmland or grazing areas [53]. In our study, gains in "native forest" (5161 ha) were primarily derived from "scrubland" (10,127 ha), "pastures" (1172 ha), and "bare soil" (87 ha) (Table A1). Overall, forests provide a broader and more robust range of ecosystem services than the mentioned land cover types, particularly regarding climate regulation, carbon storage, and water regulation [83], which may be interpreted as a positive change. Nevertheless, evidence from the Aysén region indicates that native forest regeneration is uneven and heterogeneous in terms of structure and composition, reflecting functional differences when compared to mature forests [84]. Therefore, field validation is required to determine the extent to which this recovery represents a functional restoration of the ecosystem.

The most relevant differences between property types are found in "plantation" and "urban" categories. To better understand this dynamic, Table 9 presents land covers with changes between 2014 and 2024 in the left column, followed by the number of patches equal to or greater than 0.5 ha for each cover type and their average area. In undivided properties, "plantation" growth is more intensive and extensive, with a greater number of patches and larger average area. In contrast, subdivided properties present more "urban" patches but with smaller average size compared to undivided properties. Undivided properties have fewer buildings but of larger size, suggesting an association with productive uses (such as large sheds for storing hay or wood), while subdivided properties exhibit more scattered and smaller-sized urban growth, possibly associated with residential uses (such as housing, small sheds, and self-consumption greenhouses).

Table 9. Number of patches and average patch size in land cover types that changed between 2014 and 2024 on subdivided and undivided properties.

Land Cover	Subdivided Properties		Undivided Properties	
	No. Patches $\geq$ 0.5 ha	Average Patch Size (ha)	No. Patches $\geq$ 0.5 ha	Average Patch Size (ha)
Native forest	2723	1.2	2702	1.3
Plantation	234	2.6	397	3.5
Scrubland	2060	1.2	1953	1.6
Pastures	1025	1.2	1162	1.1
Bare soil	219	1.1	327	1.2
Water bodies	1	0.6	0	0.0
Snow	0	0.0	0	0.0
Urban	38	1.4	10	2.2
Other coverages	0	0.0	0	0.0
Shadow	0	0.0	0	0.0

Exotic pine plantations alter hydrological services due to their higher evapotranspiration rates compared to native *Nothofagus* forests, while also altering habitat, facilitating the spread of forest fires, and decreasing biodiversity resilience [24,65]. Dispersed residential development fragments habitats and introduces contamination sources that compromise water quality regulation [24,56].

While current land cover changes in the study area do not yet represent alarming net magnitudes, their consideration is crucial given the region's unique position. The relatively low anthropogenic intervention compared to other Chilean and global regions [50,52,53] presents a strategic opportunity to implement sustainable development pathways before irreversible impacts on ecosystem service provision occur, allowing proactive management that balances development with preservation of critical water regulation and biodiversity conservation functions [65,66].

Land subdivision and associated land cover changes create interconnected pathways that jointly influence water resource demand and ecosystem service functions. The contrasting development patterns—a 420.4% increase in plantations (1626.9 ha) on undivided properties versus a 115.5% increase in scattered residential development (69 ha) on subdivided lands—represent different trajectories that simultaneously affect water conservation and biodiversity protection services. These results suggest that attention should be paid to the dynamics of anthropization in the interface zone, considering the global trends in accelerated land use change around PAs [12,20].

4.2. Private Properties and Legal Water Demand

While our study quantified the amount of water allocated in CWR, we recognize that they do not reflect actual consumption patterns. However, Chile's Water Code reform is aimed precisely at addressing the overestimation of demand by CWR. To this end, the reform has prioritized domestic subsistence needs and sanitation as priority uses and has implemented measures to control speculation, such as the payment of fees for non-use and termination of rights if use does not become effective within five years [62].

Our research found that 68.3% of CWR are located on subdivided properties, with most falling into the <10 L/s category, which is typically associated with domestic use [85]. This pattern is reinforced by the finding that CWR density per hectare remained stable on undivided properties between 1988 and 2023, while on subdivided properties it doubled between 2012 and 2023. This differentiated concentration indicates that subdivision and residential expansion drive domestic water demand, potentially reducing water availability for ecosystem functions such as native forest recovery, which is essential for carbon storage. Although the region gained 5161 ha of native forest, this recovery could be compromised by intensifying water stress resulting from increased legal water demand and projected precipitation decreases under climate change scenarios [28,57,58].

We recognize that this dynamic raises important questions about water resource optimization that our current analysis cannot fully address. However, we believe that our research reveals marked differences between subdivided and undivided properties regarding urban expansion and legal water demand, which should be considered when examining these aspects in greater depth. Such examination would improve understanding of the specific impacts of residential growth in sectors adjacent to PAs and enhance management of both human uses and natural habitats [9,10,14].

4.3. Lessons for Territorial Planning

Rural land subdivision can trigger significant problems when conducted without adequate control. Recognizing the need for robust regulations and active monitoring of activities in Chile's rural spaces [42] represents an important first step toward improving planning processes and advancing sustainable development. This effort requires both policy and legal improvements as well as the integration of scientific information to align with international sustainability frameworks [1–4].

The trends identified in our study confirm anthropogenic pressure in PA interface zones [11,13,33]. While the increase in "native forest" (5160.8 ha) can be positive for ecosystem services provision [83], the combined increase in "urban" and "plantation" areas (2489 ha combined) could represent habitat loss for some species [10,21], highlighting the need to control their development [13,14]. Urban growth occurred in areas distant from established population centers, intensifying the existing scattered settlement pattern. The subdivision analysis identified 34 properties with 20 or more lots, including mega-developments with up to 207 divisions. This figure is significant in the local context, considering that Puerto Ingeniero Ibáñez, the most populated center within the study area, has only 764 inhabitants [67]. If a household were established in each of those 207 lots, and considering that the average number of people per household in the Aysén Region is 2.5 [86], this would create a residential complex of 517 people. Without adequate planning, situations may arise where each household manages its own supply and sanitation services, rather than developing collaborative projects that optimize time and resources. This is especially relevant considering that uncontrolled rural urbanization generates multidimensional socioenvironmental impacts that extend beyond land use change. The proliferation of access roads—each subdivision typically requires new road construction—fragments wildlife corridors and increases erosion points. Furthermore, it exacerbates spatial equity imbalances and challenges to economic development, for example by altering market values and property prices, thus becoming a source of ecological risk and decreasing overall ecological resilience [14,47]. At the same time, communities report processes of social fragmentation, with long-term residents expressing concerns about the erosion of reciprocal labor practices and the weakening of local organizations as property ownership disperses [19]. The influx of amenity migrants further inflates land prices, making it unattainable for younger generations to acquire property, thereby accelerating the rural out-migration of working-age populations [19].

Moreover, the study results provide evidence supporting the integration of IWRM into regional planning to improve sustainability standards and better define the interface area between protected and private lands around CCNP [61,66]. Our study allows us to propose specific regulatory measures: greater enforcement of legal protection for water sources, as specified in Chilean law but rarely applied in rural areas; the implementation of progressive water pricing that encourages efficient use in critical areas for conservation, such as zones surrounding PAs; and the requirement for cumulative analyses of water resources and ecological connectivity in environmental impact assessments for subdivisions generating more than 10 lots. At the technical level, the following is suggested: the deployment of real-time water monitoring systems in critical areas, based on the subdivision hotspots and concentration of CWR identified in this study; and the implementation of community solutions for access, waste collection, and grey-water treatment. At the same time, community participation mechanisms are proposed, such as participatory water quality monitoring programs that strengthen citizen co-responsibility; and the implementation of negotiable development rights that allow potential subdivisions to be moved from sensitive areas to areas with consolidated infrastructure. These proposals are aligned with the reform of Chile's Water Code, which requires the formulation of Strategic Water Resource Plans [61], and underscore the relevance of watershed perspectives and IWRM in planning actions [63,65].

Our results indicate that contrasting patterns between subdivided and undivided properties generate edge effects that can alter habitat quality and continuity. This suggests that simple metrics of land cover change may mask deeper ecological impacts linked to spatial configuration and connectivity. To address these challenges, and in line with watershed-based perspectives that emphasize interactions among components and the maintenance of ecosystem health and integrity [29,30,66], we propose a first step toward the geographic delimitation of buffer zones around PAs. Specifically, watersheds that extend within and beyond PA boundaries could serve as a basis for defining appropriate spatial levels (e.g., basin, sub-basin, or sub-sub-basin). Geographic information systems (GIS) and satellite image processing can further support this approach by providing critical data on land cover dynamics, enhancing the understanding of ecosystem pressures across scales, and generating actionable inputs for decision-makers [4,53,61].

Finally, the importance of adequate governance mechanisms for decision-making stands out. The literature identifies mixed models that integrate diverse viewpoints from public, private, and civil society actors as effective alternatives, both generally [1,2,39] and specifically for PA management and interface zones [8,43,66], and under the IWRM perspective [31,61,65].

Despite implementation challenges, a feasible path for operationalizing this approach is emerging in Chile. The recent Water Code reform [62] establishes that each watershed must have a Strategic Water Resources Plan, developed by Chile's General Water Directorate in collaboration with the Ministry of Environment; Ministry of Agriculture; Ministry of Science, Technology, Knowledge, and Innovation; and the Regional Climate Change Committees [61]. Plan development requires comprehensive watershed diagnosis and establishment of water security objectives, providing an opportunity to consider the subdivision of properties in addressing the challenges of legal water allocation in watershed management decisions. These plans must also align appropriately with current territorial planning and management instruments and policies, potentially contributing to unified efforts and avoiding overlaps. The creation of a Strategic Water Resources Table for each watershed is also specified, convening representatives from involved institutions, surveillance boards, companies and trade associations, sanitary service companies, rural sanitary services, small agricultural producers and farmers, and research centers or universities with watershed interests, among others, while also considering contributions from the Indigenous population [61]. This important public participation component and consideration of local knowledge aligns with IPBES guidelines [2] and represents a promising pathway for developing "bottom-up" processes that integrate different knowledge forms and empower communities in sustainable development [66].

5. Limitations and Future Research

This research presents a descriptive study and therefore entails limitations that must be acknowledged. A key limitation lies in the inability to establish direct causal relationships. The study quantifies trends in land subdivision, LULCC, and the location of CWR as an initial step, but it does not directly determine the interrelationships among these dynamics. Future research could further investigate causal linkages through econometric modeling, statistical analysis, and mixed-methods approaches that integrate both quantitative and qualitative evidence. Another limitation is that our use of CWR data reflects legal entitlements rather than actual consumption. Water rights may be held but not fully exercised, or conversely, actual use may exceed allocated rights during peak periods. Additionally, we did not assess water use efficiency across different sectors or examine competitive relationships between agricultural, domestic, and tourism-related water uses. Understanding these dynamics would require detailed consumption monitoring and sector analysis beyond the scope of this study. Finally, the 30 m Landsat resolution cannot detect structures smaller than 900 m^2, potentially underestimating scattered rural development. Future work should employ high-resolution imagery ($\leq$5 m) or data collection using unmanned aerial vehicle surveys for more accurate building detection.

Future studies should prioritize (1) multi-scale analysis incorporating plot, property, and landscape levels; (2) integrated monitoring combining remote sensing with field measurements; (3) longitudinal designs tracking the same properties over decades; and (4) participatory approaches incorporating landowner perspectives and management objectives.

6. Conclusions

This study demonstrates incipient trajectories of anthropization associated with rural land subdivision, LULCC, and increasing legal water demand, which collectively compromise the capacity of the CCNP interface zone to sustain conservation objectives. Between 2011 and 2023, subdivisions increased nearly fourfold, driving two distinct but interconnected degradation pathways: (1) subdivided properties fragment the landscape through dispersed residential development (115.5% increase in urban coverage), while also concentrating 68% of CWR, primarily for domestic use; and (2) undivided properties exhibit a 420.4% expansion in exotic plantations, with potential impacts on hydrological cycles and habitat provision.

This bifurcation in land use trajectories suggests that subdivision is a critical factor in reconfiguring land use and resource demand. In particular, the concentration of 68% of water rights on subdivided land and the doubling of legal water demand during the period analyzed show cumulative impacts that transcend the property scale and could affect key ecosystem services such as water supply. Our results underscore that the effectiveness of PAs depends on managing a broader landscape matrix beyond their administrative boundaries, through integrated legal, technical, and governance actions that recognize the interdependence between land tenure, water resources, and ecosystem processes.

The transformation of the interface zone through these anthropization trajectories reflects the need for improved rural planning. Although the magnitude of these transformations remains moderate, their relevance is heightened by the strategic condition of the region, characterized by comparatively minor human intervention in both national and global terms. This context creates a distinctive window of opportunity to advance sustainable development pathways before irreversible effects on ecosystem services emerge, facilitating proactive governance that reconciles development pressures with the safeguarding of essential functions related to water regulation and biodiversity conservation.

This study provides theoretical and methodological contributions to better understand the socioecological dynamics in the PA interface zones. From a theoretical perspective, it demonstrates that property subdivision functions as an active element in the dynamics of change around PAs and is not simply a consequence of development pressure. This challenges uniform responses of private land to market forces and points to different ecological outcomes depending on property structure. Considering that subdivision is likely to trigger the construction of housing, infrastructure, and demand for CWR and other basic services (sometimes years after it occurs), it serves as a key indicator for anticipating territorial planning actions. From a methodological standpoint, the integration of cadastral records, remote sensing, and CWR data provides a replicable framework for analyzing coupled human and natural systems. However, the descriptive nature of our study highlights the need for direct measurements of ecological processes and resource use. Overall, the results illustrate how global processes materialize through local decisions that affect ecological and social dynamics in high-conservation-value landscapes. These insights provide critical evidence for governance frameworks aligned with the IPBES vision of transformative change and Target 3 of the Kunming–Montreal GBF, which emphasize the importance of proactive and equitable strategies to safeguard biodiversity in increasingly interconnected and pressured territories.

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Claude AI (Anthropic) and ChatGPT (OpenAI, GPT-5) to structure the conclusions section. The final paper was then developed by Trace Gale (co-author) in English, without the use of AI.

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Abbreviations

The following abbreviations are used in this manuscript:

PA	Protected areas
LULCC	Land use/land cover change
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
OECD	Organization for Economic Cooperation and Development
CCNP	Cerro Castillo National Park
CWR	Consumptive water rights

Appendix A

Table A1. Transition matrix of the area occupied by private properties. NF: Native forest; Pl: Plantation; Sc: Scrubland; Pa: Pastures; BS: Bare soil; WB: Water bodies; Sn: Snow; U: Urban; OC: Other coverage; Sh: Shadow.

Land Cover	NF	P	Sc	Pa	BS	WB	Sn	U	OC	Sh	TOTAL 2014
NF	45,036.3	657.2	4880.4	669.1	70.0	0.9	0.0	5.3	0.1	0.3	51,319.5
Pl	38.7	929.0	7.2	3.0	0.3	0.0	0.0	0.0	0.0	0.0	978.1
Sc	10,126.6	1398.7	28,865.8	5.237.5	468.8	0.5	0.0	23.6	1.4	0.4	46,123.3
Pa	1172.2	385.2	5321.5	43,496.1	656.6	0.0	0.0	57.5	0.4	0.1	51,089.5
BS	86.7	0.5	119.7	272.8	1497.7	0.3	0.5	10.4	0.3	0.0	1988.9
WB	0.0	0.2	0.0	0.0	0.4	1159.6	0.0	0.0	0.0	0.0	1160.1
Sn	19.0	0.0	40.3	79.3	23.0	0.0	19.1	0.0	0.2	0.0	180.8
U	0.0	0.0	0.0	0.5	0.1	0.0	0.0	62.7	0.0	0.0	63.3
OC	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3011.5	0.0	3011.5
Sh	0.9	0.0	0.2	0.1	0.1	0.0	0.0	0.0	0.0	120.5	121.8
TOTAL 2024	56,480.3	3370.8	39,235.1	49,758.2	2716.8	1161.3	19.6	159.6	3013.8	121.2	156,036.8

Table A2. Transition matrix of the area occupied by subdivided private properties. NF: Native forest; Pl: Plantation; Sc: Scrubland; Pa: Pastures; BS: Bare soil; WB: Water bodies; Sn: Snow; U: Urban; OC: Other coverage; Sh: Shadow.

Land Cover	NF	P	Sc	Pa	BS	WB	Sn	U	OC	Sh	TOTAL 2014
NF	17,505.2	164.5	2502.5	362.7	18.9	0.9	0.0	4.4	0.0	0.3	20,559.4
Pl	15.3	568.8	5.0	2.1	0.0	0.0	0.0	0.0	0.0	0.0	591.1
Sc	4894.0	421.3	13,283.6	2655.2	166.7	0.5	0.0	19.2	0.1	0.1	21,440.7
Pa	641.8	202.1	2715.2	20,155.3	276.8	0.0	0.0	38.9	0.0	0.0	24,030.2
BS	37.7	0.1	51.8	80.1	441.4	0.2	0.0	6.5	0.0	0.0	617.8
WB	0.0	0.0	0.0	0.0	0.0	655.8	0.0	0.0	0.0	0.0	655.8
Sn	5.0	0.0	7.6	11.4	0.1	0.0	0.0	0.0	0.0	0.0	24.1
U	0.0	0.0	0.0	0.0	0.0	0.0	0.0	59.7	0.0	0.0	59.7
OC	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	199.9	0.0	199.9
Sh	0.7	0.0	0.1	0.0	0.1	0.0	0.0	0.0	0.0	86.0	86.9
TOTAL 2024	23,099.8	1356.8	18,565.8	23,266.8	904.0	657.5	0.0	128.6	200.0	86.4	68,265.6

Table A3. Transition matrix of the area occupied by undivided private properties. NF: Native forest; Pl: Plantation; Sc: Scrubland; Pa: Pastures; BS: Bare soil; WB: Water bodies; Sn: Snow; U: Urban; OC: Other coverage; Sh: Shadow.

Land Cover	NF	P	Sc	Pa	BS	WB	Sn	U	OC	Sh	TOTAL 2014
NF	27,531.1	492.7	2377.9	306.4	51.1	0.0	0.0	0.9	0.1	0.0	30,760.1
Pl	23.4	360.2	2.3	0.9	0.3	0.0	0.0	0.0	0.0	0.0	387.0
Sc	5232.6	977.4	15,582.2	2582.3	302.1	0.0	0.0	4.4	1.4	0.3	24,682.6
Pa	530.4	183.1	2606.3	23,340.8	379.7	0.0	0.0	18.6	0.4	0.1	27,059.3
BS	49.0	0.5	67.9	192.7	1056.3	0.1	0.5	4.0	0.3	0.0	1371.2
WB	0.0	0.2	0.0	0.0	0.4	503.7	0.0	0.0	0.0	0.0	504.3
Sn	14.0	0.0	32.8	67.9	22.9	0.0	19.1	0.0	0.2	0.0	156.7
U	0.0	0.0	0.0	0.5	0.1	0.0	0.0	3.1	0.0	0.0	3.6
OC	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2811.6	0.0	2811.6
Sh	0.2	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	34.5	34.8
TOTAL 2024	33,380.6	2013.9	20,669.3	26,491.4	1812.9	503.8	19.6	31.0	2813.9	34.8	87,771.2

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