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Land Management Drifted: Land Use Scenario Modeling of Trancura River Basin, Araucanía, Chile

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Abstract: Modeling land use scenarios is critical to understand the socio-environmental impacts of current decisions and to explore future configurations for management. The management of regulations and permits by central and local governments plays an important role in shaping land use, with different complexities arising from site-specific socioeconomic dynamics. In Chile, the complexity is even more evident due to insufficient binding land regulations, fragmented government procedures, and the primacy of cities over rural areas. Yet land use must be managed to support sustainable development. This research integrates several state management dynamics into scenario modeling to support decision making at the basin scale through 2050. We employed a mixed qualitative-quantitative approach using interviews with state officials and local stakeholders as the basis for the Conversion of Land Use and its Effects (CLUE) model, which resulted in three scenarios with spatially explicit maps. Key findings indicate that opportunities for developing normative planning tools are limited, leaving state management without clear direction. However, current management practices can address problematic activities such as second-home projects and industrial monocultures while promoting small-scale agriculture. Scenario modeling is useful for understanding how the specifics that arise from the scalar dynamics of state management affect land use change and how existing management resources can be leveraged to achieve positive outcomes for both the ecosystem and society.

Keywords: scenario; land use modeling; LULCC; land use management; rescaling; land use policy; Curarrehue; Araucanía; Chile

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1. Introduction

Land use and land cover change (LULCC) plays a critical role in safeguarding the planet's capacity to support life within viable thresholds in the future. LULCC has pervasive effects on the climate system [1], the hydrological cycle [2–4], biodiversity [5,6], food security [7], and long-term geological change [8]. Moreover, it has been identified as one of the leading causes of ecosystem degradation, undermining nature's capacity to sustain us [9–11]. Land use activities have transformed a large part of the Earth's surface, in which changes in management play an essential role [12].

In this context, simulation of LULCC scenarios through spatially explicit modeling has increased in environmental studies within land change science [13] and is an essential tool to inform management and planning [14]. Scenarios can be understood as plausible narratives, described in words and numbers, of alternative co-evolutionary futures of socio-ecological systems [15,16]. They can effectively complement uncertainties, support policies, and make decisions [17]. Usually, the spatially explicit models result from a mix of quantitative and qualitative data to enhance their performance [15,18,19]. Qualitative data is often based on classification of remotely sensed imagery into pixels that represent different land use classes [20], and the simulation results are derived from numerical descriptions of rates, types and spatial allocations of uses [19].

Consequently, scenarios provide policy support by providing numerical results [18] and have the advantage of coupling with biophysical simulations, such as hydrological or soil phosphorus levels models [19]. On the other hand, qualitative scenarios are based on developing storylines, which present as a method to integrate assumptions of the future into narratives [21] and provide valuable insights into the likely outcomes of alternative decisions [19]. In addition, they offer the advantage of representing the perspectives of multiple stakeholders and, unlike fully quantitative models, provide understandable and engaging narratives to convey future information [18]. This is particularly important because it involves the participation of stakeholders who are not normally considered experts, but who have a deep understanding of the realities and conflicts that affect their respective sites [22,23].

Scenarios have been used to evaluate changes in socio-ecological systems across different scales, ranging from local assessments at the basin level to global analyses [21,24,25]. An illustrative example of scenario assessment using mixed methods is the Intergovernmental Panel on Climate Change (IPCC) Shared Socio-Economic Pathways (SSP), which integrates different global qualitative narratives into quantitative scenarios to understand future climate. In these scenarios, LULCC management holds significant potential in mitigating the effects of greenhouse gas emissions and enhancing carbon uptake [26,27]. It builds from integrating essential driving socio-economic factors related to LULCC, such as human and livestock diets, waste, urbanization, land use policies and management [26,27]. However, analyzing a global environmental phenomenon tends to hide the obvious fact that the world comprises different political systems associated with nation-states with different policies and regulations [28]. Through its policies and institutions, the state is a relevant agent that can influence land use change [29,30].

1.1. Land, State and Rescaling

The connection between land and state has a long-standing historical significance. Its is both a fundamental component of the territorial structure of the state and a spatially bounded natural resource in which wealth, power, and advantage are articulated, exercised, and contested [31]. It is essential to recognize the continued significance of state systems in land management and shaping processes, which is particularly important when addressing the potential crises associated with climate change, as they often exceed the capacity of citizens, social movements and private and non-profit organizations while acknowledging their potential participation in beneficial outcomes [32]. Only the state possesses the muscle, economic capacity and political legitimacy to effectively respond to these crises at aggregate scales [32]. Moreover, the state plays a central role in environmental regulation, and the relationships embodied within the state are pivotal in numerous environmental conflicts [33]. Even in property rights, the state acts as the "ultimate landlord" managing the use values of natural resources; distinct from possession, rights are an abstract concept that relies on territorial power, which means that behind every owner, there is the state, enforcing them when necessary [32,34]. Regarding political organization and power, the state remains a highly relevant entity, as it is the legitimate monopoly of coercion that operates through the administrative apparatus, comprising national governments, institutions, departments, agencies, and state officials [35].

However, political ecology literature argues that research examining the anthropogenic impact on non-human nature has primarily overlooked the state as a relevant player [28,31,32,35,36]. The main reasons are the focus on the decline of national power caused by globalization and climate change and the simplified understanding of the state as a fixed form of governance [35]. This relegation to a secondary role has been called "State denialism" by rescaling theorists [37,38]. The Rescaling concept challenges the previous emphasis on the fixed background of the national scale of political power, recognizing it as a processual and contested dimension of socio-economic relations [39–44]. Moreover, several land use policies and regulations interact in each geographical context; thus, national definitions and regulations are constantly interpreted and contested at the subnational scale [37]. In this line, state power is not merely transferred to other influential actors such as citizens and private and non-profit organizations. However, it draws attention to an interplay of changing policy arrangements through relational influential actors within and beyond the state [39,44,45]. These dynamics refer to how state institutions are mobilized to regulate social relations and influence local geographies in scalar and site-specific ways [39,40]. Similarly, LULCC research has emphasized that the causes of change are usually complex and site-specific, and that it is essential to understand the underlying processes and structures of specific contexts [12,46–49].

This article applies the state rescaling concept to analyzing the potential spatial impact of current state land use management practices within Chile's political and institutional framework. The relevance of focusing on management over other land-related concepts, such as governance [50], regulation [51], and planning [52], is based on three premises. First, it has been identified as a significant driver in LULCC studies [12,53]. Second, it is defined as overseeing diverse land use activities and resources through policies, processes, and institutions [54]. Third, in the Chilean context, it comprises a critical stance in the absence of planning policy instruments, which involves formulating plans to achieve objectives or define a future territorial model. Instead, management implies exercising state authority to issue permits, modify regulations, or impose penalties for unauthorized activities in specific locations from various state sectors [55,56]. In this context, this conceptualization allows us to bridge the gap between the legal framework and what actually happens in the administrative processes that affect land use. state rescaling of land use management is the existent dynamics through which social, political, and economic forces affect how land use is managed through state policies, regulations, and other pressures within and beyond the state, at the subnational level.

1.2. Land Use (Mis) Management in Chile

Over four decades, market-led policies and extractive-oriented economies have undermined the capacity to reconcile productive demands with essential ecosystem services provided by land, including soil, water, and biodiversity [57]. Moreover, the current legal framework for land use, consisting of laws, policies, decrees, plans, and instruments is created by a variety of institutions, with sectoral organization taking precedence over spatial integration [58]. These institutions include the ministries of the environment, housing and urban planning, agriculture, economy, development, and tourism, as well as various services dependent on them, the regional governments, and municipalities [59]. According to national land use management and planning, scholars have created a complex institutional framework [58,59] that often results in fragmented and case-by-case management, prioritizing specific sectors such as housing, water, forests, and agriculture, which can lead to conflicts and unsustainable depletion of natural resources [55,60]. The predominant problem in this institutional context is that there is virtually no land use planning, with most of these existing instruments primarily focused on urban settings, leaving rural areas overlooked [58].

Moreover, the Chilean state does not currently have a specific legal framework that fully recognizes the hybrid dimension of land use and land cover change, where land use reflects human objectives shaped by social forces, and land cover refers to biophysical conditions with environmental consequences [61]. Although there is an ongoing project exists to create a single "framework law" that recognizes the social and environmental aspects, the timing of its enactment is still uncertain [62]. However, land use planning and management has gained momentum by adopting policies [63,64] to respond to problematic land use activities [65–70], still faces major challenges [55,56,58,63,71,72].

Previous studies conducted in the southern region of Chile have used simulations with a wide range of socioeconomic factors and policies to examine the potential consequences of the continued application of the DL 701 policy, which has promoted the establishment of large-scale commercial tree plantations in Chile since 1974 [30,73,74]. This study continues this research by adding three novel aspects. The first one builds from the rescaled state effects on environmental studies on water. The first one builds from the rescaled state effects on environmental studies on water [75], pollution [76], forest [45], agriculture [77], and food [78]. The second inquiry challenges the implemented consequences of Chile's purportedly complex institutional framework [59]. We argue that despite the absence of explicit instruments for land use planning and management, the state still exercises direct and indirect land management through a fragmented institutional framework, leading to unexpected negative side effects [55,56,58,66]. The third aspect within the emerging field of modeling research in Chile visualizes the potential consequences of land use management by integrating it into spatially explicit future scenarios.

This research aims to integrate different rescaled state dynamics into scenario modeling, to support decision making at the basin scale through 2050. We use the mountainous Trancura River Basin (TRB) as a case study, where land use and land cover change is not driven by a single and overwhelming policy but by a combination of different policies and institutions influenced by the unique geographic and socioeconomic context. Our hypothesis suggests that even in the absence of explicit land use planning instruments and taking into account the weight that other socioeconomic actors have in shaping the spatial configuration of the study area, the states still has the potential to manage land use change for the benefit of society and ecosystems.

2. Materials and Methods

This research considers LULCC as a spatial reflection of the historical dynamics of the social, political, economic, and ecological context of the study area. In this sense, our methods build from the concept of state rescaling, which holds that the current land use patterns reflect a site-specific state intervention that are influenced and complemented by market forces, local actors, and other anthropogenic factors. Section 2.1 provides a general description of the study area and a listing of the prominent institutions responsible for managing land use activities. Section 2.2 describes the participatory methodology used to develop plausible future scenarios build on trends described by stakeholders with essential roles within the system [79]. The hierarchical structure of the Chilean state involves policymakers at the top and lower-level officials responsible for enforcement and decision-making at the bottom. In this work the focus is put on the latter, as their decisions during the implementation phase have a substantial impact on its final outcomes [80]. Additionally, it is complemented by key stakeholders involved in the main land use activities in the study area. Section 2.3 describes all the data processing required for implementing the Conversion of Land Use and its Effects (CLUE) model. Finally, Section 2.5 describes the development of four future land use scenarios up to 2050.

2.1. Study Area

The Trancura River basin (TRB) is located (Lat. 39°20′24″ S, Long. 71°34′12″ W) in the southeast of the Araucanía region in southern Chile (Figure 1). This mountainous basin has a pluvio-nival hydrological regime [81], with elevations ranging from 353 to 3740 m.a.s.l. It has a drainage area of 1402 km^2, defined at the "Trancura River antes de Llafenco" streamflow station. It is characterized by a large native forest cover at the Andes Mountains' foot [82]. Due to the ongoing dynamics, LULCC modeling in the Trancura River Basin is highly relevant.

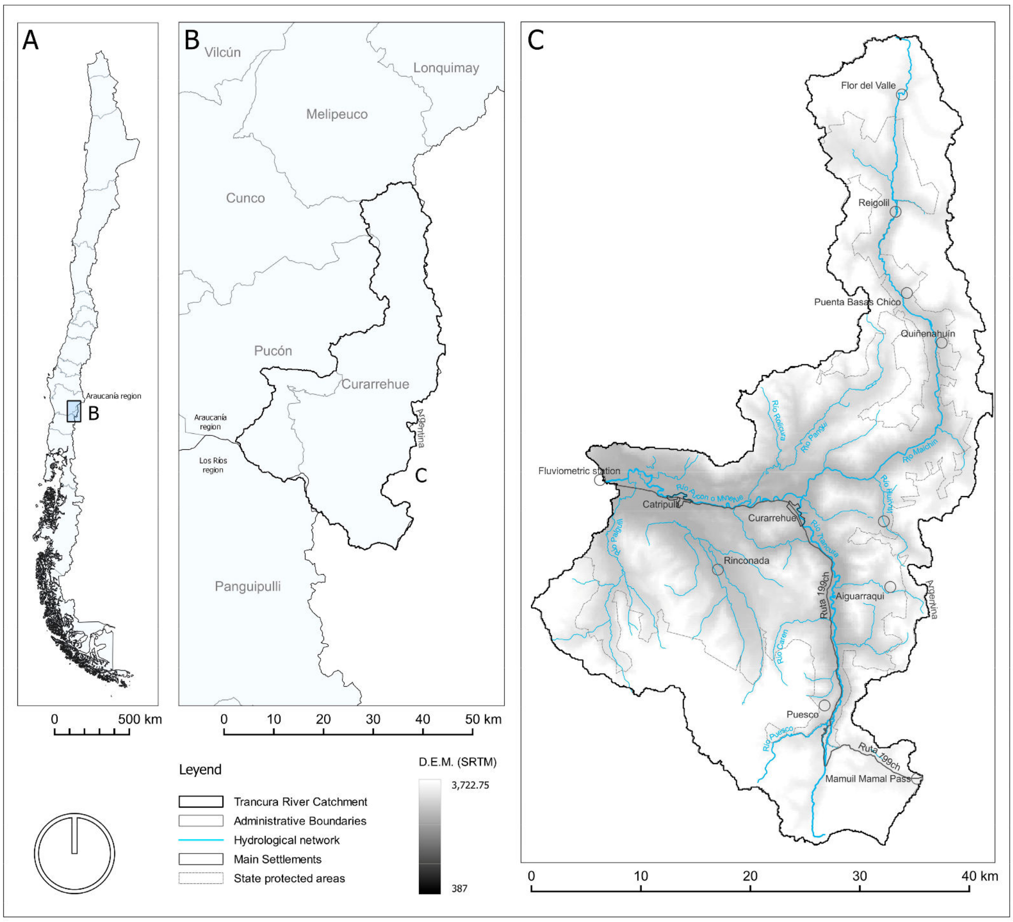

Figure 1. (**A**) Chile and regional division. (**B**) Basin and Municipalities (**C**) Trancura River Basin.

The historical land use is found in low-elevation areas, which have historically been historically used for human settlements, self-consumption farming, and livestock. In recent decades, however, the development of logging activities and fruit farms, a rapidly increasing tourism associated with the beauty of its native forest, and real estate-driven land use change for second housing have become mayor drivers of LULCC. These changes significantly affect the region's land use and require careful modeling and analysis. Land cover description is available in Appendix A. The TRB is located within the administrative boundaries of the Curarrehue (80.3%) and Pucón (19.7%) counties. It has 10.505 inhabitants, of which 7.397 corresponds to Curarrehue and 4.437 to Pucón [83]. In Curarrehue 30% of the population lives in the urban center and 70% is in rural sectors, with 50.27% of indigenous population [83].

The Chilean state has historically played a significant role in shaping land use patterns in the study area. Initially, a Chilean state military campaign framed in the "Pacification of the Araucanía" resulted in the occupation of central territory, leading to the migration of Mapuche communities to the foothills of the basin. While the mountainous landscape lacked fertile land for cultivation, it provided a strategic refuge during persecution [84]. After the economic crisis of 1930, the TRB began to be settled by people attracted by agriculture and cattle breeding activities [83]. Subsequently, in the 19th century, the Chilean state began promoting the control of the Araucanía mountain range for geopolitical purposes and economic exploitation [85], which took two expressions in the study area: a new frontier control, led by the Agricultural and Livestock Service (SAG), and the creation of the Law of Fiscal Forest Reserves (1879), which served as a legal precedent for the creation of the Villarrica National Reserve (1912) by the Ministry of Industry and Public Infrastructure, and the Villarrica National Park (1940) by the Chilean Ministry of Lands and Colonization, which attempted to regulate forest conservation [85,86]. In this context, we identified and examined state institutions influencing land use change in the last decades. Based on existing spatial management literature [55,56,66], the following institutions were found to impact land use change in the study area. This background revision is relevant as it highlights the political and historical context of each institution.

CONAF (1970), The National Forestry Corporation is a private corporation under the Ministry of Agriculture, whose main task is to administer Chile's forestry policy. Despite the private nature of CONAF, they have some public powers granted by the "Law on Native Forest Recovery and Forestry Development". Currently, the Villarrica National Park and Reserve are predominant in the study area, part of the National System of state Wildlife Protected Areas (SNASPE) administered by CONAF and legally owned by the Ministry of National Assets.

SAG (1967), Agricultural and Livestock Service, is responsible for supporting the development of agriculture, forests, and livestock by protecting and improving animal and plant health. The Decree Law No. 3516 on Rural Land Division is a legal milestone for rural land use change, primarily aimed at subdividing rural land only for agricultural, livestock, or forestry purposes. However, this law has become intertwined with the real estate market and is often used to transform a rural area into a housing project for secondary residences. Since 2020, the real estate market boomed as an unexpected effect of the pandemic. Home office work for the professional segments decoupled jobs from urban areas [87]. On the other hand, the pension fund emergency withdrawal allowed access to pension savings and generated unprecedented conditions for land speculation [88].

INDAP (1962), the Agricultural Development Institute operating under the Ministry of Agriculture. It focusses on modernizing and industrializing agriculture and reducing poverty in rural areas through conventional methods. However, there has been a growing recognition of the importance of agroecological approaches [89].

MINVU (1965), the Ministry of Housing and Urbanism of Chile, is responsible for developing and implementing housing, urban planning instruments, and policies. In the Araucanía region, there is a lack of spatial planning instruments. In the study area, there is no land use planning instrument for the management of rural areas, and the Municipal Regulation Plan (PRC), intended only for urban areas, has been under construction since 2011 [90].

SERNATUR (1975), the National Tourism Authority, is an institution that indirectly influences land use change in Chile. Martínez [91] recognized the involvement of the Chilean state (1900–1940) in the construction of an imaginary narrative associated with tourism in the study area, even before the creation of SERNATUR. This was achieved through advertising and infrastructure development, which integrated the area into national and international market networks. SERNATUR has continued this process with the support of the recently created Undersecretariat of Tourism (2010) and has reinforced this vision with the Lake Tourist Interest Zone (ZOIT Lacustre), which proposes a public–private management model that includes three municipalities and other entities [92].

Curarrehue Municipality was established in 1981, previously under the jurisdiction of Pucón [83]. In a cyclical pattern, the political administration of the Municipality has alternated between right-wing and left-wing mayors over 32 years since the return to democracy in 1989.

CONADI 1993, National Corporation for Indigenous Development was initially forged in the New Imperial Pact of 1989 as a commitment between indigenous organizations and the Concertación political coalition (centre-left), which overthrew the Pinochet dictatorship [93]. It aimed to recognize indigenous peoples constitutionally, ratify the International Labour Organization (ILO) Convention 169, and establish a new indigenous law [94]. However, the government's limited success in fulfilling these commitments has resulted in the loss of trust and an increasingly confrontational Mapuche movement [94] (p. 12). In the study area, an ethnic-environmental conflict arose over the Añihuerraqui hydroelectric power plant project, further highlighting the perceived inability of the institution to resolve conflicts effectively [95].

GORE (1993), Regional Government is an autonomous institution responsible for the administration and development of the Araucanía region. The implementation of the regional land use planning instrument (PROT) is underway.

MMA (2010), the Ministry of Environment in Chile, is the government institution responsible for environmental matters. However, Chilean environmental policymaking has primarily focused on facilitating market activities instead of enforcing regulations, deviating from conventional expectations [96]. The Ministry's involvement in the negotiations of hydroelectric projects in the study area has been criticized for its inadequate citizen participation [95].

2.2. *Qualitative Data*

Qualitative data from thirty participants were collected in two phases through semi-structured interviews, as they provide valuable input for the model simulations involving stakeholders [19]. We designed two interview questionnaires to address the difference between state officials and local actors' participants. Table 1 provides a qualitative data summary.

Table 1. Qualitative data summary.

Category	**Characterization**			**Interviews**	**People**
Interview Local actor	Mapuche community member			1	1
	Mapuche community member/Rural Sanitary Services (SSR) managers			1	1
	Mapuche community member and local farmer			1	1
	Local farmer/Tourism entrepreneur/sustainable logger			1	1
	Rural Sanitary Services (SSR) managers			1	1
	Conservationist NGO representative			1	1
	New entrepreneurs/recently arrived residents			1	3
Participatory process	Participatory process in the framework of the design of the communal regulatory plan in Catripulli and Reigolil localities.			2	
Informant	Ministry of National Assets/MBN/Ministerial Cabinet			-	-
Category	**Institution**	**Department**	**Acronym ***	**Interviews**	**People**
Interview state official	Curarrehue Municipality	Mayor's office	Municipality	1	1
		Planning Secretary		1	1
		Local Development Unit		1	1
	Regional Government	Regional Planning and Development Division	GORE	1	1
	Ministry of Environment	Regional secretary	MMA	1	1
	Ministry of Social Dev.	National indigenous development corp.	CONADI	1	2
	Ministry of Agriculture	National Forestry Corporation	CONAF	2	3
		Agricultural Development Institute	INDAP	1	1
		Agricultural and Livestock Service	SAG	1	1
	Ministry of Economy, Development and Tourism.	Undersecretary of Tourism	SUBTURISMO	1	1
		Regional Direction National Tourism Service	SERNATUR	1	1
	Ministry of Health	Regional secretary/Water Unit	MINSAL	1	1
	Ministry of Housing and Urbanism	Urban development and infrastructure; Plans and Programs; Rural habitability	MINVU	1	3
	Ministry of Public Infrastructure	General Directorate of Water	DGA	2	2
		Direction of hydraulic works	DOH	1	1

* Acronym in Spanish.

The first phase involved fieldwork conducted in November 2021, which consisted of nine semi-structured interviews with local stakeholders and state officials, and observation of two participatory processes of a municipal land planning instrument in two rural areas. The initial sample for this study was made based on the project team's connections with the Curarrehue Municipality. Then, through a snowballing process, other key stakeholders in the study area were identified, including Rural Sanitary Services administrators, farmers, and members of indigenous communities.

In the second phase, eighteen online interviews were conducted with state officials from institutions responsible for land use management in the study area at the regional, provincial, and municipal levels. The initial selection of stakeholders was derived from previous studies identifying institutions that directly or indirectly influence the land use change process through their management practices [55,56,66], and additional interviewees were recommended in the process. The outreach strategy consisted of sending a letter to each target institution introducing the funding research projects, informing about its main objectives, and requesting the collaboration of officials involved in land use or environmental areas.

In both phases, we obtained informed consent from each interviewee, and the Scientific Ethics Committee of the "Universidad de la Frontera" granted permission for human subject research. Interviews were recorded and stored using a code name to preserve anonymity. All interviews were transcribed and imported into a MS Excel matrix for qualitative analysis. The main questions are included in the Appendix A.

2.3. Data and Model Calibration

To model future land use changes from past and current settings we used the Conversion of Land Use and its Effects (CLUE) framework [14,97,98], as implemented in the lulcc v1.0.4 R package [99].

CLUE simulates a spatially explicit pixel map outcome from the interaction and competition between different land uses, represented by different cell values. A CLUE process iteratively allocates cell values based on the demands of each land use. CLUE uses beta coefficients from a regression, assuming each cell (i) has a maximum probability conversion (P_{tot}) associated with each land cover (Lc) over a specific time (t). The total probability is obtained by summing the location suitability ($Ptot_{i,t,lc}$), neighborhood suitability ($Pnhb_{i,t,lc}$), conversion elasticity ($Elas_{lc}$), and competitive advantage ($Comp_{t,lc}$). The process is summarized in the following equation:

$$P_{tot} = Ptot_{i,t,lc} + Pnhb_{i,t,lc} + Elas_{lc} + Comp_{t,lc}$$

The CLUE methodology requires a series of modeling steps. Some are included in the lulcc R package, and the rest is carried out by other modeling tools. The land use change simulation in the study area is based on previous studies [14,74,100], and it is explained below.

First, a series of land cover maps were generated for the years 2004, 2009, 2013, and 2018, using 30-m Landsat 7 ETM+ and Landsat 8 satellite imagery, following a supervised classification process employing the Random Forest algorithm [101]. The precision of the resulting land cover maps was assessed through comparison to high-resolution imagery obtained from Google Earth. The fourteen land cover classes obtained for a greater area, were reclassified to suit the TRB prominent land classes until obtaining the following set of eight land cover classes: Native Forest (1); impervious surfaces (2); Tree farms (3); Shrubland (4); Grassland (5); Fruit trees (6); Snow and Ice (7); and Bare land (8). Then, the resulting 8 land cover maps were resampled to match the lower 90-m resolution of the topographic data obtained from the USGS Shuttle Radar Topography Mission (SRTM) [102]. Watercourse areas are assumed to remain unchanged throughout the simulation and remain as a NULL value. The simulation of land cover change used only the 2004 and 2018 maps, whereas 2009 and 2013 were used for quality control purposes. Initially, the fruit tree class was merged with the grassland class due to its small quantity, but it was later separated into a distinct land use class based on interview feedback. Also, the identification of Build-up areas, which are essential for human settlements, was adjusted based on the interviewee's feedback. The change amounts for every land class from 2004 to 2018 are exposed in Table 2.

Table 2. Cross tabulation of change between observed 2004 and 2018 imagery in hectares.

2004/2018	Nat. Forest	Built-Up	Tree Farms	Shrubland	Grassland	Fruit Farm	Snow/Ice	Bare Land	Total 2004
Nat. Forest	89,199	75	384	4436	241	61	0	2	94,397
Built-up	0	369	0	0	0	0	0	0	369
Tree Farms	1959	33	213	1213	689	156	0	0	4263
Shrubland	2093	104	19	12,685	1715	160	0	846	17,622
Grassland	528	268	24	1520	5354	727	0	2	8425
Fruit Farm	14	15	1	8	105	163	0	0	306
Snow/Ice	0	0	0	0	0	0	1609	511	2121
Bare Land	2	19	2	51	1	2	247	6848	7171
Total 2018	93,795	883	644	19,913	8104	1268	1857	8209	134,672

Second, spatially explicit analysis is essential for evaluating the influence of spatial factors on land cover transitions. Building from modeling literature [74,100], we selected explanatory factors that could influence LULCC. In this study, we utilized the QGIS v3.22 software to prepare explanatory factors, which must be aligned with the same spatial extent, resolution (90-m), and Geographic Coordinate System (UTM 19 S) as the previous land cover maps. We used the digital elevation model (DEM) from the Shuttle Radar Topography Mission product to obtain elevation, slope, and sun exposure. Spatially explicit data such as roads, waterbodies, hydrography, land parcel geometry, protected areas, indigenous communities, and water infrastructure, were obtained from the official Chilean geospatial repositories. We then employed Spearman correlation to assess the relationships between the spatial explanatory factors compiled, in which highly correlated factors were subsequently filtered out. To model the land cover transitions, logistic regression was initially conducted for each land cover class, employing a stepwise selection procedure to optimize the inclusion/exclusion of explanatory factors. We then employed the Variance Inflation Factor (VIF) to identify and eliminate variables with VIF values exceeding 5, indicating the presence of multicollinearity [103]. Although logistic regression is commonly used for predictive models of LULCC, we opted to utilize the random forest algorithm due to its flexibility and non-parametric nature. Unlike logistic regression, random forest does not assume a linear relationship between predictors and the outcome variable. It constructs an ensemble of decision trees based on the data, allowing for adaptive modeling without making any assumptions. We employed the Receiver Operating Characteristic (ROC) method to evaluate the models' performance, which provides a tool for assessing both individual regressions and the overall model [20,104]. In our study, we compared the performance of logistic regression and random forest process, with the latter demonstrating superior performance. Table 3 provides information on the analysis of spatial factors.

Third, the non-spatially explicit data is prepared, which consists of Land Demand and Transition Rules. CLUE needs an area for each land cover class for every time step, and this parameter is called Land Demand. Transition Rules consist of Conversion Elasticity and a transition Matrix. The conversion elasticity is a value ($0 \leq n \leq 1$) that represents the temporal stability of a land cover class, which was obtained from an analysis of land cover change from 2014 to 2018. The size of the Transition Matrix was defined by the number of land use classes, in this case, 8×8. In the matrix, a value of one allows transition between categories, while a value of zero prohibits change. This rule prevents unlikely transitions, like urban areas converting to native forest. In this phase, the model is run manually and iteratively, modifying the elasticity coefficients and the transition matrix until the best result is obtained. The Demand and transition rules that best fit the calibration process are included in Table A1 in Appendix B.

Table 3. Spatially explicit analysis. Relations between explanatory factors and land use class results were evaluated with logistic regression and random forest. Significant logistic regression coefficients (β) were estimated for each variable and land use type. The whole model was evaluated with the Random Forest algorithm. Response operator curve (ROC) of Random Forest model performance for each land use class. The percentage of variance explained indicates the model's ability to capture and explain the variation in the land use class.

Explanatory Factor	Native Forest	Built-Up Areas	Tree Farms	Shrubland	Grassland	Fruit Farm	Snow/Ice	Bare Land
Elevation (m)	-	-	-2.62×10^{-3}	-	-	-	5.96×10^{-3}	-1.04×10^{-3}
Exposition (dummy)	2.90×10^{-3}	-1.64×10^{-3}	-1.40×10^{-3}	-3.54×10^{-3}	-1.51×10^{-3}	1.73×10^{-3}	4.80×10^{-3}	-
Slope(degrees)	3.17×10^{-2}	-4.70×10^{-2}	-1.77×10^{-2}	1.59×10^{-3}	-6.10×10^{-2}	-9.18×10^{-1}		-2.35×10^{-2}
Distance to complete road network (m)	2.28×10^{-4}	-3.49×10^{-3}	-	-	-9.89×10^{-4}	-	-2.56×10^{-5}	-
Distance to forest industries (m)	-	-1.31×10^{-4}	9.52×10^{-5}	-	-7.97×10^{-5}	-	-	-
Distance to watercourses (m)	3.30×10^{-4}	-1.60×10^{-3}	-	-1.60×10^{-4}	6.75×10^{-4}	-	-1.13×10^{-4}	-1.16×10^{-4}
Distance to Population Entities (m)	-	-	-4.20×10^{-5}	-	-	-	-	-
Distance to tourist trails (m)	-3.72×10^{-5}	-4.23×10^{-6}	5.90×10^{-5}	-7.67×10^{-5}	1.91×10^{-5}	-	1.08×10^{-4}	1.73×10^{-5}
Distance to indigenous communities (m)	-	-	-	-	-	-1.42×10^{-5}	-	-
Distance to wetlands (m)	-	-	-1.88×10^{-5}	-	-	-	-	-
Total land area per parcel (ha)	6.18×10^{-6}	-2.68×10^{-5}	-6.99×10^{-6}	-3.45×10^{-6}	1.23×10^{-6}	-1.26×10^{-5}	-	-
Private conservation initiatives (dummy)	9.07×10^{-1}	-	-6.48×10^{-1}	-	-1.00×10^{0}	-		$-1.12 \times 10^{+1}$
Snow line (dummy)	-1.95×10^{0}	7.97×10^{0}	8.36×10^{-1}	-6.01×10^{-1}	1.78×10^{0}	-	2.96×10^{0}	2.87×10^{0}
Average apparent density soil depth (g/cm^3)	$-1.20 \times 10^{+1}$	6.90×10^{0}	1.42×10^{0}	5.21×10^{0}	3.20×10^{0}	7.88×10^{0}	$1.14 \times 10^{+1}$	$1.46 \times 10^{+1}$
State-managed wilderness areas (dummy)	2.78×10^{-1}	-7.68×10^{-1}	-6.63×10^{-1}	-	-5.45×10^{-1}	$-1.68 \times 10^{+1}$	-	1.81×10^{0}
Distance to international route (m)	-	-	-	-	-	-	-	-
Distance to consumptive water rights (m)	-	1.06×10^{-4}	-5.49×10^{-4}	-	-	-	-	-
Distance to rural sanitation services (m)	-	-1.22×10^{-3}	-6.35×10^{-3}	-	-2.79×10^{-3}	-3.29×10^{-3}	-	-
Random forest ROC	0.9439	0.9871	0.9871	0.9078	0.9577	0.9866	0.9501	0.9963
Random forest % Var explained	58.26%	27.14%	26.78%	36.93%	42.61%	20.09%	62.34%	71.24%

Fourth, the calibration process of the CLUE model aims to match the demand for land use categories in the simulated model to the actual reference map for a specific year, in this case, 2018. The goal is to achieve convergence, where the land cover map produced by CLUE allocates the same amount of land than the reference map for each category, with an average standard error of ±30 pixels. After calibration, the validation compares the observed land cover maps for different years (2004 and 2018) with the simulated 2018 map. The Fuzzy Kappa Simulation (FKS) index was used to assess the overall and specific differences between the simulated and observed maps. The FKS index ranges from −1 to +1, with negative or near-zero values indicating random simulation and 1 indicating a perfect match. In literature a FKS value of ≥0.2 is deemed as acceptable [105,106]. In this study, we obtained an FKS value of 0.26 and an average similarity of 0.91. The benchmark recommended is a minimum value of 0.2. Table 4 shows the total area corresponding to each map used as reference, both 2004 and 2018. In this paper, we did not include neighborhood influence. Figure 2 compares the observed imagery of 2004 and 2018 and the simulated 2018.

Table 4. Land use surface by land class in hectares year comparison.

Land Use	Observed 2004	Observed 2018	B-A-U 2050
Native Forest	94,466	93,642	89,668
Built-up areas	379	888	1964
Tree Farms	4270	666	420
Shrubland	17,835	20,017	21,039
Grassland	8436	8103	7902
Fruit Farm	330	1267	2002
Snow/Ice	2139	1878	1549
Bare Land	7274	8669	10,153

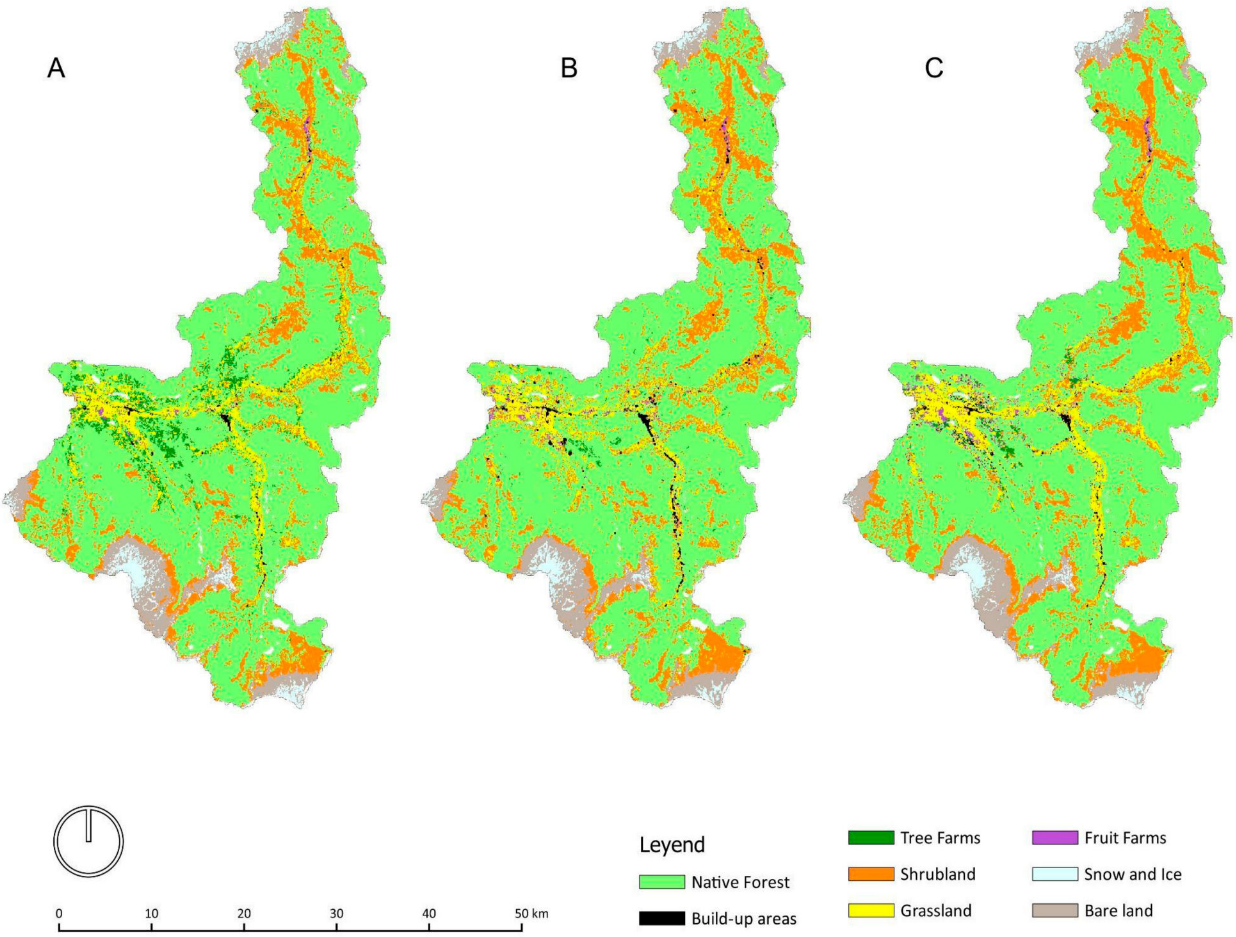

Figure 2. Observed imagery and land cover classes simulated by CLUE. (**A**) 2004 land cover (**B**) 2018 land cover. (**C**) Modeling output of the basic simulation of 2018 land use.

2.4. Translating Qualitative Data into Models

Translating qualitative data into scenario modeling has been recognized as a weak aspect of the land cover simulation process [18], and the importance of clearly defined criteria to ensure transparency in the translation process is fundamental [107]. The first criterion combines stakeholder engagement with desk-based [108] quantitative data available to generate land cover scenarios [107]. The second criterion addresses data discrepancies and limited accessibility in which assumptions are made based on interview information [107]. The third criterion emphasizes a clear and transparent translation process [108]. The criteria associated with each land use class are outlined below.

Build-up areas were quantified using mixed data. We extracted raster building footprints from Google Earth in 2022, resampling them to a 90-pixel resolution. We focused on areas where buildings accounted for 30% or more of the total area. Additionally, we incorporated the projected expansion based on the Municipal Regulatory Plan for urban areas. Land ownership information and subdivisions smaller than or equal to half a hectare were considered future second housing units. Rural subdivisions smaller than half a hectare allowed landowners to construct up to 10% of the plot, while roads and other structures could extend the build-up coverage to 30%.

For Native Forest, we assumed a successional process parameter used in previous work in the Araucanía region [74,109]. New native forest primarily emerges from shrubby vegetation. The maximum Native Forest demand was determined as 1% above the highest surface obtained in the 2009 land cover data. The minimum demand represents a projection of native forest loss in high-demand areas, changing into shrubland due to degradation or potentially being replaced by monoculture activities like Tree Farms and Fruit Farms.

Shrubland can easily transition into Grassland, build-up areas, tree farms, or fruit farms. It also signifies rural abandonment. The quantity of shrubland is determined as an exchange in each scenario. If there is forest recovery, shrubland diminishes, but shrubland increases to cover grassland if the labor matrix shifts from traditional agricultural practices to service areas.

Grassland, representing traditional agricultural and ranching practices, reaches the maximum capacity based on historical land cover records. In the Like Pucón scenario, grassland diminishes by half.

The increase in fruit farms is justified by stakeholders' belief that this form of industrial production is growing, and recent appearances of European Hazelnuts detected in the agricultural census further support this trend [110]. It is quantified based on a document released by the Regional Government of the Araucanía Region, which highlights the Development of Fruit Innovation Poles program [111]. Specifically, nearby areas experienced a 363% increase in hazelnut cultivation from 2007 to 2019.

Tree farm surface variation was conducted by considering participants' descriptions of past logging activities. We assumed that tree farm management adheres to a standardized approach with limited constraints on expansion. The scenarios encompassed a range of possibilities, from a reduction in tree farm surface compared to the observed trend between 2004 and 2018, to a return to the surface area observed in 2004.

Bare land and snow and ice surfaces were found to remain consistent in all scenarios, as no significant changes were identified in the literature review or interviews.

2.5. Scenario Modeling

The initial procedure for modeling scenarios to the year 2050 was to build a baseline or "Business-As-Usual" (BAU) scenario. In this reference scenario, the transition rules are maintained from the calibration result (2004–2018), and the demand is obtained through a Markov Chain analysis to 2050. We used the MARKOV module of the TerrSet 19.0.7.software to calculate transition probabilities and estimate land demand according to two-period coverage maps [112]. Since the Markov chain is based mainly on past data, its trend behavior is the basis for establishing a demand-based land change model, which informs the development of other scenarios. The transition probability matrix was obtained by overlaying the 2004 and 2018 maps (Table A2). Then, the demand is obtained by specifying the final prediction date. Table 4 compares the 2004 and 2018 surface areas with the demand obtained for 2050, and Figure 3 plots the demand trend to 2050.

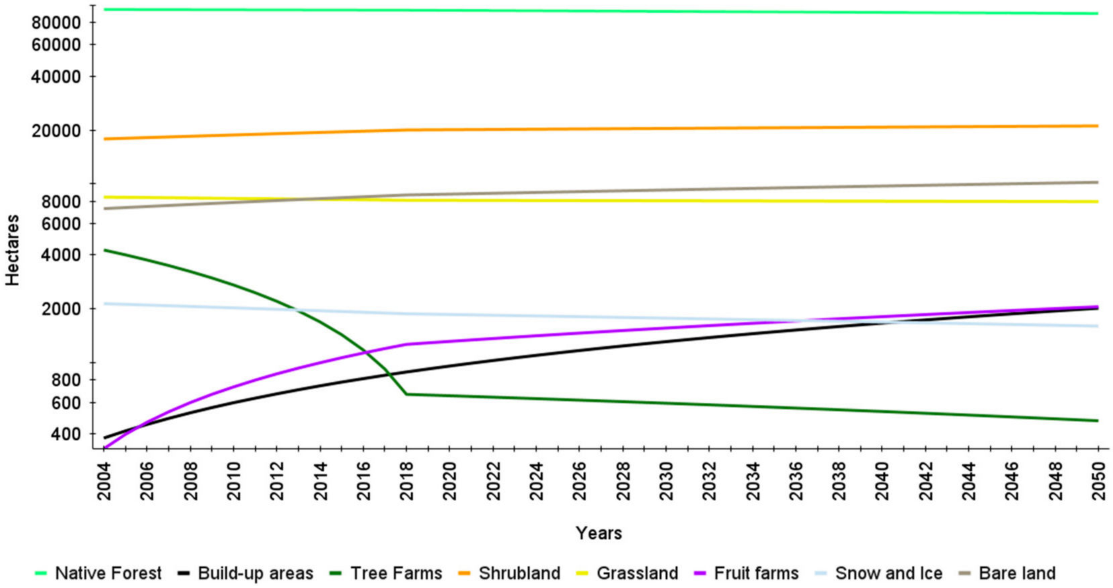

Figure 3. Line graph of demand trend change by land use class from 2004 to 2050.

The BAU scenario is used as the statistical basis for constructing the other scenarios. From here, the land use modeling process engages in the translation of narrative scenarios into demand, elasticity, and transition parameters that vary according to scenario-specific characteristics. The model calibration from 2004 to 2018 is then extended to 2050 using the transition rules and scenario-specific demands described in Appendix B in Tables A3–A5. Figure 4 summarizes the main methodological steps.

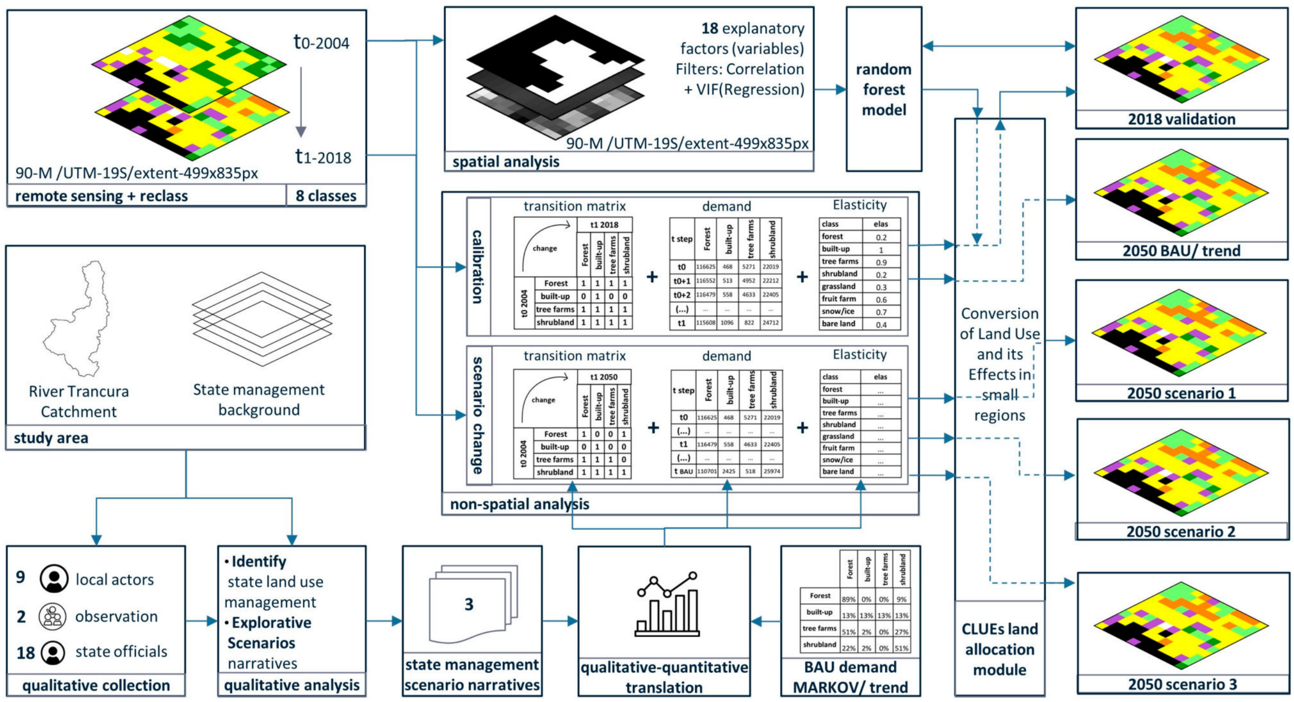

Figure 4. Graphical summary of methodological steps.

3. Results

In this section, we present the findings of what we have called the rescaling of state land use management in the study area. After verifying the absence of legally binding land use planning instruments (Appendix C), we identified critical factors embedded in management dynamics that influence land use change according to the methodological approach. On the one hand, these were part of the internal and multisectoral institutional operations, and on the other hand, a process deeply related to contextually specific socio-economic forces. From the former, the participants shared that the centrist condition of the state influenced the main institutional procedures that ultimately affected land use change, the political willingness to act, the communication between institutions, management attributions and the budget. The latter revolves around significant players that wield land use change activities in which the state has management attributes. By managing these activities, they recognized the influence of external actors on the institutional apparatus. Conflicts and synergies arise between these actors and the state, challenging effective management. In which certain actors exert high pressure, limiting the autonomy of state management and forcing changes, while other activities are embraced and integrated into the institutional management system. Despite the objective nature of institutions and policy application, officials acknowledge that political processes, such as changes in institutional leadership, can influence the project agenda. Given that the bureaucratic process for implementing a public investment project involves multiple interdependent institutions, the approval of each institution is essential for the project to progress. However, communication among these institutions is optional within the institutional process and depends on officials' goodwill.

3.1. Rescaled state Management Dynamics

Grassland plays a vital role in the Trancura River Basin. It hosts agricultural activities such as livestock and small-scale farming, one of the earliest to alter land cover significantly. As a result, INDAP is one of the most relevant institutions in the study area due to the numerous rural populations. To illustrate, the beneficiaries of Curarrehue in Pucón-Curarrehue district comprise 70% of the total and receive 65% of the funding. However, it is perceived as a highly bureaucratic procedure leading to practical tensions. In this context a municipality official highlights the collaborating with INDAP as they do not break out of their legal structure. Additionally, highlighted the obstacles they face when their rural and isolated location meets centrally designed policies. In this regard, even when farmers receive subsidies, they have significant constraints, as the institutions are poorly communicated, so even if they received funding for irrigation, they sometimes do not have the water rights delivered by the water-related institutions. Also, the participants perceived a conflict between industrial production and small-scale family farming. Municipality officials detected that almost 90% of the people living in rural areas had orchards for self-consumption during the pandemic. They highlight that their farmers operate on small budgets, driven by their love for farming and adherence to sustainable practices. The Municipality supports entrepreneurs by providing project development and consulting services. They prioritize the development of the mountain economy, with a focus on family farms engaged in self-consumption, surplus sales, and agroecological apiculture. SAG and INDAP officials stress the importance of small-scale agriculture for local consumption. They are concerned about the potential loss of agricultural land and the subsequent reliance on imports, leading to higher vegetable prices.

Conversely, the municipality officials are against industrial production of monoculture practices such as fruit farms and tree farms. These land uses are perceived as hazardous foreign activity associated with chemical fertilization, producing water and other crop pollution. However, the plausibility of increasing the area of fruit trees has conflicting views. On the one hand, the Municipality considers the availability of land suitable for monoculture fruit tree plantations limited and expects minimal growth. On the other hand, some residents believe that the water scarcity in the lower valley localities will drive the expansion of fruit growing towards the mountainous area of Trancura, disrupting agroecological expectations. While the area of forest plantations associated with pine and eucalyptus differs from the regional trend, the basin has seen a significant decrease concerning the logging past and the 2004 satellite images, which is perceived as a local achievement, and a return to that configuration would be negative.

Native Forest is a source of great pride for many of the interviewees. CONAF officials acknowledge that management challenges arise from the centralized nature of the state. They highlight the case of Villarrica National Park, which has been prioritized for tourism development in conjunction with the creation of the Undersecretary of Tourism. All public projects, including ski centers, campgrounds, and lodges, are subject to evaluation by an inter-ministerial committee at the central level. The officials express concern that this new institutional player significantly diminishes their involvement in the decision-making process. In this context, officials emphasize that CONAF lacks sufficient authority. The state relies on CONAF management when conserving protected areas, as it holds specific public powers. However, CONAF poses unique challenges regarding management practices due to its hybrid nature as a private entity under state control. They continue by highlighting that even though there are proposals to transform CONAF into a public entity, allowing its members to operate as public officials, the implementation is a matter of the political will of decision-makers.

The rangers point out that they must clean the restrooms, clean the trails, repair, build, manufacture interpretive panels, and investigate wildlife through camera-trap monitoring, ecological education, and community work. Due to the high workload and a shortage of park rangers with limited authority, effectively monitoring the forest becomes a nearly impossible task. With significant implications for land use change as the authority of this institution extends beyond the boundaries of protected areas. Trail construction subsidies for landowners with native forests can expand human activities into the park, disturbing the natural balance of plants and animals. Individuals have been observed entering the park on motorcycles with their pets or livestock in areas designated as primitive forests.

Additionally, CONAF is responsible for reviewing management plan requirements for cutting native forests for projects such as second housing construction. However, their limited capacity to monitor legal and illegal logging becomes more problematic as a great deal of Native Forest surface is allocated outside protected areas. The effect increases when these projects are located near park boundaries. In this context, they point out that native forests may maintain a beautiful structure and scenery, but the ecosystem services are in peril. While we were developing this research, park rangers from almost every state-managed park in Chile rose on strike due to precarious labor conditions, poor salaries, and lack of equipment and infrastructure [113].

Regarding the Build-up land use class, rural land subdivision for second housing purposes was among the most frequently mentioned activities. Most projects submitted to the provincial SAG office fall under decree 3.516 [114], accounting for 90% of the total files in the Natural Resources Area. Conversely, perceived as a positive outcome of central decisions is the enactment of Circular 475 [115] that supports Law 3.516 [114] monitored by SAG and introduces a set of new constraints aimed at preventing rural subdivisions from turning into real estate second housing projects. According to SAG officials, these changes represent a significant improvement as they address critical issues to mitigate the impact of subdivisions that have been explosive. Before Circular 475, SAG primarily served as a technical body for planimetric review, and most subdivision files were approved without scrutiny. Therefore, the analysis now takes a more comprehensive approach, considers various aspects and involves other supervisory multisectoral steps, including CONAF, MMA and MINVU, to assess the intentionality of the projects. However, SAG officials suggest that there are still pending matters, and the real estate industry will adapt because it is a very profitable business.

Consequently, continued house construction, support buildings (e.g., warehouses), and livelihood practices can cause damage to the forest ecosystem. An NGO representative expresses the same concerns as they observe that newcomers from cities often lack knowledge of rural living and continue city lifestyles in the countryside, resulting in lifestyle shifts that often lead to clearing native forests and irresponsible pet ownership. The representative also highlights the misuse of a legally bound private conservation mechanism. Some real estate projects use "real conservation rights" (DRC) as a marketing strategy, in which registrations have a limited duration, leading to the possibility of being sold for housing after attracting environmentally conscious buyers. Furthermore, not only is the forest affected, but SAG officials also point out that in the study area, a critical issue that needs to be addressed is the impact of real estate projects on agricultural soils because of their scarce surface. SAG and CONAF officials also point out that there are no physical constraints to allocate to these projects, as they can be situated near national parks and even on steep slopes, which is why the Circular is so essential. This Circular has sparked controversy and has led to an ongoing legal response from the real estate industry [116,117], so its management stability is still pending. Related to the above, a SAG official says second housing projects are not the only driver of Build-up areas in rural settlements. It is common for rural residents to form dwelling communities. The Ministry of National Assets plays a crucial role in managing land division by implementing Law 2.695, which resolves historical cases of irregular possession, such as inherited properties or land obtained through fraud. In response to ecosystem disturbances caused by densification, the Ministry's current administration is shifting its scope towards land sustainability and promoting the concept of "good living." declining most permits as they may affect ecosystems.

Tourism is a prominent activity in the study area intertwined with various land use types. From a national level, an Undersecretary of Tourism officials explains that the area that comprehends the tourist interest area (ZOIT in Spanish) attracts tourists throughout the year and may pose risks to the ecosystem. Officials acknowledge the importance of assessing the area's capacity and highlight the government's commitment to environmental protection and sustainable practices. Conversely, the growing tourism industry is acknowledged as a significant shift in the local economy, creating employment opportunities in the service sector. Residents, SAG, and INDAP officials interviewed worry that tourism is being prioritized over agriculture, which may have negative consequences for farming self-consumption practices. One local shared a concern that builds from the belief that a change in the productive matrix will diminish agricultural activities and, by extension, grassland surfaces. At the Municipality, the tension builds around tourism. The current administration perceives the tourism practices of Villarrica and Pucón as an ominous industrial activity. According to an official, they are working to build the first municipal tourist ordinance to try to stop this conundrum attributed mainly to adventure tourism promoted and managed by outside tour operators. They perceive that the lack of proper tourism planning has led to resource consumption and ecosystem disturbances. Some local actors interviewed feel that institutions like SERNATUR may not fully understand their perspectives. Conversely, a CONAF ranger claims that traditional practices like livestock rearing and deforestation have shifted towards tourism, contributing to the recovery of private native forest-damaged areas.

We discovered that water management dynamics actively influence land use change during the interview process. The water deficit (96%) has remained unchanged since 2002, with a percentage of the population relying on water trucks during the summer tourism high season. Additionally, the sewage system poses a significant problem as urban Curarrehue discharges 100% of its untreated wastewater at seven points into the Trancura River. In this context, municipality officials highlight the importance of implementing sanitary solutions for housing and productive activities. To address these concerns, municipal officials established a local water management unit. Although they have limited power to address local water problems on a large scale, they provide subsidies for water-related projects. It is necessary because, on the one hand, regional water institutions are not giving solutions.

On the other hand, water scarcity has created difficulties, including the need for new irrigation systems that were previously unnecessary. The municipality officials attributed the disruption of their projects to the DOH institution. Meanwhile, the latter acknowledges that Curarrehue Municipality faces particularly complex cases, and the delays are attributed to reasons such as design problems, administrative summaries, and changes in the project's requirements due to the growth in the number of buildings to be supplied. In addition, obtaining water project permits is a challenging and costly process, particularly for emerging businesses in the mountain economy sector. MINSAL requires extensive documentation, which can be financially burdensome for small businesses.

Conversely, for real estate projects, the cost of developing water systems is considered minor compared to overall operations. Despite apprehensions regarding differences among activities, representatives from MINSAL affirmed that projects meeting the requisite criteria are typically approved. Another major obstacle for activities that require water is the uneven distribution of water rights, which the DGA regulates. In the basin, this imbalance manifests as some owners have abundant consumptive water resources. In contrast, the Rural Sanitary Services (SSR), responsible for community water supply, struggle to secure adequate water rights. Water-related officials are aware of the existing management issues, and there is optimism regarding the potential of the new water code reform (Law 21.435, 2021) to address these challenges. Officials highlight a crucial change in the reform where water rights that are not declared within 5 to 10 years may be reclaimed by the state for redistribution.

Ultimately, the interaction between CONADI and Mapuche communities significantly impacts the management of land use changes. However, the practical implementation of this influence encounters substantial challenges. Mapuche communities are a relevant actor and have been widely acknowledged by the stakeholders interviewed. Municipality officials highlighted that neighborhood councils are less relevant in the study area than indigenous communities, which form the foundations of territorial organization. In this context, CONAF has historically collaborated with them through governance panels, and officials recognize them as one of the most essential stakeholders in the basin's parks management. Also, according to a SERNATUR official, the lack of indigenous consultation has led to the cancellation of projects even in advanced stages. For example, one hundred Mapuche communities successfully halted a tourism project in the Villarrica National Park due to the absence of consultation. MINVU officials believe it is crucial to conduct an indigenous consultation whenever indigenous communities are present in the territory. However, the Mapuche participants interviewed perceive a fundamental difference between their perspectives and the state. In this context, as articulated by a CONADI representative, a fundamental issue in the state's engagement with indigenous communities lies in the divergence of perspectives. The state's structure is compartmentalized into various sectors, resembling a system theory approach, whereas the Mapuche viewpoint is holistic (Quote C.8.). Additionally, officials point out that one of the significant difficulties of exercising their position is that indigenous peoples have rights is new, so other state institutions see it as a process that takes time and money. Even though their work seeks to ensure the development of indigenous communities, CONADI is a small institution, so they depend on the commitment of the whole state to engage in a multisectoral fashion. They see that whenever the state and indigenous communities have conflicting objectives, the former considers the situation impossible to overcome instead of fostering greater participation and continuous dialogue.

3.2. Scenario-Narratives

The results described in the previous section define the bases that frame the current land use management dynamics to design the scenarios. This process was necessary as it connected site-specific management with the calibration process. It is also complemented by the last section of the questionnaires that aimed to elaborate scenarios with plausible outcomes described by the participants. The connection of these sections builds from the general management concepts identified. Consequently, the interaction of the scenarios is determined by management capacities, budgets, political will, national or local linkage, communication between institutions, and conflicts. These are grouped into three scenarios in which different land-use changes are considered based on a narrative that unifies and justifies change trade-offs. Table 5 summarizes the connection between narratives, management changes, and transition dynamics.

Table 5. Scenario translation from qualitative to quantitative. Adapted from Hauck et al. [48] (p. 206).

2050 Scenarios	Key Component	Management	LULCC	ha	%
1. Agroecology	The Municipality remains with the same political stance. INDAP budget and support trigger increment in small-scale farming. SAG, maintain regulation (Circ. 475) and increase monitoring capabilities. CONAF, increase budget and management attributions in the basin. MMA, MINVU, Municipality, MINAGRI and BBNN jointly oversee land use changes as Built-up areas and industrial agriculture. National and Regional tiers support local perspectives. The conception of tourism is local development due to political will. CONADI and Mapuche communities opportunely detain external land use through confrontation. Water project blockage unravels.	Municipality ▬ Tourism ▶◀ Water ▲M SAG ▲M INDAP ▲$ CONAF ▲$ ▲M MMA ▲M CONADI ▲M, ≠ BBNN ▲M GORE ▶◀ National ▶◀	↑ Native Forest ↑ Built-up ↓ Tree farms ↓ Shrubland ↑ Grassland ↓ Fruit trees - Snow/Ice - Bare land	100,995 4106 167 9951 9641 300 1623 9089	74.33% 3.02% 0.12% 7.32% 7.10% 0.22% 1.19% 6.69%
2. Parcelopoly	Overall, institution segmentation and management stay the same. The municipality keeps changing its political stance and, in some periods, gives construction permits for all housing construction. INDAP observed a decreasing trend in small farming, losing budget. SAG capabilities remain (Circ. 475), but second housing perseveres. CONAF remains the same, and clearance of forest increases for housing projects. CONADI and indigenous communities are still in conflict. The latter does not raise the alarm of housing projects. National, regional, and tourism institutions stay the same. New inhabitants and NGOs join efforts for conservation purposes. Water project blockage remains.	Municipality ≠ Tourism ▬ Water ▬ SAG ▬ INDAP ▼$ CONAF ▬, ≠ MMA ▬ CONADI ▬, ≠ GORE ▬ BBNN ▬ National ▬	↓ Native Forest ↑ Built-up - Tree farms ↓ Shrubland ↓ Grassland - Fruit trees - Snow/Ice - Bare land	88,076 8794 667 18,504 7841 1277 1623 9089	64.82% 6.47% 0.49% 13.62% 5.77% 0.94% 1.19% 6.69%
3. Like in Pucón	Overall, institution segmentation and management stay the same. Municipality changes its political orientation to economic development INDAP observed a decreasing trend in small farming, losing budget. SAG attributions diminished, and Circular 475 was revoked, which provoked a real estate projects boom. CONADI does not raise the alarm and conflicts with communities. CONAF remains the same, and informal clearance of native forests increases. National, regional, and tourism institutions promote industrial development. MMA remains the same and in conflict with local communities. The water project blockage is partly solved.	Municipality ◀▶ Tourism ◀▶ Water ▬ SAG ▬ INDAP ▼$ CONAF ▬, ≠ MMA ▬, ≠ CONADI ▬, ≠ GORE ◀▶ BBNN ▬ ▼M National ◀▶	↓ Native Forest ↑ Urban ↑ Tree farms ↑ Shrubland ↓ Grassland ↑ Fruit trees - Snow and Ice - Bare land	73,515 8794 4273 25,300 5000 8277 1623 9089	54.11% 6.47% 3.14% 18.62% 3.68% 6.09% 1.19% 6.69%

Management Iconography: ▲M = More attributions; ▼M = Less attributions; ▲$ = More budget; ▼$ = Less budget; ▬ No change; ▶◀ = local oriented; ◀▶ = national and global oriented; ≠ = Conflict
Land use change Iconography: ↑ = increase; ↓ decrease; - No change

3.2.1. Agroecology

This scenario builds from the identification of officials of the desire of many inhabitants to return to a rural agricultural past. So, it relates to the importance of low-scale agriculture for self-consumption and sale of surpluses detected and supported by agricultural-related officials. They also recognize that the development of small-scale agriculture is fundamental for the basin's autonomy and resistance to future crises. In this regard, the Municipality, INDAP and a farmer support its plausibility as in the past, there was an agricultural diversity which consisted of vegetables, cereals, and livestock. Also, it depends on increasing the agricultural incentives budget for agroecological practices. In this sense, agricultural production is a nature-friendly activity because it needs the ecosystem's biodiversity to sustain itself. The Municipality's current territorial approach remains the same. CONAF receives more budget and management capabilities. This scenario does not disregard tourism entirely but instead promotes its integration with local agricultural activities on a small scale, emphasizing the importance of local relevance. In this regard, sustainable native forest harvesting practices are also allowed, which goes hand in hand with the disentanglement of water provision and sewage projects. Rural land subdivisions are only allowed far from park boundaries and prohibited in ecological corridors due to a tight MMA, CONAF, MINVU and SAG collaboration. Mapuche communities, as strong territorial players, defend these perspectives. Finally, national, and regional tiers accommodate their economic development to this setting through an empowered MMA. A participant words synthesize this scenario as follows:

> "That is the future bet, and this is the good way of living. I believe that deep down, these are Mapuche cultural concepts. Good living has to do with harmony with

> the environment, with respect for what we call in Wingka femün biodiversity, while in Mapudungun, we call it Itrofill Mogen".

3.2.2. Parcelopoly

This scenario explores the consequences of increased land subdivision for second housing on land identified during the pandemic. In this regard, SAG cannot supervise subdivisions that do not comply with the agricultural, livestock, or forestry role. As a result, the progression of second housing projects occurs gradually, following the guidelines outlined in circular 475, which allows for the development of up to 80 plots at a time. The Municipality and the Ministry of Health continue to grant construction and water project permits, respectively. This gradual process goes unnoticed by indigenous communities until it reaches an advanced stage. Also intertwined with the sustained water public projects conflict, the projects that can proliferate have the economic means to acquire water rights and design and implement water projects. The fears expressed by agricultural sector institutions materialize, with agricultural land decreasing and food prices rising, making it more challenging to rely on local activities for sustenance. The service sector related to tourism has replaced agricultural labor as a result. The role of INDAP and MMA remains relatively unchanged. CONAF and private conservation initiatives receive support from real estate companies and landowners. However, this support primarily focuses on maintaining the scenic beauty of forests rather than preserving their ecosystemic functions. A participant captured the essence of this scenario with the following statement:

> "Today we are also experiencing a real estate phenomenon where many real estate companies are also arriving lotting of 200 plots, 250 plots in the headwaters of the basin, places where there is primary forest. And this is basically in what we call the Parcelapolis, the Parcelopolis, which are places where there is a large concentration of population without basic services, where there is no electricity, where there is no sewage system, and they are, as I said, practically virgin headwaters of the basin".

3.2.3. Like in Pucón

This scenario explores the potential consequences of extending the economic development model of Pucón Municipality to the entire basin area. It represents a future where external perceptions of development prevail. Consequently, it suggests that traditional agricultural land may no longer be essential for meeting the basin's tourism-oriented objectives, as food can be imported from external sources. Simultaneously, the region's industrial development, which differs from the Municipality's current political perspective, is gaining momentum. To a certain extent, it is already happening as Municipal officials highlight that many people work in pisciculture, touristic activities in Pucón and even go to northern localities to work in mining.

Consequently, it allows the monoculture of fruit and tree farms to thrive. Also, land subdivisions are rapidly increasing, disregarding the regulations outlined in Circular 475 due to pressure from real estate associations. Consequently, native forests, both inside and outside protected areas, are facing degradation. The existing institutions, such as SAG, INDAP, and CONAF, continue with their current practices, needing more resources to address the challenges faced by small farmers and conservation efforts. Through the Regional Development Strategy, the Regional Government includes Curarrehue as an asset for fruit export and international tourism destinations. In subsequent periods, supported by political campaign backers from outside the basin, the Mayors adopted an industrial development perspective. They aligned politically with international strategies to increase the country's gross domestic product. CONADI and The Ministry of Environment can not react due to outside forces' intense pressure and strength. The water blockage of public water services is partially solved, as most irrigation projects are privately financed and work well enough to support some rural tourism enterprises that maintain the facade of local development. The phrase expressed by a participant summarizes this scenario.

"the Pucón municipality, I feel that they destroyed their environment, that is, was heavily exploited, unleashed it, and profited from everything they wanted".

3.3. Modeling Results

Since our main objective was to model the spatial outcome of different scenarios in line with different rescaled state management dynamics to help decision-making, we compared the result under the main concerns of the participants, which are recognized as the loss of native forest cover, loss in grassland related to agricultural activities, increase in built-in areas, increase in industrial, agricultural activities related to fruit farms and tree farms. Figure 5 contains the land use results for the different scenarios. The BAU scenario determines the benchmark, which was the result of the current trend comprehended between 2004 and 2018 observed data. In this regard, the first comparison is between BAU and 2018 observed imagery. To help the map reading, Figure 6 shows the differences in land cover amount per class of each scenario in percentage.

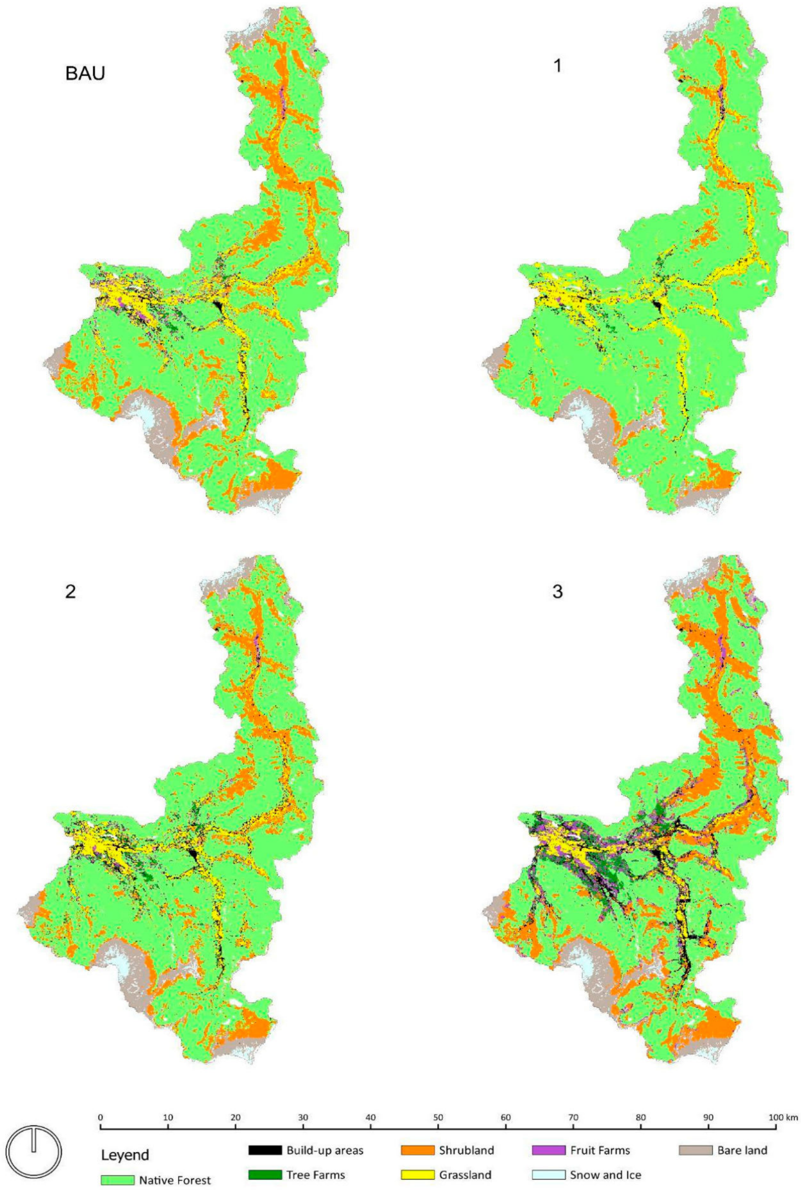

Figure 5. Simulation outputs of the different state management scenarios. BAU Business-as-usual, (1) Agroecology, (2) Parcelopoly, and (3) Like Pucón.

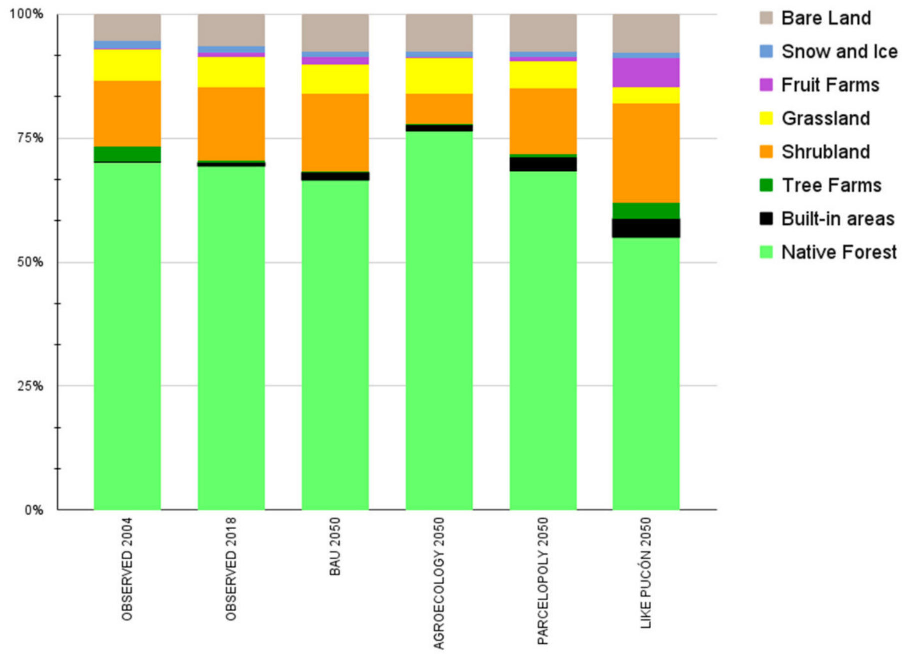

Figure 6. Differences in land cover per class of each scenario in percentage.

Business as usual model BAU scenario presents an increase in Built-up areas and fruit farms in the west side of the basin in Pucón's vicinity. Also, an increase in Build-in areas appears around the international route to Mamui Malal Pass to Argentina, which also is the entrance to Villarrica National Park. On the North side, in the Reigolil locality area, there are no significant gains in built-in areas and fruit trees, although a notorious increase in shrubland and loss of native cover is observed.

From the designed scenarios, Agroecology shows a significant change from shrubland to native forest cover due to enhanced management of native forest conservation institutions. There is a mild increase in built-in surfaces in the Pucón and next on the side of the international route. Fruit farms are scarce, but a small amount remains in the north and southwest basin areas. In comparison, the grassland containing agricultural and livestock activities has increased in their traditional location in low height and light slope. The Parcelopoly scenario shows an increase in build-in areas by densifying pre-existing urban areas with some scattered presence near protected areas and within native forest areas. The shrubland native forest ratio is almost the same as in the BAU scenario, and even when the transition rules and conversion elasticity changed, the spatial outcomes were similar. There are slight differences due to this scenario decreasing fruit farms and an increase in built-up areas. In terms of land use change, the Like Pucón scenario presented the most drastic changes as it represents the worries of most of the participants. The mix of industrial monoculture covers departures from the southwest basin area of Pucón and grows over Curarrehue urban center. However, it leaves out the north basin area, a notorious increase in shrubland due to degraded native forest and farmland abandonment. The built-in areas keep densifying near roads and previous urban concentration but also show a more scattered outcome than in the previous scenario, allocating near Villarrica National Park.

In all scenarios, there is a trend to allocate tree farms and fruit farms near the Pucón area, the built-up areas in the south near Pucón, and the international route to Argentina. A trend observed is that trade-offs between native forest and shrubland cover represent the main changes in the northern area with more difficult access. Another observation that can only be read in context is the recognition of the resemblance between the Parcelopoly 2050 scenario and the 2018 Pucón imagery in Figure 7.

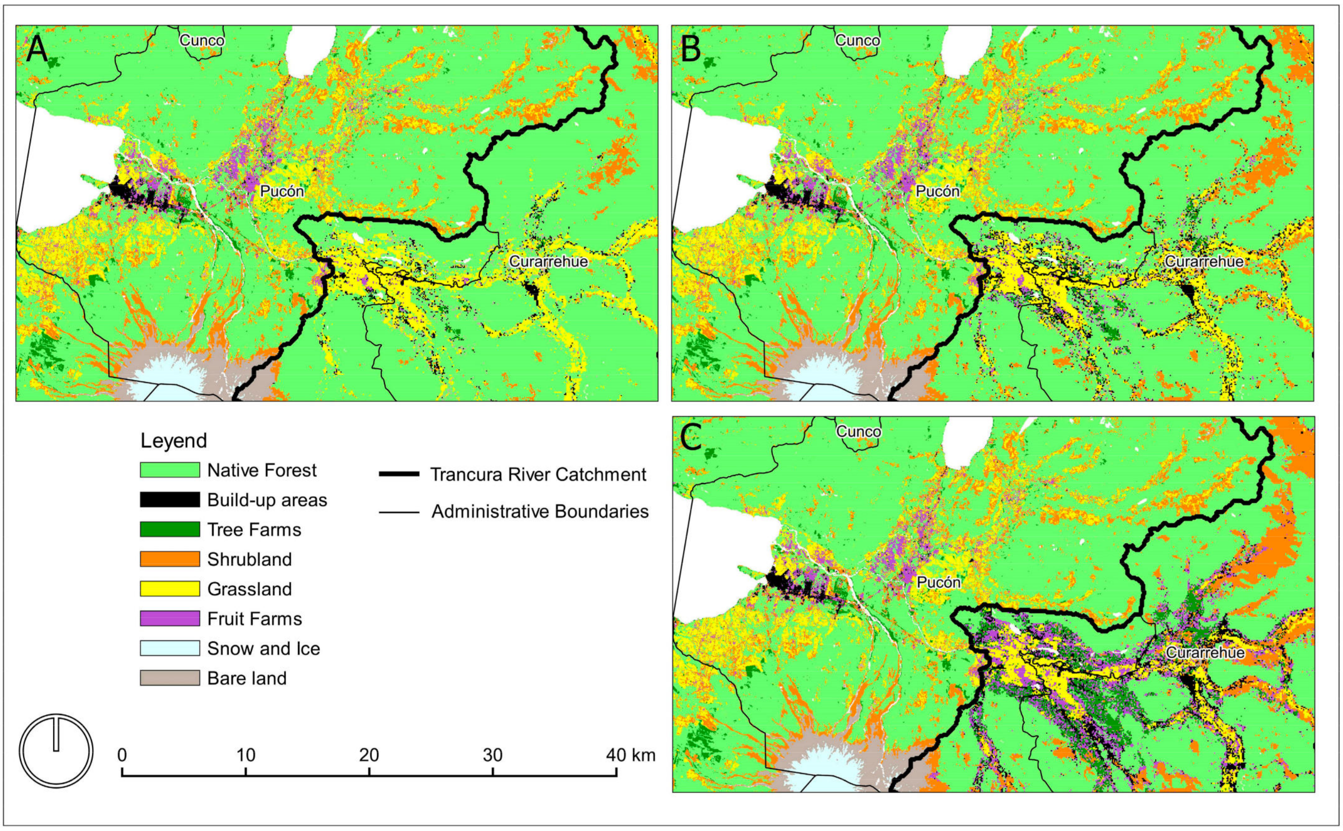

Figure 7. Comparison between the Pucón imagery from 2018 and the projected scenarios for 2050. The basin limits indicates the cut. (**A**) Agroecology, (**B**) Parcelopoly, and (**C**) Like Pucón.

4. Discussion

Despite shared concerns about land use changes occurring in the study area, the current state rescaling of policies and regulations does not meet the specific territorial needs expressed by Chilean state officials and residents. This lack of alignment must be revised to recognize the social importance of land a in providing essential resources and functions for human well-being. State officials are bystanders to current land management practices and even witness the degradation of protected areas. State's land use management is adrift, lacking evidence of appropriate and consistent approaches to address potential outcomes and challenges. The focus on various institutional agendas, the marginalization of the territory in the administrative process, and the prioritization of market-oriented policies, such as the regional government's annual budget, have relegated land to a secondary role.

Our findings revealed that participants expressed a desire to develop planning instruments to manage territorial conflicts caused by land cover changes driven by private interests. These aspirations are consistent with existing theoretical and legal frameworks in territorial planning that aim to incorporate ecological awareness, participatory engagement, and normative regulations into planning instruments. However, it also became clear that it is a major challenge to develop these instruments in a timely manner, while ensuring the inclusion of rural and urban areas. Given the rapid changes that are occurring in the study area, exploring alternative management, and planning approaches is of utmost importance. Traditional planning instruments, which are slow to develop and rapidly becoming obsolete in the study area, tend to conform to conventional notions of planning rooted in the modernist paradigm [118]. As Friedmann [119] points out, the timing of planning should be responsive to everyday events and take into account political considerations and strategic thinking, which does not mean that we should discard planning instruments altogether. Instead, it is an opportunity to rethink a more flexible approach that recognizes different rates of change and can adapt to site-specific and rapidly evolving socio-spatial events, which traditional static land use plans often cannot do.

In this context, the hypothesis that the state is capable of managing land use can provide a pragmatic perspective. A deeper understanding of state management can be used effectively to achieve positive socio-ecological outcomes even without land use planning. We found that considering the rescaling with the influence of site-specific socioeconomic characteristics has been valuable in identifying influential LULCC factors at the subnational level. Factors such as political attitude, political will, communication, social pressure, management attributions, degree of centralization, and market pressures should be considered beyond proper institutional alignment [53]. Given the global and local importance of land use change [2,12,45] and its rapid, unprecedented, and uncertain pace [54], explicit inclusion of these factors is essential. Moreover, this problem directly overlaps with a significant modeling challenge, where insufficient consideration of the underlying causes of change and inadequate stakeholder engagement compromise the ability of modeling to inform management and decision-making [13,55].

This is especially important in Chile, where there is an ongoing political debate between those who support a free market approach with minimal state intervention and those who criticize it. As it has been observed, the free market approach to environmental management does not necessarily imply a reduction in state regulation, but often involves a process of re-regulation to ensure the smooth functioning of the market [120]. For example, the Chilean state has been promoting the use of site-specific resources for more than four decades, transferring planning responsibility to the regions. However, they need more resources to perform this task effectively [56]. Numerous studies have shown how social and economic actors with specific interests influence state management in Chile in specific contexts [30,121–123]. Because the state is permeable and relies on institutions composed of people, it internalizes the interests of different actors [124]. In practice, specific state apparatuses tend to favor "some actors, some identities, some strategies, some spatial and temporal horizons, and some actions over others" [44] (p. 124).

The observed disparities among the resulting scenarios effectively illustrate this trend. For example, the Agroecology scenario relies on concrete state support to foster local initiatives in small-scale agriculture. It requires political will to solve water blockages and enable local economic activities. In contrast, the Parcelopoly scenario depends on a smooth permitting process that is attuned to the economic demands of the real estate market. It also requires a visually appealing forest, though not necessarily one with complex ecosystem services. Furthermore, in the Like in Pucón scenario, there is a fear of neighboring land use economic activities moving upstream of the Trancura River due to water crises in downstream settlements. On the one hand, activities with sufficient resources, such as rural real estate projects and monoculture crops, can be developed smoothly and quickly into the basin. On the other hand, local economic land use activities with fewer resources tend to develop more slowly or remain illegal due to existing state management practices. In summary, management, or the lack of it, selectively influences different land use change processes.

Interestingly, our study found that the TRB has not experienced any recent prominent market-oriented public policy targeting land use, such as promoting tree plantations supported by DL 701 [30,73,74,125]. Instead, the prominent phenomenon observed was a political–economic struggle that raised concerns and provoked rejection among most interviewees. This struggle revolved around the impact of Circular 475, the newly introduced policy that restricts the subdivision of rural areas and affects real estate market developers. Throughout our study, legal disputes arose between the Ministry of Agriculture, responsible for implementing Circular 475, and the "Chile Rural" Association, representing real estate players involved in project development and rural subdivisions [116,117]. The resolution of this conflict is still pending and serves as a clear example of the significance of incorporating struggles into the analysis of land use change.

Initially, the study area appeared to be a context free of problems, with most of its native forests protected by the state. As our understanding deepened, we observed the significant rise in rural subdivisions alongside other land-use dynamics changes. At this point, we recognized that the input to land management models should rely on more than just integrating seemingly disconnected land change processes. As highlighted by Sepulveda [126] the surfaces near protected areas are equally important to the ecosystem integrity. They depend highly on their morphology as an ampler extension in touch with the unprotected outside. Like the Trancura River Basin, the Pyrenees, a mountainous region, has witnessed problematic land transformations due to tourism and second housing activities, resulting in the loss of forest cover and agricultural heritage [127]. The interplay between the influx of "amenity migrants" [128] and the previous economic incentives for tourism provided by the state [91] served as a compelling reason to investigate the phenomenon of second housing in conjunction with other land use change dynamics.

4.1. Modeling Process

At this stage, integrating these dynamics into modeling gains relevance, as it shows the spatially explicit location to address our efforts or provoke a discussion around the plausibility of the map's outcomes, especially in a context where the institution's budgets are low, as in the CONAF case. To this effect, the R lulcc v1.0.4 package was a practical framework for land cover simulation, delivering all the benefits of the R programming language [99]. In this sense, the logistic regression and random forest models achieved an adequate predictive capacity. Also, it enhanced the integration of other modeling stages, such as the spatial explanatory factor filtering procedures. However, this is still far from "easy to use and accessible for users with varying levels of programming experience." [99] (p. 3617). At some point, we desisted from integrating Markov chains analysis and used Terrset v19.0.7 user-friendly software. Also, the Fuzzy Kappa Simulation process was developed externally. Additionally, the iterative process of assigning transition rules and elasticity conversions could be perfectly incorporated into the code. In conclusion, this handcrafted work can be automated after a coding process.

Another important point with the lulcc v1.0.4 R package and CLUEs is that the model process performs well with large land use percentages per class. However, their predictive capability decreases when the percentage is approximately less than 5%. In this study, we considered two land use categories, namely fruit trees and build-up areas, which exhibit a low percentage and consequently reduce the model's predictive capacity. Nevertheless, these categories were included due to their importance in the study's scenarios and their significance in the interviews. They provide valuable information when considering future projections up to 2050. Furthermore, their inclusion is justified by the recent nature of these land use changes and the benefits of using a mixed-method approach. Although there are no previous records of large build-up areas or extensive fruit tree plantations, participants expressed concerns about the proliferation of these land uses and perceived them as plausible changes.

However, testing the accuracy of Trancura River Basin land use models is crucial. These models can be combined with other biophysical models to aid decision-making. To investigate this, the following research phase will examine how well these models work with hydrological models. In addition, we suggest improving communication by using various visualization tools along with pixel maps to convey potential future outcomes clearly and efficiently [58,59].

4.2. Study Limitations

Modeling socio-ecological systems can be seen as a heuristic device. Reducing complex interactions to systemic abstractions is necessary for developing recommendations for decision-makers [129]. In this regard, we made the following assumptions. First, this research did not include an essential aspect of land management through litigation and the court process, when certain land uses related to projects that could go against citizen principles are avoided. This process involves the SEA (Environmental Assessment Service) and SMA (Superintendency of the Environment). Second, it is essential to acknowledge that Mapuche individuals and communities cannot be considered homogeneous. In this research, we learned that the diversity within their community can have varying impacts on land use. In this study, we only incorporate the perspectives of state officers and a few community members, so additional perspectives from Mapuche individuals should be considered for a more comprehensive understanding. Third, we did not include climate change variables that can reduce forest growth ratios and avoid natural regeneration [30]. Fourth, we assume that no stochastic change will occur by 2050. Fifth, data limitation was an essential obstacle in this study. Information availability is a common constraint in land use modeling [74,107]. The primary problem with data is reflected in the selection of Explanatory Factors in the calibration process. This is reflected in the assumption that geographic land ownership data for 2013 stayed the same in the period from 2004 to 2018. It also reflects that we only use static variables and no dynamic ones. Finally, in the interviews, we also detect an understandable reluctance of state officials to speak freely about conflict and political bias.

5. Conclusions

Land use scenario modeling investigates the potential impact of various human decisions on land configuration. In the absence of legally binding, spatially explicit land use policies, our study incorporates the perspectives of state officials to understand how land use management operates at the basin scale and how it might change in the future. This approach allowed us to examine the existing land use management practices and their interactions with socio-political and economic forces. Through a participatory process, we uncover the implications of State rescaling beyond spatially focused agendas and nationally standardized policy enforcement. The interviews reveal that existing land management is a complex interplay of historical processes and rescaled national policies combined with site-specific socio-ecological contexts. In this regard, our findings are organized in different state management dynamics to inform that different interplay between their institutions can result in different land use configurations.

The BAU scenario was developed as a baseline, and the other three scenarios were designed to express the participants' central narratives of the participants: (A) Agroecology, (B) Parcelopoly and (C) Like Pucón. We build the interplay of the scenarios results from current state management. The interaction of the scenarios results from current state management. In this sense, they are determined by different institutional conditions, such as management capacity, budgets, political will, global, national, or local bound, communication among institutions and conflicts. In this context, the Agroecology scenario represents small-scale farming and a native forest regeneration. The Parcelopoly scenario expresses a future in which real estate projects for second housing increase significantly. Finally, the Like Pucón scenario is based on the shared concern of several participants about the development model of their neighboring community.

Using statistical modeling, we can identify the areas where a trade-off process is most likely to occur. The Agroecology scenario shows how native forest regenerates inside and outside protected areas. The scenario most similar to the BAU is Parcelopoly. The Like in Pucón scenario shows more fragmentation of the native forest. Near the Villarrica Reserve, native forest and shrublands are shifted northward due to regeneration degradation. In contrast, the increase in fruit trees, tree farms and built-up areas is more likely in the southern part of the TRB, near the international route and the municipality of Pucón.

Modeling spatially explicit land use maps provided valuable insights into the spatial and temporal dynamics of land use change and allowed us to gain a comprehensive understanding of the urgency to address territorial concerns and aspirations. By visualizing patterns and trends of land use change, we can identify areas where interventions are needed and the appropriate timing for action. This research shows that the implementation of land use policies and instruments faces challenges and delays, resulting in a persistent cycle of ineffective management. This suggests that state land management lacks a coherent and proactive approach, relying instead on the capabilities of various institutions that understand the functions of land beyond just land leasing. To address these issues, targeted efforts are needed to raise awareness of the implications of state rescaling and to use existing management instruments to drive positive change for ecosystems and society.

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Informed Consent Statement: Informed consent was obtained from all subjects interviewed in the study.

Data Availability Statement: Data sharing is not applicable to this article.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Appendix A.1. Land Cover Description

According to 2018 Land Cover Data developed by the team, 69.2% of the surface area consists of native forests. It is characterized by the presence of araucaria trees *Araucaria araucana*, stunted lenga *Nothofagus pumilio*, coihue *Nothofagus dombeyi*, oak *Nothofagus obliqua*, coligue *Chusquea culeou*, within low altitude areas are influenced by natural and human disturbances [130]. Shrubland covers 14.8% *Escallonia virgata*, *Chiliotrichum rosmarinifolium y Berberis empetrifolia* L. [130]. Tree farm cover with 0.5% have significantly diminished compared with the region trend and are composed mainly of *Eucalyptus nitens*, *Eucalyptus globulus*, *Oregon Pine Pseudotsuga menziesii* and *Pinus radiata* [110]. While the fruit trees with 0.9% have recently increased with notorious European Hazel *Corylus avellana* and to a lesser extent and in Chestnut *Castanea sativa*, Cherry *Prunus avium*, Apple, *Malus domestica* among others in fruit orchards [110]. Approximately 6% of the land is occupied by grassland, including agricultural areas, while 0.7% is classified as built-up areas. Both are predominantly found in low slope settings, which have historically been used for human settlements, self-consumption family farming, and cattle raising. The remaining consists of 6.5% of bare ground including rocky areas, and 1.4% covered by snow and ice.

Appendix A.2. Local Actors Questionnaire

Context: "What was this area like before? What activities or tasks were most important? Did that change and why do you think it changed? What is the area like today? Can you identify relevant actors that influence the basin territory? Have you identified new actors in the last 5 years?"; State Rescaling: "Do you recognize differences from changes in the administrative direction? Do you recognize conflicts with and between other state institutions and other actors? Are there some actors that bring about more change than others? How do state institutions function in the area and what do they pay more attention to?"; Scenario Narratives: "What do you think this place will be like in 30 years? On whom does it depend?".

Appendix A.3. State Officials Questionnaire

State Rescaling: "What are the main policies, laws, regulations that your institution works with in the basin ? Do you consider that they influence how the territory is organized? Have these procedures undergone any changes in the last 5 years, and if so, what changed? Are there certain procedures that are more likely to occur than others? Which and how does your institution relate to other institutions? Do you recognize differences with and between other state institutions? Do you recognize any differences based on changes in your institution's administrative direction?" State Spatial Strategies: Which and how does your institution relate to other actors? Do some actors cause more changes than others? Do you recognize conflicts with and between other actors?" Scenario Narratives: "What do you think the basin area will be like in 30 years? On which institutional process does it depend on?".

Appendix B. Modeling Parameters

Table A1. Calibration parameters. In blue includes demand for scenario B-A-U.

CALIBRATION PARAMETERS										
TRANSITION MATRIX										
Change 2004/2050		**Nat. Forest**	**Built-up**	**Tree Farms**	**Shrubland**	**Grassland**	**Fruit Farm**	**Snow/Ice**	**Bare Land**	**CONVERSION ELASTICITY**
Nat. Forest		1	1	1	1	1	1	0	0	0.2
Built-up		0	1	0	0	0	0	0	0	1
Tree Farms		1	1	1	1	1	1	0	0	0.9
Shrubland		1	1	1	1	1	1	0	1	0.2
Grassland		1	1	1	1	1	1	0	0	0.3
Fruit Farm		0	1	0	1	1	1	0	0	0.6
Snow/Ice		0	0	0	0	0	0	1	1	0.7
Bare Land		0	1	0	1	0	0	1	1	0.4
DEMAND										
t0	2004	116,625	468	5271	22,019	10,415	408	2641	8980	
t0<n>1	2005–2017	(. . .)	(. . .)	(. . .)	(. . .)	(. . .)	(. . .)	(. . .)	(. . .)	
t1	2018	115,608	1096	822	24,712	10,004	1564	2319	10702	
t1<n>2	2019–2049	(. . .)	(. . .)	(. . .)	(. . .)	(. . .)	(. . .)	(. . .)	(. . .)	
t2	2050	110,768	2492	585	26,041	9823	2539	1979	12,601	
%		66.4%	1.5%	0.4%	15.6%	5.9%	1.5%	1.2%	7.6%	

Table A2. Markov transition potential with the probability of switching to another land class, developed in the Terrset land use change module. Unlike a linear extrapolation, it relies on the previous state of the system and the transition probabilities between different states to predict future land use change demand.

2004/2018	Native Forest	Built-Up	Tree Farms	Shrubland	Grassland	Fruit Farm	Snow/Ice	Bare Land
Native Forest	88.93%	0.24%	0.41%	8.72%	1.17%	0.21%	0.00%	0.33%
Built-up	12.50%	12.50%	12.50%	12.50%	12.50%	12.50%	12.50%	12.50%
Tree Farms	50.85%	1.96%	0.44%	26.71%	14.68%	3.60%	0.01%	1.74%
Shrubland	22.44%	1.65%	0.18%	50.61%	13.96%	2.18%	0.23%	8.75%
Grassland	14.25%	6.35%	0.26%	26.66%	41.52%	9.71%	0.01%	1.25%
Fruit Farm	10.78%	8.81%	0.25%	19.55%	36.26%	23.64%	0.00%	0.70%
Snow/Ice	0.01%	0.09%	0.01%	0.24%	0.01%	0.01%	54.46%	45.17%
Bare Land	0.19%	0.59%	0.04%	1.32%	0.13%	0.05%	6.46%	91.23%

Table A3. Transition rules and demand for scenario 1, changed parameters in blue changes.

SCENARIO 1. AGROECOLOGY											
TRANSITION MATRIX											
Change 2004/2050		**Nat. Forest**	**Built-up**	**Tree Farms**	**Shrubland**	**Grassland**	**Fruit Farm**	**Snow/Ice**	**Bare Land**	**CONVERSION ELASTICITY**	**Calibration**
Nat. Forest		1	0	0	1	0	0	0	0	0.8	0.2
Built-up		0	1	0	0	0	0	0	0	1	1
Tree Farms		1	1	1	0	1	1	0	1	0.4	0.9
Shrubland		1	1	1	1	1	1	0	1	0.3	0.2
Grassland		1	1	1	1	1	1	0	1	0.7	0.3
Fruit Farm		1	1	0	0	0	1	0	1	0.4	0.6
Snow/Ice		0	0	0	0	0	0	1	1	0.7	0.7
Bare Land		0	1	1	0	1	1	1	1	0.4	0.4
DEMAND											
t0	2004	116,625	468	5271	22,019	10,415	408	2641	8980		
t0<n>1	2005–2017	(. . .)	(. . .)	(. . .)	(. . .)	(. . .)	(. . .)	(. . .)	(. . .)		
t1	2018	115,608	1096	822	24,712	10,004	1564	2319	10,702		
t1<n>2	2019–2049	(. . .)	(. . .)	(. . .)	(. . .)	(. . .)	(. . .)	(. . .)	(. . .)		
t2	2050	127,230	2425	206	10,166	11,983	371	1912	12,534		
%		76.3%	1.5%	0.1%	6.1%	7.2%	0.2%	1.1%	7.5%		

Table A4. Transition rules and demand for scenario 2, changed parameters in blue changes.

SCENARIO 2. PARCELOPOLY											
TRANSITION MATRIX											
Change 2004/2050		**Nat. Forest**	**Built-up**	**Tree Farms**	**Shrubland**	**Grassland**	**Fruit Farm**	**Snow/Ice**	**Bare Land**	**CONVERSION ELASTICITY**	**Calibration**
Nat. Forest		1	1006	0	1006	0	0	0	0	0.4	0.2
Built-up		0	1	0	0	0	0	0	0	1	1
Tree Farms		1	1	1	0	1	1	0	1	0.5	0.9
Shrubland		1	1	1	1	1	1	0	1	0.4	0.2
Grassland		0	1	1	1	1	1	0	1	0.3	0.3
Fruit Farm		0	1	1	0	1	1	0	1	0.5	0.6
Snow/Ice		0	0	0	0	0	0	1	1	0.7	0.7
Bare Land		0	1	1	1	1	1	1	1	0.4	0.4
DEMAND											
t0	2004	116,625	468	5271	22,019	10,415	408	2641	8980		
t0<n>1	2005–2017	(. . .)	(. . .)	(. . .)	(. . .)	(. . .)	(. . .)	(. . .)	(. . .)		
t1	2018	115,608	1096	822	24,712	10,004	1564	2319	10,702		
t1<n>2	2019–2049	(. . .)	(. . .)	(. . .)	(. . .)	(. . .)	(. . .)	(. . .)	(. . .)		
t2	2050	**113,855**	**4900**	**824**	**22,345**	**9080**	**1377**	**1912**	**12,534**		
%		**68.2%**	**2.9%**	**0.5%**	**13.4%**	**5.4%**	**0.8%**	**1.1%**	**7.5%**		

Table A5. Transition rules and demand for scenario 1, changed parameters in blue changes.

SCENARIO 3. LIKE PUCÓN											
TRANSITION MATRIX											
Change 2004/2050		**Nat. Forest**	**Built-up**	**Tree Farms**	**Shrubland**	**Grassland**	**Fruit Farm**	**Snow/Ice**	**Bare Land**	**CONVERSION ELASTICITY**	**Calibration**
Nat. Forest		1	1	1	1	1	1	0	1	0.2	0.2
Built-up		0	1	0	0	0	0	0	0	1	1
Tree Farms		1	1	1	1	1	1	0	1	0.7	0.9
Shrubland		1	1	1	1	1	1	0	1	0.3	0.2
Grassland		1	1	1	1	1	1	0	1	0.4	0.3
Fruit Farm		1	1	1	1	1	1	0	1	0.7	0.6
Snow/Ice		0	0	0	0	0	0	1	1	0.7	0.7
Bare Land		1	1	1	1	1	1	1	1	0.4	0.4
DEMAND											
t0	2004	116,625	468	5271	22,019	10,415	408	2641	8980		
t0<n>1	2005–2017	(. . .)	(. . .)	(. . .)	(. . .)	(. . .)	(. . .)	(. . .)	(. . .)		
t1	2018	115,608	1096	822	24,712	10,004	1564	2319	10702		
t1<n>2	2019–2049	(. . .)	(. . .)	(. . .)	(. . .)	(. . .)	(. . .)	(. . .)	(. . .)		
t2	2050	**91,759**	**6200**	**5275**	**33,435**	**5676**	**9679**	**1912**	**12,891**		
%		**55.0%**	**3.7%**	**3.2%**	**20.0%**	**3.4%**	**5.8%**	1.1%	7.7%		

Appendix C. The Absence of Spatial Planning

An axiomatic relevant result which demonstrated the relevance and supports this research main approach, was the concordance between the theoretical discussion and the specific case study situation. The stakeholders almost transversally agree of the urgent matter of developing legally binding land use planning instruments due to land use conflicts. During a fieldwork activity consisting of a participatory process of the Municipality Regulatory Plan (PRC), three localities were included in the process due to their "urban vocation" resulting from significant population growth and concerning issues related to sewage and water provision. Among them is the actual urban center, Curarrehue, which has the legal status of urban boundary, the most basic land-use planning instrument. The other two localities are Catripulli and Reigolil, which were previously categorized as rural areas. The residents of the latter expressed their reluctance towards the implementation of the PRC from various perspectives. They raised concerns regarding several aspects beyond urban limits, such as intensified land subdivisions for second housing purposes, historical and cultural territorial belonging of the indigenous communities, water scarcity, climate change, among others. Nevertheless, the PRC in Chile focuses solely on urban areas and lacks the capacity to effectively address rural issues. In the same line, a CONAF official worried about native forest loss claims due to the absence of local and regional planning instruments. According to a GORE official, although the upcoming Regional Land Management Plan is expected to provide a framework for land use zoning, there is still uncertainty regarding its application and suggests that an intermunicipal regulatory plan would be a more suitable approach. However, MMA and MINVU officials highlight the significant challenges and prolonged delay in the realization of the intermunicipal plan for Villarrica-Pucón, which has been stagnant for approximately 10 years. They separately agree that the extended delay has rendered the plan obsolete and is no longer relevant in this situation. The difficulties and time span in the implementation of land use related instruments forms a long-lasting loop of lack of effective management. In this context, a Regional Government (GORE) official highlights that spatial planning is not aligned with the existing economic model. They argue that it is contradictory to engage in spatial planning when the dominant practice is to prioritize economic considerations. This prioritization is reflected in the annual preliminary regional investment project and the Regional Development Strategy, which focus on economic aspects rather than spatial planning. Meanwhile, the management of the State through its sectoral structure has site-specific and distinctive effects on land, resulting in uncertain outcomes.

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