RESEARCH PAPER

MODELING LAND USE CHANGE OF MID-SIZED CITIES IN THE PROCESS OF METROPOLIZATION. CASE STUDY LA SERENA-COQUIMBO CONURBATION, CHILE

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ABSTRACT. The current urbanization trend shows a large number of conurbated medium-sized cities growing and others that could be transformed into metropolises, especially in Latin America. This has led to disparities in the provision of urban services and amenities, as well as new territorial processes and spatial fragmentation. The objective of this study is to analyze the future changes in land use and land cover in the La Serena-Coquimbo conurbation, Coquimbo Region, Chile, under two different scenarios: Business-as-usual and Spatial Planning between 2020 and 2042. These different scenarios were simulated using the CLUMondo model based on the evolution of land use/cover between 1990-2020 in order to identify the main dynamics associated with urban growth in both cities. The simulation scenarios reflect how the urban area of the conurbation will expand towards the peri-urban area. In the first scenario, urban land shows an increase of 54%, and in the second one, 45% from 2020 to 2042, reinforcing the issues of the metropolization process in the conurbation, such as spatial segregation, infrastructure deficits, loss of ecosystems and natural landscapes, and fragmentation of rural areas. Spatially explicit models have proven to be a powerful tool for decision-makers tasked with projecting urban growth, particularly in conurbated cities undergoing metropolization.

KEYWORDS: mid-sized cities, land use change, modeling, scenario simulation, La Serena-Coquimbo, CLUMondo

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INTRODUCTION

The current demographic trend shows a growing number of people living in urban areas. Although megacities contain a significant portion of the urban population, around 50% reside in medium-sized and intermediate cities with fewer than 500,000 inhabitants[1]. In this context, mid-sized cities are crucial in providing specialized services, goods, and infrastructure to both urban populations and rural areas. They occupy a strategic position between global and national metropolises, generated by globalization, which allows them to control important information and capital flows (Maturana et al. 2017). Their territorial organization in the form of networks promotes the integration and coordination of extensive areas, granting them a fundamental role in the structure and development of the territory (Llop and Cifuentes 2015).

Chile is among the most urbanized countries in Latin America with 87.7% in 2020[2]. The rapid expansion of Latin American cities reflects processes of metropolization among nearby urban centers, driven by economic dependence and the evolution of economic models in the context of globalization. This has resulted in inequalities in the quality of services and urban infrastructure, as well as new territorial processes and spatial fragmentation (Aguirre et al. 2018). Chilean cities have experienced a shift in their expansion pattern, transitioning from a relatively compact structure to diffuse urbanization towards peripheral areas, leading to a dispersed distribution (Hidalgo et al. 2009). This urbanization process includes not only the country's three major metropolitan areas (Santiago, Valparaiso, and

[1] United Nations, D. of E. and S.A.P.D. (2019). World Urbanization Prospects: The 2018 Revision. [online] https://population.un.org/wup/Publications/Files/WUP2018-Report.pdf [Accessed 03 Apr. 2023]
[2] UN-Habitat (2022). World Cities Report 2022. Envisaging the Future of Cities [online] https://unhabitat.org/wcr/ [Accessed 03 Apr. 2023]

Concepción) but also medium-sized cities that exhibit features of metropolization (Maturana et al. 2019). This process is no longer related to traditional models of Latin American cities (Borsdorf 2003) but rather involves the formation of conurbations among intermediate cities (Orellana 2020).

Many small and medium-sized cities in Latin America are growing rapidly and in the future, some may reach the level of a metropolis. However, there are no studies that allow exploring and forecasting these changes using spatially explicit urban simulation models. In this sense, the "new science of cities" provides a reference point for modeling and analysis of cities (Batty 2013). In this context, land use and land cover change (LUCC) models, are tools used to support the analysis of this type of change to understand the functioning of the complex earth system, which integrates socio-economic and biophysical dimensions (Verburg et al. 2004). Simulation models, according to Batty (2013), are crucial in the study of cities under different scenarios to represent, analyze and predict their behavior, which allows the assessment of decisions and policies for better development and management (Salazar et al. 2020).

From a geographic perspective, modeling land use changes uses Remote Sensing and Geographic Information Systems (GIS) in an integrated and systemic manner provides a spatially explicit view. The scale of study plays a significant role as it determines the information about the social organization of the territory and helps identify spatial factors that influence the patterns of LUCC (Henríquez 2014; Henríquez and Azócar 2007; Veldkamp and Lambin 2001; Verburg et al. 2004). Land use change (LUC) models, classified by (Mas et al. 2014) use different methodological approaches, theoretical foundations, and techniques, depending on the scientific discipline used (Henríquez 2014; Henríquez and Azócar 2007; Islam et al. 2021; Pokojska 2019).

Studies of this nature are widely developed in the United States, Europe, and Asia. In contrast in developing countries there is a little research regarding urban area expansion (Henríquez-Dole et al. 2018), intermediate and mid-sized cities (Azócar et al. 2003; Puertas et al. 2014; Romero and Vásquez 2009), with less representation of those in the process of metropolization (Maturana et al. 2021), which shows the importance of studying the issue in this field.

Consequently, it is imperative that urban modeling, particularly within the purview of urban planning and Strategic Environmental Assessment (SEA) proactively anticipates the demands of urban expansion and proposes alternative strategies for comprehensive and strategic development. The incorporation of a more explicit and sustainable vision into the formulation of urban alternatives through the projection of prospective scenarios using the CLUMONDO model (van Asselen and Verburg 2013), enables the integration of the strategic aspects outlined in the SEA as well as the possibility of calculating demand based on what is considered in the regulatory plans.

In light of the significance of the growth of intermediate cities in the metropolization process, the application of this approach represents an innovative contribution to the development of planning instruments. Thus, it provides a valuable tool for formulating and evaluating development options within the framework of the SEA and other planning instruments in Chile. Studies of future metropolization are scarce (Jande et al. 2020; Salazar 2020). Therefore, the novelty of this study lies in its contribution to understanding future metropolization through spatially explicit simulations, presenting the case of a mid-sized cities with accelerated growth under an explicit modeling approach, the results of which help decision-making processes.

In this regard, the following question is posed as a guiding principle: Can a mid-size city in the process of conurbation potentially evolve into a future metropolis? The objective of this study is to analyze the future changes in land use and land cover (LULC) in the La Serena-Coquimbo conurbation, Coquimbo Region, Chile, under two different scenarios: Business-As-Usual (BAU) and Spatial Planning (SP) between 2020 and 2042. These scenarios are determined using the CLUMONDO model, which is based on the evolution of LULC between 1990 and 2020. This analysis aims to identify the main dynamics associated with urban growth, which contributes to a more precise delineation of the boundaries of both mid-size cities, La Serena and Coquimbo, as well as future urban expansion areas. The projected configuration of the conurbation provides insight into how both cities will develop in their transition to becoming a future metropolitan area.

MATERIALS AND METHODS

Study area

The region is located in the southern section of the north of Chile, known as the "Norte Chico" and is bordered to the north by the Atacama Region, to the south by the Valparaiso region, to the west by the Republic of Argentina and to the east by the Pacific Ocean (Fig. 1). La Serena is the regional capital. According to the geographical characteristics, both municipalities comprise a series of longitudinal marine terraces that increase in height towards the east, crossed by ravines and river valleys. La Serena-Coquimbo conurbation is located in an area prone to natural hazards, such as earthquakes and tsunamis, tidal waves, and landslides (Ortiz et al. 2002).

The population distribution is heavily concentrated around the regional capital of La Serena and the port of Coquimbo. According to the last Census of the National Statistical Institute (INE in Spanish acronym) in 2017, the population at the regional level reached 757,586 inhabitants, of which 448,784 inhabitants are located in the municipalities of La Serena (221,054) and Coquimbo (227,730), which concentrates 59,2% of the regional population (INE 2019).

The conurbation La Serena-Coquimbo, since the mid-sized cities of La Serena and Coquimbo constitute a conurbation currently undergoing a process of metropolization (Hidalgo et al. 2009). The accelerated growth of La Serena-Coquimbo, as part of the expansion of mid-sized cities in Chile since the 1990s, exacerbates issues such as socio-spatial segregation, an increase in illegal land seizures, and poor urban transport planning. Residential expansion, driven by the demand for housing, raises urban land costs, contributing to the concentration of social housing in disadvantaged areas with inadequate services and accessibility. The growing preference for low-density housing results in the formation of numerous scattered nuclei, especially through the subdivision of rural land. As a consequence, pressure is generated on high-yield agricultural areas and threatens valuable ecosystems in the region, further complicating the metropolization process.

Datasets and processing

The classification of LULC was made using Google Earth Engine (GEE) cloud computing platform, which

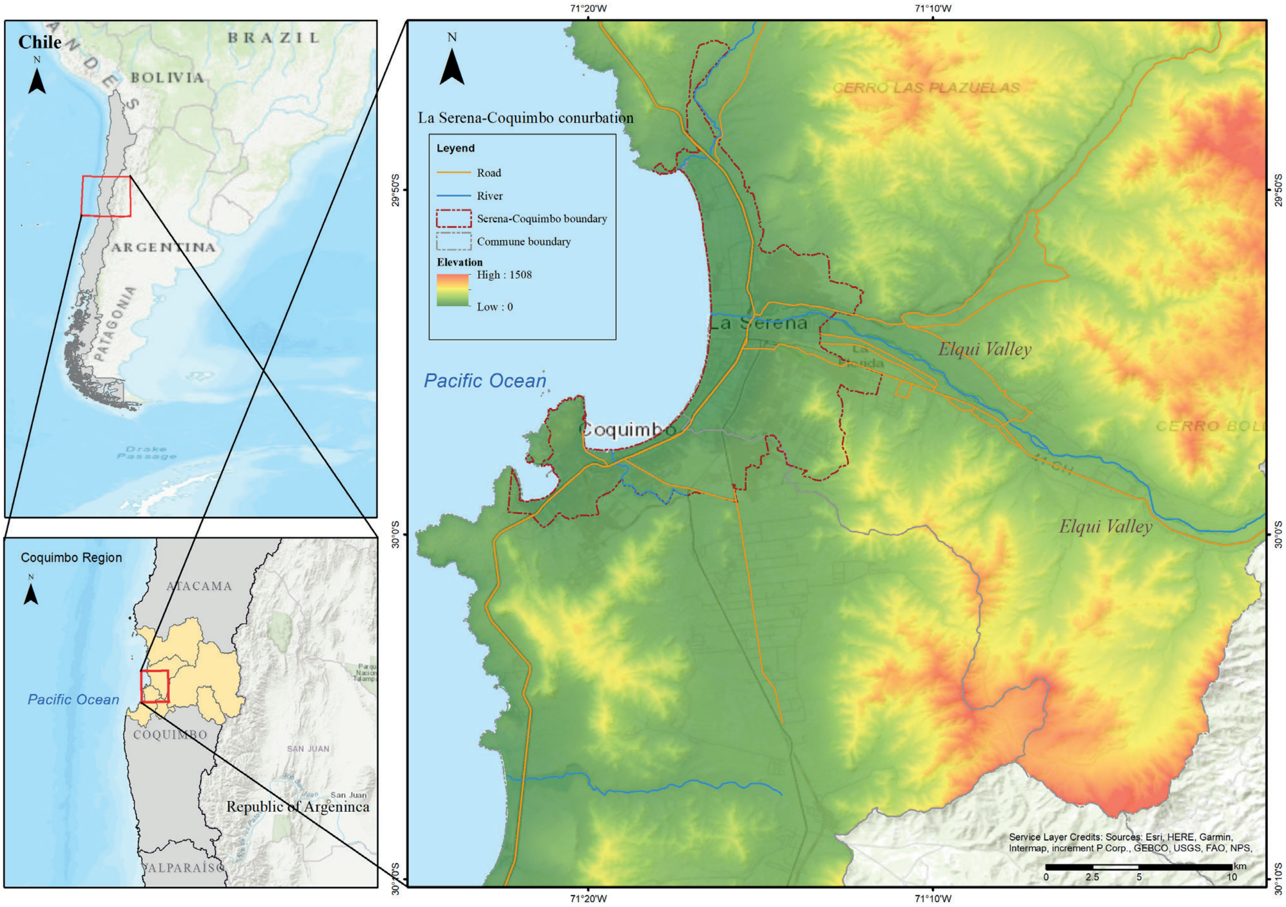

Fig. 1. Geographical location of the study area (La Serena-Coquimbo conurbation)

provides access to satellite images from the United States Geological Survey (USGS) Landsat. For the purpose of this study, we used Landsat Collection 1 Tier 1, because the images in this collection are orthorectified and have well-characterized radiometry, as well as inter-calibration across different Landsat instruments. The georegistration of Tier 1 scenes is consistent and complies with image-to-image tolerances of ≤ 12-meter radial root mean square error (RMSE) (USGS, n.d.). To determine land use for the years 1990, 2000, 2010, and 2020, Landsat 5 Thematic Mapper (TM), Landsat 7 Enhanced Thematic Mapper Plus (ETM+), and Landsat 8 Operational Land Imager (OLI) satellite images were used, with a spatial resolution of 30 meters and the World Geodetic System (WGS) 1984 reference system (Table 1).

Training points were generated by visual inspection of high-resolution imagery available in Google Earth Pro for 1990, 2000, 2010, and 2020. A random forest decision tree classification algorithm (Breiman 2001) was used to classify the satellite images. This algorithm is one of the most widely used for LULC classification (García-Álvarez et al. 2022; Huang et al. 2017; Midekisa et al. 2017) as it allows greater differentiation between different LULC given its multidimensional characteristics (Rodriguez-Galiano et al. 2012) The land use and land classification were based Anderson's system (Level 1) (Anderson 1976), of which seven categories were selected, according to the geographical characteristics of the study area: urban (U), agricultural land (A), water (W), wetland (We), barren land (B), rangeland (R), and forest land (F). For the validation process, 70% of the training points were randomly selected from each class to act as training data, and the rest (30%) was used as the validation dataset.

The challenge of collecting on-site training points necessary for the validation process, crucial for more accurate classification, is acknowledged as one of the limitations of this study.

The framework used in this work is shown in Fig. 2.

Accuracy assessment of the land use maps

For the accuracy assessment of the land use/cover maps for 1990, 2000, 2010 and 2020 confusion matrices were generated based on validation points, from which statistical accuracy measures such as overall accuracy, user's accuracy, and producer's accuracy were calculated (Olofsson et al. 2014). Additionally, the Kappa coefficient (κ) was derived to assess the level of spatial agreement between the classified map and the reference data. The producer's accuracy defines the probability that a reference pixel is correctly

Table 1. Imagery of study area

Sensor	Year	Date	Images	Bands
LANDSAT 5 /C01/T1_TOA	1990	07/09/1990-22/10/1990	3	B1-B7, except B6
LANDSAT/LE07/C01/T1_TOA	2000	12/07/2000-26/11/2000	5	B1-B7, except B6
LANDSAT/LT05/C01/T1_TOA	2010	11/09/2010-31/11/2010	5	B1-B7, except B6
LANDSAT/LC08/C01/T1_TOA	2020	01/07/2020-01/12/2020	2	B2-B7

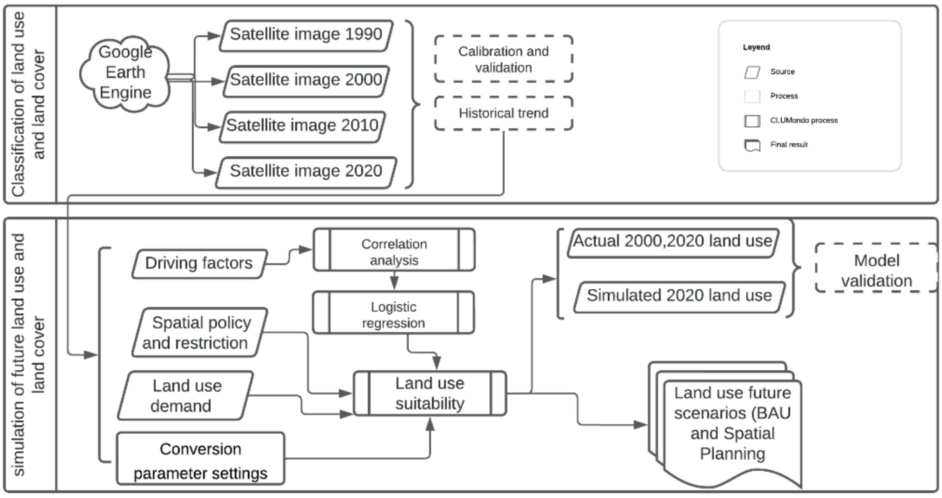

Fig. 2. Methodology flowchart to obtain future land use scenarios

classified (omission error). The user's accuracy defines the probability that a classified pixel in a map represents that category on the ground (commission error). All accuracy parameters have index values between 0 and 1, where 0 signifies low classification accuracy and 1 signifies strong classification accuracy or agreement (Jande et al. 2020).

Simulation of future land use and land cover

The CLUMondo (Conversion of Land Use on Mondial scale) model is an update to Dyna-CLUE that focuses on land systems (van Asselen and Verburg 2012), which makes it possible to model on a global scale by introducing macro-level demands (top-down) and at the same time to configure the model according to local factors (bottom-up) (van Asselen and Verburg 2013). Ornetsmüller et al. (2016) implement this new CLUMondo approach to model land use changes in the Lao People's Democratic Republic (Laos) based on three scenarios. This spatially explicit model integrates socioeconomic, demographic and environmental variables to simulate future land use changes (Arunyawat and Shrestha 2018; Malek and Verburg 2018).

Two scenarios were considered to simulate the future projection of LULC BAU and Spatial Planning (SP). The first one establishes a trend scenario where the current conditions of the territory do not change. It also incorporates the national protected areas as restriction zones for any change in land use. The second is based on the projected urban areas of the Intercomunnal Regulatory Plan of Elqui Province (PRI Elqui, in Spanish acronym) approved in 2019 (SEREMI 2013a; SEREMI 2013b), as well as restriction zones composed of green areas and protection zones at the district level of the municipalities of La Serena and Coquimbo (Municipality of Coquimbo 2014; Municipality of La Serena 2020) and at the intercommunal level (La Serena-Coquimbo conurbation).

The CLUMondo model (van Asselen and Verburg 2013) was used to project yearly time step land uses until 2042, coinciding with the PRI Elqui's projected year (SEREMI 2013a). Unlike other models, CLUMondo does not assume a hierarchy when allocating LULCs. Instead, it simultaneously addresses multiple demands (van Vliet and Verburg 2018).

The model requires four main inputs: location suitability, spatial policies and restrictions, land use demand, and land use conversion settings. In this study, the demand for goods and services is not used. Instead, the surface area demand for each land use type is predefined. As result, land system are allocates based on transition potential at time (t) and location (i) for each land system (LS) and the demand for that specific year (Eq. 1). The transition potential (*Ptrans t,i,LS*) is calculated as sum of local suitability (*Ploc t,i,LS*), the conversion resistance (*Pres LS*) and neighboorhood effect (*Pneigh t,i,LS)* as well as a competitive advantage of a land system (*Pcomp t,LS*) (van Vliet and Verburg 2018).

$$Ptrans\ t,i,LS = Ploc\ t,i,LS + Pres\ LS + \\ + Pneigh\ t,i,LS + Pcomp\ t,LS \quad (1)$$

The local suitability of a location is estimated from the relationship between driving forces and land use. Logistic regression is used for each land category separately to estimate the probability of occurrence for each cell. Prior to the regression, Pearson's correlation analysis (R^2) was performed to discard highly correlated variables whose value exceeds 0.9.

A total of 17 variables were selected and grouped into three main categories: geographic, urban, and demographic (Table A.1). Altitude and slope variables were derived from the Digital Elevation Model (DEM) from Alos Palsar (2016) accessed through Alaska Satellite Facility - Distributed Active Archive Center (ASF-DAAC[3]).

The selection of the driving forces consists, firstly, of the researcher's knowledge of the study area and its territorial dynamics. Various bibliographic sources and case studies were reviewed to identify these driving forces (Geist and Lambin 2002; Verburg et al. 2021; Verburg et al. 2004; Zondag and Borsboom 2009). In addition, various regional and local stakeholders involved in the territorial planning process of the study area were consulted. Secondly, the significance value (less than 0.05), indicates how closely related the independent variable is to the specific land use. The accuracy of the logistic regression is calibrated from the Area Under the Curve value (AUC) (Pontius and Schneider 2001).

In terms of spatial policies and restrictions, the main sources of information to identify the policies that restrict urban development (restriction) and those that facilitate its expansion (location specific) were the territorial planning instruments corresponding to the study area, both at municipalities (Municipality of Coquimbo 2014; Municipality of La Serena 2020) and intercommunal scales (SEREMI 2013b, SEREMI 2013a). For the Spatial Planning scenario, location specific preferences were added as part of the spatial policies, corresponding to urban extension zones. These areas indicate the model's high probability for

[3] https://asf.alaska.edu

urban growth (preference), specified in the parameters by assigning weights to each land use.

Land use demands were calculated independently of the CLUMondo model and need to be specified for each scenario. In this study, the demand for goods and services is not used, but rather the demand for surface area is predefined for each land use type. This parameter restricts the simulation by defining a specific land use growth. The LULC demand for the two scenarios up to 2042 was calculated from a simple regression curve based on the observed area in the period from 1990 to 2020. For the Spatial Planning scenario, the demand for urban land use was calculated based on data from the PRI Elqui regarding urban and extension areas. The assumption was defined as "the water land use will maintain the same surface area as observed in 2020.

The conversion rules determine the temporal dynamics of the simulations and two sets of parameters: (1) conversion resistance and (2) land use transition sequences that must be specified before running the model. The conversion resistance parameter determines the strength or elasticity of one land use to change to another. The second set of parameters requires setting the conversion matrix and order. The first indicates the possible transitions between the land uses allowed in the model, while the second one tells the model the possibilities for land use change to satisfy demand.

Model validation

To validate the results, the methodological approach of Pontius et al. (2008) was applied in this research, which consisted of two phases. In the first phase, three maps were superimposed together: time reference map 1 (2000), time reference map 2 (2000), and time prediction map 2 (2020).

The results were entered into a three-dimensional table, where five possibilities were identified: correct for observing change and predicting change (hits); correct for observing persistence and predicting persistence (correct rejections); wrong for observing change and predicting change in the wrong category (wrong hits); wrong for observing change and predicting persistence (misses); and wrong for observing persistence and predicting change (false alarms) (Pontius et al. 2008). These results were used to calculate three proposed complementary statistical measures by Pontius et al. (2008): the figure of merit, producer's accuracy and user's accuracy.

RESULTS

Land use dynamics from 1990 to 2020

The spatio-temporal dynamics of the La Serena-Coquimbo conurbation over the observed period reveal significant transformations indicative of socio-economic and environmental dynamics, with changes measured in hectares (Fig. 3). The expansion of urban areas by 11,034 hectares highlights a notable trend towards urbanization. This growth reflects the increasing need for residential, commercial, and industrial spaces, raising concerns about the sustainability of such expansion in terms of ecosystem degradation and occupation of agricultural lands.

In this sense, agricultural land experienced a dynamic shift, with a net decrease of 6,396 hectares despite a gain of 8,103 hectares. This fluctuation is attributed to the conversion of previously non-agricultural lands to farming and the loss of agricultural areas to urban development, illustrating the complex balance between food security, urban expansion, and land use policy. Barren land shows the most significant decrease, with a loss of 18,748 hectares, indicating a shift toward more productive or developed land uses.

Given the dominance of rangelands in the study area, there was a net increase of 2,812 hectares, reflecting both losses and gains. The forest category loses 285 hectares, noting that this classification includes areas covered by natural trees and plantations. In this context, areas of crops previously classified as agricultural land were categorized under this one in the process of satellite image classification. The correction was made in the post-processing of the LULC classifications, leading to the observation that the forest exhibited the highest loss in the study area. In general, agricultural land, water, and rangeland maintained a positive balance during the analyzed period.

The remaining LULC, such as water and wetland experienced losses of 102 and 641 hectares, respectively, along with marginal gains. These changes emphasize the vulnerability of aquatic and semi-aquatic ecosystems to human activity and climatic fluctuations, necessitating enhanced conservation efforts to protect these ecologically significant areas.

The accuracy of the LULC classification shows that the overall accuracy of the classification is 0.91 (1990), 0.93 (2000), 0.97 (2010), and 0.99 (2020), which indicates a strong accuracy of the classification performed (Table A.1). The Kappa index result for the four years studied is above 0.8, which corresponds to a very good level of spatial agreement between the classified map and the reference data. The average values of

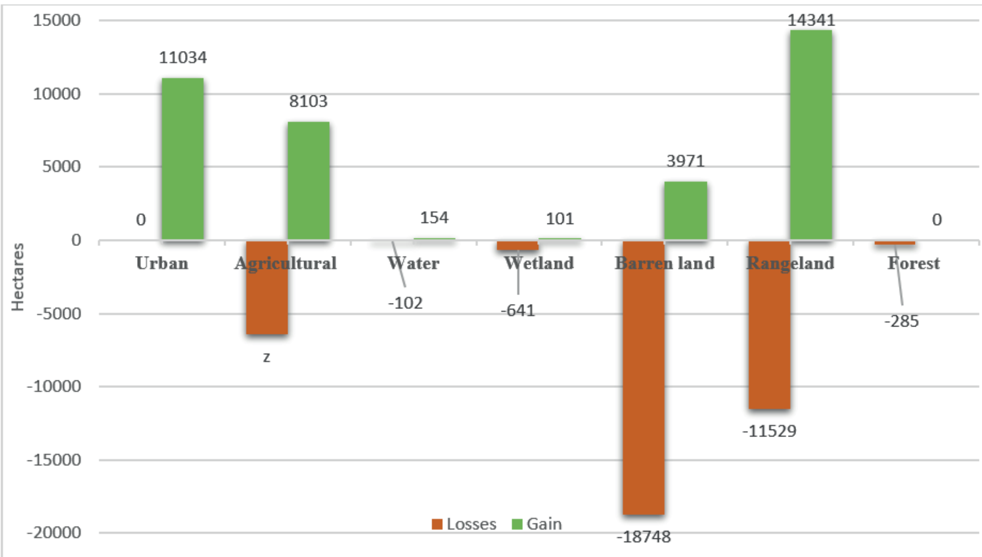

Fig. 3. Gains and losses of land use and land cover, 1990-2020

producer and user accuracy are higher than 0.9 so a good result is observed between commission and omission errors (Zhang et al. 2021).

The result of the evolution of land use change between 1990-2020 emphasizes the need to implement management and planning strategies for sustainable land use. These strategies should facilitate adaptation to urbanization demands, enhancing agricultural productivity, preserving ecosystems, and adapting to climate change.

Model result under two scenarios

BAU scenario. The increase in urban land use is caused by the displacement of other land cover and uses and extends both inside and outside the La Serena-Coquimbo conurbation. The urban land will cover 10% of the total area in 2042 and it will increase 54% between 2020 and 2042 (Fig. 4). The demand for urban land continues to exhibit an upward trend in both scenarios until 2042. In the BAU scenario, the demand for urban land will reach 21,610 ha by 2042, representing a 54% increase compared to 2020.

Agricultural land tends to disappear towards the coastal area of the conurbation due to the expansion of urban land, with some patches of barren land and wetland (Fig. 5a). The ratio of agricultural land is 12.6% of the total surface area of the study area, with the major concentration in the lower sector of the Elqui valley, where several urban areas are located close to the conurbation. The loss of wetland is 34.3% compared to the modeled year. Consequently, a large part of the wetland systems in the study area will disappear by 2042, and those that remain will react to the restrictions of this scenario.

The spatial distribution of urban land determines the configuration of a series of spatial patterns of urban land growth, which correspond to the form of urban sprawl. The first urban growth pattern can be seen in the advance of urban sprawl in the immediate proximity of the conurbation boundary, which is more evident towards the east of La Serena and south of Coquimbo. Likewise, urban sprawl increases towards the north of the conurbation. The second spatial pattern is identified around the study area's main communication axes and is characterized by a linear urban land expansion. The third pattern is presented as dispersed urban patches and focuses Elqui Valley's lower section and the study area's southeast. This type of growth is concentrated on higher terraces up to almost 300 m above sea level, with a slope steepness of more than 15°.

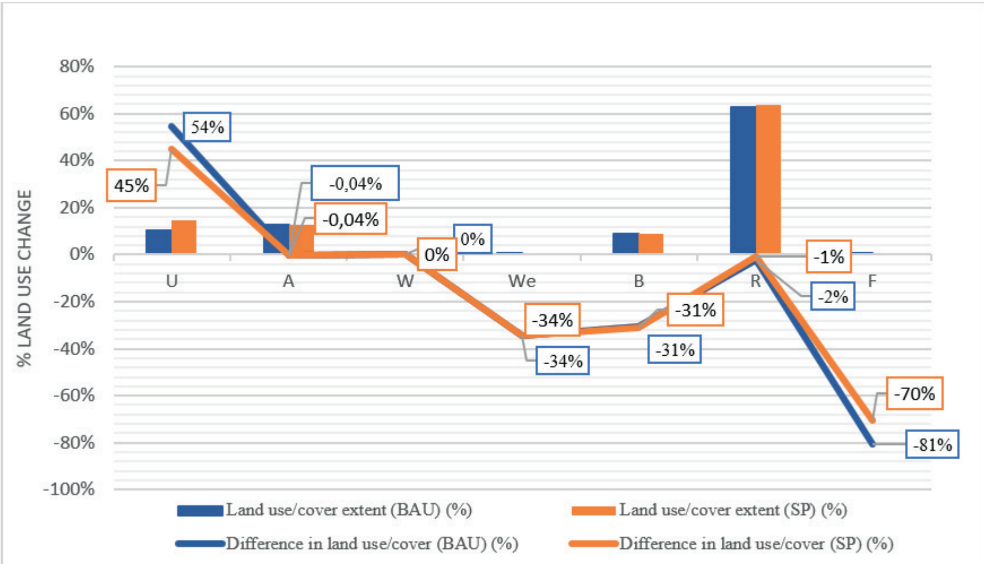

Fig. 4. Land use change between 2020-2042 for BAU and Spatial Planning (SP) scenarios according to the different land uses and land covers

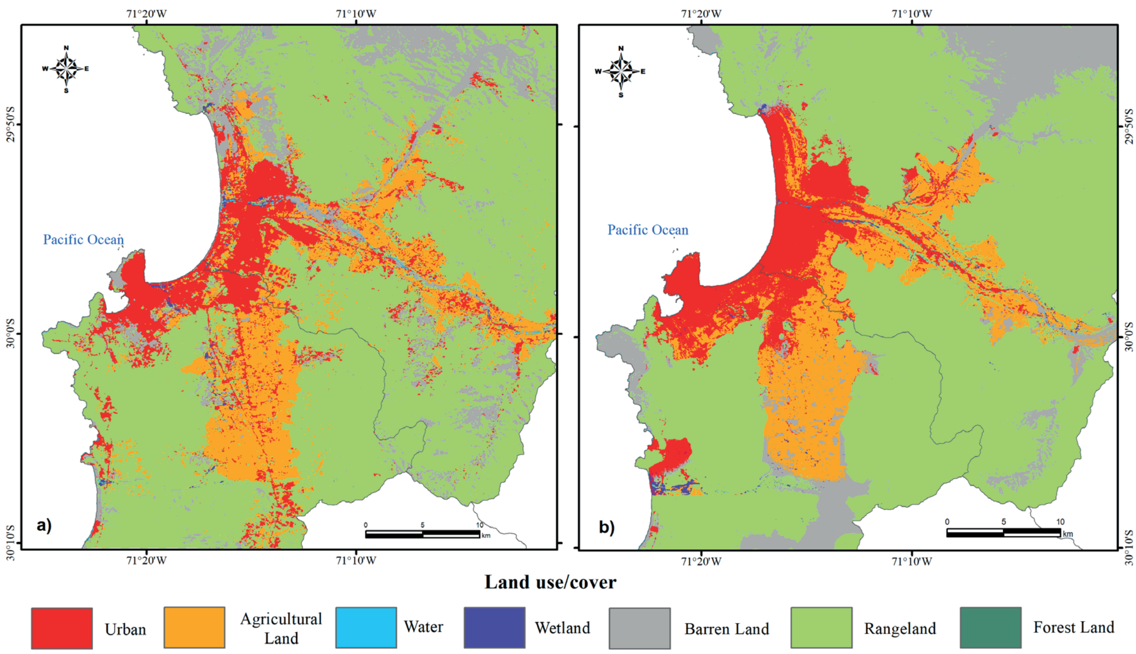

Fig. 5. Simulated scenarios of land use and land cover by 2042. a) BAU, b) Spatial Planning

Spatial Planning Scenario. The demand for urban land use in the Spatial Planning scenario is lower than in the previous one. Urban land growth is observed both in the coastal zone and in the urban extension areas proposed by the planning instruments. The projected urban land area for 2042 is 20,302 ha, a 45% increase from 2020, representing 14.6% of the total area. This figure aligns with the proposed 30% growth indicated by key stakeholders participating in the territorial planning process in the study area, as confirmed during interviews to validate the modeling results. The growth of the urban LULC area in 2042 is 45% compared to 2020 and its ratio reaches 15% of the total area (Fig. 5b).

Under this scenario, agricultural land use is better represented within the urban limits of the conurbation; however, its ratio is similar to that of the BAU scenario (13%) (Fig. 3). The permanence of agricultural land in these sectors is due to the fact that these areas concentrate important agricultural production at the regional level. Although the surface ratio of wetlands, such as agricultural land, is the same as in the BAU scenario (0.3%), the spatial representation is more evident and responds to restriction configuration to protect important ecosystems in the conurbation. However, the trend indicates a loss of almost 35% of wetland area by 2042. Forest land will experience the most significant losses by 2042, both in the BAU and SP scenarios.

In this scenario, three spatial urban growth patterns are evident, as in the BAU scenario. The expansion of urban land towards the periphery of the conurbation, where the change of urban land use over agricultural land is patent, and the growth around the main road axes of the conurbation. The third spatial pattern, corresponding to urban patches, is more prominent in this scenario and is concentrated in three specific sectors. First, toward the east of the study area (lower section of the Elqui Valley). Second, to the southeast of the conurbation, where patches are isolated among agricultural land. Third, to the west of Coquimbo, where urban land consolidation is observed by the merger of small urban patches and a strong urban land expansion to the south of the study area.

Analysis of the logistic regression results reveals that the most important variable is migration density, although in the reverse direction (Table A.2). This driving force is an important component of the demographic dynamics of La Serena-Coquimbo, as statistics show an exponential increase in migration at the regional level between 1992-2017, which corresponds to the census periods. Upon consulting with key actors on this aspect, it was found that, in the Coquimbo region, migration increased during the time of the COVID-19 pandemic in the period 2020-2022.

The second most important variable was the commercial value of land, which showed a strong relationship with urban and agricultural land use and land cover. This results from the neoliberal model installed in Chile since 1973, where urban land ceases to be a scarce resource and its profitability depends on market trends. In this context, the real estate industry represents a powerful actor that can generate land speculation and change the direction of urban land occupation, as well as tighten the problem of spatial segregation by presenting more significant opportunities for higher socio-economic groups.

Agricultural land, as opposed to urban land, has an inversely proportional relationship with the commercial value of land, as the price tends to rise within the urban boundary and fall as it moves away from it. Hence, there is an increase in the number of residential plots and an increase in interest in settling in these areas. This is consistent with the observed dynamics of the evolution of LULC in the La Serena - Coquimbo conurbation between 1990 and 2020.

The sensitivity analysis was carried out while interpretating collinearity and logistic regression of driving forces. In this regard, out of the 20 variables initially stipulated for the model, three (distance from commercial establishments, schools, and tourist attractions) were discarded as they did not show significant relevance for the change in urban land use according to the coefficient (β). The retained variables were those identified as the most important in the literature and those considered relevant at the local level, such as the commercial land value. This analysis is critical because it allows for refining and optimizing the model by eliminating variables that do not contribute significantly, thereby improving its accuracy and applicability in predicting changes in urban land use.

Integration of the model to metropolization

The results of the validation of the CLUMondo model by quantitative analysis determine the spatial agreement between an observed and a simulated image for the same period (Fig. 6). The observed image (time 1) corresponds to the year 2000 and the reference and prediction map (time 2) to 2020. The three-way comparison indicates that there is a 23% success rate for observing change and predicting change (hits). The rest is distributed among different types of errors, where the maximum value corresponds to false alarms with 34%, then misses with 29%, and finally, wrong hits with 14% of the total. The validation statistics variables record the results of a figure of merit of 23%, producer accuracy of 35% and user accuracy of 33%.

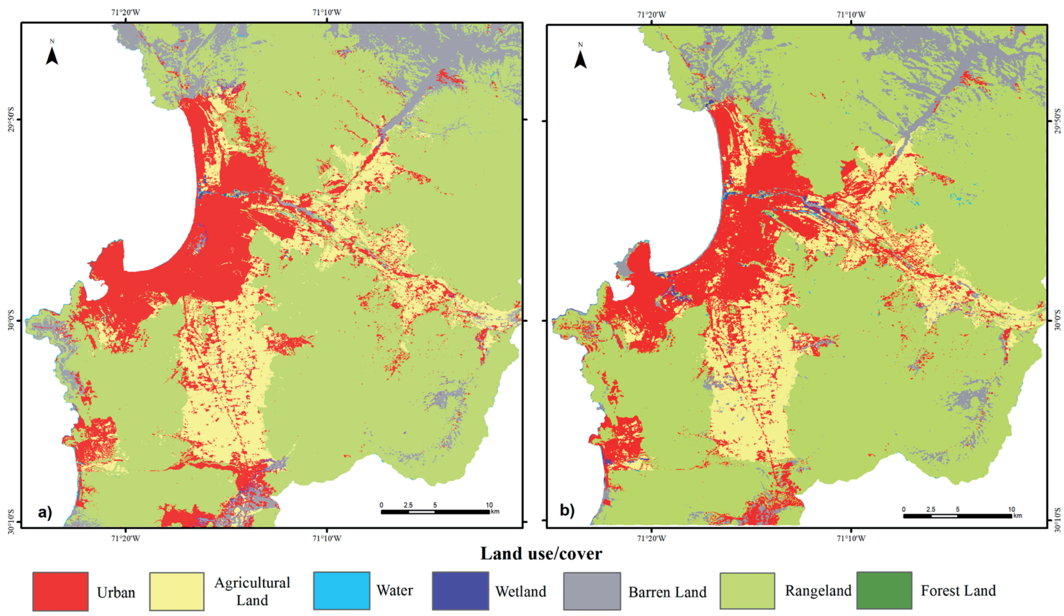

Fig. 6. Actual (a) and predicted (b) land use and land cover maps, 2020

The simulation models under the BAU and Spatial Planning scenarios using the CLUMondo model project change in LULC to 2042. The projection anticipates that the conurbation's growth will follow the trend of annexing territories at the edges of cities, which consolidate as urban areas due to pressure from changes in agricultural land use. This expansion is driven by the need to find available land at lower prices, contributing to the increase in informal settlements and illegal land occupations in Chile. The demand for urban land reflects on the one hand, a scenario that continues the trend of urban land growth without many obstacles and, on the other hand, a scenario that is in line with the proposal of the Intercommunal Regulatory Plan of the Elqui province. The demand for agricultural land remains stable, following a historical trend, as does the demand for rangeland. In contrast, the rest of the land uses show a decreasing trend in surface area. Under the BAU scenario, wetland and forest show the highest loss of land area, while agricultural land, water, and rangeland are the least affected by 2042.

The simulation result under the BAU and Spatial Planning scenarios shows a very similar spatial distribution. However, the first scenario contemplates a higher dispersion of urban patches throughout the study area, while in the second scenario, urban land expansion is more confined and controlled. Under this logic, the Spatial Planning scenario is identified as the most likely as it integrates the urban extension zones proposed by PRI Elqui. Therefore, it indicates to the model the areas of preference for change for urban land. This scenario also contemplates green and protected areas based on territorial instruments at the district and inter-communal levels in order to restrict future land use change.

In this context, it is expected that in the future La Serena-Coquimbo conurbation will be established as a metropolitan area, which answers the research question posed. The legal conditions set out in Article 4 of Decree 98 (2019[4]) are fundamental for establishing metropolitan areas in Chile. These areas must be formed by two or more municipalities of the same region and each of these municipalities must have a population of more than 250,000 inhabitants. Furthermore, it is important to have a spatial continuity in the urban fabric that facilitates mobility and accessibility between the different municipalities within the metropolitan area. This promotes greater connectivity and a better distribution of urban services and complements the functions between the municipalities that form them.

DISCUSSION

Patterns and modeling

The spatial and temporal evolution of the La Serena-Coquimbo conurbation from 1990-2020, according to its LULC configuration, presents the characteristics of the contemporary Latin American city model in its last phase of development: the fragmented city identified by a sectorial-linear tendency and a marked cellular growth of cities (Bähr and Borsdorf 2005).

The growth of the intermediate conurbation cities of La Serena and Coquimbo occurs in a fragmented manner, which responds to a historical process of territorial occupation by separate sectors (Orellana 2020). Urban sprawl occurs progressively between 1990 and 2020, where urban land spreads over other land uses and extends urban sprawl by the annexation of these areas to the boundaries of the agglomeration (Nasar et al. 2021). The road infrastructure of the conurbation, as well as geographical elements such as the Elqui River and the mountain range, are elements that affect the problem of fragmentation of the conurbation system, as they inevitably divide the territory into consolidated and physically separated centers.

While the trend between 1990-2020 shows that fragmentation appears to be less and less intense within the La Serena-Coquimbo conurbation, the increase in the number of isolated urban patches exacerbates the problem of socio-spatial segregation in both cities, as the residential plots are upper-middle and high socio-economic housing, while those living in camps are generally below the poverty or extreme poverty line (Hidalgo et al. 2009).

The result of the spatial evolution of land cover and land use from 1990 to 2020 is consistent with the multi-temporal study of land use variation in the La Serena-Coquimbo conurbation conducted by the Directorate of Extension and External Services (DESE in Spanish acronym) of the Faculty of Architecture at the Pontifical Catholic University of Chile (DESE 2016).

Linear interpolation based on the historical trend from 1990-2020 was used to calculate future demand in this study, and then demand was calibrated based on the information obtained from the sources consulted. Yang et al. (2022) applied the same method for a land use modeling study in the Yanhe watershed, China using CLUMondo under three different scenarios. In contrast to the results obtained using other models, such as the Land Change Modeler module used by Henríquez and Hidalgo (2023) to model the growth of mid-sized Chilean cities, the projection of future demand in CLUMondo allows more control over possible land use changes by projecting demand for the entire land classification system.

The comparison with Waiyasusri and Chotpantarat's study of Koh Chang, Thailand (2022) reveals similarities in the behavior of selected variables like population density, altitude, and slope. However, in the case of La Serena-Coquimbo, the most important demographic variable is migration density. The logistic regression result emphasizes the significance of the local context in each territory. Although both studies focus on tourist cities, the authors do not include the perspective of key actors in their variable selection stage which enriches the variable selection and adds an additional layer of contextualization.

The urban expansion of La Serena-Coquimbo, according to the urban growth patterns observed in the simulation, resembles the situation observed in the city of Temuco, where the real estate industry plays a decisive role in the diffuse and fragmented configuration of the conurbation (Maturana et al. 2021). In the case of the metropolization of Quito (Salazar et al. 2020), a similar model (Dyna-CLUE) was used considering driving forces associated with proximity to urban equipment and infrastructure, transportation, and slope.

Strengths and weaknesses of the model approach

The prospective modeling of land use changes using the CLUMondo model proves to be effective in projecting spatially explicit scenarios, as it considers a series of parameters such as spatial policies and growth restrictions that can be configured according to the sustainability

[4] Ministry of The Interior and Public Security. Undersecretary of Regional and Administrative Development. Decree number 98 of 2019. Approves the regulation that sets the minimum standards for the establishment of metropolitan areas and establishes rules for their constitution.

criteria established in the process of the SEA within the framework of the PRI Elqui.

It is important to highlight that the CLUMONDO model allows the introduction of no more than seven variables for each land category, which can be considered a limitation in its methodology. The precision required to select the most pertinent driving forces for LULC necessitates meticulous consideration by the researcher. Another limitation to highlight is the difficulty of collecting spatial data for all the analyzed years, so it was decided to use the data closest to the year 2020, such as demographic and urban data, as well as land use capability.

On the other hand, although the model allows the user to control and anticipate territorial conflicts between various land uses through spatial policies, its effectiveness depends largely on the quality of the base information and the precision with which spatial policies are configured. Furthermore, the model´s capacity to anticipate the transition between land use and land cover may be limited by the complexity and dynamics of territorial processes, as well as by the uncertainty in future projections.

Another limitation is that, while the simulated scenarios can provide future trends for the territory, they cannot anticipate all the potential changes and events that may occur in the future. This limitation can restrict their utility in the formulation of territorial planning instruments. Therefore, it is necessary to complement modeling with other approaches and consider its results as one of the many tools in decision-making rather than an exact prediction of the future.

The utility of modeling through the CLUMONDO model for the planning process and the evaluation of development options within the framework of the SEA lies in its ability to comprehensively incorporate parameters based on the objectives and environmental factors of the EAE of the PRI Elqui. These objectives include the conservation of soils with high agroecological value, the preservation of biodiversity, and the safeguarding of the coastal landscape. Including these elements strengthens the representation of relevant environmental, social, and economic factors. Additionally, this tool allows for the rapid incorporation of changes in demand and future projects that may be reflected in the proposed plan for the sustainable growth of the study area.

The participation of key stakeholders in the construction and validation of the model reinforces its robustness and relevance (Henríquez et al. 2022). This ensures that regional and local perspectives are duly considered, thereby contributing to more informed decision-making and the design of development strategies that align effectively with sustainability goals and territorial planning.

Future metropolization

The projected modeling scenarios show the future trend of urban expansion, configured from the analysis of the spatial evolution of LULC, which evidences a future conformation of the fourth metropolis in the country. Thus, the growth of urban land continues to move towards other uses, which generates the loss of land of high agro-ecological value, both inside and outside the urban boundary, and a substantial decrease in natural environments, such as the wetland systems present in the study area.

Henríquez and Hidalgo (2023) estimate that the La Serena-Coquimbo conurbation population will grow to over 650,000 inhabitants and the surface of the urban area will be around 14,000 ha by the year 2065. The research results project that the consolidated area will be 9,935.65 ha for the BAU scenario and 9,376.29 ha for the Spatial Planning scenario by 2042. If the trend of population and urban area growth in the conurbation continues at the same rate as in the last three decades, it can be expected that by 2065 the size of the urban area will be close to the results of Henríquez and Hidalgo (2023), and the conurbation will be considered a metropolitan area with more than 500,000 inhabitants. These conditions ensure that such areas are adequately equipped to address the challenges of urbanization, promote regional development, and provide better living conditions for their residents. By meeting these criteria, metropolitan areas can play a vital role in fostering sustainable and integrated urban development in the country.

The various urban forms identified in this study as spatial patterns of urban growth, as well as the spatial dynamics of the territory, react differently to the processes of metropolization, some being more resistant than others, as it presented in a study case of the city of Algiers (Mezoued 2022). The author states that the new transport infrastructure, particularly tramway routes, aimed to reduce the spatial fragmentation of the city, reveals a transformation in the urban fabric and its adaption to change. This case study contrasts with La Serena-Coquimbo, which undergoing metropolization.

However, in order to establish itself as a metropolitan system, La Serena-Coquimbo conurbation faces major challenges at a different scale, either as mid-sized cities at the district level or as a common urban area recognized by the PRI Elqui. The geomorphology of the territory presents natural barriers to urban development and contributes to a high vulnerability to tsunamis, while the real estate dynamism and the fluctuation of the seasonal floating population exacerbate the problem of road congestion (Aguirre, Olivares and Orellana 2018).

The analysis of spatial dynamics in the La Serena-Coquimbo conurbation provides not only a methodology but also valuable information about spatial patterns and future urban expansion. These results, obtained from spatially explicit models like CLUMondo, offer valuable insight and allow the anticipation and mitigation of potential environmental impacts and challenges. Using a spatial modeling perspective, it is possible to enrich the understanding of similar processes in intermediate cities undergoing metropolization globally. In this sense, the simulation can help decision-makers identify areas suitable for urban growth while preserving natural ecosystems, aiding in the development of sustainable urban development strategies.

CONCLUSIONS

Spatially explicit models have proven to be a powerful tool for decision-makers tasked with projecting urban growth, particularly in conurbated cities undergoing metropolization. These future metropolises will demand substantial coordination and governance efforts to address complex management issues, which the simulation model helps to visualize to achieve more articulated and sustainable cities. The integration of CLUMondo´s results into policymaking can lead to more informed decisions regarding sustainable urban development, infrastructure planning, and climate change adaptation. Ultimately, it contributes to strengthening the knowledge base in the field of sustainable urban development. Thus, it is possible to avoid processes of fragmentation, dispersion, and diseconomies in the governance of a metropolitan area, contributing to the creation of more resilient and efficient cities.

For a more accurate projection of future scenarios and further development of a research topic, it is essential to enrich the CLUMondo model with a broader perspective, including economic variables such as agricultural and livestock production. These variables are crucial for understanding the interactions between economic development and land use, which allows to evaluate how the economy affects urban expansion and the transformation of rural areas. Likewise, incorporating dynamic variables such as demographics, migration, and urban development is fundamental. These factors, reflecting population changes and infrastructure demands, are key to modeling how population movements and demographic growth foster urban expansion and land demand, influencing land planning and environmental sustainability. Such an approach not only improves the analysis of future scenarios but also strengthens decision-making in urban planning and land management, facilitating the anticipation and mitigation of conflicts between socioeconomic development and environmental protection.

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APPENDICES

Table A.1. List of Driving forces

Category	Driving forces	Variable code	Unit of measure	Information source
Geographic	Elevation	V1	m	Alos Palsar, 2016
	Slope	V2	Grades	Alos Palsar, 2016
	Distance to hydrographic network	V3	m	Geospatial Data Infrastructure of Chile (IDE), 2021
	Land use capacity	V4	Classes (I - VIII)	Natural Resources Information Center (CIREN), 2014
		V5		
Urban	Distance to operational drinking water territory	V6	m	Superintendence of Sanitation Services (SISS), 2020
	Faucets	V7	m	SISS, 2020
	Distance to irrigation channels and wells	V8	m	IDE, 2022
	Distance to urban centers	V9	m	Ministry of Urbanism and Constructions (MINVU), 2020
	Distance to road network	V10	m	IDE, 2022
	Distance to airports and ports	V11	m	Google Map, 2022
	Distance to camp areas	V12	m	National Registry Camps of MINVU, 2022
	Commercial land value	V13	Uf/pixel	Internal Revenue Service, 2020
	Rural property size P	V14	hectares	CIREN, 2014
Demographic	Population density	V15	Pob/hectares	IDE Chile, 2017
	Housing density	V16	Housing/ hectares	IDE Chile, 2017
	Migration density	V17	Mig/hectares	IDE Chile, 2017

Table A.2 Logistic regression coefficient results of land use and land cover in La Serena-Coquimbo conurbation

Driving force	Urban	Agricultural	Water	Wetland	Barren Land	Rangeland	Forest
Constant	-0.91074	0.07242	-4.00874	-1.74695	-2.11176	-0.84544	-6.05188
Elevation	-0.00502	0.00026	-0.01567	-0.01588	-0.00124	0.00203	-
Slope	-	-0.12368	-0.12992	-0.0287	-0.04794	0.07712	0.13289
Distance to hydrographic network	-	0.00013	-0.00014	-0.00045	0.00004	-0.00011	-
Land use capacity (I-IV)	-	0.00013	-	-	-	-	-
Land use capacity (VI-VIII)	-	-	-0.00021	0.00026	-	-0.00013	0.00057
Distance to operational drinking water territory	-	-	-	-	-	-	-0.00033
Distance to irrigation channels and wells	-	-0.00033	-	-	0.00015	-0.00004	-0.00053
Distance to urban centers	-	-	-	-0.00011	-0.00001	-	0.00036
Distance to road network	-0.0001	-	-	-	-0.00011	-	-
Distance to airports and ports	-	-	-	-	0.00009	-	-
Distance to camp areas	-0.00003	-	-	-	-	-	-
Commercial land value	0.31835	-0.38208	-	-0.05533	-	-	-
Rural property size	-	-0.00013	-	-	-	-	-
Population density	-0.93248	-	-	-	-	-	-
Housing density	0.02734	-	-	-	-	-	-
Migration density	0.04943	-	-	-	-	-	-
AUC	0.906183	0.912179	0.902306	0.93791	0.770421	0.936038	0.927431