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Landscape Heterogeneity and Transition Drive Wildfire Frequency in the Central Zone of Chile

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Abstract

Wildfire regimes are closely linked to changes in landscape structure, yet the influence of accelerated land use transitions on fire activity remains poorly understood, particularly in rapidly transforming regions like central Chile. Although land use change has been extensively documented in the country, the specific role of the speed, extent, and spatial configuration of these transitions in shaping fire dynamics requires further investigation. To address this gap, we examined how landscape transitions influence fire frequency in central Chile, a region experiencing rapid land use change and heightened fire activity. Using multi-temporal remote sensing data, we quantified land use transitions, calculated landscape metrics to describe their spatial characteristics, and applied intensity analysis to assess their relationship with fire frequency changes. Our results show that accelerated landscape transitions significantly increased fire frequency, particularly in areas affected by forest plantation rotations, new forest establishment, and urban expansion, with changes exceeding uniform intensity expectations. Regional variations were evident: In the more densely populated northern areas, increased fire frequency was primarily linked to urban development and deforestation, while in the more rural southern regions, forest plantation cycles played a dominant role. Areas with a high number of large forest patches were especially prone to fire frequency increases. These findings demonstrate that both the speed and spatial configuration of landscape transitions are critical drivers of wildfire activity. By identifying the specific land use changes and landscape characteristics that amplify fire risks, this study provides valuable knowledge to inform fire risk reduction, landscape management, and urban planning in Chile and other fire-prone regions undergoing rapid transformation.

Keywords: intensity analysis; fire regime; fire frequency; land use change; Mediterranean ecosystems; wildfire

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1. Introduction

Wildfires are major ecological drivers that influence vegetation structure, species composition, and ecological succession, while also playing an essential role in ecosystem functioning and management [1–4]. However, in recent decades, the frequency and intensity of uncontrolled wildfires have increased globally, often exceeding the capacity of existing Fire Prediction Systems (FPSs) to anticipate and manage these events [1,5]. This growing discrepancy has exposed limitations in current fire prediction approaches, contributing to heightened uncertainty in anticipating fire variability, particularly in human-modified landscapes [6–8].

A critical step toward improving fire risk management is understanding the natural and anthropogenic factors driving fire regime changes [9–11]. While fire frequency, intensity, and spatial variability are central to fire risk assessment [1], the underlying drivers of fire activity have shifted over time [12]. Historically, fires were predominantly triggered by natural factors such as lightning and drought; today, however, human activities combined with climate stressors are increasingly responsible for fire ignition and spread [2]. Despite this shift, most FPSs still rely heavily on climatic variables alone to predict fire occurrence [1,6,13], overlooking the influence of rapid land use and land cover (LULC) change. Within human-dominated landscapes, abrupt LULC transitions, such as agricultural expansion, plantation establishment, and urban growth have been directly linked to increased fire activity and ecosystem degradation [14,15]. Consequently, fire frequency has risen in regions undergoing intense socio-economic and land use transformations, including tropical forest frontiers and urban–wildland interfaces [16,17]. Despite growing evidence connecting LULC change to wildfire risk, there is a pressing need to integrate landscape transitions into fire prediction and management, particularly in fire-prone regions such as Mediterranean-type ecosystems [18–20].

Mediterranean ecosystems, globally recognized for their high biodiversity, are increasingly threatened by human-induced fires [19,21]. Chile contains the largest Mediterranean ecosystem in the Southern Hemisphere, with significant biodiversity conservation potential, where approximately 75% of the native vegetation remains relatively undisturbed by direct human land use [22]. Yet, recurrent wildfires have severely altered these ecosystems, contributing to the loss of more than half of the native forests [23]. Wildfire activity has become one of the most significant threats to Chile's biodiversity and natural resources [24]. Over the past four decades, fire frequency in Chile has increased nearly eightfold [25], with satellite-based systems such as NOAA's Active Fire System detecting alarming levels of simultaneous fire events across the country [26]. Similar dynamics have been observed in other Mediterranean-type ecosystems worldwide, including the western United States, southern Europe, and parts of Australia and South Africa. In California, for instance, rapid urban expansion into fire-prone wildland areas has increased both fire frequency and severity [27]. In the Mediterranean Basin, land abandonment followed by natural vegetation regrowth has altered fuel structure and continuity, contributing to more intense wildfires [28]. Australia has also experienced rising wildfire risks linked to both climate extremes and changes in land management practices [29]. These global parallels highlight the broader relevance of examining how LULC transitions influence fire regimes across different socio-ecological contexts. Notably, more than 80% of fires in Chile are linked to human activities, particularly those associated with productive land use [25]. Moreover, LULC changes within the urban–wildland interface have been identified as one of the primary factors driving elevated fire risk in several regions [30,31].

Chile's landscapes have experienced accelerated and extensive transformations since the 1970s, driven by agricultural expansion, forest plantation establishment, and urban development [32–34]. Between 1986 and 2001, the country saw a rapid transition toward large-scale tree plantations [33], contributing to the reduction in native forests to just 21% of the national territory between 1975 and 2000 [35]. Within Chile's Mediterranean ecosystem, the area occupied by forest plantations expanded dramatically from 5% to 36% during the same period [33,35]. These land use transitions have been accompanied by substantial changes in rural production systems [36,37] and rapid urban expansion, with urban areas doubling in size over the last four decades [37]. Despite numerous studies analyzing short- and long-term LULC change in Chile [31,35,37–39], the comprehensive effects of these accelerated transitions on fire activity remain poorly understood. Moreover, similar knowledge gaps persist worldwide, particularly in rapidly changing regions where LULC

transitions may be reshaping fire regimes [18,40–43]. Addressing this gap is essential for improving the understanding of how the speed, extent, and spatial configuration of LULC transitions influence fire frequency, providing a foundation for more effective fire risk reduction and land management strategies.

In response to the unprecedented rise in fire activity and increasing evidence of the role of landscape transitions in shaping fire dynamics, this study investigates the relationship between LULC change and fire frequency in central Chile. Specifically, we aim to (i) identify the land use transitions driving landscape change; (ii) characterize the spatial configuration of these transitions; (iii) determine which transitions and landscape characteristics influence fire frequency; and (iv) assess whether the speed of landscape transitions affects fire frequency within the timeframe analyzed. By addressing these objectives, this research provides insights relevant to fire management and urban planning in Chile and offers broader implications for other regions undergoing rapid LULC change. Furthermore, this study extends traditional land cover analyses by integrating transition intensity metrics with landscape spatial configuration to assess their combined influence on fire frequency. This methodological integration provides a more comprehensive lens for understanding how both the pace and structure of landscape change shapes wildfire regimes.

2. Materials and Methods

2.1. Study Area

The central zone of Chile is a landscape mosaic characterized by dense human populations and Mediterranean-type ecosystems [44]. Administratively, Chile is divided into regions, which are further subdivided into comunas, the smallest territorial units in the country (Figure A1). The study area includes five major regions and 194 comunas, representing approximately 73% of Chile's population (Table A1). This region has undergone significant land use transformations, driven by agricultural crop production, vineyards, fruit farms, and extensive timber plantations (Table A2), with annual increases of approximately 1.1% in the area occupied by these activities [45]. Given its high population density and accelerated land use transitions, the central zone provides a representative case for assessing the relationship between landscape change and fire frequency.

2.2. Land Use and Land Cover (LULC) Classification

Multi-temporal satellite imagery from Landsat 8 OLI/TIRS Level 1, acquired in January 2014 and January 2017, was obtained from the USGS Earth Explorer (Table A3). To ensure spatial and temporal consistency, all scenes were selected for the summer season with less than 10% cloud cover. Spectral bands 5, 6, and 7 were selected for LULC classification after comparative analyses of spectral and surface profiles, which identified these bands as providing the highest separation between LULC classes. The imagery was spectrally normalized, mosaicked, and geographically corrected prior to classification.

An unsupervised ISODATA classification was applied using ERDAS Imagine software V16.5 to derive four LULC categories: forestland (including plantations), bare land, farmland, and urban areas (Table A4). ISODATA employs a minimum distance algorithm to iteratively refine class means and assign pixels to specific classes [46]. Classification parameters included 150 clusters, 50 iterations, and a 99% convergence threshold to maximize accuracy [47]. Classification accuracy was assessed using 800 stratified random reference points (200 per LULC category) based on Catastro thematic maps [48], Google Earth Pro, and CONAF reference maps. Overall accuracies were 86.5% and 88.8% for 2014 and 2017, respectively (Table 1), with consistent producers' and users' accuracies between years, ensuring reliable change detection [49,50].

Table 1. Accuracy assessment for the 2014 and 2017 LULC * classifications. Output based on 800 reference points, equally distributed between classes.

Year	Class Name	Producer's Accuracy (%)	User's Accuracy (%)	Overall Accuracy
2014	Forestland	84.26	91.00	86.50
	Bare land	87.00	97.00	
	Farmland	93.22	76.39	
	Urban area	76.74	58.93	
2017	Forestland	88.83	91.96	88.78
	Bare land	88.32	94.50	
	Farmland	91.80	82.96	
	Urban area	80.70	70.77	

* LULC = Land use land cover.

2.3. Landscape Change and Transition Analysis

Post-classification change detection was performed to quantify LULC transitions between 2014 and 2017. Intensity analysis was applied to assess the type, magnitude, and spatial distribution of landscape transitions, including the quantity, exchange, and shift components, as well as transition intensity relative to uniform intensity expectations [51,52].Transitions were categorized as stationary (slower than the average transition rate, <UI) or non-stationary (faster than the average transition rate, >UI).

The spatial configuration and fragmentation of the landscape were evaluated using the Shannon Evenness Index (SHEI), which reflects land use homogeneity based on LULC proportions [53]. Additionally, patch characteristics, including shape, area, and aggregation, were quantified using FRAGSTATS 3.3 (Table A5) [54] to assess landscape fragmentation patterns [55]. These metrics were calculated for both raw and majority-neighborhood-adjusted LULC classifications to ensure robustness [55].

2.4. Fire Frequency Data and Analysis

Fire frequency data for 2000–2017 were obtained from NASA's Fire Information for Resource Management System (FIRMS). Historical fire frequency trends were analyzed using Optimized Hot Spot Analysis (OHSA) across the country for 2000–2014, with significant hot spots identified at >90% confidence intervals (Figure 1).

Fire frequency for each comuna was calculated based on fire counts from 1 August to 30 July of each year, following the annual fire season curve established by CONAF (Figure A2). To account for potential climatic influences, weather data for the same period were obtained from Chile's Climate Explorer tool. Where no weather stations were present, precipitation (mm) and average temperature (°C) were spatially interpolated using a cokriging approach with 1 km resolution elevation data as a covariate (Global 30 Arc-Second Elevation, GTOPO30a) [56].



Figure 1. Historical fire frequency clusters between 2000 and 2014 in Chile based on an Optimized Hot Spot Analysis.

2.5. Statistical Analysis

The relationship between fire frequency and landscape patterns was assessed using two multiple linear regression models, each designed to capture distinct drivers of fire activity. Predictor variables were preprocessed and standardized following Santon et al. (2023) [57] to ensure comparability and reduce biases across spatial units. The first model evaluated the influence of static landscape characteristics on fire frequency, where fire frequency (FF) represents the total number of fire counts for each comuna *i* (Equation (1)).

$$FF_i = \beta_0 + \beta_1 \cdot SHEI_i + \beta_2 \cdot NFP_i + \beta_3 \cdot NPUB_i + \beta_4 \cdot PDF_i + \beta_5 \cdot PDBL_i + \beta_6 \cdot PDUB_i + \beta_7 \cdot PAF_i + \epsilon_i \quad (1)$$

In Equation (1), FF_i is the total fire frequency (fire counts) recorded in comuna *i*. The intercept term β_0 represents the baseline fire frequency when all predictors are zero. The coefficients β_1 through β_7 correspond to the effects of each landscape variable: Shannon Evenness Index (SHEI), which quantifies landscape homogeneity; the number of forest

patches (NPF); the number of urban patches (NPUB); the densities of forest (PDF), bareland (PDBL), and urban patches (PDUB); and the mean patch area of forestland (PAF). The residual term ϵ_i accounts for unexplained variation in fire frequency for each comuna.

The second model analyzed how changes in land use classes between 2014 and 2017 influenced changes in fire frequency (Equation (2)), denoted as ΔFF_i, the difference in fire counts for comuna i.

$$\Delta FF_i = \beta_0 + \beta_1 \cdot CF_i + \beta_2 \cdot CBL_i + \beta_3 \cdot CAG_i + \beta_4 \cdot CUB_i + \epsilon_i \quad (2)$$

In Equation (2), ΔFF_i represents the change in fire frequency for comuna i. The intercept β_0 reflects the average fire frequency change when all land use changes are zero. The coefficients β_1 to β_4 capture the effects of proportional changes in forestland area (CF), bareland (CBL), farmland (CAG), and urban areas (CUB) on fire frequency changes. The residual ϵ_i represents variation in fire frequency change not explained by these land use changes.

For both models, a stepwise variable selection procedure based on the Akaike Information Criterion (AIC) was used to identify the most parsimonious model with optimal explanatory power. The overall fit of the selected models was assessed using the coefficient of determination (R^2). To account for spatial dependence among comunas, a spatial weights matrix was constructed based on shared borders (contiguity). Moran's I statistic was calculated on model residuals to test for spatial autocorrelation [58,59]. When significant spatial autocorrelation was detected, spatial regression methods were applied to ensure reliable inference and minimize bias from spatial structure.

3. Results

3.1. Landscape Transitions and Intensity Analysis

Land use and land cover (LULC) transitions were substantial across the study area, with 27% of the total area experiencing change between 2014 and 2017. These transitions were not spatially uniform, varying significantly among regions and LULC types (Figure 2, Tables 2 and 3). Notably, farmland decreased while forestland expanded in four of the five regions analyzed. The regions of Valparaíso and Biobío exhibited the highest annual forestland gains, with increases of 5.14% and 2.26%, respectively. Conversely, the most pronounced farmland reductions occurred in Maule and Biobío, with annual losses of 2.61% and 5.42%, primarily concentrated along coastal areas. Among all regions, Biobío experienced the highest overall landscape transformation, with 29.17% of its area undergoing LULC change.

Table 2. Change detection analysis comparing the LULC change between the central zone of Chile regions and LULC classes.

Region	Persistence (%)	Change (%)	Annual Change by LULC (%)			
			Forestland	Bare Land	Farmland	Urban Area
Maule	73.18	26.82	0.03	−0.53	−2.61	11.51
Metropolitana de Santiago	73.15	26.85	1.10	1.82	−1.59	−10.95
Libertador General Bernado O'Higgins	72.75	27.25	−0.51	−1.33	−0.09	15.71
Valparaíso	77.96	22.04	5.14	1.63	1.12	−16.78
Bio Bío	70.83	29.17	2.26	−0.4	−5.43	4.15
Total	72.74	27.26	Change Rate per Year = 9.08%			

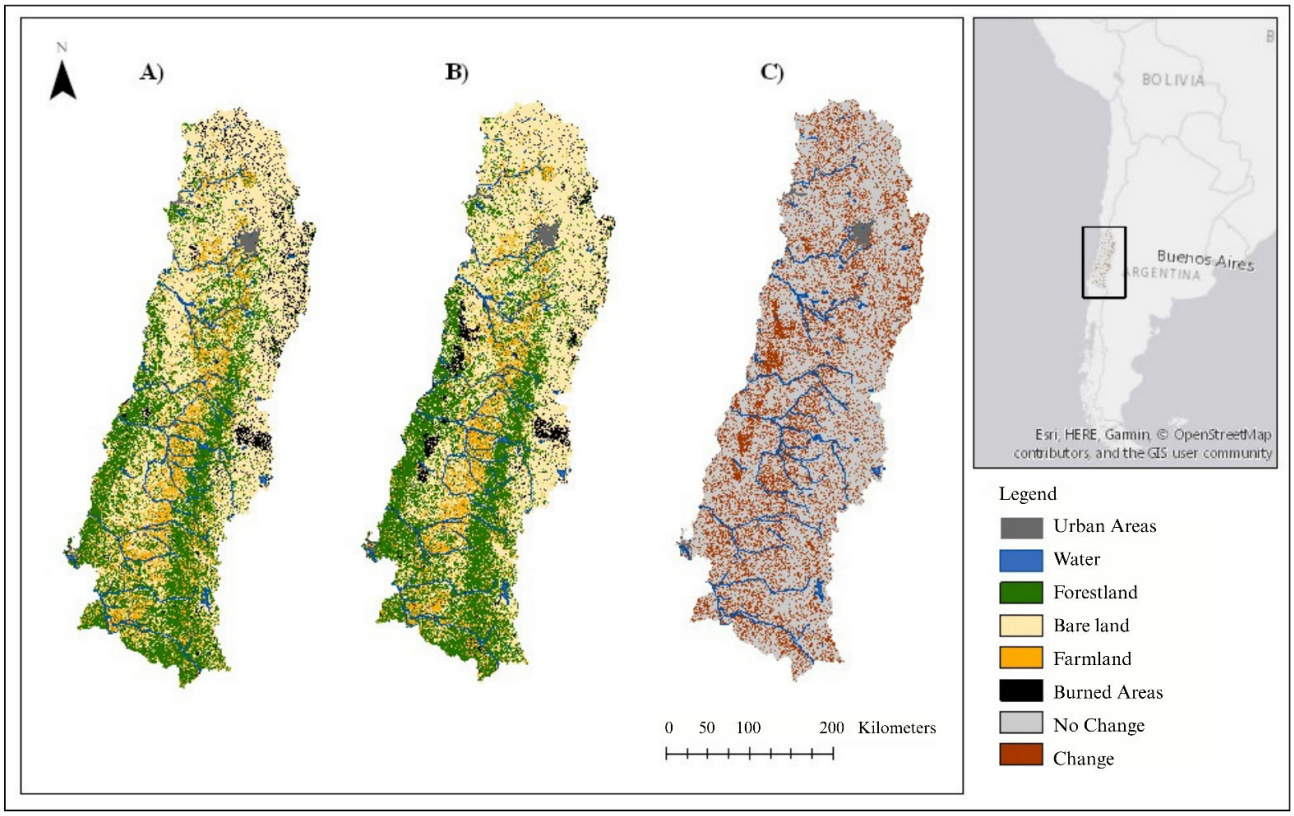

Figure 2. Change detection analysis for the central zone of Chile. (**A**) Land Use and Land Cover (LULC) classification for 2014; (**B**) LULC classification for 2017; and (**C**) map of detected changes showing areas of change versus no change between 2014 and 2017.

Table 3. Proportion of land use and land cover (LULC) change by region between 2014 and 2017, expressed as percentages. Positive values indicate an increase in the area covered by a given LULC class, while negative values indicate a decrease in area for that class over the study period.

Maule	**Forestland**	**Bare Land**	**Farmland**	**Urban Area**
Total 2014	36.29	43.18	15.18	5.35
Total 2017	36.31	42.50	13.99	7.20
Change (17–14)	0.08	−1.59	−7.84	34.52
Annual Change	0.03	−0.53	−2.61	11.51
Metropolitana de Santiago	Forestland	Bare land	Farmland	Urban area
Total 2014	11.46	68.75	8.43	11.37
Total 2017	11.83	72.50	8.03	7.63
Change (17–14)	3.29	5.47	−4.76	−32.85
Annual Change	1.10	1.82	−1.59	−10.95
Libertador General Bernardo O'Higgins	Forestland	Bare land	Farmland	Urban area
Total 2014	25.01	56.54	12.79	5.65
Total 2017	24.63	54.29	12.76	8.32
Change (17–14)	−1.52	−3.98	−0.26	47.13
Annual Change	−0.51	−1.33	−0.09	15.71

Table 3. *Cont.*

Maule	Forestland	Bare Land	Farmland	Urban Area
Valparaíso	Forestland	Bare land	Farmland	Urban area
Total 2014	8.98	75.40	5.21	10.41
Total 2017	10.36	79.08	5.39	5.17
Change (17–14)	15.42	4.88	3.36	−50.34
Annual Change	5.14	1.63	1.12	−16.78
Bio Bío	Forestland	Bare land	Farmland	Urban area
Total 2014	49.98	27.22	20.56	2.24
Total 2017	53.37	26.90	17.21	2.52
Change (17–14)	6.79	−1.19	−16.28	12.45
Annual Change	2.26	−0.40	−5.43	4.15

The dominant type of LULC transition during the study period was Exchange (23%), followed by Shift (3%) and Quantity (2%) changes. At the category level, bare land and forestland experienced the greatest area gains, while farmland showed the largest losses. Both farmland and urban areas exhibited intensity rates exceeding the Uniform Intensity (UI) threshold (9.08%), classifying them as active, or non-stationary, LULC types characterized by transition rates faster than the regional average (Figure 3).

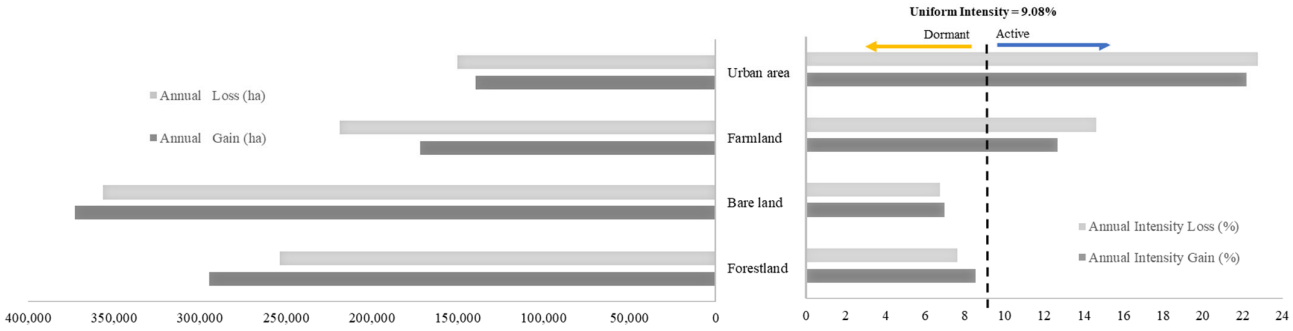

Figure 3. Analysis of annual area change and transition intensity between LULC categories. Horizontal bars extending to the left of zero represent the annual net area change (ha), indicating gains or losses in each category. Bars extending to the right represent the corresponding annual change intensity, expressed as a percentage. Transition stationarity is assessed using the Uniform Intensity Percentage (UI), shown as a dashed vertical line. Categories with intensity values below the UI are considered dormant (stationary), indicating slower-than-expected change rates. In contrast, categories with values above the UI are classified as active (non-stationary), reflecting faster-than-expected transitions.

At the transition level, targeted and avoided categories were identified, indicating which LULC types were more likely to gain or lose area beyond expected rates. Bare land and farmland were the largest contributors to forestland expansion. Specifically, the rate at which forestland gained area from farmland (8.83%) exceeded the UI for forestland (3.95%), classifying farmland as a targeted donor category for forestland increase (Figure 4). Similarly, both urban areas (4.94%) and farmland (4.44%) were targeted recipients of land converted from forestland, reflecting patterns of deforestation (Figure 5).

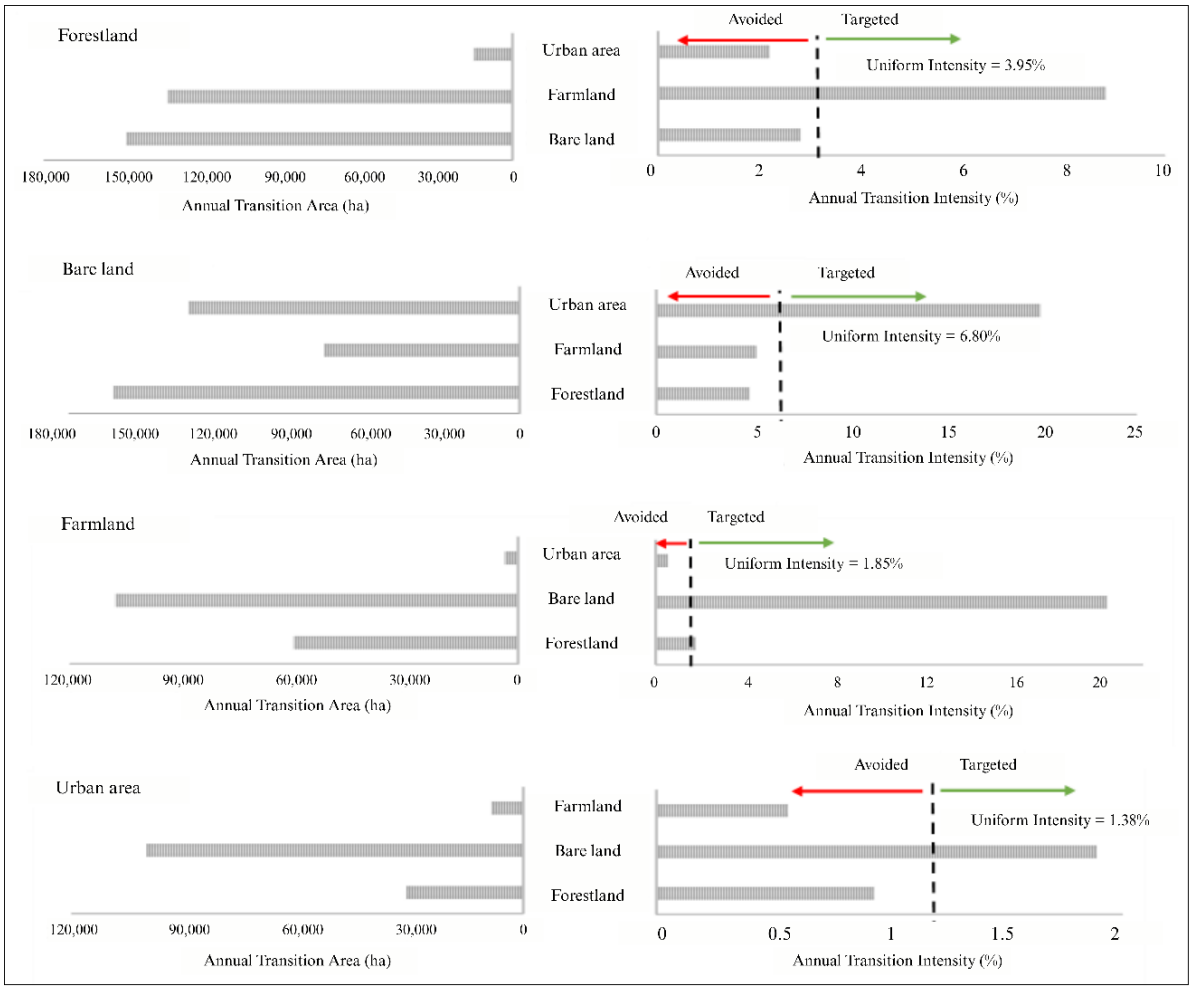

Figure 4. Analysis of area gain and transition intensity by LULC category. Bars extending to the left of zero represent the annual area gained (ha) by each recipient category, while bars extending to the right represent the annual transition intensity (%) from each donor category. Each plot evaluates transitions 'TO' the focal category (listed in the upper left corner as the 'land receiver') and 'FROM' contributing categories (listed on the y-axis as 'land donors'). This approach enables the identification of specific directional LULC shifts between classes. Transition intensity is further classified as either 'avoided' or 'targeted,' using the Uniform Intensity Percentage (UI) as a threshold (indicated by the dashed vertical line). Donor categories with transition intensity values below the UI are considered avoided (less likely to contribute area), while those above the UI are considered targeted (more likely to contribute area to the receiving category).

Increases in bare land were primarily associated with reductions in forestland and urban areas, with urban land showing a particularly high likelihood of conversion to bare land (20.01% compared to a UI of 6.80%). Farmland (7.97%) and urban areas (15.93%) also received substantial areas from bare land, patterns often linked to crop rotation cycles and construction processes. In contrast, farmland gains from bare land reductions (2.04%) were modest and aligned with seasonal agricultural practices, while farmland losses to forestland establishment (3.83%) were more pronounced, underscoring the role of forest expansion in landscape change. Urban areas exhibited dynamic exchanges with bare land, simultaneously gaining (1.89% > 1.38% UI) and losing (2.47% > 1.48% UI) area, reflecting ongoing urban development and land clearing.

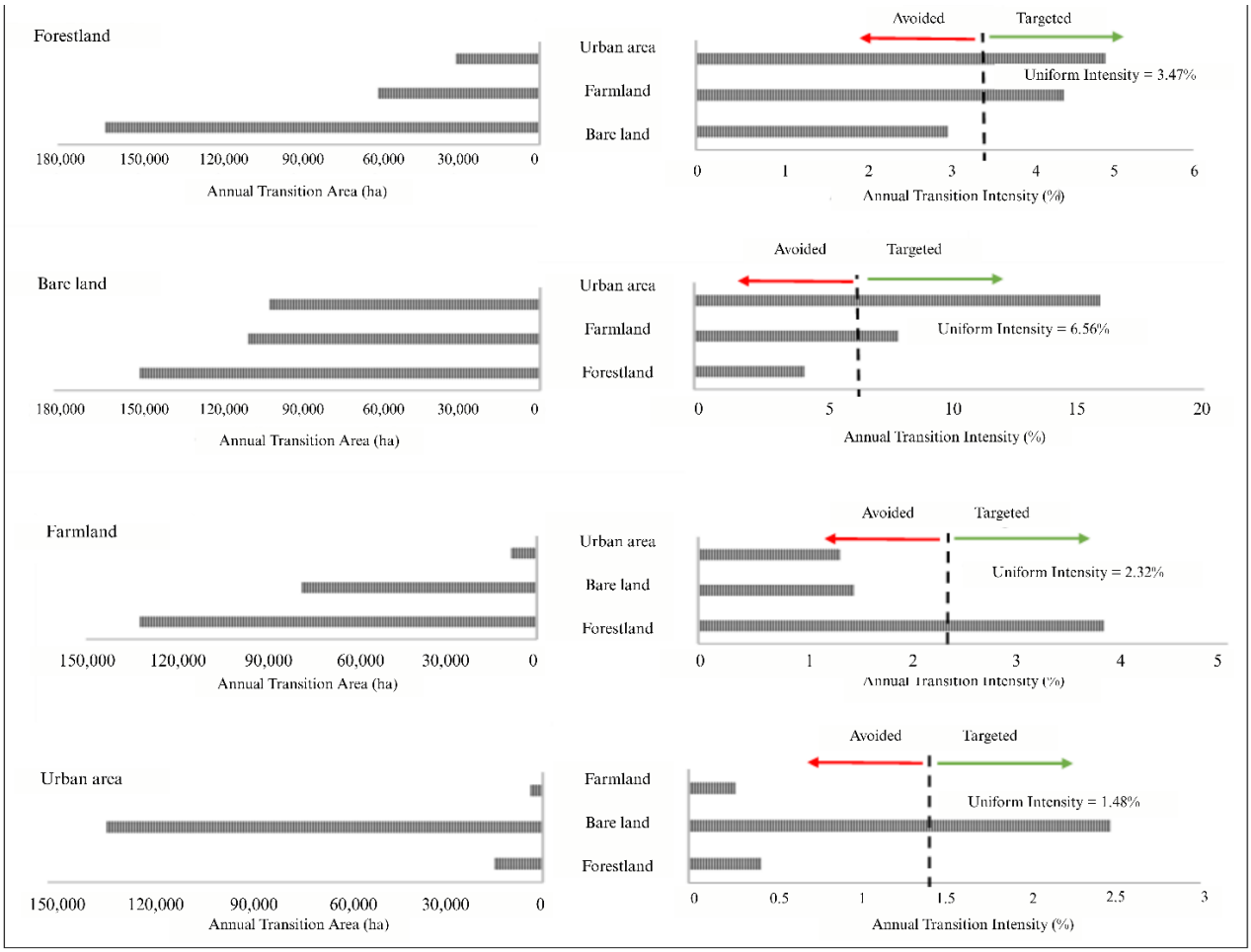

Figure 5. Analysis of annual area loss and transition intensity between LULC categories. Bars extending to the left of zero represent the annual area lost (ha) by each donor category, while bars extending to the right represent the annual transition intensity (%) toward each recipient category. Each transition is analyzed directionally: 'FROM' (the donor LULC class, indicated in the upper left of each plot) and 'TO' (recipient LULC classes listed on the y-axis within each plot). This representation allows identification of specific LULC transitions between classes. Transition intensity is further categorized as 'targeted' or 'avoided' based on the Uniform Intensity Percentage (UI), shown as a dashed vertical line. Transitions with intensity values greater than the UI are considered targeted, indicating they received more area than expected under uniform transition. Conversely, those with intensity values below the UI are considered avoided.

3.2. Fire Frequency Patterns and Drivers

The changes in landscape configuration and LULC transitions significantly influenced fire frequency patterns across the study area. Patch characteristics and transitions collectively explained fire frequency changes between 2014 and 2017 ($F7, 186 = 29.41$, $R^2 = 0.507$, $p < 0.01$) (Table 4). First, spatial heterogeneity emerged as a key driver of fire activity. Increases in the Shannon Evenness Index (SHEI), representing higher landscape heterogeneity due to diverse LULC types, were positively associated with fire frequency. Conversely, areas dominated by large, homogeneous forest patches experienced reduced fire occurrence, highlighting the role of forest structure in modulating fire risk. Additionally, decreases in the number and density of urban and bare land patches, typically found in rural areas, were linked to increased fire frequency ($F4, 189 = 20.79$, $R^2 = 0.291$, $p < 0.01$) (Table 5). In contrast, temporal dynamics revealed that increased landscape homogeneity toward forest and urban dominance was associated with higher fire frequencies over time ($F1, 192 = 32.16$, $R^2 = 0.13$, $p < 0.01$). This suggests that while spatial heterogeneity reduces fire

risk in the short term, rapid transitions favoring specific LULC types can elevate long-term fire vulnerability.

Table 4. Best-fit linear regression model describing the relationship between land use and land cover (LULC) patch characteristics and fire frequency measured as fire counts per comuna. Predictor variables include the following: Shannon Evenness Index (SHEI), number of forest patches (NPF), number of urban area patches (NPUB), density of forest patches (PDF), density of bare land patches (PDBL), density of urban area patches (PDUB), and mean patch area of forest (PAF).

Variables	Estimate	Std. Error	T Value	Pr (>|t|)
SHEI	1.460	0.852	1.714	0.088
NPF	0.000	0.000	5.628	<0.01
NPUB	−0.000	0.000	−2.451	0.015
PDF	−0.064	0.028	−2.261	0.024
PDBL	−0.074	0.034	−2.177	0.032
PDUB	−0.033	0.011	−3.040	0.002
PAF	0.053	0.002	2.638	0.009
Fire Frequency Model: $F_{4,189} = 29.41$, $R^2 = 0.507$, $p < 0.01$				

Table 5. Best-fit linear regression model describing fire frequency changes as a function of land use and land cover (LULC) changes by class. Predictor variables include the following: change in forestland (CF), change in bare land (CBL), change in farmland (CAG), and change in urban area (CUB).

Variables	Estimate	Std. Error	T Value	Pr (>|t|)
Forestland	3.196	0.957	3.337	0.001
Bare land	−0.236	1.440	−0.164	0.869
Farmland	−3.358	0.920	−3.647	<0.001
Urban area	2.939	0.452	6.490	<0.001
Fire Frequency Change Model: $F_{4,189} = 20.79$, $R^2 = 0.290$, $p < 0.01$				

Regional patterns further illustrate these dynamics. The Maule region experienced the largest increase in fire frequency, primarily driven by transitions from forestland to bare land. In Biobío, farmland and bare land conversions to forestland were the dominant contributors to increased fire frequency (Figure 6). Specific LULC transitions significantly influenced fire frequency changes. Transitions from farmland to forestland, bare land to forestland, bare land to urban areas, and forestland to urban areas were all positively associated with fire frequency increases ($F15, 44 = 3.53$, $R^2 = 0.392$, $p < 0.01$). Among these, the transition from bare land to forestland was the only stationary change occurring at rates below the UI that significantly impacted fire frequency. In contrast, transitions classified as active or non-stationary, including farmland to forestland, bare land to urban area, and forestland to urban area, showed both accelerated transition rates and significant effects on fire frequency. Overall, regions experiencing a combination of rapid, non-stationary landscape transitions and increasing landscape heterogeneity were more likely to exhibit heightened fire frequency.

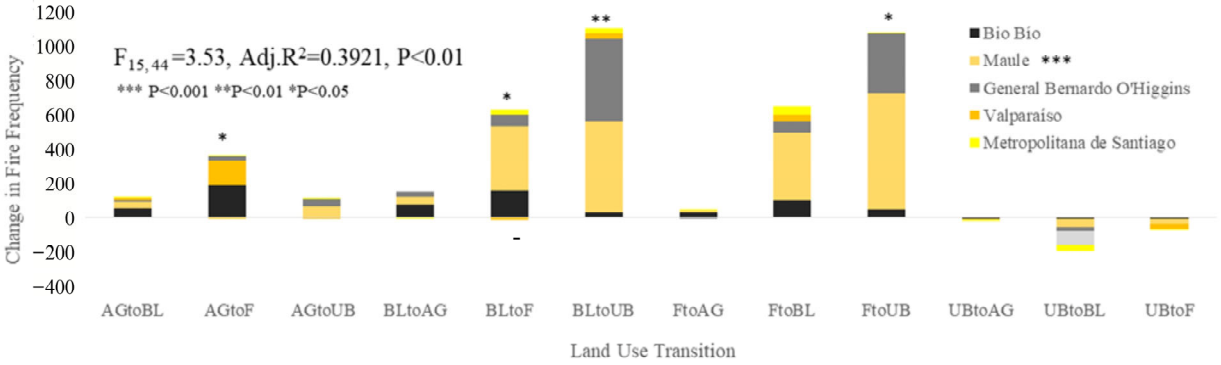

Figure 6. Fire frequency changes between 2014 and 2017 as a function of land use and land cover (LULC) transitions across regions in central Chile. LULC transition codes are as follows: AG = Farmland, BL = Bare Land, F = Forestland, and UB = Urban Areas.

4. Discussion

4.1. Landscape Transitions and Their Role in Fire Dynamics

The central zone of Chile is undergoing accelerated land use and land cover (LULC) transitions that are reshaping its landscape structure and increasing its vulnerability to wildfire activity. Consistent with previous studies documenting high transition rates across recent decades [16,33,37,60], our results confirm a continued reduction in farmland and expansion of forestland between 2014 and 2017. These patterns reflect longstanding trends tied to national production shifts, where native forests and agricultural areas have been progressively converted to commercial tree plantations, particularly along the coastal zones of the Maule and Biobío regions [32,33,35].

Economic drivers such as the expansion of the timber industry, land fragmentation, and migration from rural to urban areas likely explain the persistent reduction in farmland [61,62]. Moreover, historical episodes of intensive monoculture, soil degradation, and exotic species introduction [63–65] set the foundation for the landscape transformations still observed today. Our results also highlight the dynamic nature of forestland transitions, where plantations are not only expanding but also undergoing cycles of clearing and re-establishment. These rotations contribute to the creation of bare land patches, which are subsequently converted to human settlements or replaced by new plantations [65–67].

Patch-level landscape changes reveal additional insights into fragmentation and configuration trends. High patch density in both forestland and urban areas suggests simultaneous fragmentation of native forest remnants [68,69] and expansion of tree plantations into formerly continuous agricultural landscapes [32,70]. These spatial patterns are critical to understanding fire dynamics in the region.

4.2. Linking LULC Change to Fire Frequency Increases

Our findings demonstrate a clear connection between rapid LULC transitions, changes in patch characteristics, and increased fire frequency across the central zone of Chile. Regions experiencing the most pronounced landscape transformations, particularly Maule and Biobío, also exhibited the highest increases in fire activity. These results align with previous work linking plantation expansion, forestland rotation cycles, and increased fire risk [24,31].

The widespread establishment of fast-growing, flammable plantation species such as Pinus radiata and Eucalyptus globulus, coupled with post-harvest fuel accumulation, has been shown to increase fire susceptibility [33,66]. Our results support this mechanism, as transitions between forestland and bare land significantly affect fire frequency. Moreover, spatial patterns revealed that increased landscape heterogeneity near urban peripheries

reduces the urban–wildland interface in some areas, yet also creates fragmented, patchy systems that facilitate human-driven fire ignition and spread [71,72].

Over time, landscape transitions toward homogeneity, particularly dominance by forestland or urban areas, increased fire frequency. This paradox suggests that while heterogeneity may buffer fire spread at certain spatial scales, rapid transitions toward large, continuous patches of flammable vegetation or urban expansion elevate long-term fire risk [72].

Crucially, specific LULC transitions emerged as key contributors to fire frequency changes. Transitions from forestland to urban areas amplified fire risk, consistent with previous studies highlighting increased human ignition sources along settlement boundaries [31,73]. In addition, the conversion of farmland to forestland was associated with elevated fire occurrence, reflecting the heightened susceptibility of newly established plantations adjacent to agricultural areas, where prescribed burns and land clearing are common practices [65,74].

Collectively, our results emphasize that both the speed and spatial configuration of LULC transitions are central to understanding fire dynamics in rapidly changing landscapes.

4.3. Broader Implications and Limitations

This study makes two key academic contributions. First, it introduces an integrative, spatially explicit approach that combines transition intensity analysis with detailed landscape configuration metrics to understand fire frequency dynamics. This extends beyond conventional LULC change detection by capturing the role of speed and spatial form in modulating fire frequency. Second, it fills a notable regional gap by applying this methodology in central Chile, a Mediterranean-type ecosystem where fire risk is growing but where empirical, spatially detailed fire research remains limited.

The patterns observed in central Chile reflect broader fire–landscape dynamics documented in other fire-prone regions, underscoring the generalizability of our findings. Similarly to Mediterranean ecosystems in Spain, California, and Australia, our results show that accelerated LULC transitions involving forest plantations and urban expansion are key drivers of increased fire frequency [18,30,75–77]. By providing a spatially explicit, quantitative assessment of how both patch characteristics and transition intensities influence fire activity, this study contributes to the growing body of literature linking landscape transformation with fire regimes. Importantly, it does so in a region that has been underrepresented in global wildfire studies, offering a novel case that helps broaden the empirical foundation for theory-building. From a practical perspective, our approach offers valuable insight for fire preparedness, land use planning, and urban expansion regulation in Chile and other rapidly changing landscapes. The analysis highlights how active (non-stationary) transitions can be used as early warning indicators of elevated fire risk. These findings are particularly useful for informing fire prevention strategies in the urban–wildland interface, where socio-economic development and vegetation dynamics converge. While this study focused on Chile as a case study, the methodology and indicators are transferable to other countries undergoing accelerated LULC change, allowing for cross-regional comparison and policy translation.

Despite these contributions, several limitations should be acknowledged. First, the relatively short temporal window analyzed (2014–2017) was chosen as a case study period due to the high frequency of fire events captured during these years, which provides valuable insight into fire-landscape interactions under intense fire activity. However, this limited timeframe constrains the ability to detect long-term fire regime shifts or potential delayed effects of LULC transitions. Future studies should expand the temporal scope to strengthen the robustness of the findings and better capture the dynamics of fire regimes over longer

periods. Second, while remote sensing combined with intensity analysis allowed for reliable detection of LULC changes at the landscape scale, finer-scale variables, such as vegetation structure within plantations, fuel characteristics, and socio-economic drivers influencing land management were beyond the scope of this study but remain important factors influencing fire behavior. Additionally, our broad classification of forestland did not distinguish between native forests and plantations, which may obscure key ecological and flammability differences. Future studies should aim to separate these forest types to more accurately capture their distinct roles in shaping fire regimes and landscape dynamics. Finally, although fire frequency data (fire counts) offer a useful proxy for fire occurrence, they do not reflect fire severity or ecological impacts, which may vary independently from frequency and are critical for comprehensive fire risk assessment.

Future research should therefore prioritize incorporating longer-term datasets, integrating socio-ecological and management variables, and expanding analyses across other fire-prone regions and countries. Such efforts will enhance the theoretical understanding of how landscape transitions influence fire frequency and severity in diverse contexts, thereby strengthening the generalizability and innovation of this research. Moreover, this study exemplifies how spatially explicit assessments of LULC change and fire frequency can support forest fire management and urban planning, particularly in regions experiencing rapid landscape transformation like central Chile. Building on this foundation, future work could integrate land use and land cover transitions directly into fire prediction models to improve wildfire forecasting accuracy. Machine learning approaches, leveraging complex interactions between environmental, socio-economic, and landscape variables, hold strong potential to advance predictive capabilities. Communicating these findings and tools to local authorities and fire management agencies will be essential for translating research into effective wildfire preparedness and mitigation strategies.

5. Conclusions

This study demonstrates that landscape heterogeneity, combined with the speed and specific characteristics of LULC transitions, exerts a dominant influence on fire frequency in central Chile. Unlike many fire prediction systems that emphasize climate variables, our findings highlight that in rapidly transforming human-dominated landscapes, such as those in Chile's Mediterranean ecosystem, fire frequency is more strongly driven by landscape dynamics than by climate alone. This underscores the critical role of human activities, particularly forest plantation rotations, urban expansion, and farmland reduction, in shaping wildfire patterns. The novelty of this work lies in its integrative, spatially explicit analysis that couples detailed patch-level metrics with transition intensity analyses to quantify how both the structure and pace of landscape change affect fire frequency. This approach provides a robust framework to disentangle complex fire–landscape interactions in regions undergoing accelerated land transformation, a topic that remains underexplored in wildfire research. The implications of these results are significant for wildfire management and land use planning. By identifying landscape configurations and transition rates associated with increased fire frequency, decision-makers can better target prevention and mitigation efforts, especially in vulnerable urban–wildland interfaces. Incorporating landscape transition metrics into fire risk assessments can enhance the accuracy of fire prediction systems and inform policies aimed at balancing development with ecosystem resilience. Ultimately, this study underscores the need to consider the dynamic nature of land use changes in managing fire-prone landscapes, providing practical insights for Chile and other regions experiencing rapid socio-ecological transformations.

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investigation, M.V.-C.; resources, M.V.-C., G.S. and D.F.J.; data curation, M.V.-C.; writing—original draft preparation, M.V.-C.; writing—review and editing, G.S. and D.F.J.; visualization, M.V.-C., G.S. and D.F.J.; supervision, G.S. and D.F.J.; project administration, G.S. and D.F.J.; funding acquisition, M.V.-C. and D.F.J. All authors have read and agreed to the published version of the manuscript.

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Appendix A

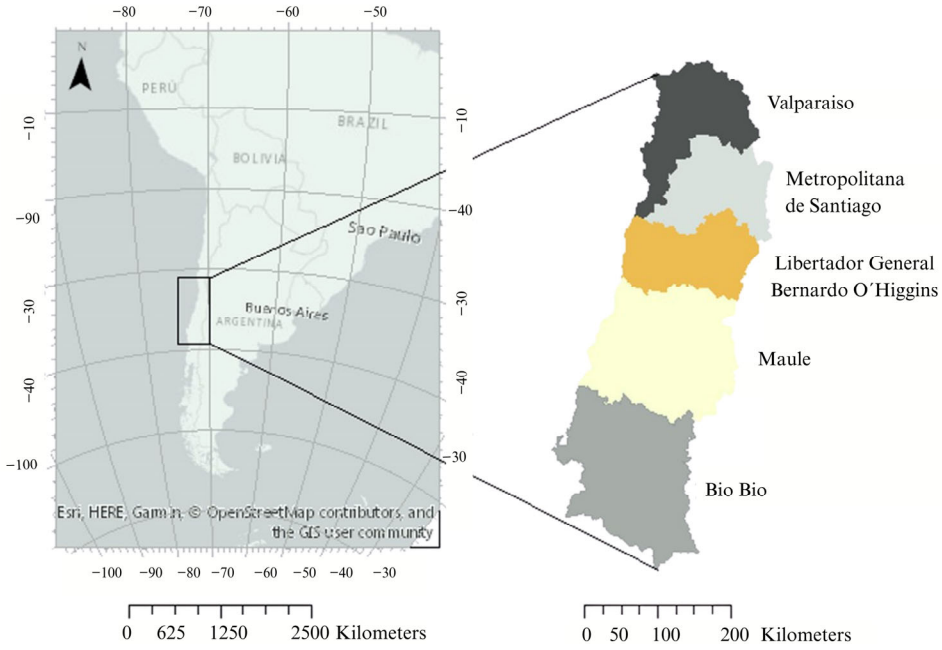

Figure A1. Location of the study: Left-side figure depicts Chile's location and the right-side figure corresponds to a zoom of the regions located in the central zone of Chile.

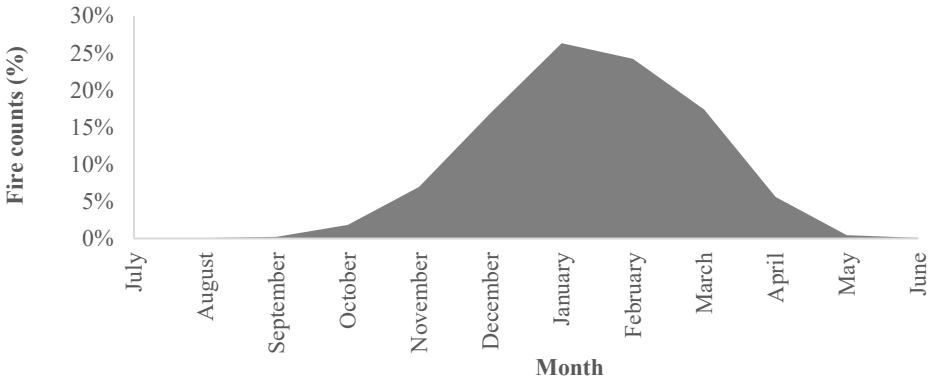

Figure A2. Fire annual seasonal distribution for the center zone of Chile [25].

Table A1. Description of the population, area, and climate characteristics of the regions located within the central zone of Chile.

Region	Population 2017	%Population	Area (km^2)	Climate
Valparaiso	1,859,672	10.10	16,396.10	Temperate Mediterranean
Metropolitana	7,482,635	40.72	15,403.20	Mediterranean
Libertador General Bernardo O'Higgins	934,671	5.08	16,387.00	Temperate Mediterranean
Maule	1,057,533	5.75	30,296.10	Temperate Mediterranean
Bio Bio	2,141,039	11.65	37,068.70	Temperate, humid, and dry

Table A2. Regional production distribution among crops in the central zone of Chile [78].

Region	Regional Production (%) *	Production
Valparaíso	37.7	Tree Plantations
	34.2	Fruit Plantations
	10.7	Forage Plants
Metropolitana de Santiago	35.8	Fruit Plantations
	17	Vegetables
	14.4	Forage Plants
	10.7	Cereals
	8.2	Vineyards
Libertador General Bernardo O'Higgins	38.8	Tree Plantations
	21.5	Fruit Plantations
	15.6	Cereals
	9.9	Vineyards
Maule	94	Tree Plantations, Cereals, Fruits, Forage, Vineyards
Bio Bío	79	Tree Plantations

* Percentage of the total production of the region.

Table A3. Description of the Landsat 8 OLI TIRS Level 1 scenes used for the unsupervised classification. Map projection UTM Zone 18–19, Datum WGS84 (cell size = panchromatic 15 m, reflective and thermal 30 m).

Dataset Scene	Acquisition Date	Path	Row	Scene Cloud Cover (%)
LC82330832014025LGN00	25 January 2014	233	83	3.32
LC82330872014025LGN00	25 January 2014	233	87	6.49
LC82330852014025LGN00	25 January 2014	233	85	0.56
LC82330842014025LGN00	25 January 2014	233	84	3.51
LC82330822014025LGN00	25 January 2014	233	82	0.69
LC82330862014025LGN00	25 January 2014	233	86	0.25
LC80010852014032LGN00	1 February 2014	1	85	0.02
LC80010842014032LGN00	1 February 2014	1	84	0.01
LC82330862017017LGN00	17 January 2017	233	86	1.14
LC82330832017017LGN00	17 January 2017	233	83	0.68
LC82330852017017LGN00	17 January 2017	233	85	0.12
LC82330842017017LGN00	17 January 2017	233	84	0.49
LC82330872017017LGN00	17 January 2017	233	87	5.13
LC82330822017017LGN00	17 January 2017	233	82	0.95
LC80010852017024LGN00	24 January 2017	1	85	5.33
LC80010842017024LGN00	24 January 2017	1	84	0.61

Table A4. Description of the LULC categories used for the unsupervised classification based on Schulz et al. (2010) [45] parameters.

Forestland	Dense (>75%) canopy cover and timber plantations.
Bare land	Exposed rock, sand, or dry riverbeds, dunes, cleared land, and degraded areas.
Farmland	Includes shrubland, grasslands and irrigated and non-irrigated agriculture, fruits, and vineyards.
Urban area	Areas with domestic or industrial infrastructure and burned areas, both categorized as disturbance. In addition, water and ice represent a small fraction of this category (<10%), but based on most data related to disturbance, the name of the category is based on urban and burned areas (>80% of category data)

Table A5. List of the acronyms of the patch characteristics evaluated per LULC (Forestland, Bare land, Farmland, and Urban area) in the central zone of Chile comunas based on Dezhkam, Jabbarian Amiri, Darvishsefat, and Sakieh (2016); Pijanowski and Robinson (2011) [54,55] parameters.

SHEI	Shannon Evenness Index
NP	Number of patches
PD	The density of patches (number of patches per 100 ha)
PA	Mean patch area (m^2)
PShape	Patch Shape
LPI	Large Patch Index

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