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Spatial patterns and drivers of urban expansion: An exploratory spatial analysis of the Metropolitan Region of Santiago, Chile, from 1997 to 2013

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ABSTRACT

Urban expansion is a global phenomenon rapidly transforming the earth's land surface, causing negative social and environmental impacts. Analysing its spatial patterns and underlying factors is crucial to promoting sustainable urban forms, especially in developing countries experiencing further increases in expansion. This study quantifies and explores the spatial pattern of the Metropolitan Region of Santiago (Chile) between 1997 and 2013, correlating it with explanatory factors at the municipal level using land cover maps and a Moran Index. The results reveal an urban expansion of 124 %, mainly towards rural and peri-urban municipalities, concentrated in the north and south of the region. The bivariate analysis highlights a positive correlation between factors such as population growth rate, household income, slope, and urban regulations with urban expansion, concentrated in rural-peri-urban areas. On the other hand, the urban area defined by the Santiago Metropolitan Regulatory Plan (PRMS) and population density negatively correlates with urban expansion. The study suggests that the city expanded into municipalities outside the urban area defined by the PRMS, and urban regulations promoted expansion into agricultural and public land. This research has important practical significance for understanding the spatial patterns of urban expansion and its drivers. The study has practical significance in understanding the spatial patterns and their drivers, highlighting priority areas that require urban policy intervention to promote sustainable urban forms.

1. Introduction

Urban expansion has transformed land use on a global scale, altering land surfaces at an unprecedented rate and scale (Güneralp & Seto, 2013; Puertas et al., 2014). Consequently, this phenomenon has found its place in international urban sustainability agendas, including the New Urban Agenda, adopted during the United Nations Conference on Housing and Sustainable Urban Development (Habitat III) in Ecuador (Barton & Ramírez, 2019). In general terms, urban expansion is the increase in land cover of built-up areas, associated with an urban form in contrast to the compact city model (Seto et al., 2011; Terfa et al., 2019). Thus, urban expansion has occupied large natural areas and has encroached on farmland, fragmenting territories, affecting biodiversity, and promoting climate change (He et al., 2021). Therefore, it is crucial to understand the evolving spatial pattern of urban expansion, as regional land use will influence global urban sustainability (Zhong, Li, et al., 2020; Zhong, Lin, He, Zhou and Yuan, 2020).

Researchers generally study urban expansion through remote sensing and GIS, analysing urban expansion patterns by tracking physical and land changes over time (Rawat & Kumar, 2015; Zhao et al., 2020). Urban expansion through land use and land cover change refers to the modification of the Earth's land surface by human activities (Gashu & Gebre-Egziabher, 2018). Studies have identified urban expansion with unsustainable urban forms, which produce high land consumption through forms of occupation with low land-use efficiency (Zhang et al., 2022).

States have established policies to control and guide expansive urban development to address the negative consequences of urban expansion. These strategies are mainly implemented through urban planning and land use regulation, highlighting urban growth boundaries (UGB), greenbelts, zoning and infill growth (Chettry & Surawar, 2021; Gennaio et al., 2009; Schuster Olbrich et al., 2022; Tarabon et al., 2020). Consequently, the adverse effects of urban expansion reveal the need to guide and regulate expansive urban development (He et al., 2021). Thus, urban planning has evolved globally as a policy tool to manage the expansion of urban development. Understanding how urban expansion is affected by urban regulations and planning, primarily through zoning or urban growth boundaries, is essential for promoting more compact and sustainable urban patterns (Dempsey et al., 2017).

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2. Spatial analysis and drivers of urban expansion

According to the literature, urban expansion results from a complex interaction between physical, geographical, social, economic and political-institutional factors (Lambin et al., 2003; Pagliarin, 2018). Identifying these factors is crucial for understanding the mechanisms of urban expansion and coordinating regional urban growth (Jing et al., 2022). Demographic changes and economic growth are the literature's most studied drivers of urban expansion in the literature (Tan et al., 2005; Seto et al., 2011; Jiang et al., 2016). Population becomes a key factor, as accommodating an increasing number of people in a territory generally implies that more space is needed (Lambin et al., 2003). Furthermore, urban expansion has been established by the literature as an almost inevitable consequence of economic development with different intensities, driven through GDP growth (Artmann et al., 2019). Other physical factors, especially slope and elevation, have also been found to affect urban expansion, thus influencing land cover change (Thapa & Murayama, 2010).

Urban expansion is also influenced by planning and urban regulatory factors (Colsaet et al., 2018; Zhao et al., 2020). Urban planning is a public tool for planning and managing urban space development. Urban plans often balance expected urban expansion with cities' economic development and housing. Urban planning should also avoid losing agricultural land and open space (Barton & Ramírez, 2019; Mu et al., 2016).

Urban planning and regulation play critical roles in guiding, controlling, and limiting urban expansion, determining factors in limiting or promoting expansive urban growth in cities (Dempsey et al., 2017; Hersperger et al., 2018). Through zoning and the urban growth boundary, land use planning can control land use decisions, establish protective measures and guide market forces that drive land use change (Gennaio et al., 2009). Nevertheless, some studies have documented that urban planning can contribute to urban expansion, for example, by reducing densities, or that small decisions at the local scale can contradict strategic decisions at larger scales (Abrantes et al., 2016; Pagliarin, 2018; Silva & Vergara-Perucich, 2021; Vicuña, 2013). Consequently, the literature indicates that more attention needs to be paid to understanding the complex political and legal relationships that govern urban space (Andrews & McCarthy, 2014; Musakwa & Van Niekerk, 2014).

According to Tobler's law, "everything is related to everything else, but things close to each other are more related to each other" (Jing et al., 2022). Numerous studies have used exploratory spatial data analysis (ESDA) methods, such as Moran's I and the local indicator of spatial association (LISA), proposing practical tools to explore the aggregation and heterogeneity of urban expansion (Jing et al., 2022; Salvati & Margherita, 2014; Zhong, Lin, et al, 2020; Zhong, Lin, He, Zhou and Yuan, 2020). Understanding the spatial patterns of urban expansion is fundamental to achieving sustainable development (Musakwa & Van Niekerk, 2014). Thus, Moran's Global and Local I-indexes were selected in the present study, as they allow for the effective identification of hotspots, clusters and outliers of urban expansion, allowing measuring the tendency of similar urban expansion patterns to cluster spatially (Zhang et al., 2023). The Moran Index allows for the identification of areas that may require the application of urban policies, as they allow detection of the presence of clustering or dispersion patterns of the study phenomenon (Musakwa & Van Niekerk, 2014). The interpretation of a city's Moran Index depends on the context analysed. It is relevant to consider the city's local context, as cities with different contexts may show very different patterns of urban expansion, even if the same scale of analysis is used (Steurer & Bayr, 2020). Moreover, different scales can reveal different patterns of spatial autocorrelation, with the local scale being a scale that fits for urban plan implementation analyses (Dempsey et al., 2017). However, researchers have conducted most of this work in developed countries, and more research is needed to understand urban growth patterns in developing countries (Hassan, 2017). Thus, there is a lack of studies that delve into the relationship between expansion and urban planning as an urban growth management tool in cities in the Global South (Colsaet et al., 2018; Bovet et al., 2020). Additionally, more studies analyse the effects of land regulations and the urban growth boundary on housing and land prices. Fewer studies have examined their effects on developing new built-up areas (Dempsey et al., 2017).

In addition, in order to explain the spatial correlation between urban expansion and explanatory factors with an emphasis on urban planning and regulation, the bivariate Moran Global and Local was used to measure the spatial correlation at the local level across the study area (Wang et al., 2023). Despite implementing various urban plans, evidence analysing the correlation of planning with urban expansion through land change is limited (Hersperger et al., 2018).

From this perspective, the present study mainly seeks to contribute to regional planning and urban studies through ESDA-based approaches by identifying urban expansion patterns and their priority areas through a case study, guiding urban planning towards more sustainable urban development (Salvati & Margherita, 2014; Terfa et al., 2019). In addition, it can provide some reference for the government, such as policymakers and urban planners in the region (Zhong, Lin, He, Zhou and Yuan, 2020). For the above, the present study aims to: a) Analyse the pattern of expansive urban growth at the municipal level in the Metropolitan Region of Santiago (Chile) between 1997 and 2013; b) Examine the spatial relationship of urban expansion at the municipal level in the region; c) Explore the spatial correlation of urban expansion with explanatory factors with emphasis on urban planning and regulation.

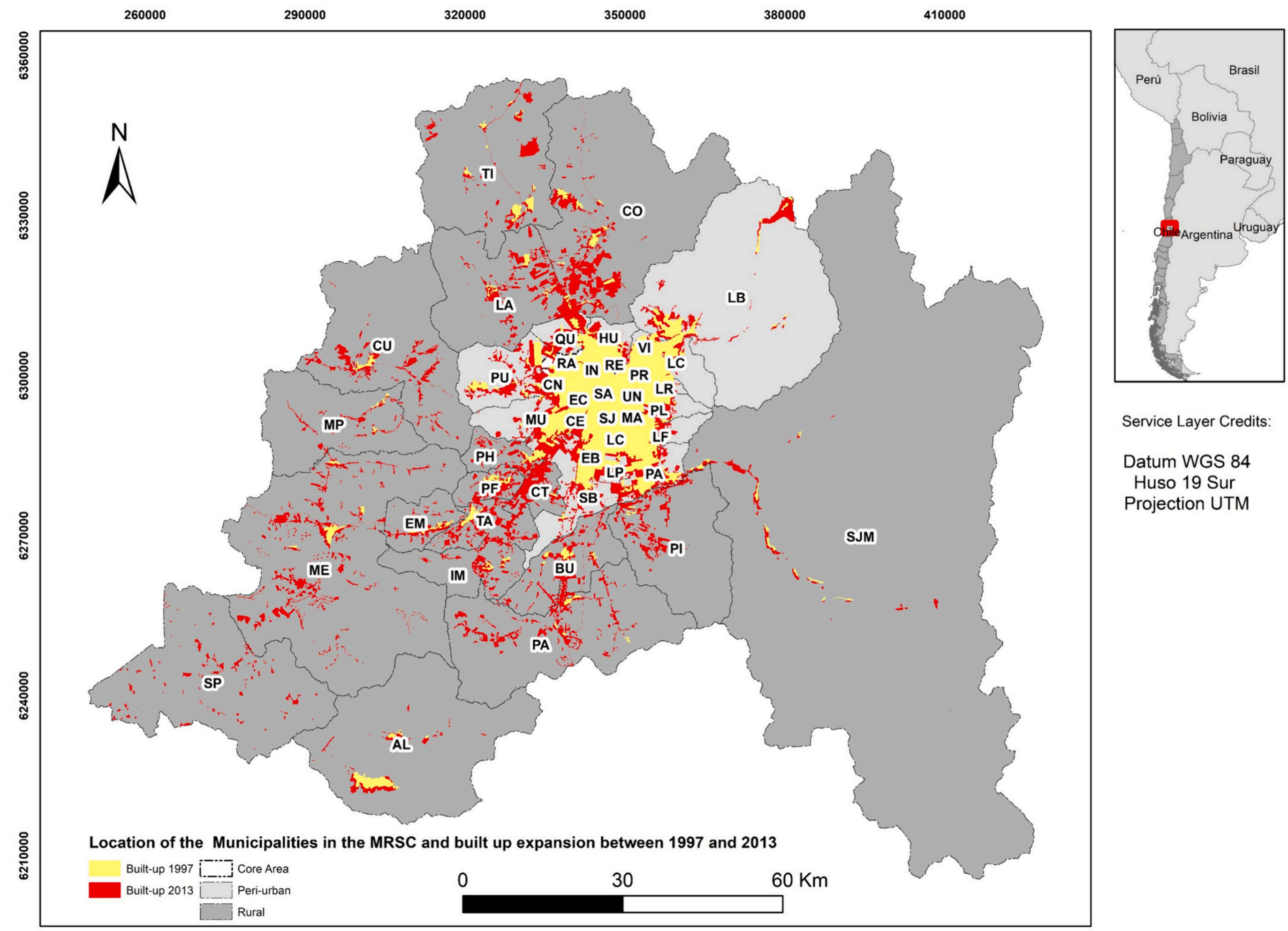
3. Material and methods

3.1. Study area

The Metropolitan Region of Santiago Chile (MRSC) has 7,112,808 inhabitants, representing 40 % of the total population of the entire country (INE, 2018). The Santiago Metropolitan Region has the City of Santiago at its centre, which is the capital of Chile. The MRSC is administratively divided into 52 municipalities, classified according to the continuity of urban area. The "core municipalities" correspond to the municipalities located in the centre of the region where the historical city is located. Secondly, the "peri-urban municipalities" correspond to those municipalities located on the edge of the core zone, being the city limits. Finally, "rural municipalities" are those municipalities in the regional area that are physically separated from the contiguous urban area outside of the contiguous urban area (De Mattos et al., 2014): (1) Core: Cerrillos (CE), Cerro Navia (CN), Conchalí (CL), Estación Central (EC), Independencia (IN), La Cisterna (LC), La Granja (LG), Lo Espejo (LE), Lo Prado (LP), Macul (MA), Nunoa (UN), Pedro Aguirre Cerda (PAC), Providencia (PR), Quinta Normal (QN), Recoleta (RE), Renca (RA), San Joaquín (SJ), San Miguel (SM), San Ramón (SR) and Santiago (SA); (2) Peri-urban: El Bosque (EB), Huechuraba (HU), La Florida (LF), La Pintana (LP), La Reina (LR), Las Condes (LC), Lo Barnechea (LB), Maipú (MU), Penalolen (PL), Pudahuel (PU), Puente Alto (PA), Quilicura (QU), San Bernardo (SB) and Vitacura (VI); (3) Rural: Buin (BU), Calera de Tango (CT), Colina (CO), Curacaví (CU), El Monte (EM), Isla de Maipo (IM), Lampa (LA), Padre Hurtado (PH), Paine (PA), Penaflor (PF), Pirque (PI), San José de Maipo (SJM) and Talagante (TA), Melipilla (ME), San Pedro (SP), Alhue (AL), María Pinto (MP), and Til-Til (TI) (Fig. 1).

3.2. Built-up area

For this study, we define the built-up area as "urban land cover and land use, impervious surfaces and other manifestations of the built environment" (Seto et al., 2011). The definition of built-up has also been used in other studies that are based within the Santiago Metropolitan Region of Chile (RMSC) (Hernández-Moreno & Reyes-Paecke, 2018). We



Alhue	AL	El Monte	EM	La Reina	LR	Melipilla	ME	Pudahuel	PU	San Miguel	SM
Buin	BU	Estacion Central	EC	Lampa	LA	Nunoa	UN	Puente Alto	PA	San Pedro	SP
Calera de Tango	CT	Huechuraba	HU	Las Condes	LC	Padre Hurtado	PH	Quilicura	QU	San Ramon	SR
Cerrillos	CE	Independencia	IN	Lo Barnechea	LB	Paine	PA	Quinta Normal	QN	Santiago	SA
Cerro Navia	CN	Isla de Maipo	IM	Lo Espejo	LE	Pedro Aguirre Cerda	PAC	Recoleta	RE	Talagante	TA
Colina	CO	La Cisterna	LC	Lo Prado	LP	Penaflor	PF	Renca	RA	Tiltil	TI
Conchali	CL	La Florida	LF	Macul	MA	Penalolen	PL	San Bernardo	SB	Vitacura	VI
Curacavi	CU	La Granja	LG	Maipu	MU	Pirque	PI	San Joaquin	SJ		
El Bosque	EB	La Pintana	LP	Maria Pinto	MP	Providencia	PR	San Jose de Maipo	SJM		

Fig. 1. Metropolitan Region of Santiago, Chile and administrative political division at the municipal level according to distance to the core area. (Source: Own elaboration based on CONAF and MINVU.)

calculate urban expansion as the difference in built-up area between 1997 and 2013 in Hectares at the municipal level (6.25 Ha per pixel). We use an official land cover database, that was produced by the National Forest Corporation (CONAF), to quantify the built-up expansion, using GIS (Montoya-Tangarife et al., 2017; Schuster Olbrich et al., 2022).

3.3. *Explanatory factors*

We identified and analysed physical (Dewan & Yamaguchi, 2008; Puertas et al., 2014), socioeconomic (De Mattos et al., 2014; Gennaio et al., 2009) and urban planning and regulation factors related to urban expansion (Barton & Ramírez, 2019; Jiménez et al., 2018; Silva & Vergara-Perucich, 2021) (Table 1). For the analysis, we calculated area, elevation and slope variables using GIS. For area, we used the total area in hectares of each municipality using the CONAF database. To examine the effects of slope (degrees) and elevation (meters above sea level), values for the municipalities were calculated from a digital elevation model (DEM) from the Natural Resources Information Centre (CIREN) (Thapa & Murayama, 2010). We calculated the mean of each municipality per raster pixel (12.5 m per pixel) (Dewan & Yamaguchi, 2009). The annual growth rate of housing units and population were extracted from the National Institute of Statistics (INE) at the municipal level. At the same time, we added the income of the household head based on a survey by the Ministry of Social Development (MIDESO). We use the annual growth rate (AGR) according to the study by Seto et al. (2011) (Schuster Olbrich et al., 2022). In addition, we calculated a dummy variable on whether the municipality had access to a highway. Finally, from the INE data, we use the building permits that allow construction, using the total m2 approved by each municipality (De Mattos et al., 2014; Naranjo, 2017).

The application of the land-use plan called the Santiago Metropolitan Regulatory Plan ("Plan Regulador Metropolitano de Santiago", PRMS), specifically the variable "Urban area delimited by PRMS". The PRMS is the Plan established at the regional level and establishes the urban (and non-urban) area of the municipalities through an urban growth boundary (UGB) and a zoning associated with the urban area. Thus, the

Table 1
Built-up expansion and driving factors (N = 52).

Dimension	Variable	Description	Time lapse	Source	Median	N	Percentage	Std. Dev	Min	Max
Built-up	Built-up difference (Ha)		1997–2013	CONAF	956.5	52		1753.5	−45	7477
	% of Built-up difference (Ha)		1997–2013	CONAF	5.7	52		11,1	−3	40
Physical	Area (Ha)		2013	CONAF	5515.4	52		72,923.2	629	494.113
	Elevation (Meters)		2006	CIREN	562.1	52		489.9	243	3141
	Slope (degrees)		2006	CIREN	6.2	52		6.4	2	28
Socio-economic	Highway across the municipality (unit)	No Yes	2012	GORE		10 42	19.2 80.8	0.4	0	1
	Housing AGR		1992–2017	INE	4.4	52		2.6	0	12
	Population AGR		1992–2017	INE	2.3	52		2.6	−2	11
	Population density (Ha/ inhabitants)		1992–2017	INE/CONAF	93.4	52		46.7	0	235
	Income of the household head AGR		1992–2017	MIDESO	9.9	52		3	0	16
	Built permits (unit m^2 approval)		1996–2019	INE	1414,961	52		3247,527	67.76	15.843,727
Urban Planning and Urban Regulation	Urban area delimited by PRMS in 1994 at the municipal level (UGB)	Not apply Apply	1994	MINVU		15 37	28.8 71.2	0.5	0	1
	Urban area delimited by PRMS in 1997 at the municipal level (UGB)	Not apply Apply	1997	MINVU		12 40	23.1 76.9	 0.4		
	Decree-Law (DL) 3516 of agricultural plots		1994–2006	SAG	185	19		438	1	1859
	Decree-Law (DL) N°2695 of National Assets		2009–2020	NATIONAL ASSETS	132	52		159.2	2	942

(Source: Own elaboration.)

PRMS was applied to only 37 municipalities (71.2 %) in the original period (1994), leaving out of the Plan a total of 15 municipalities (28.8 %). In 1997, the Plan was extended to a total of 40 municipalities (76.9 %) leaving out of the Plan a total of 12 municipalities (23.1 %); and finally in 2006, the Plan was applied to all municipalities in the region, a total of 52 (100 %) (Table 1). For the analysis, we focus on the statistical work of Liu et al. (2005), Musakwa and Van Niekerk (2014) and Steurer and Bayr (2020), which incorporate the planning variable as a categorical dummy variable, since the PRMS was partially implemented at the municipal level. Thus, the value 1 corresponds to the municipality being subject to the PRMS, and on the other hand, the value 0, if the municipality had been left out of the Plan in that period.

On the other hand, regarding urban regulation, two variables were identified: Decree Law (DL) N° 3516 and Decree Law (DL) N° 2695. The first law allows the subdivision of 0.5 ha to build single-family homes on agricultural land. The second law allows the regularisation of low-value housing on public land. These variables represent the number of resolutions granted by the public administration to authorise each subdivision or regularisation. The total number of resolutions allowing the application of DL 3516 and DL 2698 per municipality was used. The information was obtained through the SAG and the Ministry of National Assets (Naranjo, 2017; Silva & Vergara-Perucich, 2021).

3.4. *Spatial autocorrelation analysis*

We used the Global and Local Moran Index for the spatial data analysis at a local scale (municipality level) in the region, based on the Exploratory Spatial Data Analysis (ESDA). For this purpose, a first-order queen contiguity matrix has been used, because in this way the relationships in all directions are explored (Gutiérrez & Delclòs, 2016) (Table 2).

Table 2
Moran Index description.

	Type		Description
Moran Index	Univariate	Global	The Global Univariate Moran Index assesses the overall spatial autocorrelation of an individual variable across the entire geographic dataset.
		Local (Lisa Maps)	Assesses the spatial autocorrelation of each spatial unit individually to its close neighbours. Provides information on whether a specific spatial unit is surrounded by similar or different areas in terms of the variable being analysed.
	Bivariate	Global	A measure used in spatial analysis assesses the spatial autocorrelation between two different variables in a geographic dataset.
		Local (Lisa Maps)	Determines whether areas with similar (or different) values of one variable tend to be close to areas with similar (or different) values of the other variable.

(Source: Own elaboration from (Salvati & Margherita, 2014).)

First, we use the univariate Global Moran Index to analyse the spatial autocorrelation of urban expansion and whether it tends to cluster spatially at the municipal level (Zhao et al., 2020). When interpreting the results of the Global Moran Index, it should remember that it is an inferential statistic and should be interpreted in the context of its null hypothesis. The null hypothesis states that the spatial processes that promote the observed pattern of values are random (Musakwa & Van Niekerk, 2014). In this regard, the Global Moran Index is an indicator of spatial autocorrelation that explains the extent to which urban expansion tends to be spatially clustered (positive spatial autocorrelation, values tending to 1), dispersed (negative spatial autocorrelation, value close to −1), or randomly distributed (values close to 0).

On the other hand, Moran's Global Index treats the territory as if a uniform whole, so stronger or weaker correlations may be invisible in certain parts of the territory. In this sense, spatial autocorrelation analysis allows the calculation of Local Index of Spatial Association (LISA) maps (Anselin, 1995). For this reason, the analysis focuses on the LISA maps, as they allow the identification of areas with high and low values, classifying the results into four groups: High-High (HH), High-Low (HL), Low-High (LH) and Low-Low (LL) cases can be mapped better to understand the spatial distribution of hot and cold spots and to see where clusters occur. Municipalities classified as HH are characterised by high urban expansion, being located close to other municipalities with a high expansion value (spatial clustering). At the same time, the HL classification indicates high-expansion municipalities surrounded by low-expansion municipalities or vice versa (LH) (spatial outliers). Conversely, municipalities with low expansion surrounded by municipalities with low urban expansion are classified as LL (Steurer & Bayr, 2020; Zhao et al., 2020).

Second, we use bivariate spatial autocorrelation to explore the spatial correlation between urban expansion and the explanatory factors. The bivariate analysis measures the correlation between both attributes, allowing us to study two attributes that occur simultaneously in a given geographic unit (Gómez-Varo et al., 2021). The bivariate Global Moran Index produces statistics that indicate the strength and direction of the spatial autocorrelation between the two selected variables. The bivariate Global Moran Index can be positive, negative, or close to zero. Thus, a significantly non-zero value of the Bivariate Global Moran Index suggests that the two variables are spatially correlated in the geographic dataset, implying that similar values of one variable tend to cluster together with similar values of the other variable. If it is negative, it means that there is a tendency towards spatial dissociation or dispersion between the values of the two variables in the study area. Specifically, the closer the value of the coefficient is to −1, the stronger the negative correlation, indicating a greater spatial disparity between the variables (Zhang et al., 2023).

On the other hand, the bivariate Local Moran Index allows analysing the local spatial correlation of urban expansion and the factors identified at the local level. The fundamental difference between the bivariate and the univariate Moran Local Index is that the spatial lag belongs to a different variable in the bivariate case. In essence, this notion of bivariate spatial correlation measures the degree to which the value of a given variable in one location correlates with its neighbours of a different variable. It also identifies spatial clusters of four groups for both variables, representing: HH) Indicates the presence of a positive spatial association between the two variables, meaning that municipalities with high values of urban expansion also tend to have high values of the analysed factor in neighbouring municipalities; LL) Indicates the presence of a positive spatial association between the two variables, meaning that municipalities with low values of urban expansion also tend to have low values of the analysed factor in neighbouring municipalities; HL) indicates the presence of a negative spatial association between the two variables, meaning that municipalities with high values of urban expansion tend to be surrounded by municipalities with low values of the analysed factor, and vice versa (LH). For example, it allows analysing whether municipalities that experience higher urban expansion are also associated with an increase in the population rate of the surrounding municipalities (Wang et al., 2023).

The variable data was systematised, processed, and represented using the tools provided by geographic information systems (GIS), specifically the ESRI ArcGIS software version 10.8©. The exploratory spatial analysis calculations and the creation of the LISA maps were carried out with GeoDa software version 1.20.0.10.

4. Results

This study quantified the urban expansion of the Metropolitan Region of Santiago (Chile) between 1997 and 2013 and analysed this expansion through a spatial autocorrelation analysis at the municipal level. This analysis used Global and Local Moran Index to identify where and to what degree the Region's expansion was concentrated. We then used a Bivariate Moran Index to explore further the degree of clustering between urban expansion and its explanatory variables (physical, socioeconomic, urban planning and urban regulation).

4.1. Urban expansion at the municipal level

In the study period, the built-up area increased from 60,130 ha in 1997 to 134,730 ha in 2013, an increase of 124 % in the region (74,620 Ha). According to Fig. 1 and Table 3, the rural municipalities had the most significant increase in built-up expansion in the study period (51,497 Ha). Secondly, the 14 municipalities located in the peri-urban area increased by a total of 22,024 ha. Finally, the 20 municipalities in the central area only increased by a total of 1099 Ha (Table 3). Hence, urban expansion increases greatly in the region's rural and peri-urban municipalities (Fig. 1).

Table 3
Built-up expansion (Ha) in the Metropolitan Region of Santiago Chile, at the municipality level.

Type of Municipality	N	Built-up (Ha)		Difference (Ha)	%
		1997	2013		
Core	20	22,436	23,535	1099	5
Periurban	14	28,775	50,779	22,004	76
Rural	18	8919	60,416	51,497	577
Total	52	60,130	134,730	74,600	124

According to Table 4, we identified that among the municipalities located in the core area (20), ten municipalities did not expand, having 0 difference in urban expansion (Lo Prado, Macul, Nunoa, Pedro Aguirre Cerda, San Joaquin, San Miguel, Santiago, Quinta Normal, Independencia). On the other hand, five municipalities (Cerrillos, Renca Lo Espejo, Recoleta, Cerro Navia) expanded between 94 Ha and 568 Ha in the study period, with Cerrillos standing out (568 Ha). On the other hand, peri-urban municipalities (14), only Vitacura and El Bosque expanded to a lesser extent (34 Ha and 2 Ha respectively), with Pudahuel (3732 Ha), Maipu (3247 Ha) and San Bernardo (3061 Ha) as the municipalities that expanded the most. Finally, concerning rural municipalities (18), all municipalities expanded by at least 1000 Ha in the period analysed, with Colina (7477 Ha), Melipilla (6681 Ha), Lampa (4439 Ha) and Paine (4345 Ha) standing out (Fig. 1).

4.2. Spatial autocorrelation of urban expansion

A positive and significant autocorrelation of urban expansion patterns is identified according to the Moran Global index of urban expansion in the region (Moran's $I = 0.452$; $p < 0.001$). That is, there is a spatial autocorrelation in urban expansion in the region, rejecting the null hypothesis of randomness (Fig. 2).

Analysing the Local Moran Index through the Lisa maps (Fig. 2), we identified 25 municipalities with significant spatial autocorrelation in the region. On the one hand, 11 municipalities (HH) have a high value of urban expansion and are surrounded by high values of urban expansion, and are distributed as follows: i) Grouped to the north: Til Til (Rural); Colina (Rural); Lampa (Rural); Curacaví (Rural); Quilicura (Periurban) iii) To the south: Peñaflor (Rural), Isla de Maipo (Rural), Buin (Rural), Pirque (Rural), Paine (Rural); vi) To the west: San Pedro (Rural). On the other hand, there are 10 municipalities (LL) with a low or almost zero expansion value, concentrated in the core zone of the region, coinciding with the consolidated urban area (Figs. 1 and 2). These municipalities have no space for further expansion and, therefore, have expansion values close to zero or almost non-existent. The set of 4 municipalities that make up the LH group consists of: Alhué (Rural), El Monte (Rural), María Pinto (Rural), Padre Hurtado (Rural), which represent municipalities with a low difference in urban expansion about the surrounding municipalities with high values of urban expansion.

4.3. Global and local Moran Index: bivariate association between urban expansion at the municipal level and its explanatory factors by dimension

In this section, we analyse the bivariate spatial autocorrelation of urban expansion and its factors by dimensions at the municipal level, using the bivariate global and local Moran Index (Table 5, Fig. 3). This is to understand the patterns of spatial association between urban expansion and its explanatory factors.

Table 4
Built-up expansion at the municipal level.

Municipality	Type	Built-up expansion (Ha)		
		1997	2013	Difference
Alhue	Rural	1479	2618	1139
Buin	Rural	586	3275	2688
Calera de Tango	Rural	81	3030	2948
Cerrillos	Core	1104	1672	568
Cerro Navia	Core	888	981	94
Colina	Rural	1053	8537	7477
Conchali	Core	1083	1094	11
Curacavi	Rural	317	3757	3440
El Bosque	Peri-urban	1415	1417	2
El Monte	Rural	337	1338	1001
Estacion Central	Core	1414	1432	18
Huechuraba	Peri-urban	1116	1,73	614
Independencia	Core	746	743	−3
Isla de Maipo	Rural	226	1883	1657
La Cisterna	Core	1009	1011	2
La Florida	Peri-urban	3028	3940	912
La Granja	Core	985	993	8
La Pintana	Peri-urban	722	1833	1111
La Reina	Peri-urban	1802	1909	107
Lampa	Rural	469	4908	4439
Las Condes	Peri-urban	3493	4121	628
Lo Barnechea	Peri-urban	2202	5200	2998
Lo Espejo	Core	689	819	130
Lo Prado	Core	660	660	0
Macul	Core	1276	1276	0
Maipu	Peri-urban	2870	6117	3247
Maria Pinto	Rural	171	1178	1007
Melipilla	Rural	746	7427	6681
Nunoa	Core	1683	1683	0
Padre Hurtado	Rural	303	1698	1395
Paine	Rural	307	4661	4354
Pedro Aguirre Cerda	Core	865	865	0
Penaflor	Rural	563	2,45	1887
Penalolen	Peri-urban	1650	2907	1257
Pirque	Rural	138	3117	2979
Providencia	Core	1323	1278	−45
Pudahuel	Peri-urban	2385	6118	3732
Puente Alto	Peri-urban	2981	5423	2442
Quilicura	Peri-urban	1017	2897	1880
Quinta Normal	Core	1177	1176	−1
Recoleta	Core	1351	1468	117
Renca	Core	1303	1503	200
San Bernardo	Peri-urban	1996	5057	3061
San Joaquin	Core	984	984	0
San Jose de Maipo	Rural	652	1860	1208
San Miguel	Core	957	957	0
San Pedro	Rural	0	1777	1777
San Ramon	Core	628	629	1
Santiago	Core	2310	2310	0
Talagante	Rural	483	3334	2850
Tiltil	Rural	1007	3575	2569
Vitacura	Peri-urban	2096	2130	34
Total	–	60,130	134,750	74,620

Note: The negative value relates to the difference in remote sensing resolution between 1997 and 2013.

4.4. Physical dimension

Looking at Table 5, the variables area ($i = 0.2$; $p = 0.006$) and slope ($i = 0.355$; $p = 0.001$) are spatially correlated with urban expansion. That is, this implies that similar values of urban expansion at the municipal level tend to cluster together with similar values of area and slope in the region. On the other hand, the elevation variable was not significant in the analysis. Looking at the Lisa maps, about area, there are 3 municipalities (HH) with a high value of urban expansion, surrounded by municipalities with a high value of area. On the other hand, the LL values correspond to 13 municipalities located in the core zone, indicating a positive correlation, in which there is a low value of urban expansion, surrounded by municipalities with a lower total area. In terms of slope, we identified 5 municipalities (HH) slope grouped in the

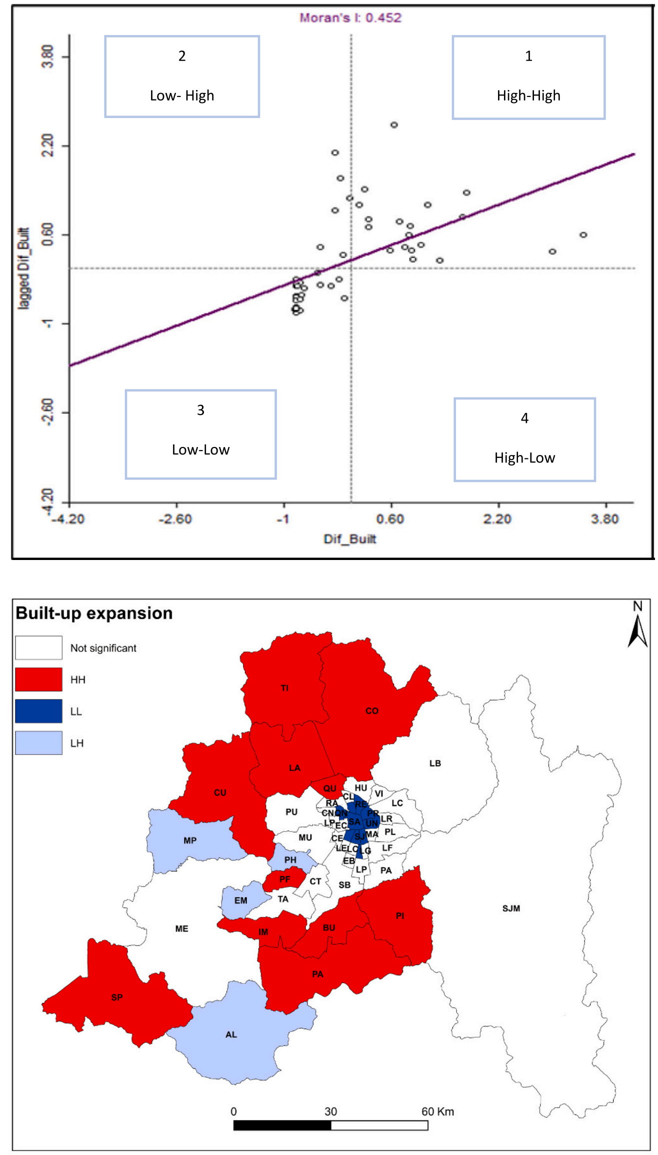


Fig. 2. Moran Index scatterplot of urban expansion between 1997 and 2013 and Lisa maps at the municipal level in the Santiago Metropolitan Region (Chile).

north and south of the region, with a high value of urban expansion surrounded by a high slope value. On the other hand, 12 municipalities concentrate on a low value of urban expansion and low values of slope, located in the core zone (LL) (Fig. 3 a).

4.5. Socioeconomic dimension

The annual growth rate of population ($i = 0.470$; $p = 0.001$), housing units ($i = 0.436$; $p = 0.001$) and household income ($i = 0.294$; $p = 0.001$) are variables with a positive overall Moran Index, and thus tend to cluster with similar values of urban expansion in the region (Fig. 3 b). That is, high (or low) values of urban expansion at the municipal level tend to cluster with high (or low) values of annual housing stock, population and household head income. Furthermore, building permits ($i = -0.111$; $p = 0.019$) and population density ($i = -0.306$; $p = 0.001$) give rise to a negative index, thus suggesting that these values are not spatially correlated with similar values of urban expansion. In this context, municipalities experiencing higher urban expansion tend to have lower population density in their surroundings, and vice versa.

Table 5
Global Moran Index of urban expansion (Ha) between 1997 and 2013 and its explanatory factors by dimension.

Dimension	Variable	Global Moran Index (i)	p value
Physical	Area	0.2	0.006*
	Elevation	0.069	0.114
	Slope	0.355	0.001*
Socio-economic	Built permits	−0.111	0.019*
	Housing AGR	0.436	0.001*
	Income of the household head AGR	0.294	0.001*
	Population AGR	0.47	0.001*
	Population density	−0.306	0.001*
	Highway across the municipality	−0.095	0.056
Urban Planning and Urban Regulation	Urban area delimited by PRMS in 1994 at the municipal level	−0.461	0.001*
	Urban area delimited by PRMS in 1997 at the municipal level	−0.346	0.001*
	Decree Law N°3.516	0.27	0.002*
	Decree Law N°2.965	0.239	0.003*

Note: p (*) Significant correlation <0.05.

Finally, the presence of a highway in the municipality appears as a non-significant variable in the analysis.

Looking at the Lisas maps, about population (Fig. 3 b), a total of 4 (HH) municipalities, concentrated in the north of the region, were identified as municipalities with a high value of urban expansion surrounded by municipalities with a high value of population growth rate. In addition, 5 municipalities (HH) clustered to the north of the region were identified as having a high value of urban expansion spatially correlated with the increase in the annual housing rate of surrounding neighbours. In addition, 3 municipalities (HH), located north and south of the region, presented a positive spatial correlation of high urban expansion with high values of increasing Household head income AGR. On the other hand, when observing the Lisa map, the population density variable highlights 4 municipalities classified as (HL) located in the north and west of the region. Possibly, in these municipalities there is a high expansion through the increase of built-up areas and, therefore, density decreases. The variable of building permits presents an HH clustering pattern only in one municipality north of the region.

4.6. Urban planning and urban regulation

Looking at Table 5, we observe that there is a positive spatial correlation between urban expansion and the presence of the urban regulations analysed: Decree Law N°3516 ($i = 0.270$; $p = 0.002$) and Decree Law N°2695 ($i = 0.329$; $p = 0.003$). Thus, the high (or low) values of urban expansion at the municipal level tend to be concentrated with the higher (or lower) number of resolutions that allow the application of DL 3516 and DL 2698 for each municipality (Fig. 3.c). On the other hand, we identify that the urban area delimited by the Santiago Metropolitan Regulatory Plan (PRMS) in 1994 ($i = -0.461$; $p = 0.001$) and in 1997 ($i = -0.346$; $p = 0.001$) have variables that present a negative spatial correlation with urban expansion. This possibly suggests that those municipalities that concentrate a high value of urban expansion are those that were left out of the PRMS. On the other hand, the municipalities that concentrated on a low value of urban expansion were those that the PRMS integrated in the analysed period.

Analysing Lisa's maps (Fig. 3 c), we identify a (HH) pattern observed in the southwest of the region in applying the urban regulation (Decree Law N°3.516 and Decree Law N°2.695). That is, there is a grouping of municipalities with high urban expansion and a higher number of applications of such regulations in neighbouring municipalities. On the other hand, the urban area delimited by the PRMS in the variables (1994 and 1997) shows a primarily (HL) result, mainly clustered in the southwest of the region. The result (HL) indicates a concentration of municipalities in the southwest with a high value of urban expansion, surrounded by municipalities that were outside the application of the PRMS. The (LH), on the other hand, suggests a concentration of municipalities with low urban expansion values in the region's core zone, surrounded by municipalities where the PRMS was applied. Finally, it should be noted that there were 3 (LL) municipalities.

5. Discussion

5.1. Urban expansion and spatial analysis

The Metropolitan Region of Santiago (Chile) in the period between 1997 and 2013 exhibited an urban expansion mainly towards rural and peri-urban municipalities, according to other studies on the region (De Mattos, 2010; Karen C. Seto et al., 2012; Fuentes & Pezoa, 2018). Furthermore, less expansion towards the east and in the core zone of the region was identified, mainly for two reasons. First, the Andes Mountains act as a natural barrier, preventing the city's eastward expansion. Second, the core zone is dominated by the densification of existing urban areas (Vicuña, 2020).

Subsequently, we find that this expansion is positively autocorrelated, having a spatial dependence at the municipality level in the region, a trend similar to the analysis of growth patterns in other cities (Feng et al., 2019). Thus, the region presented a concentration of urban expansion mainly in the north and south of the region meaning that the expansion of urban areas at the municipal level in that sector tends to occur similarly in other nearby municipalities (Puertas et al., 2014; Silva & Vergara-Perucich, 2021). In this regard, the Moran Index was a useful tool to detect clusters of urban expansion through the identification of hot spots and cold spots, and could be useful for the identification of areas to intervene (Jing et al., 2022).

5.2. Physical factors

Regarding physical factors, it was observed that the factors of area and slope of the municipality were relevant for the region, being identified as variables related to urban expansion. For example, in a study applied to Spanish cities, it was observed that the higher the percentage of open space, the higher the level of urban expansion (Gómez-Antonio et al., 2016). Slope also plays a relevant role in urban expansion, as there is a tendency for urban expansion to expand towards places with less slope. The present case follows this trend identified in the literature by identifying the central area as LL as it is flat and corresponds to the consolidated urban area (Dewan & Yamaguchi, 2009; Thapa & Murayama, 2010). Also, the presence of mountains hinders expansion, as they act as a natural barrier and make development more costly (DeSalvo & Su, 2019).

5.3. Socio-economic factors

The urban expansion tends to concentrate with population growth values, similar to the trend of other related studies applied to the MRSC, in which population growth in central municipalities tends to stagnate, thus distributing the metropolitan population towards peri-urban and rural municipalities (De Mattos, 2010; Hernández-Moreno & Reyes-Paecke, 2018). Similar trends have also been documented in other Latin American and world cities (Cruz-Muñoz, 2021; Gómez-Antonio et al., 2016). However, they differ from the case of European cities, where there is urban expansion but the annual rate of population decline (Kasanko et al., 2006).

Population density was a significant variable in the present study, showing spatial dissociation with urban expansion according to the Global Moran Index. In this specific context, municipalities experiencing higher urban expansion tend to have lower population density in their surroundings, and vice versa, similar to what has been observed by other

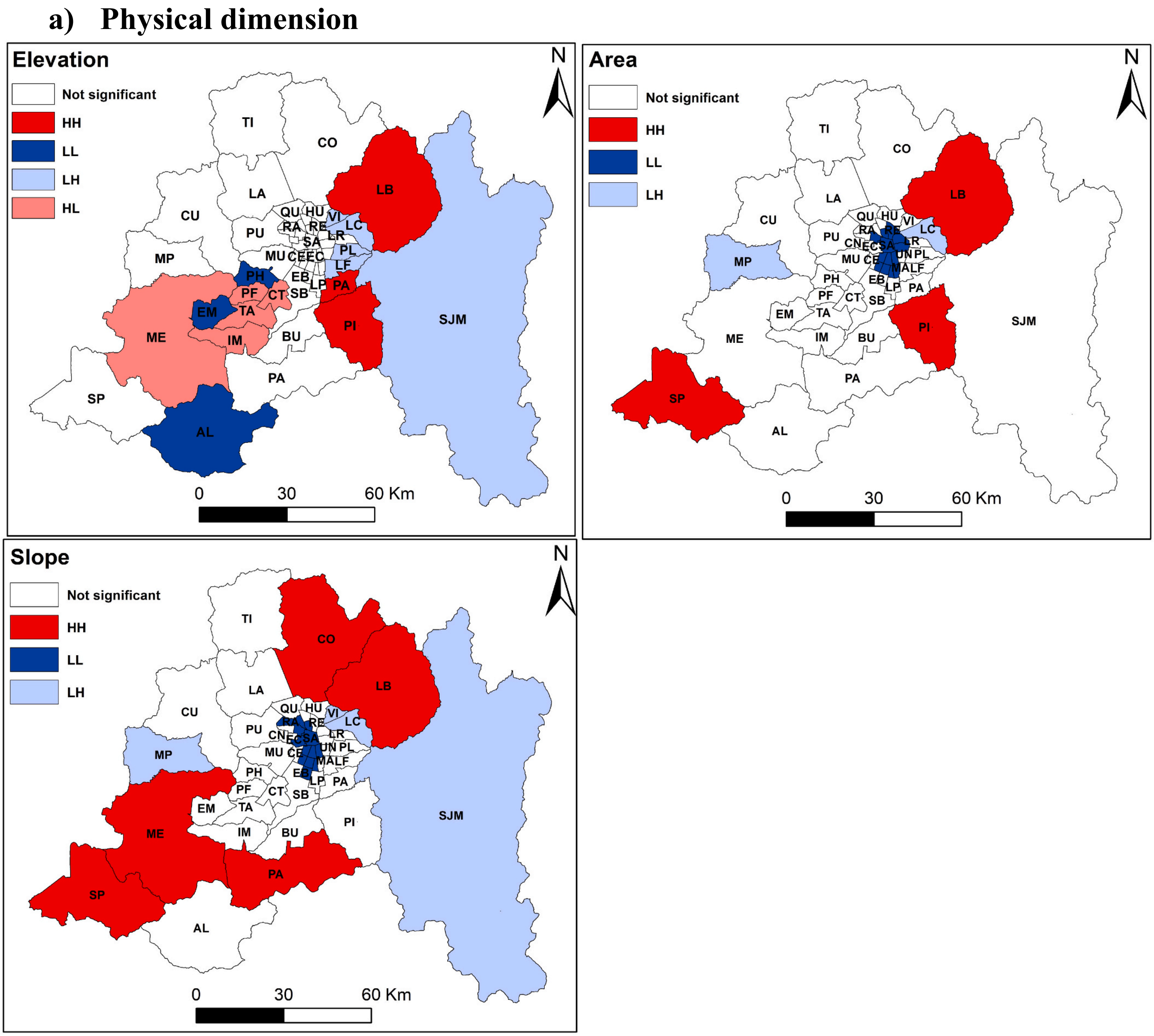


Fig. 3. Lisa maps of urban expansion (Ha) between 1997 and 2013 and the explanatory factors by dimension.
a) Physical dimension, b) Socioeconomic dimension, c) Urban planning and urban regulation.

studies (Aquino & Gainza, 2014; Naranjo, 2017). Furthermore, the city has possibly expanded to a greater extent than its population rate, mainly by developing low-density housing, which is generally a symptom of expansion (Robinson et al., 2005).

The increase in the annual housing rate shows a spatial pattern correlated with urban expansion that is more towards the north and west of the region. This pattern may be due to the implementation of a legal reform called "conditional urban development". This mechanism allows the installation of new real estate projects in agricultural areas, converting them into new urban areas. Such a mechanism allows the development of new projects whose urbanisation costs are passed on to developers (Vicuña, 2013; Jimenez et al., 2018). Moreover, it is consistent with urban expansion towards the north, considering that between 2002 and 2011, 40,000 new dwellings were added, representing >10 % of the housing stock in the period (De Mattos et al., 2014).

The variable representing municipalities with access to an inter-municipal highway was found to be positive but not statistically significant. Possibly because there was an increase in new urban developments near the highway starting in the 1990s, prior to the time frame of the study (Hidalgo & Borsdorf, 2007). Moreover, possibly because there were already new urban developments outside the city core, even prior to the development of highways (Figueroa & Rodríguez, 2013). Finally, since it was not possible to disaggregate the GDP variable at the municipality level, the annual increase in average income per household head by municipalities was analysed. The results show similar patterns to those identified in other studies, with an increase in income and urban expansion in the northern sector of the region. This could be due to the development of single-family housing in the form of gated condominiums associated with middle and upper socio-economic groups, contributing to socio-spatial segregation, as has been documented in other studies and cities in Latin America and the United States (Le Goix, 2005; Yunda & Sletto, 2020). In addition, it has been documented in studies elsewhere in the world that rising incomes can lead to

b) Socioeconomic dimension

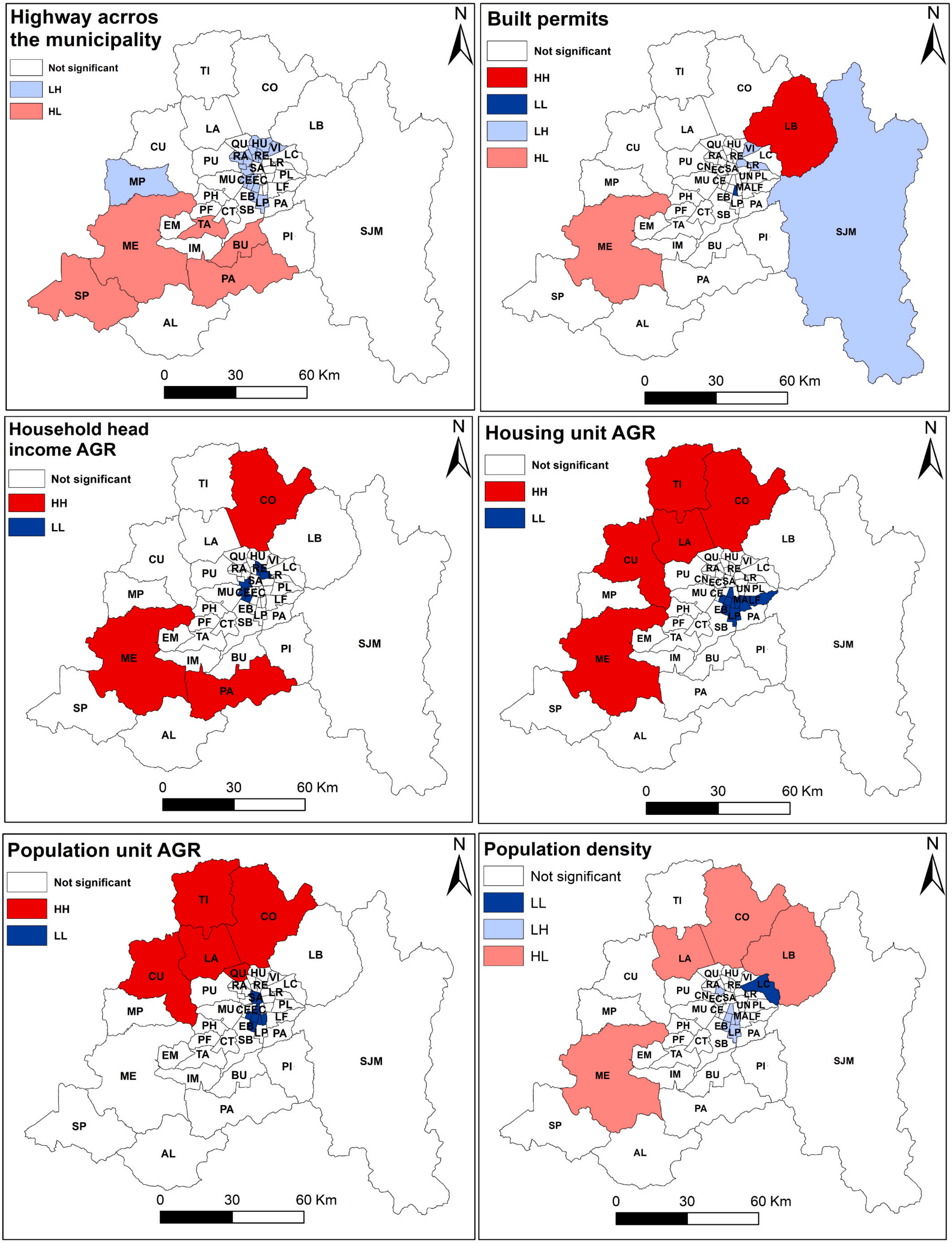


Fig. 3. (*continued*).

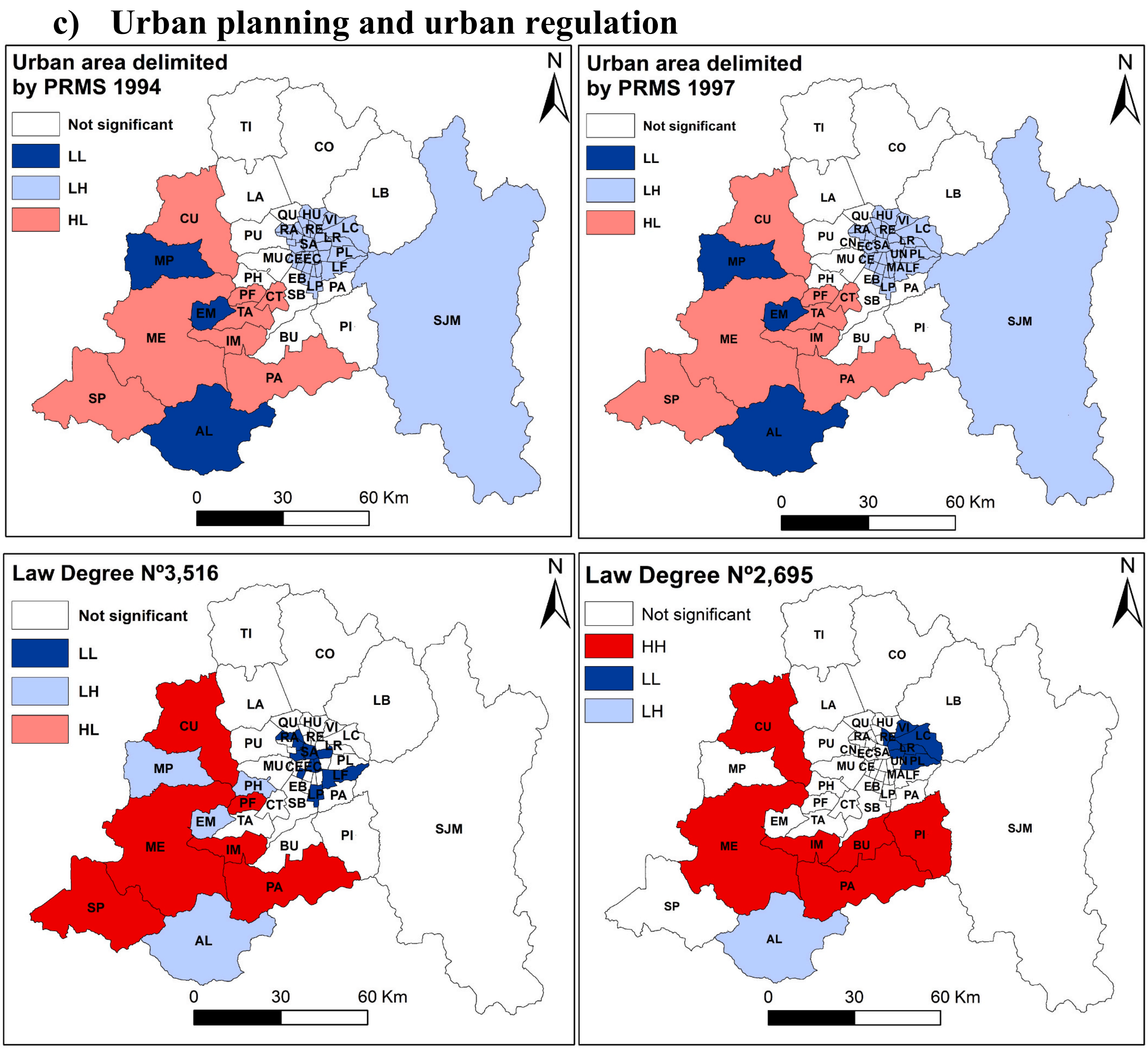


Fig. 3. (*continued*).

urban expansion, as people seek larger housing and better living conditions (Hassan et al., 2023).

5.4. Urban planning and regulatory factors

The urban planning and regulation factors in this study show that urban planning and policies can contribute to explaining urban land expansion in the region, as has been documented by other studies (Colsaet et al., 2018; Vicuña, 2013). Thus, the bivariate autocorrelation analysis with respect to the planning and regulation variables showed two different but complementary patterns. On the one hand, the spatial correlation between the urban area delimited by the 1994 and 1997 PRMS was negative, indicating a spatial dissociation with urban expansion in the region. As has been documented in other studies, this indicates that an expansion beyond the urban growth boundary (UGB) occurred towards the peri-urban and rural municipalities that were left out of the Plan (Barton & Ramírez, 2019; Petermann, 2006; Puertas et al., 2014; Schuster Olbrich et al., 2022; Vicuña, 2017). This differs from the case of the Oregon Land Use Plan in the United States, for example, where the plan limits expansion through larger-scale planning and zoning, protecting agricultural and natural lands (Dempsey et al., 2017). In this regard, there is an open debate in the literature on the spatial and temporal scale of implementing plans and their possible effects on urban expansion, especially in agricultural areas and open spaces (Nel·lo, 2010; Menzori et al., 2021).

On the other hand, the regulations analysed, both Decree Law N°3.516 and Decree Law N°2.695, tended to spatially cluster with urban expansion at the municipal level, especially in those municipalities that correspond to municipalities with large extensions of agricultural land, located in the south of the region. Decree Law N°3516 of 1980 facilitates the subdivision of rural properties into agricultural plots of 0.5 ha each, which enables low-density urban growth in agricultural areas of the region (Naranjo, 2017). On the other hand, Decree Law N°2.695 allows for the regularisation of low economic value constructions located on small public lands. Other studies have identified Decree Law N° 3516 and Decree Law N° 2695 as mechanisms that legally allow the city to expand by developing low-density housing on agricultural and public land. Thus, the case of MRSC has been referred to as "the normativity of the diffuse city" since it is legally allowed to expand through these mechanisms (Jiménez et al., 2018; Silva & Vergara-Perucich, 2021).

This element of the present case study stands out, in contrast to the case of Portugal, where there were regulations and land use planning that assigned uses and protection to rural space. However, urban expansion took place anyway, and at the expense of these areas. The allocation of uses was ineffective and did not guide urban development in complex and extensive areas, such as metropolitan areas (Abrantes et al., 2016).

It should be noted that the spatial pattern of urban expansion in the MRSC, its negative correlation with the PRMS, and its positive correlation with DL 3516 and DL 2698 at the municipal level are consistent with the literature. In 1994, the PRMS primarily applied to central municipalities with the highest population densities, excluding the peri-urban and rural municipalities from the plan. This omission allowed for the widespread application of regulations DL 3516 and DL 2698, which permit low-density urban development in these areas. Consequently, the PRMS was modified and extended to those peri-urban and rural municipalities to promote a compact city and protect open spaces. To this end, the extension of the PRMS prohibited applying the decrees in these municipalities. However, many low-density developments had already been authorized prior to this modification (Cruz-Muñoz, 2021; Jiménez et al., 2018; Naranjo, 2009).

While the present study contributes to understanding urban expansion and its explanatory factors through a spatial autocorrelation analysis, it has limitations. To consider a broader analysis of the study area, there is a challenge regarding the availability of recent public data on land cover to understand the dynamics of urban expansion clustering with a broader and more current time horizon. In addition, incorporating the temporal dimension into the ESDA analysis is an effective tool for exploring the pattern of urban expansion clustering but has difficulties conveying temporal correlations (Jing et al., 2022). Furthermore, the present study considered the municipal administrative political division because of its relevance for urban planning. It is a predominant scale of analysis in urban expansion studies, as delimitation criteria may vary from country to country (Chettry, 2023). However, for a deeper understanding of the region's reality, underlying data on urban expansion at a smaller scale should be considered, as it may hide suburban or dispersed patterns in the region, and its identification is key for the sustainable urban development of the region (Seevarethnam et al., 2021; Steurer & Bayr, 2020; Wu et al., 2021). In addition, with the development of analyses with underlying data at a smaller scale, the application of other methods, such as the Moran Index for compactness assessment through its similar values, could be explored (Salvati & Margherita, 2014; Tsai, 2005). Complementary, the Shannon Entropy Index for analysing dispersion in the urban growth pattern of the region (Chettry & Surawar, 2021).

6. Conclusions

This study quantified urban expansion between 1997 and 2013 in the Metropolitan Region of Santiago, Chile, at the municipal level. The results identified the physical, socio-economic, urban planning, and urban regulation factors that influence urban expansion. The Global and Local Moran Index was applied at the municipality level to analyse urban expansion and the explanatory factors. Our conclusions are as follows.

Urban expansion occurred by 124 % in the studied period, mainly in rural municipalities. Additionally, urban expansion tends to be spatially clustered, particularly in the northern and southern parts of the region. Consequently, the hypothesis of random urban expansion was rejected, indicating that spatial factors play a significant role.

At the factor level, through the bivariate Moran Index analysis, variables with a positive and negative coefficient with the values of urban expansion in the region stood out. That is, variables are grouped with similar values of urban expansion (positive correlation) or variables that present a dissociation in space with urban expansion (negative correlation). Regarding the Global and Local Moran Index, the variables with a positive correlation with the urban expansion at the municipality level were the annual population growth rate, housing and income of the household head, slope and the Decree Laws N°3516 and N°2965. Concerning the spatial patterns, these suggest an HH relationship between the variables and expansion in municipalities further away from the core area and LL in the core area. On the other hand, the following variables stood out with a negative coefficient: urban areas delimited by the PRMS in 1994 and 1997 at the municipal level (UGB) and population density. At the spatial pattern level, the concentration of high values of urban expansion was identified in those municipalities that remained outside the PRMS (peri-urban and rural municipalities). On the other hand, the concentration of low values of urban expansion was identified in those municipalities that were integrated by the PRMS (mainly core municipalities).

This study underscores the significance of employing the Moran Index to analyse urban expansion patterns and explanatory factors at the municipal level. In particular, the Moran Index can be a valuable tool for urban planners and decision-makers to prioritise those municipalities that require policies and interventions to address accelerated urban expansion and its negative effects. The decision-makers should establish densification and housing accessibility policies in denser areas and establish environmental and agricultural protection policies for open spaces to protect municipalities from new urban development in undesirable areas. This study has provided evidence of how an urban planning instrument's territorially partial and gradual application over time may not control and guide expansive urban development towards peri-urban and rural municipalities in the region. Moreover, urban expansion has been promoted by the application of decrees that promote low-density developments on agricultural and public lands in the region. Therefore, the authorities should limit or repeal the regulations that promote low-density urban development in the region.

Future studies should deepen the analysis of expansive patterns and urban morphology with a greater temporal dimension and a smaller scale in the region. Studies should analyse the relationship between urban expansion and the effects of planning and regulation on growth patterns and, especially, explore the spatial effects of the identified decrees on possible urban sprawl. In this regard, studies should deepen and integrate the effects of planning and regulatory factors on urban patterns as they can play a key role in promoting or limiting urban expansion, especially in cities of the Global South.

CRediT authorship contribution statement

Juan Pablo Schuster-Olbrich: Writing – review & editing, Writing – original draft, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Oriol Marquet:** Supervision. **Carme Miralles-Guasch:** Supervision. **Luis Fuentes Arce:** Validation, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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