

Relationship between social vulnerability and community resilience: A geospatial study in the context of natural disasters

Nicolás C. Bronfman^{a,b,*}, Nikole Guerrero M.^a, Javiera V. Castañeda^{a,c},
Pamela Cisternas^{a,b,d}, Paula B. Repetto^{a,c}

^a Research Center for Integrated Disaster Risk Management, ANID/FONDAP/1523A0009, Santiago (CIGIDEN), Santiago, Chile

^b Engineering Sciences Department, Universidad Andres Bello, Santiago, Chile

^c Department of Psychology, Pontificia Universidad Católica de Chile, Santiago, Chile

^d Industrial and Systems Engineering Department, Pontificia Universidad Católica de Chile, Santiago, Chile

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ABSTRACT

Social vulnerability and resilience are critical factors for disaster risk management. Despite the significant progress in research on both concepts, only some studies have explored the empirical relationship between them. The relationship between community resilience and social vulnerability to natural disasters in Chile was studied using empirical and geospatial analysis. We used the Social Vulnerability Index (SoVI) and the Community Resilience Index (BRIC), previously calculated nationally for Chile. Based on these indicators, we constructed a matrix to classify the 3100 districts into high, medium, and low levels of vulnerability and resilience. In addition, we performed a spatial autocorrelation analysis using the Global Moran Index. Our results indicate that: Vulnerability and resilience are related concepts, but are not opposite within a continuum, (II) Rather than being randomly distributed, districts with higher (or lower) capacities to prepare for, respond to, and recover from a disaster tend to cluster geographically; (III) the districts with the highest levels of resilience and lowest levels of vulnerability were located in the main cities of the country. We expect that a better understanding of the relationship between vulnerability and resilience in each territory will help institutions in charge of disaster management to identify communities most susceptible to damage and least capable of recovering from a disaster. Consequently, it will facilitate the design and implementation of policies, programs, and plans best adapted to the needs of each community.

1. Introduction

In recent decades, research on community vulnerability and resilience against natural hazards has grown due to the greater understanding that the impacts of these events are not only determined by geophysical and climatic factors but also by the social, economic, and cultural conditions of the communities affected [1,2]. The complex interaction between these dimensions has proven to be a crucial factor regarding the magnitude of the consequences and the resilience of the community. In this context, recognizing the greater susceptibility to these impacts among certain social groups and their needs to define effective preparedness, mitigation, and adaptation strategies has placed the study of community vulnerability and resilience at the center of the research and policy agenda at a global level [3,4].

* Corresponding author. Engineering Sciences Department, Universidad Andres Bello, Antonio Varas 880, Providencia, Santiago, Chile.
E-mail addresses: nbronfman@unab.cl, jvcastaneda@uc.cl (N.C. Bronfman).

Although the previous studies have been invaluable for understanding the relationship between social vulnerability and community resilience, few empirical studies have explicitly evaluated this relationship. Moreover, none of these have been developed using data from countries of Latin America, which are highly vulnerable to the occurrence of these events. According to the global risk index, more than half of the countries with medium and high disaster risk index are concentrated in the Latin American and Caribbean region [5]. From 2002 to 2021, this region accounted for 21 % of global deaths resulting from disasters and economic losses of more than 155 billion dollars [6]. Additionally, this region has high rates of social inequality that amplify the impacts of disasters, increasing the vulnerability, and extending the recovery processes [7].

Chile is one of the Latin American countries more exposed to multiple natural hazards [8]. The country has suffered significant human and economic losses in recent decades due to natural disasters. For example, between 1980 and 2011, losses equivalent to around 1.2 % of its Gross Domestic Product were recorded [9]. This situation is worsened by high economic inequality, which places Chile as the second most unequal country in the OECD [9]. Given this scenario, and to reduce the consequences of disasters it is essential to evaluate the empirical and geospatial relationship between social vulnerability and community resilience to progress in the programs proposed for Latin American countries.

Therefore, the main objective of the present study was to empirically and geospatially analyze the relationship between social vulnerability and community resilience in Latin America, specifically in Chile. The study used the SoVI and BRIC indices to measure the empirical relationship and spatial distribution of vulnerability and resilience.

1.1. Social vulnerability & community resilience

In the field of natural hazards, vulnerability research has focused on analyzing social vulnerability, that is, on measuring the social, economic, and demographic conditions that exist before the occurrence of a disaster and that may increase or decrease the capacity of social groups (or society in general) to prepare and respond to a disaster [1,10].

Many studies have made favorable progress in the characterization of social vulnerability through different approaches, with the Social Vulnerability Index (SoVI) being one of the most used and most effective methodologies to predict the impact of disasters [11, 12]. This index defines distinct levels of social vulnerability through indicators that represent socioeconomic status, quality of housing, and employment, among others [1,13]. Previous studies that replicated the SoVI nationally have concluded that social vulnerability levels are heterogeneously distributed in the territories. Additionally, rural counties, areas with less socioeconomic development and a more significant presence of vulnerable populations (e.g., older adults, women, and migrants, among others) have the highest levels of social vulnerability [14–19].

In contrast to social vulnerability, a consensus regarding the definition of resilience has been more complex to reach. While previous studies define resilience as part of an inherent capacity, others describe it as part of a process of disaster adaptation [20,21]. However, despite these differences, for the purpose of this article, resilience is defined as the ability of communities to adapt and recover from the impact of disasters [4,22].

The need to understand resilience has given rise to different indicators that have reduced its complexity and dimensional diversity, such as the Community Disaster Resilience Index (CDRI), the Resilience Capacity Index (RCI), and the Baseline Resilience Index for Communities (BRIC) [11]. Cutter et al. [23] developed the BRIC index, which empirically measures community resilience by integrating sub-indices of social, economic, social capital, institutional, environmental, and infrastructure resilience. This index is one of the most replicated and validated indexes capable of significantly explaining property damage after a disaster [11]. Previous studies suggest that by applying the BRIC index, it is possible to show that, in general, urban areas or large cities present the highest levels of community resilience in most of its dimensions due to their economic development and higher educational level, among other characteristics [24–26]. Furthermore, areas with higher economic capital, public policies against disasters, and more social capital tend to be the most resilient places [27].

Despite the remarkable progress in assessing social vulnerability and community resilience, there is still debate about how both concepts are related. While some authors point out that resilience and vulnerability are opposite concepts within a continuum [28,29], others suggest that vulnerability and resilience are related but different concepts [11,27]. Previous studies point out the difference between the two concepts, indicating that vulnerability focuses on the susceptibility of a system to the impacts of disasters [23,30], while resilience relates to the process of recovery and reorganization of a system after a disaster. Accordingly, Gallopín et al. [31] point out that vulnerability focuses on a short-term change in the conditions of communities, and resilience involves adaptation processes and long-term structural changes in systems.

Recent studies that have empirically measured the relationship between vulnerability and resilience suggest that vulnerability and resilience have elements in common, but that they are different concepts. Sherrieb et al. [30] measured the relationship between vulnerability and resilience for the counties of Mississippi (USA), finding a negative and significant correlation ($r = -0.68$) between both variables. The authors suggest that this result may indicate that communities with high levels of vulnerability tend to present lower community resilience. Also, the authors indicate that results evidence that vulnerability and resilience share common elements but are different concepts. Similarly, Bergstrand et al. [22] identified a statistically significant relationship between the SoVI and CDRI indices, concluding that the most vulnerable US counties were also the least resilient.

One of the main frameworks attempting to define the relationship between both concepts is the Disaster Resilience Of Place (DROP) model, which gave rise to the SoVI and BRIC indices [23]. This conceptual framework establishes that social vulnerability and community resilience refer to different but related concepts. By estimating both indices using information from US counties, the authors found that both concepts had a significant and negative correlation ($r = -0.5$); that is, those counties with greater vulnerability presented lower levels of resilience. Furthermore, they found 25 % of counties in which both concepts overlapped, indicating a relationship between them while remaining distinct concepts [27]. Cutter & Derakhshan [32] also examined the geospatial and

statistical relationships between the SoVI and BRIC indices of US counties twice (2010 and 2015). The authors concluded that social vulnerability and community resilience are not simply opposites within a continuum. These concepts can still be measured independently despite the overlap between SoVI and BRIC measurements.

Thus, considering the DROP model, this article aims to analyze the relationship between both capacities in the context of a country with high levels of inequality, such as Chile. It is crucial to empirically test this relationship to design effective disaster risk reduction strategies that account for both short- and long-term changes that disasters bring to communities. In addition, observing the spatial relationship between both concepts allows for identifying communities that are more susceptible to damage and less able to recover. Moreover, replicating these indices in Latin American countries that are in the process of economic development and do not always have a wide availability of data allows testing whether the conceptualization of vulnerability and resilience can be adapted to other social and cultural contexts.

2. Materials and methods

2.1. Study area

Chile is a Latin American country with a population of 17.5 million, with women constituting 51.5 %. According to the latest census data from 2017, the country is experiencing an advanced process of population aging, evidenced by a fertility rate of 1.6 and an aging index of 63.1 [33]. From a political and administrative perspective, Chile is divided into 16 regions, 56 provinces, 346 communes, and over 2749 districts [34]. Given its vast extension and economic, cultural, and geographical diversity, the regions and districts of the country can be classified into five macro-zones: Norte Grande, Norte Chico, Centro, Sur, and Austral [35].

Also, Chile is on an active continental margin and is exposed to several natural hazards (see Fig. 1). Geological hazards such as earthquakes and tsunamis are part of the events with the most significant impact. Chile registers the largest earthquake recorded in the history of humanity.¹ Furthermore, in the last decade, more than seven earthquakes over 7.5 Mw have been recorded in different locations in the country [36]. Due to its proximity to the Andes Mountains, Chile has 45 active volcanoes, three of which erupted during the last decade [37].

As several other countries, Chile is increasingly exposed to extreme weather events related to climate change, such as droughts, floods, and fires. Since 2008, the country has faced dramatic droughts, particularly in the central and southern macrozones. The climatic conditions have led to large wildfires, among which the “2017 firestorm” stands out, when approximately 120 fires co-occurred, affecting more than two thousand homes [38]. Furthermore, floods have been one of the most frequent disasters of the last decade, causing more than 13,000 victims and more than 200 deaths [6,39].

In the presence of various hazards, formulating innovative strategies and programs for disaster risk reduction becomes essential for Chile. In this context, in August 2021, Law 21.364 was enacted in Chile establishing the new National Disaster Prevention and Response System (SINAPRED) and configuring the National Disaster Prevention and Response Service (SENAPRED). This legislation emphasizes the importance of understanding and reducing factors underlying risk, including those associated with the vulnerability of people and communities. The new law also highlights the importance of having available risk maps that adequately describe the interaction of vulnerability, exposure, and other relevant elements for disaster mitigation, response, and recovery [40]. Consequently, we expect this research will contribute to the process of implementing this new regulation.

2.2. Data

Due to its broad validity and replicability, the Disaster Resilience of Place (DROP) model is the theoretical and methodological framework used in this study. The results of SoVI and BRIC obtained in previous studies in Chile were considered. These indices were selected because they allow for a comprehensive summary of the multidimensional characteristics of vulnerability and resilience, and they are the only index available in Chile to observe the distribution of vulnerability and resilience at the national level [15,41]. The social vulnerability aspect was developed by adapting Cutter et al. original methodology [1]. The index included 30 variables drawn primarily from 2017 census data (see Appendix 1), covering 3100 census districts.² It revealed a factorial structure composed of seven factors: (i) socioeconomic status of the population, (ii) population with disability, (iii) concentration of elderly population, (iv) inactive population that leads to economic dependence, (v) low quality of housing, (vi) immigration and (vii) single mothers as heads of household home (to more details see Bronfman et al. [15]).

On the other hand, to evaluate community resilience, Bronfman et al. [41] used the BRIC method developed by Cutter et al. [23]. They calculated an index that was based on 49 variables obtained from 2017 census data and the National Socioeconomic Characterization Survey (CASEN) government data from 2015 to 2017, also covering 3100 census districts. The variables in the original BRIC for Chile were grouped into six dimensions of resilience: social resilience, community capital, economic resilience, institutional resilience, infrastructure resilience, and environmental resilience.

The relationship between vulnerability and resilience was calculated using the general results of the SoVI and BRIC obtain for Chile, following the methodology by Scherzer et al. [24]. The indicators were normalized on a min-max scale between 0 and 100 to analyze the relationship between both indices properly. Normalization was carried out considering the minimum and maximum values of each

¹ This event of magnitude Mw 9.5 had its epicenter in the city of Valdivia, belonging to the South macrozone. As a result of this earthquake, a tsunami was recorded with waves of up to 25 m that caused the death of six thousand people [46].

² The census district is the division of the territory used to carry out population and housing censuses in Chile. This represents a set of zones (urban entities) and localities (rural entities).



Fig. 1. Representation of the territorial division of Chile. It includes the division according to macrozones (Norte Grande, Norte Chico, Central, Sur, and Austral), in addition to the main cities of each of the regions of the country.

variable in their original scales, according to Formula (1).

$$x' = a + \frac{(x - (x)) (b - a)}{(x) - \min(x)}$$

Formula 1. Rescaling (min-max normalization).

Where a and b are the min-max values (0–100).

After normalizing the data, the BRIC index was inverted following the same methodology of previous studies [24,27]. That made both indices oriented towards the worst state when facing natural disasters. In this way, the spatial analysis results of the relationship between vulnerability and resilience presented below must be interpreted considering that higher scores represent higher levels of social vulnerability and a lower level of community resilience, and lower scores represent low vulnerability and high resilience.

2.3. Data analysis

First, we performed a bivariate correlation analysis to evaluate the relationship between the SoVI and BRIC indices at the national and macrozone levels. Then, we conducted a mean difference analysis to assess the relationship between both indices. For this, we used the HSD Tukey multiple comparisons test.

Subsequently, we generated a national vulnerability-resilience map to illustrate the relationship between both indices. To do this, we initially constructed a 3x3 matrix that relates social vulnerability to community resilience for each of the 3100 census districts on a three-level scale: *low* (values less than or equal to the 25th percentile), *medium* (values greater than the 25th percentile and less than the 75th percentile) and *high* (values greater than or equal to the 75th percentile). Crossing both indicators allowed each district to be classified within one of nine quadrants in the matrix (see Fig. 2). Thus, those districts in the upper right quadrant represent greater social vulnerability and lower community resilience, and those in the lower left quadrant represent those districts with lower social vulnerability and higher community resilience.

Then, we conducted a spatial autocorrelation analysis using the Moran Global Index (Moran I) to assess whether districts with high vulnerability and low resilience (or low vulnerability and high resilience) exhibit any specific distribution pattern across the national territory. A negative spatial autocorrelation, indicated by Moran values less than zero, suggests that districts with high vulnerability and low resilience (or low vulnerability and high resilience) are unevenly spread across the territory. Conversely, Moran Index values greater than zero imply a positive spatial autocorrelation, indicating a more uniform distribution of districts within the geographic space. Finally, a Moran I value equal to zero indicates no spatial autocorrelation [42].

It is worth mentioning that we calculated Moran's I three times: once for quadrants of high vulnerability/low resilience and then for quadrants of low vulnerability/high resilience. Both cases involved an inverse distance analysis, where entities closer together have a stronger influence on distant ones, using a Euclidean distance type. Lastly, we calculated Moran's I and local Moran's index (LISA) for all districts.

3. Results

3.1. Relationship between social vulnerability and community resilience

Table 1 presents the results of the correlation analysis between social vulnerability and community resilience. Considering all national districts, the correlation between the SoVI and BRIC values was negative and moderate ($-0.41, p < 0.01$). This finding suggests that, in general, those districts with lower social vulnerability have greater community resilience and vice versa. The analysis at the macrozone level showed a similar trend; that is, there was a negative and statistically significant correlation coefficient ($p <$

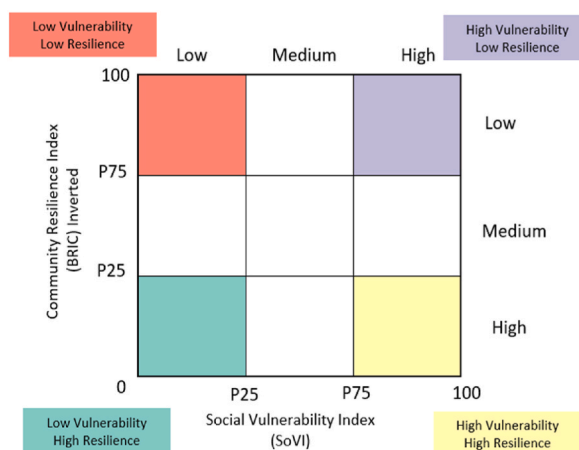


Fig. 2. Matrix of Vulnerability-Resilience interrelationships. The figure represents the nine quadrants obtained at the intersection of vulnerability and resilience. The BRIC index was inverted so that both indices are oriented towards the worst state to face a natural hazard.

Table 1
Pearson correlation between SoVI and BRIC.

Territory	N° Districts	Correlation
All Country	3100	−0.407 ^a
Norte Grande Macrozone	159	−0.531 ^a
Norte Chico Macrozone	306	−0.473 ^a
Central Macrozone	1811	−0.260 ^a
South Macrozone	712	−0.151 ^a
Austral Macrozone	112	−0.375 ^a

^a Significant correlation at the 0.01 level (bilateral).

0.01) between the SoVI and BRIC values for each of the macrozones, with magnitudes ranging from −0.15 to −0.53. These results suggest that social vulnerability and community resilience are related but different concepts.

Fig. 3 illustrates the distribution of the inverse BRIC for each macrozone when the districts are categorized according to their level of vulnerability as low (SoVI < P25), medium (P25 < SoVI < P75), and high (SoVI > P75). At the national scale, districts in the low vulnerability category had medium values of inverse resilience index ($\bar{X} = 35.22$, SD = 13.69) significantly lower ($p < 0.001$) than those in the high vulnerability category districts ($\bar{X} = 50.85$, SD = 17.28) and medium vulnerability districts ($\bar{X} = 42.54$, SD = 14.30). This last one obtained a significantly lower mean value of inverse resilience ($p < 0.001$) than that obtained by high-vulnerability districts.

Equivalent results were obtained for the Norte Grande, Norte Chico, and Central macrozones. A similar trend was maintained for the Southern and Austral macrozones, but some differences were found. In the Southern macrozone, the districts in the low vulnerability category obtained average values of inverse resilience ($\bar{X} = 38.41$, SD = 9.44) significantly lower ($p < 0.001$) than those in the medium vulnerability categories ($\bar{X} = 41.63$, SD = 10.37) and high vulnerability districts ($\bar{X} = 42.95$, SD = 9.10). On the other hand, no significant differences were observed between the medium and high vulnerability categories, suggesting that they maintain a similar level of resilience. Finally, for the Austral macrozone, only a significant difference was observed, where the districts in the high vulnerability category obtained significantly higher inverse resilience scores ($\bar{X} = 54.98$, SD = 9.13) ($p < 0.001$) than low vulnerability districts ($\bar{X} = 46.62$, SD = 11.44). Thus, our results maintain that, in general terms, the most vulnerable districts tend to exhibit less resilience.

3.2. Spatial analysis

Table 2 shows the population distribution at the national and macrozonal levels according to the four principal quadrants of the relationship between vulnerability and resilience: Low Vulnerability-High resilience, High Vulnerability-High Resilience, Low vulnerability-Low Resilience, and High Vulnerability and Low Resilience in the district where they live. While 1 % of the national population resides in districts of high vulnerability and low resilience, 30 % do so in territories of low vulnerability and high resilience. The latter is located in the Central (37 %) and Sur (20 %) macrozones, areas where the main metropolitan locations of the country are concentrated (Santiago, Valparaíso, and Concepción cities).

Table 2 shows that the Norte Grande and Norte Chico macrozones concentrate the highest proportions of the population with the lowest capacities to respond and recover from a disaster (high vulnerability and low resilience). It is essential to highlight that for the Norte Chico macrozone, none of its inhabitants reside in districts of low vulnerability and high resilience and that 25 % of its

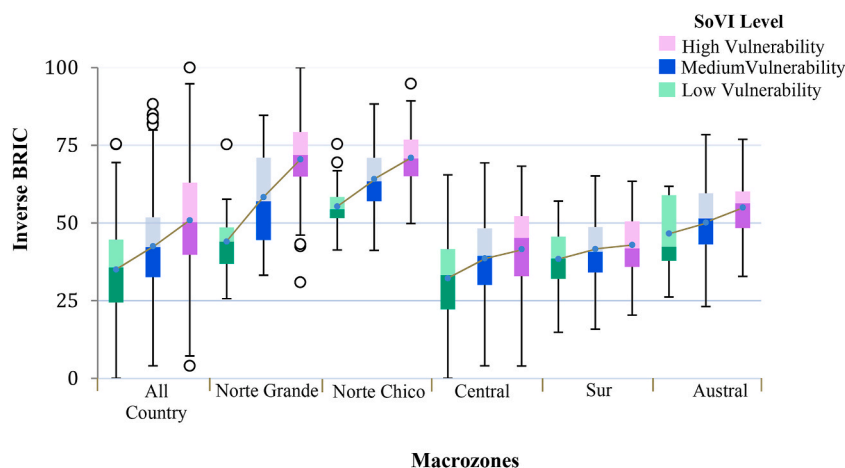


Fig. 3. Inverse Resilience Index (BRIC) vs Vulnerability Level (SoVI) by Macrozone. Box plots comparing community resilience (BRIC inverse) with the low, medium, and high vulnerability categories of each macrozone of the country. The figure also shows the statistically significant differences ($p < 0.001$) in community resilience between vulnerability categories.

Table 2

Proportion of population according to the Vulnerability (V)-Resilience (R) relationship for each macrozone and regional capital city of the country.

Macrozones and Regional Capital Cities of Chile	N° Districts	Population	Low V - High R ^a	High V - High R ^b	Low V - Low R ^c	High V - Low R ^d
All Country	3100	17,493,296	31 %	4 %	2 %	1 %
Norte Grande Macrozone	159	1,152,860	11 %	0 %	7 %	6 %
Arica	20	219,417	0 %	1 %	0 %	0 %
Iquique	17	297,962	0 %	0 %	14 %	6 %
Antofagasta	19	357,752	35 %	0 %	0 %	0 %
Norte Chico Macrozone	306	1,037,356	0 %	0 %	25 %	9 %
Copiapó	25	153,779	0 %	0 %	32 %	0 %
The Serena	37	446,296	0 %	0 %	39 %	0 %
Central Macrozone	1811	12,877,596	37 %	5 %	0 %	0 %
Valparaíso	74	946,371	25 %	2 %	0 %	0 %
Santiago	413	6,544,828	49 %	8 %	0 %	0 %
Rancagua	33	307,052	1 %	0 %	0 %	0 %
Talca	17	219,474	82 %	3 %	0 %	0 %
Chillán	24	215,292	0 %	0 %	0 %	0 %
Gran Concepción	121	966,747	43 %	2 %	0 %	0 %
Sur Macrozone	712	2,159,730	20 %	4 %	0 %	2 %
Temuco	31	357,557	36 %	2 %	0 %	0 %
Valdivia	20	165,401	58 %	0 %	0 %	0 %
Puerto Montt	34	306,470	47 %	1 %	0 %	0 %
Austral Macrozone	112	265,754	4 %	0 %	1 %	1 %
Coyhaique	14	57,517	0 %	0 %	0 %	0 %
Punta Arenas	16	129,063	9 %	0 %	0 %	0 %

*This table only shows the population distribution in the four main quadrants of the relationship between social vulnerability and resilience.

^a Low Vulnerability and High Resilience levels.

^b High Vulnerability and High Resilience levels.

^c Low Vulnerability and Low Resilience levels.

^d High Vulnerability and Low Resilience levels.

population live in a location of low vulnerability and low resilience, a situation shared by its two main regional cities: Copiapó and La Serena. Finally, Table 2 shows that, in general terms, the largest cities in the country present the highest levels of community resilience and lower levels of vulnerability. In the Central and Southern macrozones, a significant percentage of the population is in districts of high vulnerability and resilience.

The spatial distribution of the relationship between vulnerability and resilience throughout the national territory is summarized in Fig. 4.

To determine whether areas with high vulnerability and low resilience (as well as areas with low vulnerability and high resilience) tend to cluster, we applied the Moran Global Index (Moran I). Considering only the districts of high vulnerability and low resilience (those with SoVI and BRIC index greater than or equal to P75), our results indicate an evident spatial grouping (Moran I = 0.38; Z = 27.74; $p < 0.001$). Fig. 4 shows that the districts with the least favorable levels of vulnerability and resilience for preparedness, response, and recovery against natural disasters are in the Norte Grande and Norte Chico macrozones. Similarly, when we consider only districts with SoVI and BRIC values lower than or equal to P25, our results show that the least vulnerable and most resilient districts also tend to cluster spatially (Moran I = 0.33; Z = 35.74; $p < 0.001$) and are located mainly in the Central and Southern macrozones of the country.

Finally, the local Moran's index (LISA) results reveal an evident spatial autocorrelation at the country's extremes (Moran I = 0.49; Z = 248.18; $p < 0.001$), with only the central area exhibiting the lowest levels of vulnerability and the highest state of resilience (Fig. 5).

4. Discussion

Investigating the relationship between social vulnerability and community resilience is essential to develop more effective and equitable disaster risk management. Given Chile's geographic and socioeconomic diversity, understanding how these variables interact throughout the territory will allow us to identify the areas and populations most susceptible to damage and design specific interventions to strengthen their response and recovery capacity based on the local characteristics. Likewise, since is one of few studies in Latin America that addresses empirically and spatially the relationship between social vulnerability and community resilience, it offers a valuable basis for the formulation of guidelines and policies for disaster risk management in a region highly exposed to the occurrence of these events. It also highlights the need for reliable data for this purpose.

4.1. Social vulnerability & community resilience relationship

Our main results suggest that social vulnerability and community resilience are related but correspond to different concepts. This finding is consistent with previous research findings and reinforces the notion that, in general terms, communities with greater social vulnerability tend to exhibit lower community resilience and vice versa [22,27,30,43]. Also, our results show that in some communities the levels of vulnerability and resilience escape this trend, presenting low levels of vulnerability and low levels of resilience. These results reinforce the conclusion of previous studies that indicate that vulnerability and resilience are related concepts, but are

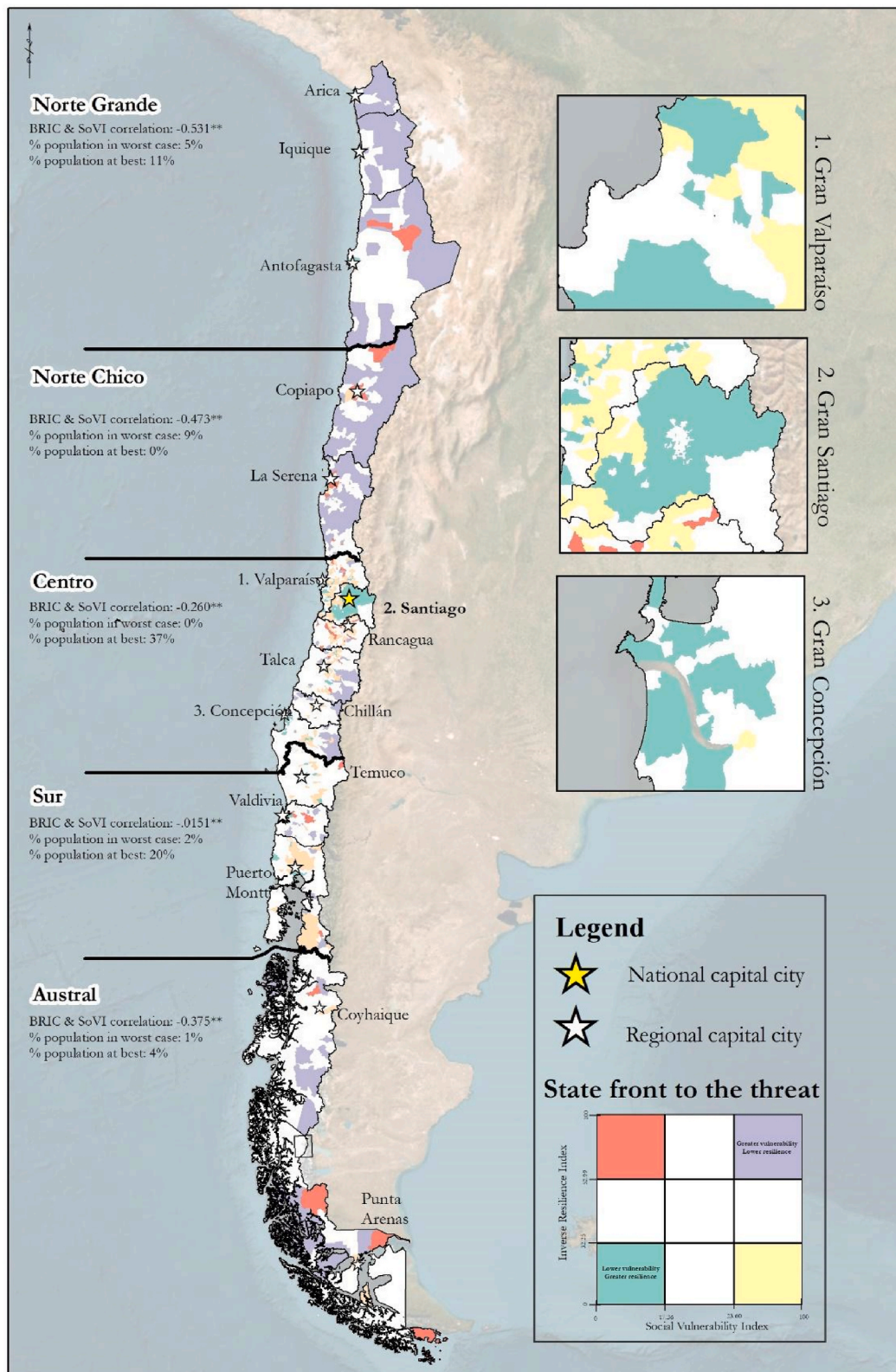


Fig. 4. Map of the association between SoVI and BRIC. The figure shows the spatial distribution of the quadrants of the matrix throughout the country. Additionally, the right side of the map presents the three most important urban areas of the country and the distribution of the relationship between vulnerability and resilience.

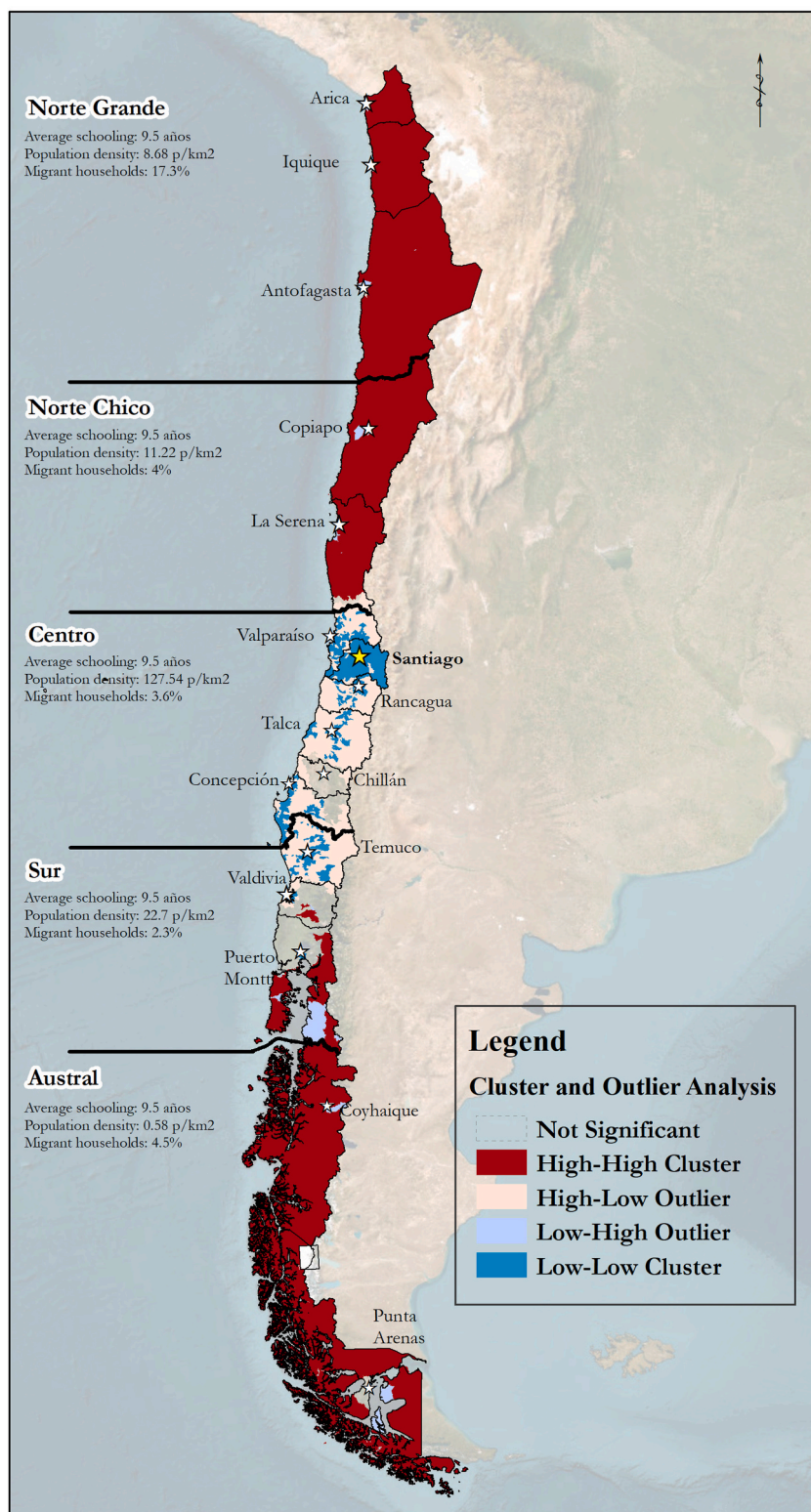


Fig. 5. Map of the local spatial autocorrelation between SoVI and BRIC. The figure shows the spatial distribution of all the quadrants of the matrix throughout the country, which reflects a grouping of the values between the extreme areas of the country in relation to the central area.

not extremes within a continuum [11,27,30].

The implications of these findings are relevant for formulating disaster risk management policies and strategies. First, the relationship between vulnerability and resilience as different concepts reinforces the importance of considering both elements to understand the conditions in which communities face disasters [27,43]. It's important to note that some communities may not follow the expected pattern of high vulnerability and low resilience levels. For example, the main cities of the Norte Chico macrozone, Copiapó, and La Serena, show low vulnerability and low resilience against natural hazards. This emphasizes the significance of not assuming that a community with low vulnerability automatically has high resilience. Also, these results indicate the relevance of conducting local studies that allow to identify of vulnerability and resilience levels within each territory and thus provide information to design disaster risk reduction strategies consistent with each place's characteristics.

On the other hand, our findings suggest implementing more comprehensive risk management strategies, focusing on the short-term impacts, attributable to the vulnerability levels of the communities are considered but also the medium and long-term effects associated with the capacities to recover and adapt [3]. The above becomes even more relevant considering the increase in the frequency of climate change-related hazards, such as droughts and floods, which require extensive adaptation and recovery processes.

Second, our results highlight the need to advance collective strategies to reduce social inequalities. Cutter et al. [23] point out in the Disaster Resilience of Place (DROP) model that the vulnerability and resilience characteristics, measured through the SoVI and BRIC index, are part of inherent elements to the population generated from the interaction of economic, natural, and social systems. Therefore, the relationship between both concepts implies that our understanding of disaster risk reduction policies must not only recognize the vulnerability of certain groups (groups of lower economic level, women, and older adults, among others) but also develop economic, educational, and infrastructure measures that reduce inequalities and promote social inclusion to increase the capacities of communities to respond and recover from disasters. Finally, understanding the relationship between vulnerability and resilience within each territory allows institutions in charge of disaster management to identify those communities most susceptible to damage and least capable of recovering from a disaster, facilitating the design and implementation of policies, plans, and focused programs better adapted to the needs of each community.

4.2. Geographic clustering of vulnerability & resilience

Our findings also reveal a clear geographic cluster of districts where localities with greater (or lesser) capacities to prepare, respond, and recover from a disaster tend to cluster geographically, suggesting the influence of specific local and regional factors that contribute to the vulnerability or resilience of the communities.

We found that districts with the lowest capacities to face and recover from a disaster were mainly grouped in the macrozones Norte Grande, Norte Chico, and Austral. On the contrary, the least vulnerable and most resilient districts were in the Central and Southern macrozones. This result could be explained by the highly centralized political administration and economic development model that characterizes Chile. The country has led to a notable accumulation of resources and population in the Central macrozone [9]. This significant centralization of resources could be the origin of the territorial disparity in various indicators of well-being and economic development, which helps to explain the variations in the levels of vulnerability and resilience between the different macrozones. Similarly, the disparity in levels of vulnerability and resilience can also be explained by a scenario of high inequality in the distribution of wealth. Elevated levels of inequality can affect communities' capacities to cope with and respond to disasters [23]. Chile is the second country among the OECD countries with the greatest income inequality [44] and ninth place within the countries of Latin America and the Caribbean, according to data registered until 2021 [45]. Consequently, these results are also important for Latin America because they suggest that these phenomena occurring in other countries in the region can affect the capacity for resilience against disasters. In this way, they show that reducing inequality is the main line of action for disaster risk reduction in Latin America.

On the other hand, our results show that districts with the highest levels of resilience and lowest levels of vulnerability are located in the country's main cities, a result consistent with previous findings [24,25]. Several reasons can explain this result. First, unlike rural or less urbanized areas, large cities are characterized by better economic conditions. In general, territories that have more favorable economic scenarios allow communities to prepare, respond, and recover more quickly from disasters and have more resources for planning and mitigation against them [25,26]. Additionally, cities tend to have a greater diversity of economic sectors and commercial activity than less urbanized areas, a characteristic that increases resilience and decreases the social vulnerability of communities [27]. Second, the level of work inactivity in large cities tends to be lower than in less urbanized areas, and, in general, work inactivity translates into greater vulnerability and less resilience to face a disaster since fewer resources are available for mitigation and recovery [2]. Third, educational levels among the population living in rural or less urbanized areas are lower than in large cities, a characteristic strongly associated with the capacity to prepare, respond, and recover from a disaster. In general, educational level is associated with the degree of knowledge of people and communities to understand natural hazards and the associated with preparedness and recovery actions [19]. Finally, unlike less urbanized areas, large cities have greater access to basic services (such as drinking water, electricity, and sewage) and communications that, in the face of a disaster, generate greater capacity for response and recovery [18].

5. Conclusions

In this study, we conclude that social vulnerability and community resilience are related, but they refer to different constructs. Furthermore, rather than being randomly distributed, localities with greater (or lesser) capabilities to prepare for, respond to, and recover from a disaster tend to cluster geographically. These results have important implications for central and local governments in charge of developing and implementing policies, programs, and plans associated with disaster risk reduction. Understanding the relationship between vulnerability and resilience in each territory will allow institutions in charge of disaster management to identify

those communities most susceptible to damage and least capable of recovering from a disaster, facilitating the design and implementation of policies, programs, and plans, which are best adapted to the needs of each community. Thus, the design of policies for disaster risk reduction must consider not only the recognition of the vulnerability of different social groups but also the development of economic, educational, and infrastructure capacities that reduce inequalities and promote social inclusion to increase the capabilities of communities to respond and recover from disasters.

For Chile, measuring and analyzing vulnerability and resilience throughout the national territory will contribute to fulfilling objectives established by the National Policy for Disaster Risk Management and Law 21.364, which gives rise to the National Disaster Prevention and Response System. (SINAPRED). Understanding the relationship between social vulnerability and community resilience is essential for advancing national resilience to natural disasters.

This study confirms the feasibility of the SoVI and BRIC indices for replication in other countries. Although this study found similar results to those of the United States and Norway, our results show that both indices allow us to investigate specific phenomena in Chile, such as centralism and economic inequality. This provides a first guide that makes it possible to replicate the index by adapting it to the particularities of each Latin American country.

Despite the relevance of the study results, there are limitations that need to be acknowledged. While the SoVI and BRIC indices are theoretically sound and widely replicable, they still need more empirical validation. Therefore, future research should focus on confirming whether both indexes can accurately predict the impact of disasters on communities. Furthermore, the study's results provide a static representation of the relationship between vulnerability and resilience. As both concepts are dynamic, the findings may change over time. Consequently, future studies should periodically measure social vulnerability and resilience. Lastly, the measures and relationships identified in this study may only be applicable to certain contexts due to the specificity of the data available in Chile.

CRedit authorship contribution statement

Nicolás C. Bronfman: Writing – review & editing, Writing – original draft, Supervision, Project administration, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Nikole Guerrero M.:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation. **Javiera V. Castañeda:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Pamela Cisternas:** Writing – original draft, Validation, Methodology, Formal analysis, Data curation. **Paula B. Repetto:** Writing – original draft, Validation, 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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Appendix A. Indicators integrated into the SoVI & BRIC for Chile

Index	Indicators	Domain ¹
SoVI	Percentage of the population with a household income between deciles 1 and 6	Socio-economic status
	Percentage of the population without a car	
	Percentage of leased housing	
	Percentage of women heads of household	Educational level
	Percentage of illiterate population over 15 years old	
	Percentage of the population ≥25 years with complete primary education	Employment
	Percentage of the unemployed population	
	Percentage of the active population (working age 15–64)	Demographics
	Percentage of the population enrolled in education	
	Percentage of women in the population	
	Percentage of single women with children	
	Percentage of population under 15 years old	
	Percentage of the population over 64 years old	
	The average age of the population	
	Percentage of retirees	
	Percentage of the population without a partner	

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(continued)

Index	Indicators	Domain ¹
BRIC	Percentage of the population with blindness	Population with a disability
	Percentage of the population with deafness	
	Percentage of the population with mutism	
	Percentage of the population with paralysis	
	Percentage of the population with mental disability	Ethnicity/immigrants
	Percentage of the population that identifies itself as being of Indigenous ethnicity	
	Percentage of the foreign population	
	Percentage of unrecoverable housing	Quality of housing
	Percentage of housing with unrecoverable walls	
	Percentage of housing with unrecoverable roofs	
	Percentage of housing with unrecoverable floors	
	Percentage of housing without access to potable water	Access to basic services
	Percentage of housing without access to sewerage	
	Overcrowding Index (persons in household/number of rooms)	
	Percentage of two-parent households with children	Social Resilience
	Percentage of households with telephone service available	
	Percentage of households without food insecurity	
	Percentage of the population affiliated with a pension fund	
	Percentage of the population with a health insurance system	
	Percentage of the population over twenty-five who reached basic ed.	
	Percentage of the population that speaks Spanish	
	Percentage population under 65 years old	
	Percentage population without disability	
	Number of doctors per 10,000 inhabitants.	
	Number of psychologists per 10,000 inhabitants.	
	Percentage voter turnout	Social-Community Capital
	Percentage of the population from another country with residence in 2012	
	Percentage of the population born in Chile	
	Percentage of the population participating in civil organizations	
	Percentage of the population participating in religious organizations	
	Percentage of the population participating in volunteering	
	Percentage gap between all genders	
	Percentage of home ownership	Economic Resilience
	Degree of employment diversification	
	Percentage population employed in non-resilient sectors	
	Percentage population working	
	Number of trading companies	
	The ratio between large and small companies	
	Km away from the regional capital	
	Number of credits and subsidies for agricultural development	Institutional Resilience
	Number of districts per region	
	Number of people trained by SENAPRED ²	
	Number of agricultural insurance policies	
	Number of governorates	
	Intercensal growth rate 2015–2020	
	Percentage of households with acceptable materiality	Infrastructure Resilience
	Percentage population with internet access	
	Percentage Homes built post. thermal standard	
	Km railway network per km ²	
	Km road network per km ²	
	Distance to airports or aerodromes in m.	
	Number of educational centers per 10,000 inhabitants.	
	Number of coastal protections works	
	Percentage of biodiversity areas	Environmental Resilience
	Percentage of soil without potential erosion	
	Percentage of surface considered as wetlands	
	Percentage of protected area	
	Percentage of arable land	
	Percentage area without land use change	
	Km of rivers per km ²	
	Km ² with water scarcity decrees	
	Number of dune fields	
	Number of forest industries per 10,000 inhabitants.	

Note.

¹ Domains correspond to the theoretical grouping of the indicators for both indices (SoVI & BRIC).² SENAPRED corresponds to the National Disaster Prevention and Response Service.

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