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Vulnerability of small-scale farming livelihoods under climate variability in a globally important archipelago of the Global South

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ABSTRACT

In recent decades, the pace of change in social-ecological systems has accelerated. The adverse effects of climate variability and extreme events put increasing pressure on rural small-scale farmers' households whose livelihoods depend on nature. However, socioeconomic, political, and institutional changes also affect this group, responsible for producing at least a third of the world's food. This study assessed the influence of climate variability on the spatial distribution of the social-ecological vulnerability of small farmers' livelihoods within a Globally Important Agricultural Heritage System (GIAHS) in southern South America. Data were collected through a questionnaire-based survey of 100 small-scale farmers' households, selected via stratified random sampling. Climate variability and extreme event data spanning 30 years were included, with spatial and temporal resolutions of 1 × 1 km and one year, respectively. Through an indicator-based approach, the study identified 17 vulnerability indicators across Exposure, Sensitivity, and Adaptive Capacity components. The Livelihood Vulnerability Index (LVI) for small-scale farming in the Chiloé Archipelago was calculated at the household level, following the IPCC vulnerability assessment framework and the Sustainable Livelihoods perspective. The findings reveal that LVI values for small-scale farmers ranged from 0.28 (least vulnerable) to 0.54 (most vulnerable). Principal Component Analysis indicated that agricultural extension support, supplementary income, social relations, and ownership of agricultural equipment enhance local adaptive capacity. Spatial autocorrelation analysis revealed clustering in exposure, sensitivity, adaptive capacity, and vulnerability patterns. The finding suggests that extension interventions should strengthen vulnerable households' adaptive capacity by supporting rural livelihood diversification.

1. Introduction

Historically, Indigenous Peoples and Local and *Campesino* Communities (IP&LCC) have employed traditional agricultural systems, based on a combination of production and consumption activities that have enabled them to satisfy their basic needs, even in adverse and challenging environmental conditions (Altieri, 1999). These systems are managed by small-scale farmers, who are responsible for producing at least a third of the world's food (Lowder et al., 2021; van der Ploeg, 2014). Moreover, some 80% of agricultural farming in Latin America corresponds to family farms (Marchant et al., 2021). These small-scale farms constitute social-ecological systems (SESs) that encompass both social subsystems (pertaining to human beings) and ecological subsystems (related to biophysical aspects), which interact reciprocally (Berkes and Folke, 2000). There is abundant evidence that the planet's climate is undergoing a social-ecological crisis, with numerous

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consequences for small-scale farming systems (IPCC, 2021; Mekonen and Berlie, 2021).

Climate change is related to changes in temperature and precipitation patterns while climate variability refers to variations in the average state of the climate and other climate statistics (e.g., standard deviations, extreme events) on spatial and temporal scales that go beyond individual weather events (IPCC, 2021; Mussetta and Barrientos, 2015). Climate-associated changes are just one facet of the social-ecological crisis (Blanco, 2016). Small-scale farming systems also face socioeconomic, political, and institutional changes that constitute a situation of global environmental change (Montaña et al., 2016). Rural small-scale farmers' households are particularly vulnerable to global environmental change which, as well as affecting agricultural production patterns, also impacts their livelihoods, undermining their ability to address and adapt to disturbances (Das et al., 2023). In developing countries, the dependence of livelihoods on farming production, combined with poor adaptive capacity and limited access to resources to mitigate the impacts of climate change, contributes to household vulnerability (Huong et al., 2019).

Assessment of vulnerability in SESs is one of the tools that can be used to quantify the extent to which global environmental change is affecting ecological functioning and social well-being (Berrouet et al., 2020). For example, the Livelihood Vulnerability Index (LVI), developed within the vulnerability framework of the Intergovernmental Panel on Climate Change (IPCC), has become the main reference for analyzing vulnerability at different scales (IPCC, 2021). In this operationalization (Equation (1)), social-ecological vulnerability is understood as a three-dimensional concept, comprising exposure, sensitivity, and adaptive capacity. Exposure has to do with the impact of the physical and meteorological events associated with climate variability on a system (IPCC, 2021) while an SES's sensitivity, which exists before the disturbance, indicates the degree to which it is affected, positively or negatively, by climatic stresses (Gallopín, 2006). Finally, adaptive capacity is understood as these systems' ability, aptitude, or potential to adjust or adapt to new or changing contexts (Adger, 2006; IPCC, 2021). Two methods can be used for the assessment: (i) the evaluation of vulnerability variables, and (ii) the indicator-based approach. The latter has been widely used in the literature as it allows an integral understanding of the three dimensions of social-ecological vulnerability, can be applied to any scale of analysis, and permits comparison of vulnerability across different systems (Acheampong et al., 2014; Hoque et al., 2022). Moreover, the goal of using indicators to measure vulnerability is to strengthen adaptive capacity (Mussetta and Turbay, 2016).

$$LVI = \textit{Exposure index} + \textit{Sensitivity Index} - \textit{Adaptive Capacity Index} \qquad \text{(Equation 1)}$$

As a means of assessing social-ecological vulnerability at the household level, the integration of the framework proposed by the IPCC with the conceptual perspective of Sustainable Livelihoods (Chambers and Conway, 1992) has gained ever more ground (Lin and Polsky, 2016). Indicators linked to the five types of capital proposed by this analytical framework (financial, human, social, physical, and natural) can be used effectively to approximate measures of adaptive capacity among different households, considering differential access to resources, where greater access, number of resources, and ability to combine types of capital increase a household's adaptive capacity (Stevens et al., 2023). This conceptual perspective also allows a multidimensional approach to a farming system (Easdale et al., 2018).

In the first application of the LVI, Hahn et al. (2009) applied the methodology to 200 households in Mozambique, finding that their socio-demographic characteristics and access to water resources were factors in the different levels of vulnerability observed. In Ethiopia, small-scale farmers are highly vulnerable to recurrent droughts and due to a low adaptive capacity and high sensitivity and exposure to these events, the impact on their livelihoods is severe (Tofu et al., 2023). In Trinidad and Tobago, limited access to drinking water, unequal access to transport, and excessive dependence on agricultural income affect the vulnerability of farmers' livelihoods in an island social-ecological context (Shah et al., 2013). In South America, current climate variability has had significant consequences in both Colombia and Peru. In Colombia, a decrease in grass and livestock production has negatively affected household incomes. In Peru, floods caused by climate variability have directly impacted crop yields (Beltrán-Tolosa et al., 2022). Similarly, in the Chiloé Archipelago of southern Chile, farmers have identified both climatic and local changes as impacting their livelihoods (Caviedes et al., 2023).

Over two decades ago, the United Nations Food and Agriculture Organization (FAO) launched its initiative on Globally Important Agricultural Heritage Systems (GIAHS) in response to global trends that posed a threat to small-scale farming systems (FAO, 2018; Kajihara et al., 2018). Since 2005, FAO, along with different national governments, has declared 89 GIAHS sites in 28 countries around the world, including the Chiloé Archipelago in southern Chile. However, given the exposure of small farmers' livelihoods to climate variability and global socioeconomic pressures, designation as a GIAHS has not reduced the threats they face (Ducusin et al., 2019). For example, the exposure of the Chiloé Archipelago to global environmental change has been reflected in variations in precipitation, recurrent droughts, difficult access to water, and political and economic pressure on important marine and terrestrial ecosystems (Caviedes et al., 2024; Llanquepi, 2021; Román et al., 2015; Frêne et al., 2022; Oyarzo et al., 2024).

In the current context of global environmental change, it is imperative that vulnerability be addressed at the household level because macro-scale assessments fail to capture the specific characteristics of smaller scales, which call for more minute analysis at a detailed spatial level (Rosero et al., 2022). The determinants of vulnerability are specific to each context and vary spatially so the indicators selected to study it must be able to incorporate local variables specific to each geographical context (Asfaw et al., 2021; Eakin and Bojórquez-Tapia, 2008; Eakin and Lemos, 2006; Kelly and Adger, 2000). In addition, spatial variations in the vulnerability of agricultural livelihoods in coastal areas to current climate variability have not been exhaustively assessed (Hoque et al., 2022). Zainab and Shah (2024) conducted a bibliometric analysis of the application of the LVI in different regions. Based on 60 studies published between 2010 and 2023, it revealed a focus on Asia and Africa and only limited work on Latin America. Finally, little attention has been paid to the social-ecological vulnerability of small-scale farmers located in a GIAHS.

In this study, we seek to answer the question: How may climate variability influence the spatial distribution of the social-ecological vulnerability of small-scale farmer's livelihoods in the Chiloé Archipelago? The objective is to evaluate this social-ecological vulnerability in an emblematic small-scale farming system in southern South America. We predict that the effects of current climate variability, including changes in temperature and precipitation patterns, may be driving the social-ecological vulnerability of small-scale farming. In addition, we predict that agricultural income and social relationships may be contributing to the adaptive capacity of small-scale farmers, thereby reducing their vulnerability. To test these predictions, we conducted surveys of small farmers and used ordination techniques to prioritize variables and Geographic Information Systems (GIS) to map and examine the spatial distribution of livelihood vulnerability.

2. Methods

2.1. Study area

We conducted the research in 100 households in the Chiloé Archipelago (41–43°S) (Fig. 1), a territory situated in the "Chilean Winter Rainfall-ValdivianForest" conservation hotspot of southern Chile. This archipelago comprises the main island, Isla Grande de Chiloé, which has

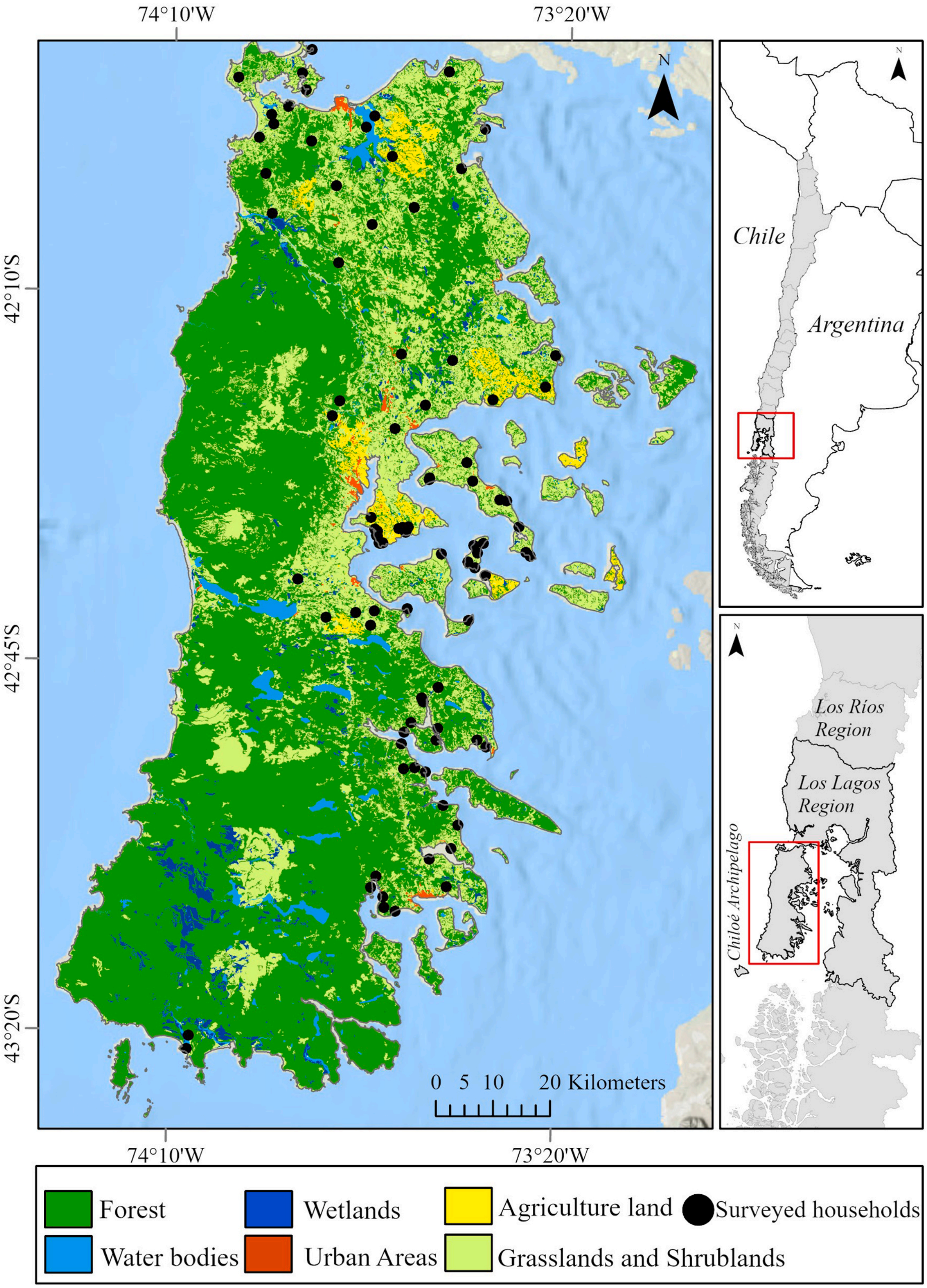

Fig. 1. Study area and location of the 100 households evaluated in the Chiloé Archipelago, a Globally Important Agricultural Heritage System (GIAHS).

an area of 8394 km^2, and 40 smaller islands located between this island and mainland Chile. The archipelago has an average temperature of 11 °C and annual precipitation exceeding 2000 mm in its eastern part, 3000 mm on its western coast, and more than 4000 mm in the higher areas of the Coastal Mountain Ranges (https://explorador.cr2.cl).

This island territory is divided into ten municipal districts and, since 2011, has been a GIAHS. It is officially recognized as a sub-center of origin of the potato (Solano, 2019). Traditionally, before the onset of agricultural modernization, its Indigenous communities and small-scale farmers cultivated some 800-1000 native potato varieties (Nicholls and Altieri, 2018). In addition, Chiloé is a fundamental reservoir of agro-biodiversity, not only because of the large variety of native potatoes cultivated by small farmers but also due to its lamb, garlic, strawberries, currants, raspberries, and apple trees (Venegas and Lagarrigue, 2018; Castro et al., 2018).

Despite the singularities that characterize this iconic archipelagic system of southern South America, increasing social-ecological changes represent a latent threat to its globally recognized small-scale farming system (Oyarzo et al., 2024). Studies indicate that local small farmers report changes in temperatures as well as the amount and duration of rainfall and an increase in the frequency and intensity of droughts (Caviedes et al., 2023; Reyes-García et al., 2022). In addition, significant demographic pressure on sensitive local water systems is generated by the subdivision of rural properties in the territory (Frêne et al., 2022).

2.2. *Data collection*

We determined the sample size using the formula suggested by Scheaffer et al. (1990). We collected the data from a representative sample of 100 small-scale farmers' households using stratified random sampling techniques (Otzen and Manterola, 2017). This number is considered adequate for studies of traditional farming systems of a scale like those in the study area (Albuquerque et al., 2014). We surveyed small-scale farmers from the main island of Chiloé and some smaller islands (Quinchao Island, Quehui Island, Chelín Island, and Lemuy Island), which ensured spatial representation from 75 rural localities across the archipelago's ten municipal districts. The fieldwork was conducted between 2022 and 2024 during the summer.

The study was approved by the Ethics Committees of the Catholic University of Chile (protocol code 190603004–24 April 2020) and the Austral University of Chile. The questionnaire, addressed to the head of household, covered the following thematic areas: the household's socioeconomic conditions, the characteristics of the family farming system, and information related to the family's livelihood.

2.3. *Livelihood Vulnerability Index*

Construction of the Livelihood Vulnerability Index (LVI) began with a review of empirical studies employing a similar methodology to compile commonly used socioeconomic and biophysical indicators. Initially, 28 indicators were identified: three for exposure, four for sensitivity, and 21 for adaptive capacity. To reduce dimensionality and permit prioritization, the latter were then subjected to principal component analysis (PCA), selecting the ten indicators with the highest contribution to assessing adaptive capacity. The LVI was, therefore, calculated using a total of 17 indicators (Table 1). The vulnerability of the small-scale farmers' households was measured using the indicator or indexing method with a balanced or equal weighting approach.

The first step in calculating the LVI was to standardize the value of each indicator (Hahn et al., 2009). This process was performed to place the indicators within a range of 0–1. Standardization of the indicators is crucial to ensure consistency and permit their relative comparison (Hoque et al., 2022). The following equation was used for this purpose (Equation 2):

$$x' = \frac{x - min}{max - min} \quad (Equation\ 2)$$

where x' is the normalized value, x is the original value, and min and max indicate the variable's minimum and maximum values. In addition, when an indicator (x') showed a negative relation with its respective component of vulnerability (such as the effect of health problems on agriculture and adaptive capacity), the normalized value for each indicator was recalculated, subtracting 1 from x' (Table 1).

2.4. *Exposure*

The variability of temperature and rainfall with respect to their mean values and the frequency of extreme events are associated with exposure to climate variability (Negatu et al., 2011). For this study, the historical changes in mean annual precipitation and temperature and their inter-annual variation were obtained from the meteorological data of Chile's Climate and Resilience Research Center (CR$_2$MET). With its spatial and temporal resolution (1 × 1 km and 1 year), this data serves for work at a local scale. The dataset includes three-hourly measurements of precipitation and near-surface temperature from 1979 to 2019. CR$_2$MET's precipitation and temperature estimates are based on statistical models that translate ERA-Interim precipitation data (Dee et al., 2011) into better regional estimates for Chile by incorporating local information (topography and temperature observations). In addition, it is calibrated with local weather stations managed by the Chilean General Water Board (DGA) and includes surface temperature data from sensors such as MODIS LST (Boisier et al., 2018).

Drought episodes between 2010 and 2019 for each farm unit were identified using the Standardized Precipitation Evapotranspiration Index (SPEI), a meteorological indicator that detects abnormally dry or wet climate conditions (Beguería et al., 2014; Scordo et al., 2018). To calculate the SPEI, monthly minimum and maximum temperature data (previously obtained from CR$_2$MET data) was required as well as precipitation data and it was necessary to estimate potential evapotranspiration (PET). For this calculation, the "SPEI" package of R software version 4.3.2 was used. Finally, to reflect the details and general characteristics of droughts in the study area and include this in the vulnerability index, drought conditions were analyzed on a monthly scale, classifying the level of drought as by Sun et al. (2021). Under this classification, there is no drought when the SPEI is greater than −0.5. A mild drought is declared when SPEI is between −1.0 and −0.5 while a moderate drought occurs when it is between −1.5 and −1.0. A drought becomes severe with a SPEI between −2.0 and −1.5 and extreme when it is equal to or less than −2.0. Therefore, the range of SPEI values considered to define these events was from −0.5 to −2.0.

2.5. *Sensitivity*

We incorporated four contextualized sensitivity indicators. To identify areas that are more or less sensitive to factors such as soil erosion and runoff, we followed Mekonen and Berlie (2021), who classify the gradient of the study area into six classes ranging between 0 and 2% (less sensitive) and >30% (more sensitive). The gradient of each farm unit was obtained from an ALOS PALSAR digital elevation model (Rosenqvist et al., 2007). In addition, the size and workforce of each household were included as indicators associated with the demographic pressure sub-component. Similarly, journey time to the nearest urban center, as reported by each survey respondent, was included as an indicator of accessibility.

2.6. *Adaptive capacity*

To assess adaptive capacity at the household level, we used ten indicators linked to the five types of capital proposed by the Sustainable Livelihoods framework (Chambers and Conway, 1992). Through survey questions, we obtained measurable indicators that were grouped into one of these types of capital (i.e., financial, human, social, physical, and natural; Table 1). For example, to evaluate the presence of government extension services, we asked each family whether they received support or not (a binary variable), taking this as an indicator of financial capital. For questions with answers divided into categories, scores that ranged from 0 to 1 were divided by the number of possible categories (e.g., for the question "How much do health problems affect farm work?", which is an indicator of human capital, the potential responses were coded as a great deal [0], somewhat [0.33], little [0.66], and not at all [1]).

Table 1
Household-scale indicators to construct the Livelihood Vulnerability Indicator (LVI) for small-scale farmers in Chiloé. References of empirical studies using a similar methodology: 1. Acheampong et al. (2014); 2. Asfaw et al. (2021); 3. Beltrán-Tolosa et al. (2022); 4. Hoque et al. (2022); 5. Huong et al. (2019); 6. Madhuri et al. (2015); 7. Mekonen and Berlie (2021); 8. Mussetta and Turbay (2016), A: Authors. Column R indicates the indicator's relation with its respective sub-component.

Component	Sub-component	Indicator	R	Functional relationship with component	Source
Exposure (E)	Climate variability and extreme events	Variation in mean annual precipitation (1990–2019)	+	The variability of temperature and precipitation, as well as the frequency of extreme events, will increase exposure to climate variability.	(1,2,4,7,8)
		Variation in mean annual temperature (1990–2019)	+		(1,2,4,7,8)
		Extreme events (droughts, 2010–2019)	+		(1,4,6,7,8)
Sensitivity (S)	Demographic pressure	Size of household	–	Households of larger sizes and with larger workforces will be less sensitive to the impacts of climate variability.	(1,2,4,6,7)
		Agricultural workforce	–		(1,4,6,7)
	Accessibility	Journey time to nearest urban center	+	Longer travel time to the nearest urban center makes access to markets, schools, and health facilities more difficult.	(7)
	Biophysical context	Gradient	+	The gradient affects drainage processes, runoff, and susceptibility to erosion.	(7)
Adaptive capacity (AC)	Financial capital	Monthly household income	+	The wealthier a household, the higher its adaptive capacity.	(1,3,4)
		Technical assistance for agricultural problems	+	The support of state technical assistance favors the development of adaptive capacity.	(8)
	Human capital	Help on the farm	+	The more help on the farm, the better its adaptive capacity.	(1,4,6,7)
		Effect of health problems on agriculture	–	Small-scale farmers' health problems negatively impact their adaptive capacity.	(5,6,7)
	Social capital	Relatives living nearby	+	Being a member of organizations and having family support networks would provide scope for developing adaptive capacity.	(A)
		Participation in groups	+		(3,8)
	Physical capital	Access to irrigation systems/ infrastructure	+	Households with better access to such elements would have better adaptive capacity to climate variability.	(2)
		Ownership of agricultural equipment	+		(8)
	Natural capital	Number of units of livestock	+		(3)
		Diversity of potato varieties	+		(A)

The same process was applied to indicators of physical capital to evaluate irrigation infrastructure (drip systems, storage, collection, and pumps or wells) and ownership of agricultural equipment and technology (mower, brush cutter, chainsaw, tiller, small tractor, vehicle, and large tractor). To calculate the units of livestock by size and metabolic rate, which are an indicator of natural capital, we followed Chilonda and Otte (2006) and Caviedes et al. (2024). Finally, the weighted scores for each of the five types of capital were added together to construct a composite index ranging from 0 (lowest adaptive capacity) to 1 (highest adaptive capacity).

2.7. Data analysis

We analyzed the data using both descriptive and inferential statistics. Minimum, median, mean, and maximum values and standard deviation were calculated for (i) the exposure of small farming to current climate variability and extreme events, (ii) the sensitivity of island farming systems, (iii) the capacity of rural households to adapt to climate variability, and (iv) the vulnerability of livelihoods (LVI). In addition, comparisons between indicators and groups were performed. Principal component analysis (PCA) was conducted using the "FactoMineR" package of R software version 4.2.3 (R Core Team, 2022). The approach used to perform the PCA in FactoMineR is described in detail in Lê et al. (2008). Adaptive capacity variables were included in this process because this is the only dimension capable of reducing vulnerability (Acevedo and Urán Carmona, 2023). The dataset comprised 100 individuals (rural households) and ten variables (indicators). The PCA minimizes the number of important indicators and highlights the most relevant elements from among a large number of associated sub-components within a collection of uncorrelated variables. By using eigenvalues, it is possible to determine the sub-component making the largest contribution to the principal components (Gupta et al., 2020). Principal components (PCs) with an eigenvalue equal to or greater than 1 were retained for subsequent data analysis (Maru et al., 2021).

Lastly, spatial autocorrelation analysis was used to determine whether there was a statistically significant correlation between the values of an attribute in adjacent geographical locations (Cárdenas-Pizarro et al., 2023). This process was conducted using Moran's index (1950) with ArcGIS Pro. This analysis was performed for livelihood vulnerability across the set of rural households as well as for its dimensions (exposure, sensitivity, and adaptive capacity). A value of Moran's index greater than 0 indicates positive spatial correlation (a clustering pattern) whereas a value of less than 0 denotes negative spatial correlation (a dispersed pattern) and a value of 0 is associated with an absence of autocorrelation (a random pattern) (Siabato and Guzmán-Manrique, 2019).

3. Results

3.1. Socio-demographic profile of rural households

Out of the 100 people surveyed for this study, 71 were women and 29 were men. In addition, 94% of the families indicated that they had their origin in the region (i.e., they self-identify as *chilotes*). Participants' ages ranged from 23 to 82 years (Mean ± SD = 58 ± 12) and 74% reported not having completed secondary education.

3.2. Exposure of small-scale farming to climate variability and extreme events

The exposure of small farmers in Chiloé to climate variability and extreme events ranged from 0.31 (less exposed) to 0.63 (more exposed), with a mean value of 0.48. Analysis of rainfall patterns in the archipelago over a 30-year period (1990–2019) shows a mean annual precipitation of 1892 mm, with a minimum of 1358 mm and a maximum of 3028 mm (Fig. 2). The records indicate maximum mean annual precipitation values of 2139 mm, 2070 mm, and 2000 mm in 1994, 2002, and 2017, respectively, while the lowest values of 1112 mm, 1326 mm, and 1363 mm were observed in 2016, 1998, and 2007, respectively. Considerable variability in the precipitation regime was also observed in the region studied, with a fluctuation in mean annual precipitation that ranged from 9.8% to 15.5%, with an average of close to 12%. In the case of the spatio-temporal variation in precipitation (Fig. 2), a higher incidence is observed in the center of the archipelago, with a decrease in

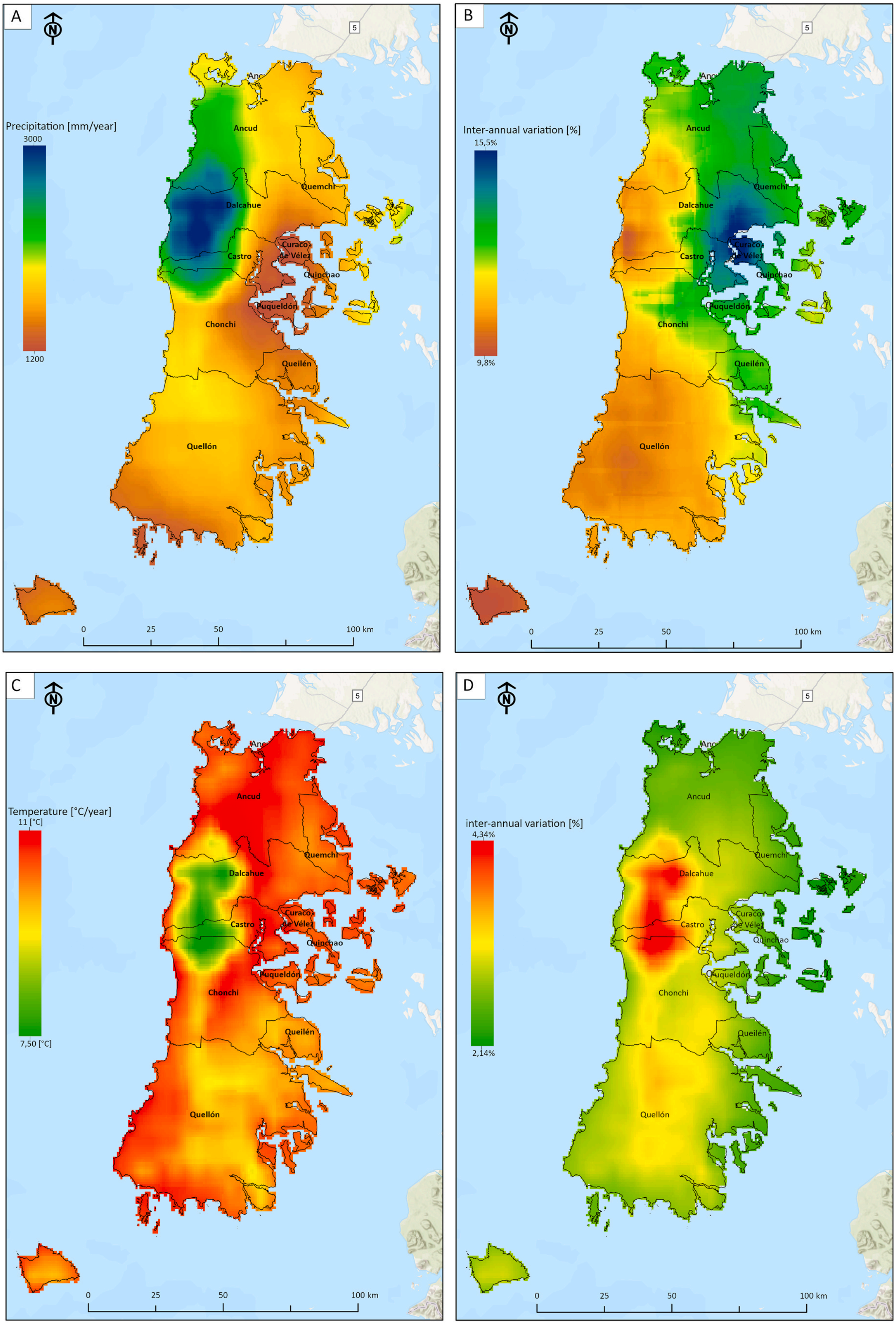

Fig. 2. Climatological analysis of the Chiloé Archipelago. The figure comprises four maps (A–D) that depict the climatological characteristics of the region between (1990–2019) maps A and B show the average precipitation and its inter-annual variability, respectively. Maps C and D illustrate the average temperature and its inter-annual variability.

variability towards the south.

Analysis of the mean annual temperature indicates significant variations in the study area. The minimum mean annual temperature recorded was 7.5 °C while the maximum mean annual reached 11.15 °C, with an annual average of 10.24 °C. The years with the lowest mean temperatures were 2007 and 2010, with 9.9 °C and 10.1 °C, respectively, while the years with the highest mean temperatures were 1998, with 11 °C, and 2016, with 11.05 °C. In terms of variability, a range from a minimum of 2.14% to a maximum of 4.34%, with a mean of 2.93%, is observed. The SPEI results indicate that between 50 and 61 drought episodes were recorded across the archipelago between 2010 and 2019 (55 ± 2.32). The range of SPEI values considered to define these events was from −0.5 to −2.0.

3.3. *Sensitivity of the island agricultural systems and extreme events*

The inclusion of the biophysical and socioeconomic indicators selected for the sensitivity analysis showed that, among small farmers in Chiloé, sensitivity levels ranged from 0.17 (less sensitive) to 0.79 (more sensitive), with a mean value of 0.43. Households with higher demographic pressure tended to be more sensitive to the effects of climate variability. Household composition ranged from 1 to 7 persons (2.55 ± 1.14) while the workforce available to each household fluctuated between 1 and 6 persons (2.33 ± 1). Moreover, the sensitivity of small-scale farming increased with journey time to the nearest urban center, markets, schools, and healthcare facilities (Mekonen and Berlie, 2021). The results showed that journey times ranged from 5 to 360 min (48.32 ± 0.15), with these wide differences explained by the geographical diversity characteristic of island social-ecological contexts. Furthermore, a farm’s biophysical context significantly influences agricultural livelihoods due to its effect on drainage and runoff processes. The gradients of the small farmers surveyed ranged from 0.5% to 31.27% (2.33 ± 1).

3.4. *Adaptive capacity of rural households in the face of climate variability*

When combining the weighted values of the indicators for adaptive capacity, the values obtained ranged from 0.04 to 0.70 (0.39 ± 0.11). In the case of financial capital, 33% of the households were found to be below the Chilean poverty line of 219,970 pesos per person.[1] The results showed that non-agricultural sources of income play a crucial role in the economy of rural households, which achieve subsistence by combining farm and off-farm earnings. On average, 71% of household monthly income came from complementary activities, underscoring the importance of pluriactivity for these small-scale farmers. Conversely, 29% of household income was derived from agricultural activities. Wage labor was the most common non-agricultural form of subsistence. In addition, 60% of the small-scale farmers received technical-scientific assistance from Chile’s National Institute for Agricultural Development (INDAP).

In the case of human capital, the small-scale farms were managed on average by two people. Out of the small-scale farmers surveyed, 47% reported health problems that affected their capacity to work the farm. On social capital, 87% of survey participants reported a “good” or “very good” relationship with their neighbors. On average, local farmers participated in three organizations, with 74% of households belonging to at least one group related to agriculture.

In relation to physical capital, such as irrigation infrastructure for water capture, the households were found to manage between one and two of these elements. In addition, as regards possession of agricultural equipment and technology, 91% of the small-scale farmers reported having at least one device. Finally, in the case of natural capital, the survey results highlighted the importance of the cultivation of different potato varieties in the small-scale households visited, with 97% of households growing at least one variety. In all, they cultivated between one and 18 potato varieties (5 ± 0.17). Similarly, 98% of households reported owning at least one unit of livestock (70.66 ± 0.11), with chickens, sheep, and cows being the most numerous.

Analysis of the dimensions of vulnerability (Fig. 3) reveals that the sub-index of exposure (A) ranges from 0.31 to 0.63 (0.48 ± 0.08), sensitivity (B) from 0.18 to 0.79 (0.43 ± 0.11), and adaptive capacity (C) from 0.04 to 0.70 (0.39 ± 0.11). Finally, the Livelihood Vulnerability Index (LVI) has a minimum value of 0.28 and a maximum value of 0.54 (0.43 ± 0.05) (see Table 2).

The results reveal similar levels of vulnerability between farmers who receive technical assistance for agricultural problems and those who do not receive this assistance. However, agricultural extension services do have a positive impact on adaptive capacity, which is higher among those who receive this support (0.42) than among those who do not (0.36). In addition, the results indicate that technical advice favors access to advanced agricultural equipment and technology as reflected in greater physical capital (0.49) among recipients compared to non-recipients (0.33). Moreover, farmers on smaller islands of the archipelago exhibit greater sensitivity (0.46 vs. 0.43), greater adaptive capacity (0.44 vs. 0.39), and greater livelihood vulnerability (0.46 vs. 0.42) compared to those living on the main island.

Based on the PCA results, the first four principal components (PCs) were retained because they had eigenvalues ≥1 (Table 3). The variability represented by the PCA in terms of PC1, PC2, PC3, and PC4 was 23.2%, 16%, 13.9%, and 12%, respectively. Thus, the four components explain ~65% of the cumulative variance of the dataset. In PC1, five indicators emerged as the most significant according to their factor loadings: ownership of agricultural equipment, participation in groups, availability of labor, monthly household income, and technical-scientific assistance for agricultural problems. In PC2, the indicator that stood out was relationship with relatives. In PC3, the impact of health problems on agriculture was identified as the main indicator while, in PC4, the number of units of livestock was the best indicator. These findings show that the indicators with the highest factor loadings contribute more to the development of adaptive capacity among farmers living in island territories and are, therefore, fundamental for reducing the vulnerability of their livelihoods.

Based on the results, the vulnerability index was classified into five inter-quartile ranges to ensure homogeneous representation of its values in five classes. Values between 0.28 and 0.38 indicate very low vulnerability; between 0.38 and 0.48, low vulnerability; between 0.42 and 0.44, medium vulnerability; between 0.44 and 0.49, high vulnerability; and between 0.49 and 0.54, very high vulnerability (Fig. 4) (see Fig. 5).

4. Discussion

This study contributes to global efforts to understand livelihood vulnerability and strengthen the adaptive capacity of small-scale farming in local social-ecological systems. Our results show the spatio-temporal variation of climate variability and extreme events, thereby helping to understand the forces driving change in a Global Biodiversity Hotspot and a Globally Important Agricultural Heritage System (GIAHS). Importantly, we found that complex insular geographic diversity affects the sensitivity of small-scale agricultural systems. Likewise, supplementary income, rural extension support, and social relationships appear vital in a household’s adaptive capacity.

Before discussing our results, it is essential to acknowledge some limitations of this study. Firstly, the selection of variables and the application of indices involve a degree of subjectivity. As a result, some variables that could have influenced the vulnerability of livelihoods in small-scale agricultural systems may have been absent. Secondly, the interactions among the components of a social-ecological system (SSE) are inherently complex, making it difficult to understand it comprehensively by analyzing only some of its elements quantitatively. Finally,

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[1] As of August 06, 2024, 1 Chilean peso = US$ 0.0010.

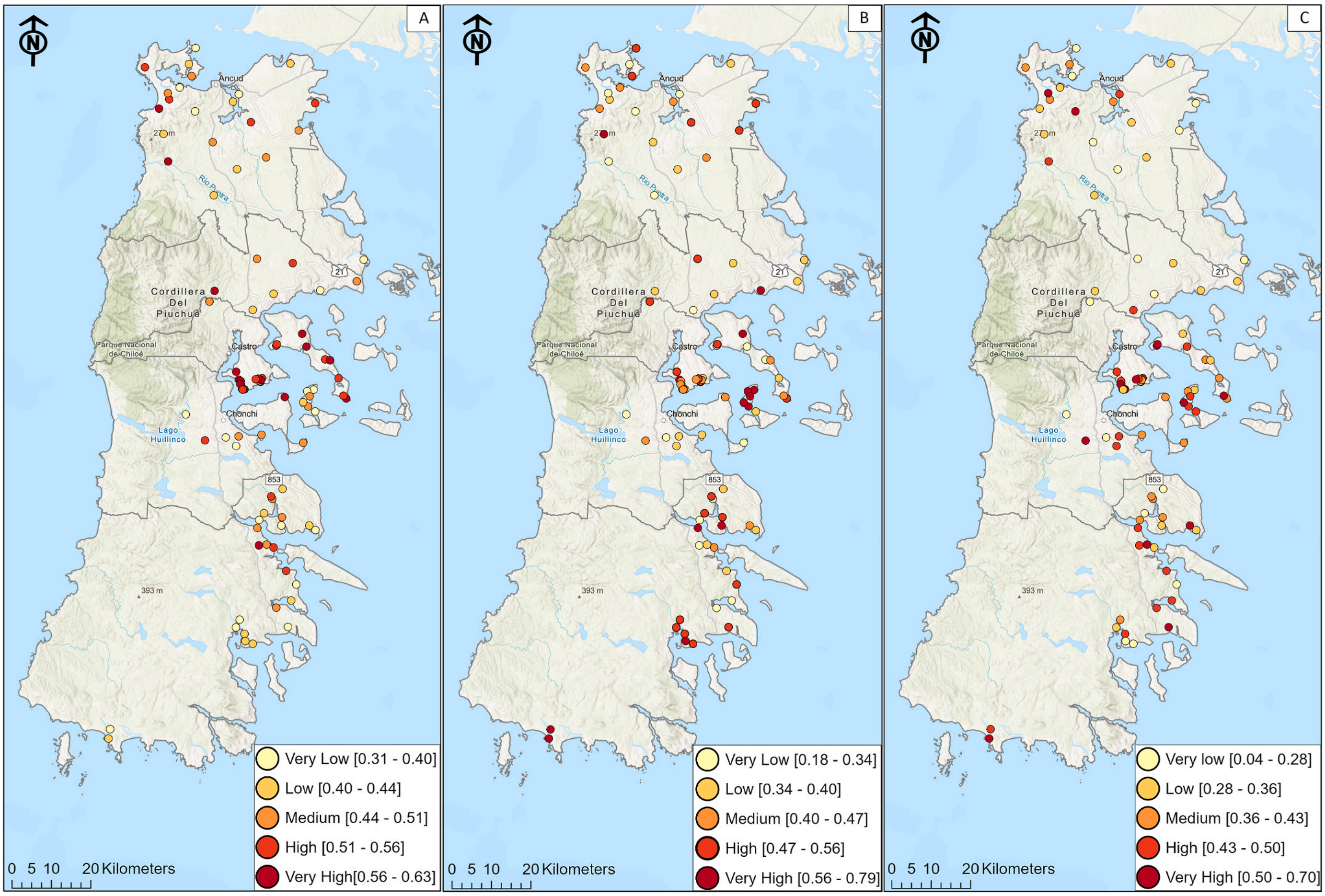


Fig. 3. Spatial distribution of exposure (A), sensitivity (B), and adaptive capacity (C) at the household level in small-scale farming in the Chiloé Archipelago. Ranges calculated using the quartile method.

Table 2
Minimum, median, mean, and maximum values of the dimensions of exposure, sensitivity, adaptive capacity, and the Livelihood Vulnerability Index (LVI) of small-scale farmers in Chiloé.

Vulnerability Component	Min	Mean	Median	Max	SD
Exposure	0.31	0.48	0.47	0.63	0.08
Sensitivity	0.18	0.43	0.44	0.79	0.11
Adaptive Capacity	0.04	0.39	0.39	0.70	0.11
LVI	0.28	0.43	0.43	0.54	0.05

Table 3
Contribution of social-ecological indicators linked to the adaptive capacity of small-scale farming in terms of factor loadings/eigenvector values in the principal component analysis (PCA).

Components	PC1	PC2	PC3	PC4
Eigenvalue	2.30	1.62	1.45	1.26
% variance	23.2	16.01	13.91	12.01
% accumulated variance	23.20	39.20	53.12	65.15
Factor loading of variables				
Monthly household income	0.55	−0.6	−0.01	−0.1
Technical-scientific assistance for agricultural problems	0.54	0.43	0.31	−0.21
Help on the farm	0.56	−0.63	0.03	−0.12
Effect of health problems on agriculture	0.15	−0.10	**0.72**	0.01
Relatives living nearby	0.15	**0.60**	0.09	−0.12
Participation in groups	0.65	0.35	0.24	−0.11
Access to irrigation systems/infrastructure	0.30	0.11	−0.69	0.07
Ownership of agricultural equipment	**0.74**	0.02	−0.01	0.42
Diversity of potato varieties	0.51	0.24	−0.48	−0.32
Number of units of livestock	0.23	0.06	0.00	**0.89**

the adoption of the weighted average approach to calculate the Livelihood Vulnerability Index (LVI), in which all indicators carry the same weight, could lead to an undervaluation or overvaluation of specific indicators. Despite these methodological challenges, our results provide valuable insight into small farmers' vulnerability to current climate variability.

Small-scale farming is characterized by restricted access to timely information about the weather and market prices, limited assets, and the inherent vulnerability of agriculture (its main source of income) to social-ecological changes (Dasgupta et al., 2014). Current climate variability is a latent threat to small-scale farming as a traditional productive livelihood in rural areas (Campbell, 2021a; Marchant et al., 2021). In Chiloé, as in other family farming systems around the world (Acheampong et al., 2014; Asfaw et al., 2021; Campbell, 2021a; Huong et al., 2019; Mekonen and Berlie, 2021), temperatures are rising, precipitation is becoming ever more irregular, and droughts ever more frequent and intense. Moreover, precipitation and temperature together affect the availability of water in the ground and, therefore, crop yields (Cai et al., 2009). Similarly, temperature changes can favor the presence of pests in crops (Beltrán-Tolosa et al., 2022). Therefore, highly exposed and sensitive areas are more prone to climate-related impacts because there is a proportional relationship between exposure and sensitivity. However, in the case of adaptive capacity, the situation is different because systems where this is greater are expected to be less vulnerable to climate variability.

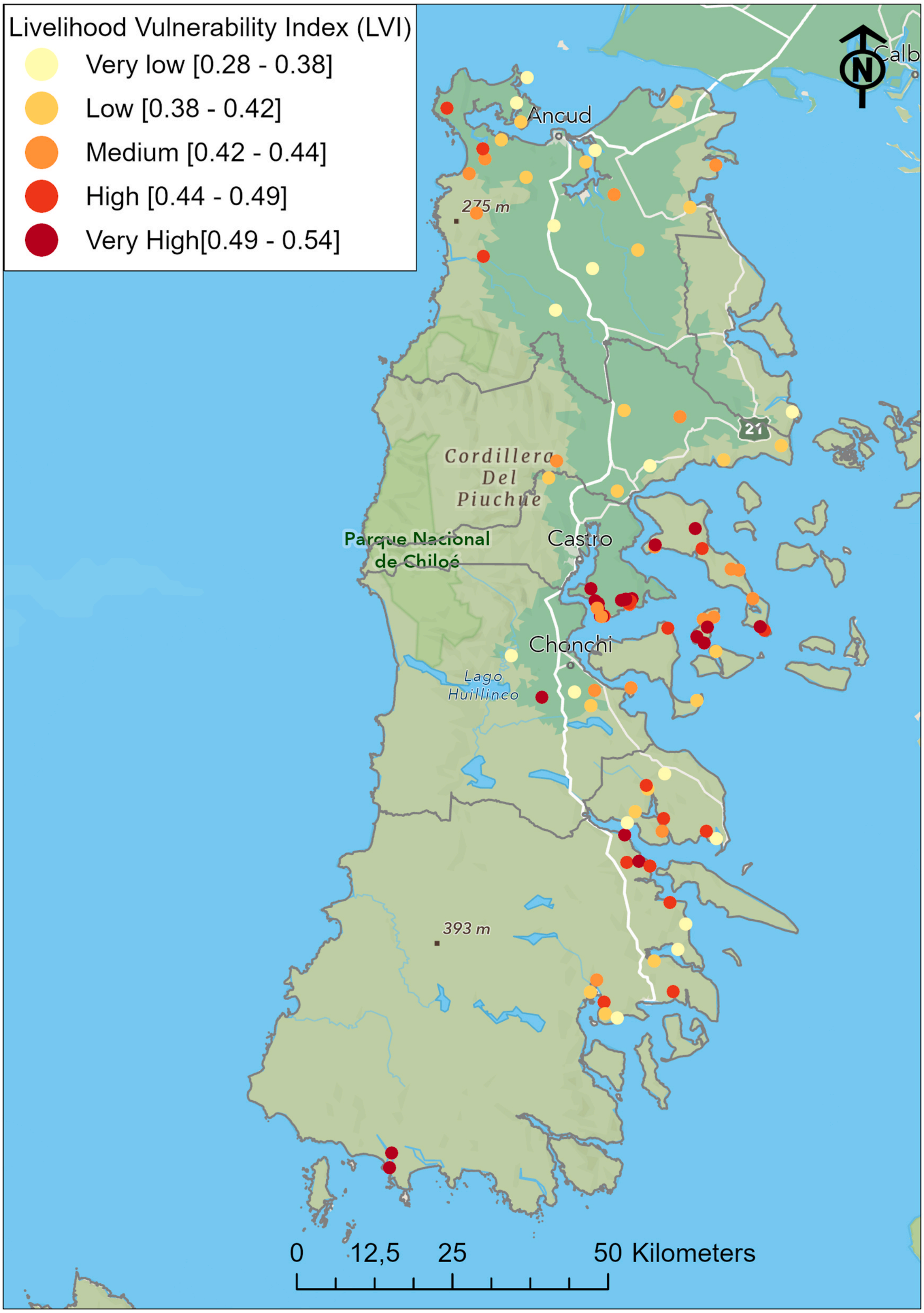
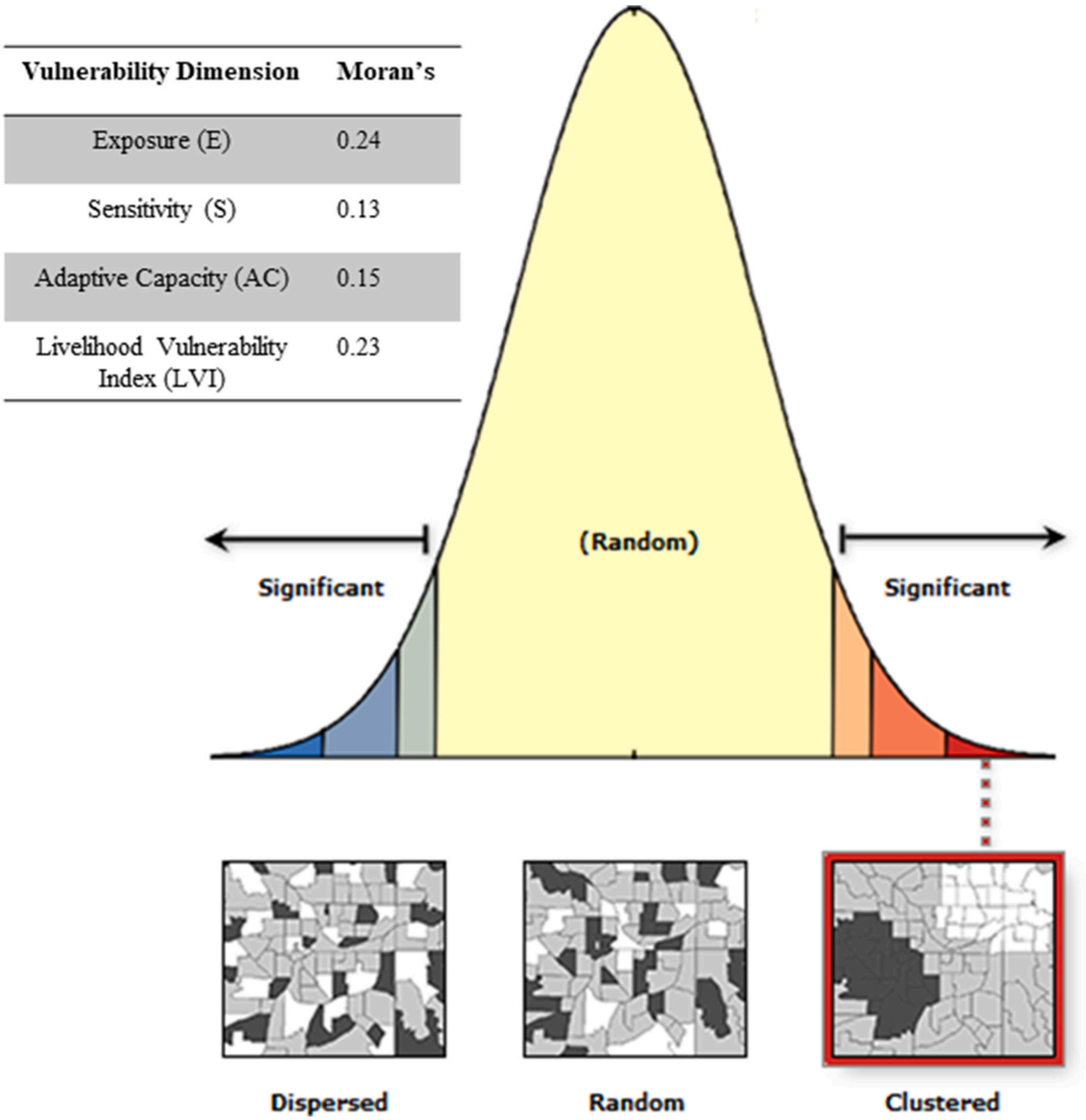


Fig. 4. Spatial distribution of the Livelihood Vulnerability Index (LVI) of small-scale farming among 100 families surveyed in the Chiloé Archipelago

Finally, the evaluation of spatial autocorrelation reveals clustering in patterns of exposure (Moran's Index: 0.24, z-score: 3.51, $p > 0.05$), sensitivity (Moran's Index: 0.13, z-score: 2.91, $p > 0.01$), adaptive capacity (Moran's Index: 0.15, z-score: 2.99, $p > 0.01$), and livelihood vulnerability (Moran's Index: 0.23, z-score: 4.62, $p > 0.01$). In contrast to exposure and sensitivity, adaptive capacity is more spatially heterogeneous or, in other words, tends to vary locally. Despite this, the positive Moran values indicate that vulnerability and its three dimensions generally show a positive spatial correlation and, thus, are not uniformly distributed across the territory.



Vulnerability Dimension	Moran's
Exposure (E)	0.24
Sensitivity (S)	0.13
Adaptive Capacity (AC)	0.15
Livelihood Vulnerability Index (LVI)	0.23

Fig. 5. Summary of Moran's Index of the LVI and its three dimensions.

Our results also show that accessibility helps to make a farming system more sensitive, particularly in more vulnerable households. This is consistent with previous research (Mekonen and Berlie, 2021; Shah et al., 2013). The small-scale farms surveyed showed important differences in journey times to the nearest urban center. The rural households located on smaller islands of the Chiloé Archipelago are more dependent on sea transport than households on the main island and there are, therefore, also important differences in travel patterns and accessibility (Lazo et al., 2024). In other words, this study confirms that journey time is not only a matter of distance but also a reflection of the development gaps that persist in rural areas. The reliance of remote areas of the Chiloé Archipelago on sea transport may, therefore, hinder the diversification of production and, even, access to basic services, the purchase of agricultural inputs, and integration into local markets.

Like the literature, this study provides conclusive support for the notion that government extension services, complementary sources of income, and strong relationships with family and/or neighbors favor adaptive capacity and reduce small farmers' sensitivity to the effects of climate variability (Asfaw et al., 2021; Beltrán-Tolosa et al., 2022). For instance, GIAHS farmers in the Philippines need strong support and assistance from local governments because the decline in traditional farming practices and the number of farmers per household limit the adaptive capacity of small-scale farming (Ducusin et al., 2019). Similarly, in Chile, government extension programs have promoted the use of conventional technological packages at the expense of traditional agricultural practices, affecting the diversity of local practices (Barreau et al., 2019; Marchant et al., 2020). This indicates that governmental influence over the type of agricultural practices employed could limit farmers' capacity to adapt to climate variability, increasing their sensitivity and vulnerability in both contexts. Agriculture extension programs must, therefore, incorporate a convergence of different sources of knowledge since this potentially contributes to the territory's food sovereignty (Ibarra et al., 2019).

Our study shows that demographic pressure and pluriactivity on the part of household members have become important features of small-scale farming in Chiloé, where complementary or off-farm earnings are very important for the economies of rural households. This trend is in line with the literature's assertion that, in family farming systems, livelihood diversification is crucial for reducing social-ecological vulnerability (Madhuri et al., 2015). Income diversification is positively associated with a greater capacity to adapt to climate crises when income from production can decrease or disappear (Madhuri et al., 2015; Mekonnen et al., 2019; Mussetta and Turbay, 2016). For example, in the Andean-Amazon foothills, an association has been found between rural livelihood diversification and lower vulnerability to climate change (Beltrán-Tolosa et al., 2022). Similarly, in El Salvador, the Special Program for Food Security (PESA) seeks to foster livelihood diversification among small farmers, training them to develop more than one type of production and access new markets (Maletta, 2011).

A narrative that is gaining recognition suggests diversification of livelihoods through supplementary income as a strategy for adapting to sociological changes (Caulfield et al., 2021). For example, income from activities outside of agriculture contributes to families' financial capital and serves as an effective mechanism that enables rural inhabitants to continue living in the locality where they grew up (Mata-Codesal, 2018). However, in other regions, it has been reported that reliance on supplementary income in the livelihoods of small farmers has encouraged unsustainable practices. For example, in the Andean province of Cotopaxi, Ecuador, agricultural households with higher incomes from outside the agricultural sector adopted mechanized tillage to a greater extent and used chemical fertilizers and pesticides (Caulfield et al., 2019).

In addition, through spatial autocorrelation analysis, this study found spatial clustering among rural households with similar levels of exposure, sensitivity, adaptive capacity, and vulnerability. In other words, these households are not randomly distributed across the archipelago. Future work should perhaps seek to identify these clusters since this is crucial for understanding how and where to focus efforts to reduce livelihood vulnerability and strengthen the adaptive capacity of small-scale farming. For example, Kapruwan et al. (2024) used local indicators of spatial association (LISA) to identify the hotspots and coldspots of climate change resilience among small farmers in the Western Himalayas (India).

There is growing recognition of the significant influence of spatial characteristics and a household's location on farmers' adaptive capacity (Lange et al., 2013). However, the relationship between local agricultural practices (organic and/or conventional) and spatial variables, such as land use coverage, distance from wetlands and water courses, and adaptive capacity is not clear (Martin et al., 2016). For example, Beltrán-Tolosa et al. (2022) show that tree cover plays a crucial role in the adaptive capacity of small farmers, especially in agricultural and pastoral contexts, because of the resulting shade and protection for animals. Finally, the study recognizes the challenge implicit in using indicators and indices to represent complex social-ecological realities since this approach tends to over-simplify our understanding of such systems (Hahn et al., 2009).

5. Conclusion

Our study has implications at multiple scales. At the local level, it contributes to a better understanding of the socio-ecological vulnerability of small farmers in unique geographical areas, such as the Chiloé archipelago, whose insularity makes them particularly vulnerable to climate change. Moreover, our work enriches the emerging body of literature on climate adaptation in Globally Important Agricultural Heritage Systems (GIAHS) sites since these face similar threats in various parts of the world. Our findings could help local communities and policymakers design more precise and effective adaptation strategies.

Small-scale farming systems face significant challenges today. These systems have always been complex, dynamic, and diverse. The Livelihood Vulnerability Index (LVI), which is supported by previous studies (Acheampong et al., 2014; Asfaw et al., 2021; Beltrán-Tolosa et al., 2022; Hoque et al., 2022; Huong et al., 2019; Madhuri et al., 2015; Mekonen and Berlie, 2021; Mussetta and Turbay, 2016), is an important tool for optimizing decision-making and guiding measures that seek to strengthen the adaptive capacity of small-scale farming. Its usefulness spans a variety of purposes and stakeholders. For example, it can be used by rural development institutions for the design of policies, programs, and projects, including improvements to technical assistance for farmers, as well as by non-governmental organizations and the research and academic community.

Our index should also be tested in other contexts, as it may be a valuable tool for improving the adaptive capacity of small-scale family farming systems in areas facing increasing social-ecological pressures. The livelihoods of small farmers are often threatened by these changes, which impact global food security and local food sovereignty. We found that climate variability, demographic pressure, and unequal levels of island accessibility contribute to the social-ecological vulnerability of small-scale agriculture. Additionally, supplementary incomes, rural extension support, and social relationships were found to be fundamental to adaptive capacity. Rural livelihoods can be positively or negatively affected by the interaction of these diverse factors. For example, a household with higher demographic pressure (reduced household size and limited labor) may experience a decrease in agricultural productivity, leading to greater dependence on external resources and increasing their vulnerability to climatic and economic stresses. In contrast, households that diversify their income sources and access community support networks will have a better capacity to adapt to these challenges.

Future research should consider incorporating participatory elements in methodologies of this type, providing opportunities for these institutions to assess, together with small farmers, the importance of the indicators selected. In summary, addressing and adapting to global environmental change calls for increased efforts to apply methodologies for assessing the vulnerability of agricultural systems (Lozano et al., 2021).

The scientific community emphasizes the importance of implementing climate change adaptations at the local level (IPCC, 2021). In line with these recommendations, legislation has recently been introduced in Chile to promote the progressive development of Communal Climate Change Action Plans (PACCC) in all the country's municipal districts, reinforcing the need for local solutions in the face of global challenges (Pinillos and Ruiz, 2024). Therefore, to develop specific adaptation policies that are territorially appropriate and reduce the negative effects of climate variability on the livelihoods of small-scale farmers, it is essential to assess vulnerability in an integral manner at the local level.

CRediT authorship contribution statement

Camilo Oyarzo: Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Conceptualization. **Santiago Kaulen:** Methodology, Investigation, Funding acquisition, Conceptualization. **Carla Marchant:** Writing – review & editing, Supervision, Conceptualization. **Paulina Rodríguez:** Writing – review & editing, Supervision, Conceptualization. **Julián Caviedes:** Investigation, Funding acquisition. **Marcelo D. Miranda:** Supervision, Methodology. **Germán Schlicht:** Writing – original draft, Investigation. **José Tomás Ibarra:** Writing – review & editing, Supervision, Methodology.

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.

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Data availability

Data will be made available on request.

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