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Pradeep K. Dubey,
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Priya Priyadarshini,
Banaras Hindu University, India

*CORRESPONDENCE
Carla Marchant
carla.marchant@uach.cl

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Social-ecological vulnerability of small-scale farming in the southern Andes: the role of Indigenous and Local Ecological Knowledge in adaptation to climate variability

Paulina Rodríguez-Díaz[1,2,3], Carla Marchant[2,3]*, Camilo Oyarzo[2,3] and José Tomás Ibarra[2,4,5]

[1]Doctoral Program in Geography, Institute of Geography, Pontificia Universidad Católica de Chile, Santiago, Chile, [2]Laboratory of Territorial Studies LabT UACh, Institute of Environmental and Evolutionary Sciences, Universidad Austral de Chile, Valdivia, Chile, [3]ECOS (Ecosystem-Complexity-Society) Co-Laboratory, Center for Local Development (CEDEL) and Center for Intercultural and Indigenous Research (CIIR), Villarrica Campus, Pontificia Universidad Católica de Chile, Villarrica, Chile, [4]Department of Ecosystems and Environment, Faculty of Agriculture and Natural Systems and Center of Applied Ecology and Sustainability (CAPES), Pontificia Universidad Católica de Chile, Santiago, Chile, [5]Cape Horn International Center for Global Change Studies and Biocultural Conservation (CHIC), Universidad de Magallanes, Puerto Williams, Chile

Small-scale farming is highly vulnerable to climate variability due to the increased uncertainty in production processes caused by short-term changes in precipitation and temperatures. We investigated the key factors behind the social-ecological vulnerability to climate variability of small-scale farming in the southern Chilean Andes. We adopted a mixed methods approach that included climate variability data at the basin level, semi-structured interviews, characterization data sheets and participant observation. The data was analyzed according to three dimensions of vulnerability: exposure, sensitivity and adaptive capacity. Our results reveal the significant interannual variation in accumulated seasonal precipitation and the frequency and intensity of drought events in the basin. Also, we found that small-scale farmers perceive social-ecological vulnerability through the impact on their daily practices and experiences. They view water as a common resource that depends not only on climatic conditions, but also on treatment of the ecosystem that maintains it. We observe that collective adaptation strategies, such as fairs, traditional festivals, and cooperatives organized by small-scale farmers, enhance adaptive capacity by increasing income, which enables investment in equipment, technology, and inputs for adapting production systems to climate variability. We conclude that individual adaptive capacity does not suffice to address the exposures and sensitivities that produce social-ecological vulnerability. It is, therefore, key to design collective adaptation strategies of a local and participatory nature that incorporate Indigenous and Local Ecological Knowledge.

KEYWORDS

Indigenous and Local Knowledge, collective action, water, adaptive capacity, local scale, Chile

1 Introduction

Small-scale farming is of paramount importance as it serves as the backbone of global food security, rural development, and sustainable agriculture (Lowder et al., 2021). These small-scale, family-run farms contribute significantly to the production of diverse crops, safeguarding biodiversity, and promoting resilient local economies (Marchant et al., 2022; Ibarra et al., 2023). Furthermore, small-scale farming plays a pivotal role in poverty alleviation, especially in developing countries, by providing livelihoods for millions of people (Brondizio et al., 2023). Small-scale farmers, however, have been considered as highly vulnerable to climate variability because it increases uncertainty in production processes (Etzinger, 2010). Climate variability refers to "variations in the mean state and other climate statistics on spatial and temporal scales beyond that of weather events." It may be due to internal processes within the climate system or external natural or anthropogenic factors (IPCC, 2014, p. 121). Water from mountain areas, for example, plays a critical role in lowland agriculture and any change in its availability will have important implications for production, land allocation and prices [Ponce et al., 2014; Instituto Interamericano de Cooperación para la Agricultura (IICA), 2016]. Similarly, climate variability implies an increase in the frequency and intensity of extreme weather events, such as droughts and frosts, which threaten production, particularly in the poorest rural communities (Seaman et al., 2014). Climate variability has effects that are seen in the short term and, particularly, at a local scale. The IPCC (2014) noted that the impacts of recent extreme climate-related phenomena, such as droughts, reveal how vulnerable and exposed are a myriad of local social-ecological systems to climate variability.

The IPCC (2022, p. 1,816) has defined vulnerability as "the propensity or predisposition to be adversely affected." Social-ecological vulnerability encompasses three dimensions, including exposure to climate variability and extremes, social systems' sensitivity, and human groups' adaptive capacity (Mussetta et al., 2017). Exposure refers to the presence of ecological and/or social assets in places and settings that could be adversely affected (IPCC, 2022). For its part, sensitivity is the degree to which a system is affected, positively or negatively, by climate variability or change, the effects of which may be direct or indirect (IPCC, 2022). Adaptive capacity is the ability of systems to adjust to potential damage, to take advantage of opportunities, or to respond to consequences (IPCC, 2022).

Mussetta and Barrientos (2015) summarize the set of capital or resources that are determinants of the adaptive capacity of agriculture: (i) economic resources (e.g., monetary capital, financial means, wealth, productive resources); (ii) technology and infrastructure; (iii) natural capital (e.g., availability of water, soil, seeds); (iv) social capital (e.g., existence of social networks characterized by trust and reciprocity); (v) institutional capital (e.g., institutional characteristics that facilitate the management of climate-related risks); and (vi) human capital (e.g., education and knowledge levels, expertise and traditional knowledge about nature and the climate). In the case of human capital, Indigenous and Local Ecological Knowledge (ILEK) is a particularly valuable resource for adaptation (Gómez-Baggethun, 2021). Indigenous Ecological knowledge as well as Local Ecological Knowledge are distinct yet interconnected forms of knowledge that arise from different cultural, historical, and experiential contexts (Ibarra et al., 2023). ILEK can be defined as "a cumulative body of knowledge, practices and beliefs about the relationships of living beings (including humans) with each other and with their environment, which evolves through adaptive processes and is transmitted from one generation to another" (Berkes et al., 2000, p. 1,252). ILEK is related to historical and contemporary knowledge, and practices about using and managing nature and its resources. Toledo (2005) proposes its classification as follows: (i) astronomical; (ii) physical related to the atmosphere, the lithosphere or the hydrosphere; (iii) biological; and (iv) eco-geographical. All are related to each other and are reflected in adaptive practices that allow their existence and transmission. Sensitivity and adaptive capacity depend on the resources that communities can access, and the availability of institutional resources provided through governance and policies (Mussetta et al., 2017; Mussetta and Hurlbert, 2020). By integrating social and ecological systems, O'Brien and Leichenko (2000) introduce the notion of double exposure to refer to "cases in which a particular region, sector, social group, or ecological area is simultaneously confronted by exposure to both global environmental change and globalization" (Leichenko and O'Brien, 2008, p. 9). Therefore, double exposure describes the interactions between two transformative macro-processes of change.

Small-scale farming often faces double exposure. One example is the situation of the poorest traditional farmers in the Limarí Basin (northern Chile) who face unequal access to water markets, a constant increase in prices and the concentration of water ownership in a few hands, as well as water scarcity (Urquiza and Billi, 2020). Similarly, Okpara et al. (2017) found that the vulnerabilities of livelihoods in the basin of Lake Chad (Africa) are conditioned by both climate variability and conflicts over water, constituting a double exposure for the area's farmers, fishers and shepherds. Bocco et al. (2019) also reported that the cultivation of *cajete* maize using a system of canals and raised beds, a cultural heritage of the indigenous communities of Mixteca Alta in Mexico, is being severely affected by its double exposure to climate variability and public policies that have promoted market agriculture at the expense of small farming. Double exposures have unequal consequences for rural livelihoods, since they are not randomly distributed, but systematically linked to contextual conditions (Leichenko and O'Brien, 2008).

Recent studies have examined the social-ecological vulnerability of small-scale farming to climate variability in mountain regions in Mexico (Bocco et al., 2019; Galicia-Gallardo et al., 2021). They consider the adaptive capacity of small-scale farming, but do not provide a full overview of social-ecological vulnerability. The social-ecological vulnerability of small-scale farming systems can be assessed through various methodologies, one of the most widely used being the Livelihood Vulnerability Index (*LVI*) developed by Hahn et al. (2009). However, given the complexity and multidimensionality inherent in the concept of vulnerability, such indices can yield divergent results, representing an important methodological limitation (Zainab and Shah, 2024). Moreover, approaches such as the *LVI* may be insufficient to capture the complexity of socio-ecological realities, as they tend to simplify both the internal dynamics and the interrelationships that characterize these systems (Oyarzo et al., 2024).

Despite this, the analysis of social-ecological vulnerability is increasingly incorporating mixed-method approaches to provide a more comprehensive understanding of the complex interactions between social and ecological systems. This shift addresses the limitations of purely quantitative methods by integrating diverse perspectives and contextual factors, which enriches the analysis by capturing the complexity and dynamism of these systems. For example, studies like the one conducted by Valderrey et al. (2023) in northern Mexico use mixed methods to assess vulnerabilities by combining quantitative data (e.g., socioeconomic indicators) with qualitative insights (e.g., community priorities) to capture the multifaceted nature of vulnerability. Another study in Tanzania used surveys, field observations, interviews, and rainfall data analysis to compare agroecological and conventional smallholders (Johansson et al., 2024). These studies provide evidence for those cases in which the data needed for the construction of indicators is unreliable, incomplete or totally lacking, and offer a local perspective with sufficient resolution to address the particularities of climate variability in small-scale. In addition, they allow the inclusion of emerging material and symbolic dimensions, as well as relationships and flows not previously considered (Figure 1).

We study the social-ecological system of the Pucón River basin in the La Araucanía Region of the southern Andes of Chile (lat. 38–44° S). Here, climate variability is seen in a decrease in precipitation and its interannual variability, with meteorological droughts of different scales, creating important challenges for small-scale farming. Since 2010, there have been persistent precipitation deficits, referred to as a "mega-drought" (Garreaud et al., 2019; Álvarez-Garretón et al., 2021). Moreover, climate projections indicate an increase in average temperatures and a decrease in annual precipitation (Marchant et al., 2021). Chile's regulatory framework for use of water further complicates this resource's management because it relies on market forces (Prieto, 2015). Under it, conflicts over access to water have proliferated (Delgado et al., 2015; Rojas, 2015) because its distribution is highly politicized. According to Budds (2004), this mode of water management has had negative social-ecological implications for *small-scale farmers* in terms of less legal access to water and greater vulnerability to drought.

This study seeks to answer the following questions: How exposed is small-scale farming in the southern Andes region to climate variability? How do farmers perceive the exposure, sensitivity, and adaptive capacity of small-scale farming to climate variability? What elements and processes favor or hinder the adaptive capacity of small-scale farming? For this purpose, the study seeks to determine the key factors affecting the social-ecological vulnerability of small-scale farming to climate variability in the Pucón River basin in the Andes of southern Chile, incorporating data on current climate trends. Finally, we discuss the main elements that should be taken into consideration in potential adaptation strategies at the local scale.

2 Materials and methods

2.1 Study area

We present an integrative analysis of the basin of the Pucón River in the southern Andes of Chile (Figure 2), as viewed from the social-ecological systems perspective (Berkes and Folke, 1998). The area has a warm temperate climate, with a short dry season (less than 4 months), average annual precipitation of over 2,000 mm and average temperatures that fluctuate between 15°C in summer and 6°C in winter. Administratively, the territory is divided into two municipal districts: Curarrehue and Pucón. This geographical area has been

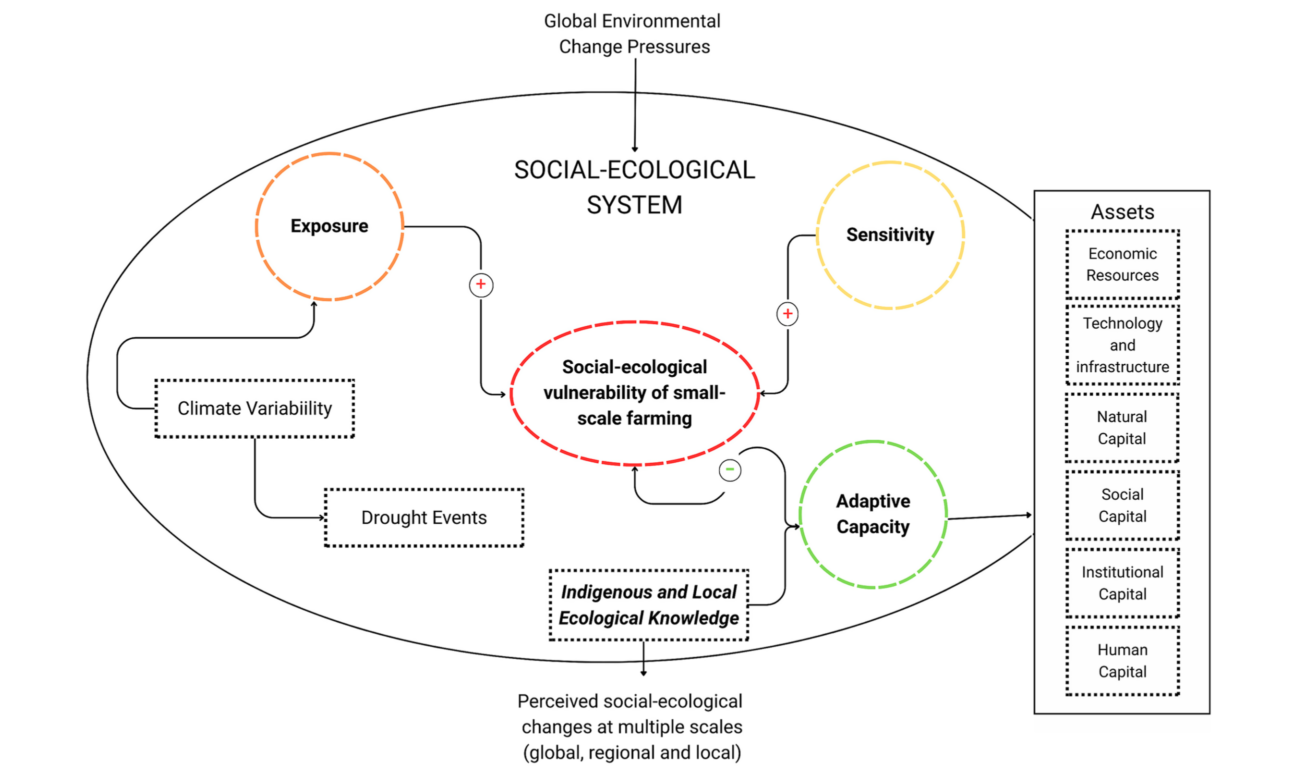

FIGURE 1
Conceptual framework social-ecological vulnerability of small-scale farming.

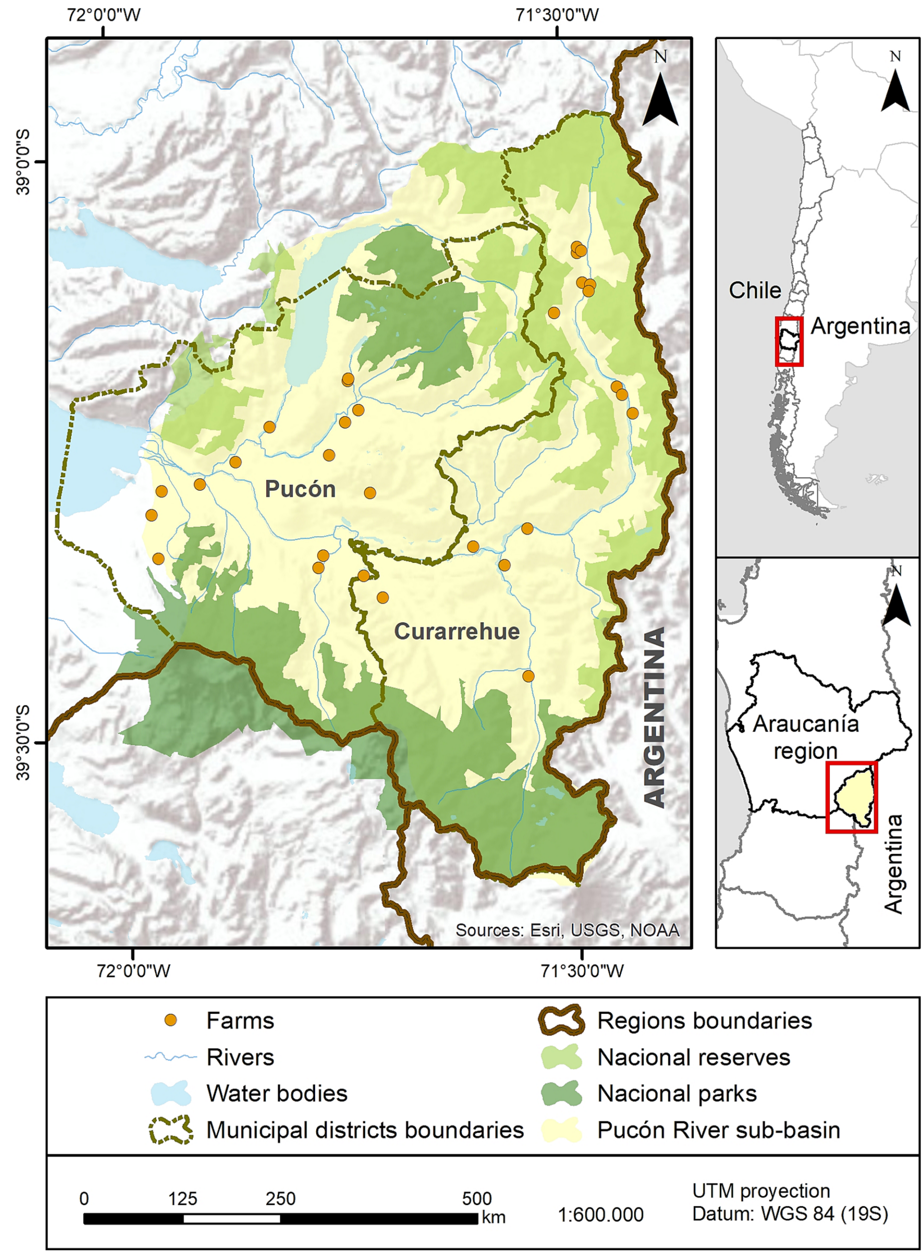

FIGURE 2
Study area in the southern Andes, La Araucanía Region, Chile.

inhabited since pre-Hispanic times by local and Indigenous *Mapuche-Pehuenche* communities, who today coexist with small-scale farmers, settlers, and neo-rural migrants (Huiliñir-Curío and Zunino, 2017).

According to the Instituto Nacional de Estadísticas (INE), (2017), the two districts together have 36,012 inhabitants, of whom 15,382 live in rural areas. Out of all those who identify as belonging to an indigenous people, 12,571 identify as Mapuche. The municipal district of Curarrehue, together with Alto Biobío, Lonquimay, and Melipeuco, forms part of the "Pehuenche Mountain Territory," which has been recognized by Chile's Ministry of Agriculture within the National Agricultural Heritage Systems Network (SIPAN). This initiative aims to highlight and safeguard small-scale agricultural systems that have historically supported local livelihoods deeply connected to their natural and cultural surroundings. In this context, the value of the Pehuenche way of life and its biocultural practices is acknowledged, reflecting a close relationship with the mountainous territory and a rich ecological and cultural diversity (SIPAN, 2023). Additionally, the study area is part of the Araucarias Biosphere Reserve, an international designation granted in 1983 by the United Nations Educational, Scientific and Cultural Organization (UNESCO).

2.2 Data collection and analysis

Taking a mixed-method approach, we adopted a case study methodological strategy. First, we analyze annual and seasonal

TABLE 1 Profile of the small-scale farmers interviewed in the southern Chilean Andes.

Municipal district	Gender of interviewees	Average age (years)	Age range (years)	Membership of an indigenous people (self-identification)	Highest educational level achieved by any member of the household
Curarrehue	13 women	52.4	30–72	12	Primary 1 Secondary 8 Post-secondary 4
	2 men	73	72–74	1	Secondary 1 Post-secondary 1
Pucón	12 women	50	34–70	8	Secondary 5 Post-secondary7
	3 men	51.7	23–80	0	Secondary 1 Post-secondary 2

precipitation trends from monthly precipitation data (2000–2020). Then, based on non-probabilistic sampling, 30 farms were distributed randomly in the study area were selected using the snowball method (Guest et al., 2006) and the farmer responsible for production was selected as the key participant (Table 1).

2.2.1 Climate variability data

Initially, we downloaded monthly precipitation data (2000–2020) for the Pucón River basin from the Climate and Resilience Research Center (CR2) using the Mawün precipitation explorer.[1] These data are derived from the CR2MET precipitation grid product, which combines ERA5 reanalysis with local topographic data calibrated by an updated national rain gauge network [DGA (Dirección General de Aguas), 2017]. In this way, we analyzed annual and seasonal precipitation trends for the aforementioned time interval.

Additionally, we quantified meteorological drought episodes between 2015 and 2020 at the basin level using the Standardized Precipitation Index (SPI) (Vicente Serrano et al., 2012). The SPI is widely used to detect and characterize droughts, where it also highlights its ability to reflect their intensity and duration at different time scales (Wang et al., 2022). This analysis was based on accumulated monthly precipitation, fitted to a probabilistic distribution, and transformed into a normal distribution (Stagge et al., 2015). In this study, given that the basin presents a pluvial-nival, hydrological regime, we followed the recommendations of Baez-Villanueva et al. (2024) and calculated the SPI on a 3-month time scale. We used the "SPEI" package of the R software version 4.3.2 for this calculation. Negative SPI values indicate below-average precipitation, while positive values represent above-average precipitation. We used the classification proposed by the Chilean General Water Directorate to differentiate drought levels which categorizes drought severity as follows: SPI values of ≥ -2.05 indicate "extremely dry" conditions, -2.05 to -1.28 represent "severely dry," and -1.28 to -0.84 correspond to "moderately dry." Near-normal conditions are observed for SPI values ranging from -0.84 to 0.84. Wet conditions are classified as "moderately wet" (0.84 to 1.28), "severely wet" (1.28 to 2.05), and "extremely wet" ($\geq$2.05) [DGA (Dirección General de Aguas), 2012]. This classification was instrumental in determining the intensity and frequency of drought and wet conditions in the study area.

2.2.2 Qualitative data

Between 2018 and 2020, we conducted 30 semi-structured interviews (Figure 3), focusing on the different dimensions that contribute to social-ecological vulnerability: exposure, sensitivity and adaptive capacity. The interviews included categories of questions about sociocultural aspects (composition of the family group, support networks and water management on the farm), ecological aspects (variations in biodiversity, pests and diseases), biophysical factors (frequency of droughts and ILEK associated with water) and economic factors (changes in production related to the drop in precipitation, extensionism, state assistencialism, income and technology) (see Supplementary material).

The farms were characterized jointly using a data sheet that included a demographic profile and the production system's characteristics, such as range of production and the agroecological practices employed. This work was complemented with participant observation of activities that included domestic tasks, work in the home garden, the sale of products and active listening to conversations. The observations, reflections, and findings from this method were incorporated through field notes and photographs, which complemented the content analysis of the transcribed interviews.

Interviews were recorded, transcribed and coded. The data obtained was subjected to content analysis (inductive and deductive), using the Atlas.ti 8.0 software, in three stages: open coding and coding by list; categorization based on the three dimensions of vulnerability; and consideration and analysis of emerging categories. Subsequently, the content analysis was integrated and triangulated with the farm characterization data sheets, field notes, and the photographic record. In this way, it was possible to obtain the network of codes and the corresponding descriptive synthesis of the three dimensions of the social-ecological vulnerability of small-scale farming in the southern Chilean Andes region.

1 https://mawun.cr2.cl

FIGURE 3
On the left, an interview with a Mapuche-Pehuenche farming couple from the municipal district of Curarrehue. On the right, a visit to a small-scale farm in Pucón. Photographs by the authors.

3 Results

3.1 Exploring current climate variability in the Pucón River basin

Our results show considerable interannual variation in cumulative rainfall and in the occurrence of drought events (Figure 4).

Despite fluctuations, precipitation has generally decreased in recent years (particularly after 2015). Years with higher accumulations (e.g., 2006 and 2011) are usually associated with periods with significant all-season contributions, especially autumn and winter. In this sense, the reduction of winter and autumn precipitation in recent years (e.g., after 2015) is a worrisome indicator, as these seasons are key to recharge surface and groundwater systems in the basin. Therefore, the decrease in accumulated precipitation and its seasonal concentration could affect the water regime of the basin, profoundly impacting activities highly dependent on climate, such as small-scale farming.

Regarding drought events, between 2015 and 2020, the Standardized Precipitation Index (SPI) shows significant fluctuations between wet (in blue) and dry (in orange) periods, reflecting a high climatic variability in the Pucón River basin. The SPI analysis allowed us to classify the months into different drought and moisture intensity categories in the Pucón River basin during the study period. We identified 42 months with standard conditions (SPI between −0.84 and 0.84), representing the most significant proportion of the total. However, 12 months were classified as moderately wet (0.84 to 1.28), three as severely wet (1.28 to 2.05), and 1 month as extremely wet (≥ 2.05). On the other hand, 8 months presented moderate drought conditions (−0.84 to −1.28), three were classified as severe drought (−2.05 to −1.28), and 1 month reached the extreme drought category (≤ −2.05).

3.2 Exposure: climate variability is perceived through changes in the water cycle

In the exposure dimension, two categories of analysis could be classified: (i) perceptions about the climate variability and their effects; and, as an emerging category, (ii) other disturbances of a natural origin.

Small-scale farmers identified changes of different magnitudes and over different time spans, noting episodes of drought and changes in precipitation patterns over longer periods (around a decade) associated with climate variability. They consider that it is no longer possible to predict the weather, and that the beginning and end of both the wet-cold period and the dry-warm period are now uncertain. In addition, these periods now sometimes overlap, resulting in either frosts or rain with high temperatures that directly impact production.

> "In September, the rain used to end, there was almost pure drought. At that time, there was pure drought and there was no grass, and now there is grass […] And that's good but, on the other hand, it's bad, because winter holds us back […] It's not good that it rains now because most people are storing grass, and what happens is that the grass for the winter, for the animals, then rots." (Woman, 30 years, and man, 37 years, Curarrehue)

The perceived effects of climate variability relate mainly to production and the farm's operation. The data show that both unexpected rain and a lack of it spoil crops while lower rainfall means insufficient water for the farm and, even, human consumption. In addition, climate variability favors pests and diseases in crops and animals. Changes in biodiversity were also observed in response to higher rainfall, longer than usual dry periods, or rain with high temperatures. All of this causes a decrease in the production of the family farm. However, the small-scale farmers recognize that the shortage of water, the increase in pests and diseases and changes in biodiversity are multifactorial, particularly in the case of the latter which is related more to human intervention (hunting, the introduction of species, the use of agrochemicals) than climate variability.

Small-scale farmers also stressed other factors that accentuate the effects of climate variability on small-scale farming, including disturbances of a natural origin that are related to the area's geographical conditions. The most common example is the eruption of the Calbuco Volcano (located 220 km south of the Pucón River sub-basin) in 2015, which generated a cloud of ash that contaminated water and the soil, causing important production losses (Figure 5).

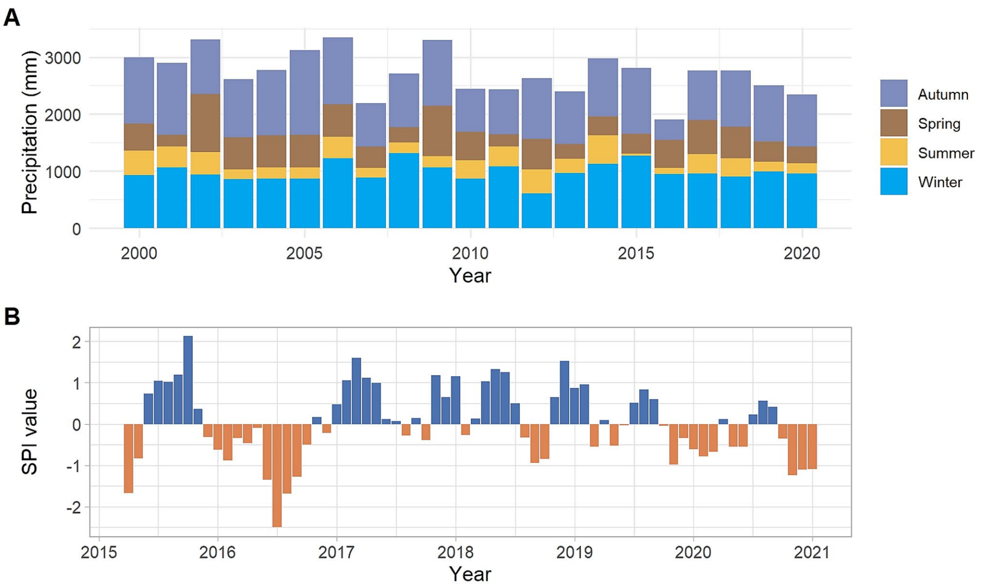

FIGURE 4
(A) Pluviometric trend and seasonal concentration of precipitation between 2000 and 2020 and **(B)** Standardized Precipitation Index (SPI-3) in the Pucón River basin (2015–2020).

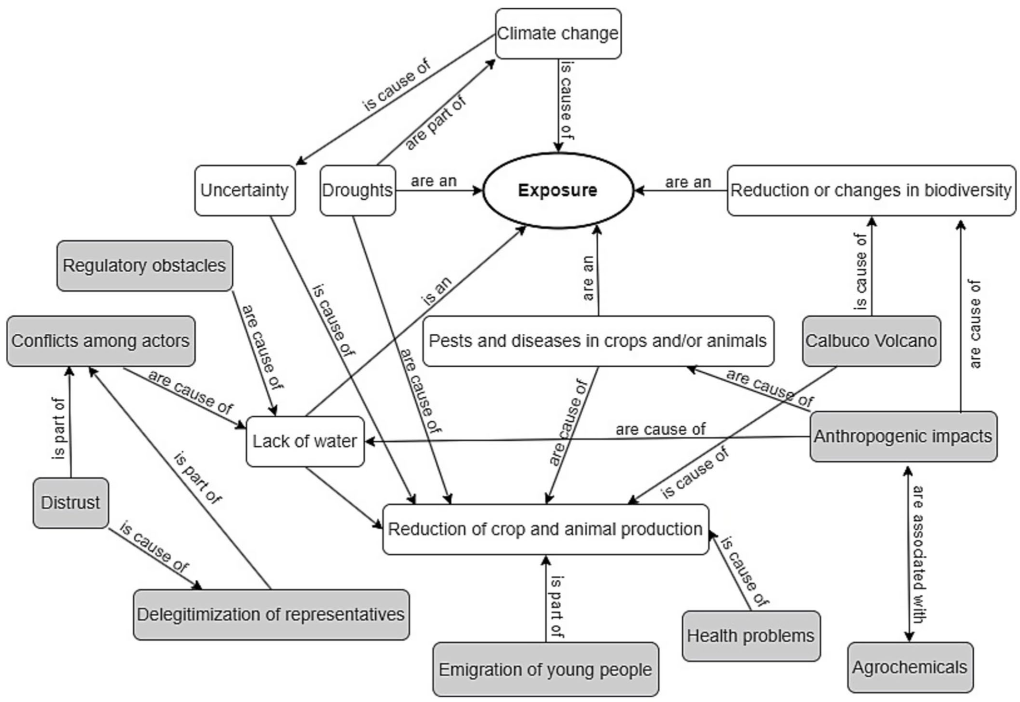

FIGURE 5
Network of exposure codes. The white labels correspond to exposure codes and the gray labels to double exposures.

3.3 Sensitivity: management practices affect the social-ecological system

The categories for the sensitivity dimension reflect sociocultural and economic aspects of the southern Chilean Andes and are: (i) socioeconomic conditioning factors; (ii) unsustainable type of management and production practices; (iii) deterioration of the social fabric; and (iv) difficulties accessing water.

The composition of the family group and the current process of change in its demographic and occupational profile stand out. Families are experiencing a process of transformation due to a rapid exodus of young people. According to the small-scale farmers, young people seek job opportunities that allow them to make use of their higher education and feel resigned in the face of the increasing difficulty of practicing small-scale, due to the shortage of water and other effects of climate variability and/or degradation of the environment because of the overexploitation of its resources. The tasks carried out by family members are also changing. Although the families whose only source of sustenance is the farm are not few, the number of family members with paid jobs outside it and, even, outside the locality is increasing. These jobs are usually seasonal or sporadic. The informal sale of products from the farm also contributes income, although most of what is produced is for the family's own consumption. All the interviewees who reported paid employment outside the farm referred to it as the family's most important source of income, over and above the farm itself.

On the other hand, unsustainable types of management and production practices were identified, such as water management practices with different levels of technification. Those related to sensitivity are reactive measures in the face of water shortage. The families come to depend on help from the municipal government which, in an emergency, uses water tankers to distribute drinking water. Consequently, families are obliged to give priority to human and animal consumption, often at the expense of crops. At the same time, production management was characterized mainly using inputs from outside the farm, obtained through government programs. However, these are believed to generate dependency and negatively impact other farm system components. One example of this is honeybees and other pollinators necessary for the ecosystem, which can be affected by pesticides.

Another category identified in the Sensitivity dimension was the deterioration of the social fabric. According to the farmers, it is easy to recognize those neighbors with practices that are harmful for the conservation of water sources and the environment in general (for example, indiscriminate logging, excessive collection of *piñones*, the fruit of the *araucaría* tree, and the hunting of native birds). This generates conflicts among neighbors that are generally the result of mistrust.

> "We have the neighbor that adjoins us. He left that thing over there bare, if you see how it looks. [...] He devoted himself to firewood, sleepers and one thing and another, and still more. And we named him 'the moth' because he was… every stick he found … on the ground, he just got it. [...] Yes, until we made him understand that he shouldn't cut any more. Because you can't live off that." (Woman, 36 years, Curarrehue)

A second form of deterioration of the social fabric identified is conflicts in associations focused on resource management. An example are associations for managing resources such as the Rural Drinking Water Committees, formed by actual or future users of a Rural Drinking Water (APR) system. It is not uncommon for the neighbors to organize themselves to request the municipal government's support for the establishment of an APR in their locality. The main obstacle is to obtain sufficient water rights to supply the community and, together, raise the money to buy them. Setting up an APR is a long process, not exempt from conflicts between partners and representatives, and calls for political will and coordination between different actors inside and outside the territory.

Water is obtained mainly from natural sources, whether *ojos de agua* (which translates literally as "eye of water," is a spring without technification. It is a place where the water of a stream emerges, flows due to gravity and is used without major interventions), wells or streams, or by collecting rainwater. Even small-scale farmers who are connected to an APR system opt to maintain their connections to natural sources, which they prefer for farm activities such as irrigation and power generation and as water for the animals. Given that APRs also use natural water sources, climatic conditions are fundamental in access to water. At times of water scarcity, natural sources decrease or dry up completely, leaving the water tankers provided by the municipal government as the only way to access water. Conflicts between relatives, neighbors and other actors in the territory also hamper access to water. Those with natural water sources on their property sometimes impede access to them, causing serious problems for families without water. In addition, the water market means that some families do not have water rights, preventing them from being part of an APR system. In this case, their access to water depends on the solidarity of their neighbors, the arrival of the water tanker or the extraction of water from informal natural sources.

> "My sister gives me [water] but I think only until December; as from January, the water tanker comes to leave me water." (Woman, 37 years, Curarrehue)

3.3.1 Sensitivities that act as double exposures

Among the characteristics of the sensitivity, two emerging categories were identified that are consequences of trade liberalization, contributing to double exposure by impacting small-scale farming on a sociocultural front: (i) deficient governance of strategic resources; and (ii) a process of depletion of the campesino population. The category of deficient governance of strategic resources revealed the existence of conflicts between actors in the territory, either over the use of a resource or due to mistrust and day-to-day problems. The delegitimization of local leaders has also aggravated the problem of the water shortage caused by climate variability. In a further factor, the difficulty of accessing water rights, due to a lack of information and excessive bureaucracy, prompts many families to ask for water from the municipal government's tankers or to obtain it informally in order to produce food and for other necessities.

Finally, the depletion of the *campesino* population is explained fundamentally by the growing exodus of young people -aforementioned-. However, health problems in those responsible for the care and maintenance of small-scale farming also directly limit its workforce. Parents encourage their children to study, which involves leaving the locality, and around half of the young people who leave do not return because of a lack of job opportunities (Figure 6).

> "It depends, if the children carry on studying, I think they want something better and they leave, I don't think they want to live in the country… I see it in their cousins, who already… that is, one of them is at university so I say, hey, why isn't he not going to be able to do [the same]?". (Woman, 36 years, Pucón)

3.4 Capacity to adapt: knowledge of the territory facilitates action

The adaptive capacity dimension comprises three categories: (i) use of Indigenous and Local Ecological Knowledge (ILEK) to develop adaptive practices; (ii) extensionism; and (iii) organizational capacity. The latter was an emerging category.

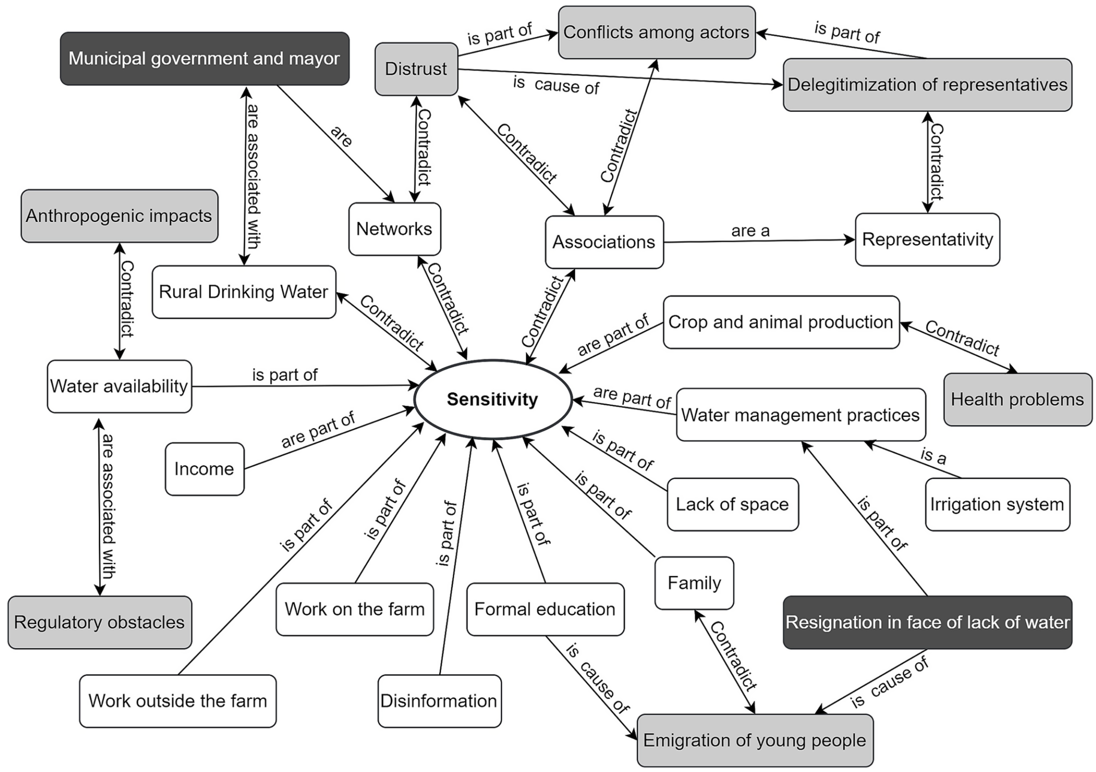

FIGURE 6
Network of sensitivity codes. The white labels correspond to sensitivity codes, the gray labels to double exposures and the black labels to non-categorized codes.

In developing adaptive practices, ILEK is very important and is ordered based on the classification of Toledo (2005) discussed above. The astronomical type of ILEK identified involves observation of the moon and its phases for predicting the weather and deciding when to sow and harvest.

> "I didn't do it before but I do now because I realized that what they said about sowing with a waning moon was true. The plant gives more fruit; when there's a waxing moon, that's when the plant produces only plant." (Woman, 60 years, Curarrehue)

Physical ILEK related to the atmosphere involves understanding the local climate system, the seasons of the year and the weather, as well as the effects of climate variability on them. This knowledge is used to make decisions related to the home garden (when to sow and harvest) and the animals (the optimal time for shearing, the planning of crossing and calving) and pastureland (the need for irrigation, time to store fodder for the winter) as well as the need to collect rainwater and other extraordinary measures. Knowledge of this type also includes the ability to predict the weather based on use of the senses or, in other words, by observing, listening to and smelling nature in general or its components in particular, whether birds, rivers or the wind, etc.

ILEK of the physical type related to the lithosphere has to do with the area's abrupt topography and is of great importance in water collection and transport practices. As indicated above, the natural water sources preferred by families are *ojos de agua* and, since they are generally located in higher sectors, advantage can be taken of the gradient to transport the water to the farm. Tanks are usually used to collect the water while, for its transport, hoses are used to increase the pressure as well as guttering and various recycled materials.

> "I'm beside a hill, that's in front and has a height of 1,500 meters and many springs and I get water from one of those springs and, because it's protected by native forest, it doesn't dry up, so I don't have water problems, but it took me blood, sweat and tears up there, I had to make a canal, put in hoses, cover them and, well, it's working, I don't have water problems." (Man, 72 years, Curarrehue)

Physical ILEK related to the hydrosphere includes knowledge about the location of the territory's different natural water sources—*ojos de agua*, streams, wetland meadows and others—and how to get to them. Biological ILEK includes knowledge about the relationship between weather conditions, crops and pests, as well as plants' specific water requirements and how to determine them. It also involves knowledge about plant species that favor the conservation of natural water sources. A number of agroecological practices based on knowledge of this type were identified, of which the most frequent were crop rotation and the use of flowers and aromatic plants to control pests. The eco-geographical type of ILEK includes knowledge about the conservation of natural water sources. It focuses on protecting riparian vegetation, particularly tree and shrub species that attract water or generate shade and humidity and moderate temperature variations. The ILEK stands out, which mainly focuses on water shortage. ILEK is crucial to achieving successful adaptation results. One of the key aspects in which the ILEK is reflected is the technology and infrastructure used to manage the water. This are mainly characterized by the use of water ponds associated with *ojos de agua*, acquiring a pump, implementing technological irrigation systems, and incorporating rainwater harvest.

Another form of adaptive capacity is extensionism, which has greatly influenced agricultural management practices. In the area studied, different institutions foster rural extensionism: universities; cooperatives and private companies; government's institutions, such as Institute for Agricultural Development (INDAP) through the Local Development Program (PRODESAL), the Indigenous Territorial Development Program (PDTI) and the Rural Women's Working Group; and municipal governments through their Rural Development Unit or Program. Out of these diverse actors, INDAP is the most influential. This reflects its broad territorial coverage and the range of benefits it offers. The broad range of benefits offered span support for investing in crop and animal farming, subsidies, loans, and training. Knowledge transfer projects include personal and collective advisory services. Whether the knowledge and practices have adaptive potential or not is judged by the small-scale farmers themselves once they have tried them. They generally indicate a preference for training in agroecological, rather than conventional, practices and evaluate it positively:

> "My mother taught us that since I was a girl, that we have to kill the pilme beetles like this and make nettle tea to eliminate aphids and all those things. We did all those things. I learned to do those things as a girl from my mother. And now I've had a bit more training from PRODESAL […] they have to teach me because I know what my mother taught me but those were other times, not like now when the thing is that without training, you have nothing." (Woman, 67 years, Pucón)

In addition, communities' capacity to organize collective adaptation to climate variability was identified as an emerging category. It corresponds to the sum of efforts, knowledge and resources through which to address the negative consequences of climate variability, expanding each family's space of individual influence. For example, in localities without an APR system and where water of natural origin is insufficient to supply all the families, the neighbors first get together to form a CAPR and, then, raise the money to buy water rights while pressuring the municipal government for the establishment of an APR. Similarly, instances organized by small-scale farmers, such as fairs, traditional festivals and cooperatives through which to market their products to the local population and tourists, can contribute to adaptive capacity by boosting families' income, enabling them to invest in the equipment, technology and inputs they need to adapt their production systems to climate variability (Figure 7).

4 Discussion

This study identified, analyzed and synthesized the key factors behind small-scale farming's social-ecological vulnerability to climate variability. With a focus on the standpoint of the small-scale farmers and their experiences, we showed that, in the mountainous basin of the Pucón River, social-ecological vulnerability is closely related to inequitable access to water, which has numerous consequences for the social-ecological system's exposure, sensitivity and adaptive capacity. The results of this study are consistent with global research highlighting how Indigenous Peoples and local communities can not only broaden and deepen understanding of climate change and its impacts on local social-ecological systems but also provide key knowledge for the design of viable and culturally relevant adaptation strategies. A comparative study in 48 sites inhabited by these people's highlights that their local knowledge is crucial for sizing the effects of climate change, as well as for informing adaptation policies and strategies in the face of loss and damage (Reyes-García et al., 2024).

A growing body of research highlights a consistent and significant association between small-scale farmers' local perceptions of climate change and their adaptation intentions, as evidenced by the adaptive

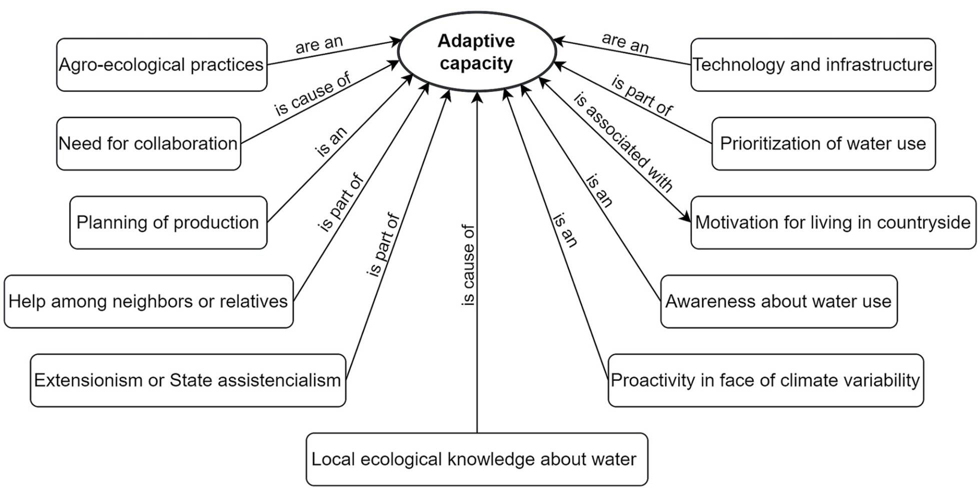

FIGURE 7
Network of adaptive capacity codes.

practices adopted within small-scale agricultural systems. This relationship suggests that heightened climate awareness can strengthen the capacity to respond to the impacts of the global social-ecological crisis (Abid et al., 2019; Azadi et al., 2019; Makuvaro et al., 2018). In this context, Caviedes et al. (2023) underscore that ILEK held by smallholder farmers in the Globally Important Agricultural Heritage System (*GIAHS*) of Chiloé, southern Chile, plays a critical role in shaping their understanding of social-ecological changes and is positively linked to the resilience of their livelihoods.

In small-scale farming, climate variability manifests itself over a shorter time span than climate change. This enables the small-scale farmers to be aware of its effects more immediately (Córdoba et al., 2019). However, this very immediacy also creates uncertainty identified as one of the principal problems created by climate variability for different productive activities. In turn, uncertainty hampers the generation of preventive and stable adaptation processes to address immediate climate fluctuations. This should be considered in planning adaptation strategies, which must be flexible to be maintained over time (Parraguez-Vergara et al., 2016), co-developed from the local (Marchant et al., 2021) and must be managed in a way that is open to the unexpected and incorporate lessons learned in the process (Folke et al., 2002).

Flexibility, which is understood as "the amount of change that a system can withstand without losing control of its functions and structures, that is, the capacity of a system to absorb impacts," is key when undertaking agricultural activities without knowing the trends in changes of parameters such as seasonality, precipitation or expected thermal fluctuations (Berkes and Turner, 2005, p. 12). In the basin of the Pucón River in the southern Chilean Andes region, families face constant uncertainty about crop and animal production and other activities, such as the collection of medicinal herbs and wild fruit and mushrooms (Barreau et al., 2016). Nevertheless, in addressing exposure, i.e., the presence of ecological and/or social assets in places that could be adversely affected (IPCC, 2022), families tend to be reactive and often act belatedly, incorporating adaptation strategies when climate variability has already caused harm. A similar situation was reported by Córdoba et al. (2019) when studying the perceptions and traditional knowledge of small-scale farmers in the Colombian Andes. This study found that the short-term agricultural measures, which were the most common strategies of adaptation to climate variability, were conducive to only limited adaptation and resilience.

Moreover, characteristics such as deficient governance of strategic resources and depletion of the *campesino* population conspire to create double exposure. These sensitivities are triggered directly or indirectly by the way in which the Chilean socioeconomic development model operates. For example, Meza et al. (2020) found that, in the far north of Chile, the gradual depletion of the *campesino* population was directly related to the concentration of productive activities and services. This depletion, in turn, poses a threat to the communities' capacity to adapt to climate variability because connection with the territories promoting individual and community resource management strategies becomes sporadic. Consequently, the local knowledge and practices, which have proved successful in the past, are forgotten and lost. In this sense, the biophysical dimension of climate variability (the mega-drought) and governance of the resource (legal access to water in a context of neoliberal policies) can be interpreted as a case of double exposure.

Our results are also in line with Delgado et al. (2015), who point out that private ownership of water has generated serious supply conflicts in Chile, even in regions where supply exceeds demand, making it necessary for municipal governments to distribute water by tanker, as occurs in the Curarrehue and Pucón municipal districts. The small-scale farmers view water as a common resource that depends not only on climatic conditions, but also on how the ecosystem that maintains it is treated. Under current legislation, water rights authorize the use of publicly owned water for private benefit (Díaz et al., 2018). In other words, a common resource is exploited by private interests.

In the Pucón River basin, adaptive capacity reflects ILEK that has been tried and tested by the small-scale farmers themselves. Practices related to this knowledge permit the creation of adaptation strategies suited to the context of each family and community. However, small-scale farmers perceive the water shortage problem as a new challenge so the creation of adaptation strategies is ongoing, as reported by Marchant et al. (2021). This is consistent with the findings of Fuentes and Marchant (2016, p. 56), who assert that "small-scale farming in Curarrehue is in an initial stage of adaptation, characterized by the promotion of water capture techniques through state resources and extensionism."

In Chile, the conception of rural extension incorporates an integral notion of development, has an interdisciplinary orientation and, in line with a neoliberal standpoint, seeks to transform the producer into an entrepreneur (Landini, 2015, 2016). The small-scale farmers recognize the benefits of extensionism for their production systems, but do not incorporate all the proposed new techniques as daily practice. They must first be tested by the small-scale farmers themselves or trusted peers and must be aligned with their conditions of operation. Such behavior is not unique to the Pucón River sub-basin. In a study in the Valparaíso Region, Cid and González (2019) reported that women small-scale farmers, who have had to adapt to reduced rainfall and water availability, look to knowledge inherited from their ancestors and based on work experience as well as that transferred by state institutions related to rural development. They identify and select those agricultural practices they regard as beneficial and "are not passive subjects, but rather interact, adapt, modify and/or resist productive disciplining" (Cid and González, 2019, p. 96), indicating that the practices finally adopted are the result of a number of different influences. The situation is similar in the Pucón River sub-basin, where ILEK and extensionism strongly influence adaptive capacity.

The capital or resources considered determinants of adaptive capacity (Mussetta and Barrientos, 2015) are not distributed evenly around the territory and their presence is not always significant. Economic resources are scarce and those small-scale farmers who can access additional productive resources do so as users of government rural development programs. Technology and infrastructure for the accumulation and use of water, both for human consumption and farm needs, show a high level of development related to different inter-related ILEK. However, efficient irrigation systems are rare, a situation that conditions production and is most pronounced in small-scale farming (Marchant et al., 2019). In other parts of the Andes suffering water scarcity, terrace farming has been adopted, establishing a hierarchy of irrigation depending on the water requirements of the different crops and also incorporating drip irrigation and canals with gates for the distribution of water (Fernández et al., 2019).

Natural capital is characterized by an availability of water and access to it that depend not only on climate variability, but also on the water market and the communities' organizational capacity. It is, therefore, very heterogeneous and dynamic. However, in the Pucón River sub-basin, it is boosted by the high level of biodiversity found in home gardens. In these small multi-purpose production systems, plants are grown for food and for medicinal, ornamental and ritual purposes (Ibarra et al., 2019). Human capital shows development in different aspects related to experience and contemporary and traditional knowledge about nature and the climate and to the knowledge transferred through rural extension. Human capital may, indeed, be the most important determinant in strengthening adaptive capacity. However, depletion of the campesino population reduces human capital. This has also been reported on the Island of Chiloé where the aging and depletion of the rural population, scarce labor, a decline in the traditional *minga* practice of moving houses from one place to another, scant state support for small-scale farming and the scarcity of water are causing the disappearance of traditional practices and farming for self-consumption (Rojas and Frêne, 2019).

Social capital is also well developed. Social networks of local and extra-local scope characterized by trust and reciprocity, albeit not exempt from conflicts, figure significantly in the accounts of the small-scale farmers.

Finally, in the case of institutional capital, as it operates at the local level in Chile, organizations are weak in terms of climate-related risk management (Schlack, 2019). The main institutions mentioned by interviewees are the municipal government, which provides drinking water at times of need, and INDAP, which proposes practices and offers training for adaptation to climate variations.

It is important to remember that river basins are complex social-ecological systems. That is why understanding the relations and linkages between humans and nature is crucial for analyzing the vulnerability of small-scale farming to climate variability. In this sense, river basin study, management, and policy development require trustworthy knowledge of these linkages. According to Agramont et al. (2022, p. 8), "a socio-ecological systems approach contributes to a better understanding of the relationships between water and society." Addressing social-ecological vulnerability as a problem for mountain small-scale farming entails the challenge of configuring the phenomenon at the correct scale to design adaptation measures suited to each context. This is important in drawing up strategies for adapting to climate variability, which must be flexible to permit their adjustment to local needs and conditions. For example, Baca et al. (2014) studied the degree of vulnerability of the livelihoods of coffee growers in Mesoamerica, identifying the specific factors that contribute to it at the national and local levels. The study concluded that they varied widely between countries, municipal districts and families, making it difficult to identify general trends. This implies that adaptation strategies must be flexible to permit their adjustment to local needs and conditions. In turn, Mussetta and Barrientos (2015) found that, according to agricultural producers in the Mendoza River basin in Argentina, economic factors are the main contributors to vulnerability, more so even than water scarcity.

These findings would not have been possible through research at a scale larger than the local level or based only on indicators, as is more usual in work of this type. Indicators quantify the social dimensions of vulnerability, establishing generalizations (Mussetta et al., 2017) that reduce and simplify the problem. As a result, they give insufficient importance to the social processes and power asymmetries that intervene in vulnerability (Birkenholtz, 2012) because they seek to establish causal relationships between events (Pahl-Wostl et al., 2013). Mixed-methods studies reveal that small-scale farmers' vulnerability to climate change is influenced by a combination of environmental, social, and economic factors. In this sense, studies like this one emphasize the need for tailored adaptation strategies that consider local conditions and resource availability to reduce social-ecological vulnerability.

5 Conclusion

Mountain areas are highly vulnerable to the effects of climate variability, and the southern Chilean Andes is no exception. This study, grounded in the perceptions and lived experiences of small-scale farmers in the Pucón River basin, shows that exposure is primarily expressed through shifts in the seasonality and intensity of precipitation. Sensitivity is linked to changes in demographic and occupational profiles, support networks, and practices related to water and production management. Adaptive capacity, in turn, is shaped by the interlinking of Indigenous and Local Ecological Knowledge (ILEK), agricultural extension services, and the communities' ability to organize collective responses—particularly in relation to water scarcity.

Importantly, our findings reveal that certain sensitivities operate as double exposures, simultaneously influenced by socioeconomic pressures and climate variability. These dynamics are not gender-neutral. Women, in particular, play a pivotal role in sustaining adaptive responses through their daily labor, community leadership, and knowledge transmission. However, their contributions are often underrecognized or constrained by existing social structures.

By highlighting how farmers—especially women—perceive and navigate vulnerability through their everyday practices, this study contributes to a deeper understanding of the social-ecological dynamics of adaptation. It underscores the need to design locally grounded, gender-responsive adaptation strategies that are attentive to power relations and promote long-term engagement. Since social-ecological vulnerability is a dynamic and context-specific phenomenon, adaptation strategies must be flexible and co-constructed with the communities they aim to support.

Based on our findings, we propose the following recommendations to address the key dimensions of social-ecological vulnerability identified in the Pucón River basin: Firstly, strengthen community-based water governance mechanisms, supporting inclusive and participatory decision-making spaces that recognize the basin as a social-ecological unit. This includes fostering collaboration between local actors, municipalities, and relevant institutions to improve water management practices and respond to climate-related stressors. Secondly, gender-responsive adaptation strategies that explicitly value and support women's roles in sustaining agricultural livelihoods should be promoted. This involves facilitating their access to training, resources, and leadership opportunities within local adaptation initiatives. Finally, reinforce locally grounded agricultural extension services by integrating ILEK and ensuring that technical support is culturally appropriate, territorially relevant, and co-developed with the communities, especially in contexts of increasing climatic uncertainty.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

PR-D: Writing – review & editing, Writing – original draft. CM: Writing – review & editing, Writing – original draft. CO: Writing – original draft. JI: Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The authors declare that no Gen AI was used in the creation of this manuscript.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2025.1601566/full#supplementary-material

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