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Assessing the Impacts of a Multi-Year Drought on Water Resources and Agriculture in the Aconcagua River Basin of Chile

Evaluación de los impactos de una sequía multianual en los recursos hídricos y en la agricultura en la cuenca del río Aconcagua de Chile

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Andes, Aconcagua Basin, agricultural expansion, climate change, water resources, water scarcity

ABSTRACT

The Aconcagua watershed in Central Chile has experienced severe drought conditions for the past thirteen years, receiving only three-fifths of its average precipitation, marking the longest drought on record. Declining rainfall has led to widespread water shortages for agriculture and human consumption, while warmer temperatures have further reduced water availability, worsening the drought's impacts. This study examines the combined effects of decreasing precipitation, reduced streamflow, warmer temperatures, and changing agricultural land use patterns to assess the environmental impacts of the drought in the Aconcagua watershed. Trend analysis reveals that the drought, coupled with rising temperatures, has depleted the snowpack in the Andes, reducing river discharge and exacerbating a drying trend that diminishes regional water availability. Agriculture in the region, which depends almost exclusively on river discharge, has been severely impacted, with an average streamflow reduction of 59% since 2010 affecting arable land. Deficient irrigation infrastructure and inefficient water governance, combined with regional drying trends favored by climate change, are likely to worsen the situation. Addressing the drought in Chile requires a comprehensive and coordinated response from the government, civil society, and the private sector. This response should include measures to promote sustainable water use and conservation, support for affected communities and industries, and efforts to address the underlying drivers of the drought, including climate change and unsustainable practices.

Palabras clave
Andes, cambio climático, cuenca del Aconcagua, escasez de agua, expansión agrícola, recursos hídricos

RESUMEN

La cuenca del río Aconcagua en Chile Central ha experimentado condiciones severas de sequía durante los últimos trece años, recibiendo solo tres quintos de su precipitación promedio, lo que marca la sequía más prolongada registrada. La disminución de las lluvias ha generado amplias escaseces de agua para la agricultura y el consumo humano, mientras que las temperaturas más cálidas han reducido aún más la disponibilidad de agua, empeorando los impactos de la sequía. Este estudio examina los efectos combinados de la disminución de la precipitación, la reducción del caudal de los ríos, las temperaturas más cálidas y los cambios en los patrones de uso de la tierra agrícola para evaluar los impactos ambientales de la sequía en la cuenca del río Aconcagua. El análisis de tendencias revela que la sequía, junto con el aumento de las temperaturas, ha agotado el manto de nieve en los Andes, reduciendo el caudal de los ríos y exacerbando una tendencia de sequí a que disminuye la disponibilidad regional de agua. La agricultura en la región, que depende casi exclusivamente del caudal de los ríos, se ha visto gravemente afectada, con una reducción promedio del 59% en el caudal de los ríos desde 2010 que afecta a las tierras de cultivo. La infraestructura de riego deficiente y una gobernanza del agua ineficiente, combinadas con las tendencias regionales de sequedad favorecidas por el cambio climático, probablemente empeorarán la situación. Abordar la sequía en Chile requiere una respuesta integral y coordinada por parte del gobierno, la sociedad civil y el sector privado. Esta respuesta debería incluir medidas para promover el uso sostenible del agua y la conservación, apoyo a las comunidades e industrias afectadas, y esfuerzos para abordar los impulsores subyacentes de la sequía, incluido el cambio climático y prácticas insostenibles.

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Introduction

Droughts can have significant and far-reaching effects on ecosystems and human societies, particularly in regions already experiencing water stress due to climate change (Dai, 2011, 2013; Diffenbaugh & Field, 2013). A drought is an extreme hydrological phenomenon marked by a deficit or lack of water in the hydrological system, evident through reduced streamflow and groundwater levels (Van Loon, 2015). The impacts of droughts are wide-ranging, including reduced vegetation cover, soil moisture deficits, changes in plant community composition, and significant economic consequences, especially in agricultural and water-intensive industries (Lobell et al., 2014; Sheffield & Wood, 2011). These impacts can lead to reduced agricultural productivity, increases in food prices, food insecurity, water scarcity, and water resource conflicts (Deryng et al., 2016; FAO, 2008). Droughts can exacerbate social inequality, disproportionately affecting disadvantaged communities and marginalized groups (Cutter et al., 2003). Furthermore, anthropogenic effects have aggravated drought conditions (Haile et al., 2020) Climate change is expected to intensify these impacts by increasing the frequency, intensity, and duration of droughts and altering precipitation patterns (Aliyari et al., 2021; Diffenbaugh & Field, 2013; Intergovernmental Panel on Climate Change, 2022; Van Loon et al., 2016). Additionally, droughts and climate change can have cascading effects on sectors such as energy, health, and infrastructure, leading to social and political instability (Sheffield & Wood, 2011). These findings underscore the need for effective adaptation measures to mitigate the impacts of drought and climate change on both natural and human systems (Intergovernmental Panel on Climate Change, 2022).

The impact of climate change on water resources has been extensively studied in significant mountain regions worldwide; however, limited research is available for the semi-arid Andes of Chile (Aggarwal et al., 2022). The ongoing mega-drought since 2010 has significantly impacted mountain ecosystems within the Andes Cordillera of central Chile, leading to notable changes in snow cover, surface water resources, mountain biota, and the ecosystem services they provide (Martel-Cea et al., 2023). In the high Andes of Argentina and Chile, hydrologic modeling projections under a warmer and drier climate suggest significant reductions in streamflow and sediment transport, highlighting the need for region-specific adaptation and mitigation strategies (Slosson et al., 2021). South American mountain grasslands are particularly susceptible to drought and increased soil erosion (Straffelini et al., 2024). Martel-Cea et al. (2023) found that since 1950, a decline in moisture has led to vegetation belt displacement. From 2010-2020, diminished snow accumulation at higher elevations in Central-Western Argentina caused a hydrological drought that impacted winter tourism, limited water availability for irrigation and household purposes, and created socio-political conflicts (Rivera et al., 2021).

Central Chile, located between 32-37°S, is a drought-prone region experiencing frequent water shortages affecting 70% of the population (Aitken et al., 2016; Boisier et al., 2018; Bozkurt et al., 2017). Characterized by significant annual precipitation variations and typically enduring one drought every decade, the region has seen a 40-50% decline in annual rainfall over the 20th century (Dirección Meteorológica de Chile, 2019; Meza, 2013; Quintana & Aceituno, 2012). The Andes' snowpack and glaciers, the primary water sources for Central Chile's rivers, are influenced by winter snowfall and changes in temperature and precipitation, resulting in high discharge variability and rising equilibrium-line altitudes (Carrasco et al. 2008; Center for Climate and Resilience Research, 2019; Corripio et al., 2008; González-Reyes et al., 2017; Masiokas et al., 2006). Since 2010, Central Chile has been experiencing the most prolonged and driest drought in the last millennium, with abnormally low rainfall and precipitation deficits of 25-50%, coinciding with the hottest temperatures recorded in the past century (Boisier et al., 2018; Center for Climate and Resilience Research, 2019; McCarthy et al., 2022). Future projections suggest a 10-20% reduction in precipitation and a 1.6°C increase in average annual temperatures by 2050 (World Bank, 2020).

Water scarcity is rapidly evolving into a critical concern in Chile, impacting multiple regions and raising concerns about the fairness and sustainability of water management. The government's concern is also increasing, as articulated in an official policy document highlighting the growing vulnerability of the country's water resources (Ministerio del Interior y Seguridad Pública, 2015). Additionally, a government report concluded that Chile's central region is undergoing a process of "drying up," confronting a state of water scarcity where demand has exceeded supply since 2010 (MOP, 2016). Central Chile, the most populous and economically significant region (INE, 2018), serves as the nation's agricultural hub. Over the past three decades, economic activities requiring significant water usage have experienced sustained growth (INE, 2018). Currently, water demand for consumptive and non-consumptive use exceeds the available natural surface flow, leading to the overexploitation of aquifers to meet the unmet demand (MOP, 2016). Climate warming and increasing water demands have resulted in a water crisis in the region (Muñoz et al., 2020; PANCD-Chile, 2016). A warmer and drier climate will increase evapotranspiration and water losses, reducing streamflow and causing negative economic impacts (Vicuña et al., 2011; Vicuña et al., 2012). Operating costs for water utility companies are likely to increase for urban and industrial users (Melo et al., 2010). The long-term sustainability of this densely populated region depends on preserving its water resources.

We present this research as a case study in the semi-arid Andes of Central Chile, establishing a fundamental baseline of spatial and temporal data needed to examine the interactions between water resources, climatic changes, and socio-economic development. This study evaluates the impact of climatic changes and climate variability on water availability in the Aconcagua River Basin, the primary water source for export-oriented agriculture, and the Valparaíso Region in central Chile. With a population of 1.8 million, this region is the country's second most populous (INE, 2020) and has the second-largest economy (ODEPA, 2019). Severe drought in the Aconcagua watershed has reduced river discharge, leading to water shortages and agricultural losses for smaller-scale family farmers (Gobierno Regional de Valparaíso, 2019). Groundwater supplies are not a viable alternative, as one-third are already overexploited (DGA, 2015a). Building additional dams and reservoirs is also unlikely to solve the problem due to runoff limitations and the exhaustion of viable sites (DOH, 2015).

Previous studies on the Aconcagua River Basin have highlighted the role of glaciers in contributing to meltwater during dry years (Crespo et al. 2020; Janke et al. 2017; Ohlanders et al. 2013). Researchers have documented the decline of glacial ice coverage due to warming temperatures (Bown et al., 2008; Coudrain et al., 2005; Malmros et al., 2016; Rivera et al., 2000, 2008) and the potential negative impact this retreat could have on long-term water availability in the region (Corripio et al., 2008). Others have linked precipitation variability in the Aconcagua to the El Niño Southern Oscillation (ENSO), with high variability during El Niño and La Niña phases driving fluctuations in streamflow (Cortés et al., 2011; Escobar & Aceituno, 1998; Martínez et al., 2012; Pellicciotti et al., 2007; Sarricolea et al., 2013;). While warming trends in the Aconcagua have been reported (Falvey & Garreaud, 2009; Pellicciotti et al., 2007), there is limited research on the impact of drought on the basin's hydrology, leaving significant gaps in our understanding. Furthermore, the ongoing drought's impact on water resources in the Aconcagua River remains unstudied, as do the consequences of expanding agricultural water usage and declining water resources due to climate disruptions (Webb et al., 2021).

This analysis aims to achieve three primary objectives: firstly, to assess the impact of climatic changes on the hydrology of the Aconcagua watershed through trend analysis of historical hydroclimatic records; secondly, to document the effect of the ongoing drought on the water resources in this already water-stressed region; and finally, to analyze the combined impact of agribusiness practices and climate disruptions on local agriculture.

Study area

The Aconcagua Basin lies in a transitional zone between the semiarid climate to the North and the dry-summer Mediterranean climate to the South (Di Castri & Hayek, 1976). The valley and coastal areas of the basin experience a dry, semi-arid, and Mediterranean climate, while the higher elevations above 3,000 m have an alpine/tundra climate with colder temperatures and snow. The winter months bring rainfall and snowpack accumulation in the high Andes, primarily from westerly frontal systems (Williams, 2017). Average annual precipitation ranges from 395 mm at the coast to 250 mm in the mid-valley to about 800 mm at high elevations in the Andes. Between 90-95% of total annual precipitation is concentrated in the Austral winter months of May-September, while the summer months of December-February are arid. Evaporation during the summer months is high: 1,361 mm in the valley at about 500 m, which increases to 2,209 mm at 1,100 m (DGA, 2015b). There is a strong correlation between the Oceanic Niño Index (ONI) and changes in the rainfall regime and snow accumulation (Escobar & Aceituno, 1998). The region is prone to experience droughts caused by La Niña events, manifesting in significant precipitation deficits of 35-100% below the climatological average (Piuzzi et al., 2013; Quintana, 2000). During La Niña, evapotranspiration and water demands increased by 30% and 20%, respectively (Meza, 2005).

The Aconcagua River stretches for 190 kilometers, flowing from the headwaters of the Andes Cordillera at an elevation of over 5,000 meters to the Pacific Ocean in the locality of Concón, 15 kilometers north of the Valparaíso-Viña del Mar metropolitan area. It is situated around 75 kilometers north of Santiago, the capital city of Chile. Although relatively small, with an average discharge of 32 m3/s and a total basin area of 7,340 km2, the Aconcagua River plays a crucial role in the region's ecosystem. The basin predominantly comprises highlands, accounting for approximately 80% of its total area. However, only a tiny proportion of the basin is suitable for human habitation and economic activities. The mid-course of the river valley widens slightly to form a floodplain used for agriculture, urban settlements, and industry.

River discharge is driven by rain during fall and winter and snowmelt during the spring and early summer, whereas glacier melt is the main contributor in the mid-to-late-summer. Even during the dry summer season, the streamflow is sustained by ice melting, ensuring the river continues flowing. The peak discharge typically occurs in December (late spring to early summer), whereas the minimum discharge is observed in April (late summer). Interestingly, the minimum precipitation during this time results in maximum discharge, which is advantageous for agriculture, agroindustry, and domestic water usage. This inverse pattern allows maximum water availability during the highest demand (Corripio et al., 2008).

The Aconcagua River Basin holds around 87,500 hectares (875 km^2) of agricultural land, with about 47% of it irrigated, making it an essential hub for specialized agriculture, including temperate fruit production, vegetables, and wine (Gobierno Regional de Valparaíso, 2019). The basin's Mediterranean climate, water resources, and easy market access provide a competitive advantage for its agriculture. The Aconcagua River Basin is home to approximately 14% of the nation's agricultural land for growing fruit crops. Over half (60%) of the valley's fruit production, which amounts to around 331,238 tons, is exported (CIREN-ODEPA, 2020). The fruit industry in the Valparaíso region generates 83% of the total revenue from agricultural exports, accounting for 33% of the country's total income from agrarian exports (ODEPA, 2016).

Materials and Methods

Hydroclimatic records

Precipitation, temperature, snowpack, streamflow, and groundwater data were obtained from the water government agency (Dirección General de Aguas, DGA), the Center for Climate and Resilience Research (CR2), the Dirección Meteorológica de Chile, and the Observatorio de Nieve en los Andes de Argentina y Chile. The DGA agency maintains more than 20 weather stations in the Aconcagua watershed. Sixteen stations with the most extended length of records and with at least 97% complete datasets were selected to analyze long-term variability. Seven stations are in the upper basin (above 1,000 m), five in the mid-basin, and the remaining four are in the lower basin to provide a range of elevations for analysis. The stations, Riecillos (1,290 m) and Resguardo Los Patos (1,220 m), are located on the two main tributaries of the Aconcagua Basin and are representative of the upper-basin precipitation regimes.

The trend analysis of observed hydroclimatic time series data was conducted for the period 1971-2020, with the 1971-2000 period chosen as a reference for the base average, representing typical climate conditions. The base period contrasts with the drought period of 2010-2020. The 1971-2000 period was selected as a base for comparative analysis of drought conditions because hydroclimatic records for this timeframe are generally more complete and available at several stations in the Aconcagua basin compared to earlier periods. This period serves as a practical choice for establishing a baseline against which recent climate trends, such as drought severity from 2010 to 2020, can be measured. It has become a convention in climatology and related fields to use recent decades (like 1961-1990 or 1971-2000) as reference periods due to the availability of comprehensive climate data and the desire to accurately capture recent trends (Marengo et al., 2009). The latter third of the twentieth century is often utilized in recent studies on drought because it represents a relatively stable and typical climate baseline for central Chile. This allows researchers to compare recent climate anomalies, such as the 2010-2020 drought, against what is considered normal or average conditions for that period (Boisier et al., 2016; Garreaud et al., 2017; Garreaud et al., 2020).

The Standardized Precipitation Index (SPI) was used to study precipitation fluctuations to represent regional rainfall trends; records are expressed in units of standard deviation from the standardized mean. A positive SPI value indicates greater than median precipitation (i.e., wet conditions), while a negative SPI value indicates less than median precipitation (i.e., dry conditions). We calculated the SPI for each station, and a single series (1971-2020) was obtained by calculating the average of the six stations.

Temperature records in the Aconcagua Basin are limited and discontinuous. However, four stations were selected with the longest and most complete records to analyze the regional trend of annual temperature. The Vilcuya station, located in the upper basin at 1,100 m elevation, is a valuable data source. This station has had 98% complete data coverage since 1971 and was selected to represent the climatic conditions in the upper basin, which is the primary source of water for the Aconcagua River Basin. The mean annual air temperature (MAAT) recorded at Vilcuya station is 15°C, ranging from 13.0°C to 17.8°C. Long-term fluctuations were analyzed using average maximum temperatures, as they have been found to capture long-term changes in central Chile better (Garreaud et al., 2017).

The Aconcagua River Basin has 11 stream gauging stations, but we obtained monthly mean discharge data from five stream gauging stations with the most complete records. These include (1) Resguardo Los Patos (in the Putaendo River), (2) the Chacabuquito (in the valley of the Aconcagua River), (3) the Blanco River, (4) the Colorado River, and (5) the Juncal River stations (the last three are tributaries located in the headwaters of the Aconcagua River). We selected these streamflow stations because they represent the hydrological mountain regimes of the main tributaries and have the longest and most complete records to analyze long-term trends and the impact of drought on discharge (Table 1). The Chacabuquito station is essential for water forecasting in the Aconcagua watershed because it is located immediately upstream from the beginning of the agricultural area.

The hydrological year (from April to March) was used to organize the records for seasonal trend analysis. There are no large dams in the basin. We used the Mann-Kendall test and Sen's slope estimator to detect the strength and direction of trends in the hydroclimatic variables. Mann-Kendall tests are widely used in hydrological analysis to discern drought periods (Wang et al., 2020). Positive values indicate an upward trend, whereas negative values indicate a downward trend in the data. Trends with p-values <0.1 are statistically significant (Sen, 1968). We performed a trend analysis of annual data for temperature, precipitation, maximum snow water equivalent (MSWE), and streamflow data for the 1971-2000 period (base average conditions) against the period 2010-2020 (the drought conditions).

ENSO

Various El Niño Southern Oscillation (ENSO) parameters have been developed to predict the onset of El Niño and La Niña phases. The Oceanic Niño Index (ONI), which measures Sea Surface Temperature (SST) deviation from the average, is the primary ENSO phase indicator used by the National Oceanic and Atmospheric Administration (NOAA). A threshold of over +0.5 indicates the presence of El Niño or its likelihood, while a value below -0.5 corresponds to the La Niña phase. Values greater than ± 1.0 typically indicate a moderate El Niño or La Niña phase. For this study, the ONI Sea Surface Temperature (SST) anomalies for the center of the equatorial Pacific Ocean (called Niño 3.4) were used. The impact of El Niño-Southern Oscillation (ENSO) on the annual distribution of precipitation during the 1971-2020 water years was evaluated by analyzing the ONI time series from NOAA and the precipitation index at the Resguardo Los Patos hydro-climatic Station (located at 32°29' S, 70°35' W and 1,218 m). Each year in which El Niño or La Niña conditions were present was classified according to strength (very strong, strong, and weak) to assess their impact on precipitation distribution.

Snowpack

To examine changes in the snowline and snow cover area in the upper basin area, we utilized the MODIS/Terra Snow Cover daily data. The Observatorio de Nieve en los Andes de Argentina y Chile processed the MODIS data to obtain the daily estimation of the mean fraction of a grid of 500 x 500 m2 covered by snow and the altitude of the snowline for the Andean river basins of the central Andes (IANIGLA-CONICET/(CR)2 2022). The analysis was based on daily values from January 2001 to December 2021 (older data since 1971 was unavailable). Notably, the fractional snow cover was only calculated when cloud cover was less than 30%. This allowed us to calculate the mean altitude of the snowline and the seasonal extension of the snow cover area, which are key indicators of snow cover dynamics in the basin.

Snowfall measurements

The Dirección General de Aguas (DGA) administers snow courses at five locations in Central Chile to obtain snow depth, density, and water content measurements of the snow cover. For this analysis, we used data from the Portillo station, located in the headwaters of the Aconcagua River at 3,000 m. The Portillo station has continuous records from 1971 and has been missing data for only two years. Winter peak Snow Water Equivalent (SWE) timing in the Andes is known to vary (Masiokas et al., 2006), occurring at any time between June and September. On average, the maximum amount of snow occurs in September. To address this variability, we analyzed the timing of seasonal peak Maximum of Snow Water Equivalent (MSWE) values for each month of the snow season (May through December). We also used the MSWE for each year to analyze inter-annual variability from 1971 to 2020.

Agricultural expansion

Land use data for the Aconcagua River Basin was collected from the Chilean Agricultural and Forestry Censuses of 1997, 2007, and 2021. The data from the twenty municipalities that make up the Aconcagua Basin were aggregated to obtain an overall picture of land use in the basin. Fruit production data were obtained from the Fruit Survey for the Valparaíso Region for the years 2002, 2008, 2014, 2017, and 2020, conducted by the Centro de Información de Recursos Naturales (CIREN) and the Oficina de Estudios y Políticas Agrarias (ODEPA). National account data were obtained from the statistical section of the Central Bank of Chile. Agricultural expansion or loss was measured using Landsat 4 and 5 TM imagery (30 m) from March 17, 1989, and March 19, 2010, because of their limited cloud cover. A Normalized Difference Vegetation Index (NDVI) was calculated to show areas where vegetation and urban growth and loss occurred. Near-infrared and red bands were ratioed to create a single-band image. Large values were filters to show where agricultural expansion occurred. Areas of each class were computed to estimate overall growth and loss; the imagery was visually inspected to determine if a spatial pattern existed.

Results

Hydroclimatic trends and changes

The ongoing multi-year drought has caused regional declines in precipitation. Table 1 illustrates a statistically significant downward trend in annual precipitation records across all stations. The Standardized Precipitation Index demonstrates a linear decrease in regional average annual precipitation from 1971 to 2020 and the impact of reduced precipitation during the current multiyear drought (Figure 1). As a result of this drought, the Aconcagua Basin has experienced mean precipitation deficits ranging from 31% to 50% (less than the historical averages of 1971-2000), with a range of 137 to 284 mm. Since 2010, the Aconcagua Basin has consistently experienced below-average precipitation every year. On average, there has been a substantial 40% reduction in precipitation within the Aconcagua watershed. The primary physical factor contributing to water scarcity is rainfall deficits affecting central Chile since 2010, caused by large-scale circulation

Table 1
Trend statistics for annual precipitation, maximum air temperature, MSWE, and streamflow at different stations. In bold are statistically significant trends at a 1% significance level

	Trend Statistics		**Change in precipitation**			
Stations/trends	**Kendall´s tau**	**p-value**	**1971-2010**	**2010-2020**	**Difference**	**(%)**
Precipitation (mm)						
Riecillos	-0.453	**0.005**	512.7	284.1	-228.6	-45
Vilcuya	-0.438	**0.006**	363.7	233.9	-129.9	-36
Rio Putaendo en Resguardo Los Patos	-0.562	**0.000**	295.2	147.3	-147.9	-50
San Felipe	-0.514	**0.001**	215.1	137.9	-77.1	-36
Catemu	-0.358	**0.025**	264.2	183.4	-80.8	-31
Lo Rojas	-0.467	**0.003**	417.0	259.8	-157.3	-38
Regional Pp. Trend	-0.026	**<0.0002**	344.7	207.7	-136.9	-40
Temperature (°C)						
Vilcuya	0.587	**<0.0001**	22.30	23.86	1.56	7
Quillota	0.382	**<0.0001**	21.60	23.21	1.61	7
Los Aromos	0.703	**<0.0001**	20.50	24.07	3.57	17
Lliu-Lliu Embalse	0.589	**<0.0001**	21.44	23.34	1.90	9
Regional Temp. Trend	0.436	**<0.0001**	21.59	23.76	2.17	10
MSWE (mm)						
Portillo	-0.338	0.009	727.0	294.0	-433.0	-60
Streamflow (m^3/s)						
Río Colorado En Colorado	-0.410	**<0.0001**	8.6	1.1	-7.5	-87
Río Juncal en Juncal	-0.369	**0.000**	6.5	4.4	-2.1	-33
Río Blanco en río Blanco	-0.514	**<0.0001**	9.6	2.1	-7.5	-78
Río Putaendo en resguardo Los Patos	-0.181	**0.071**	9.1	3.0	-6.1	-67
Río Aconcagua en Chacabuquito	-0.223	**0.026**	35.2	17.7	-17.5	-50
Regional Q. Trend	-0.530	**<0.0001**	13.6	5.6	-8.0	-59

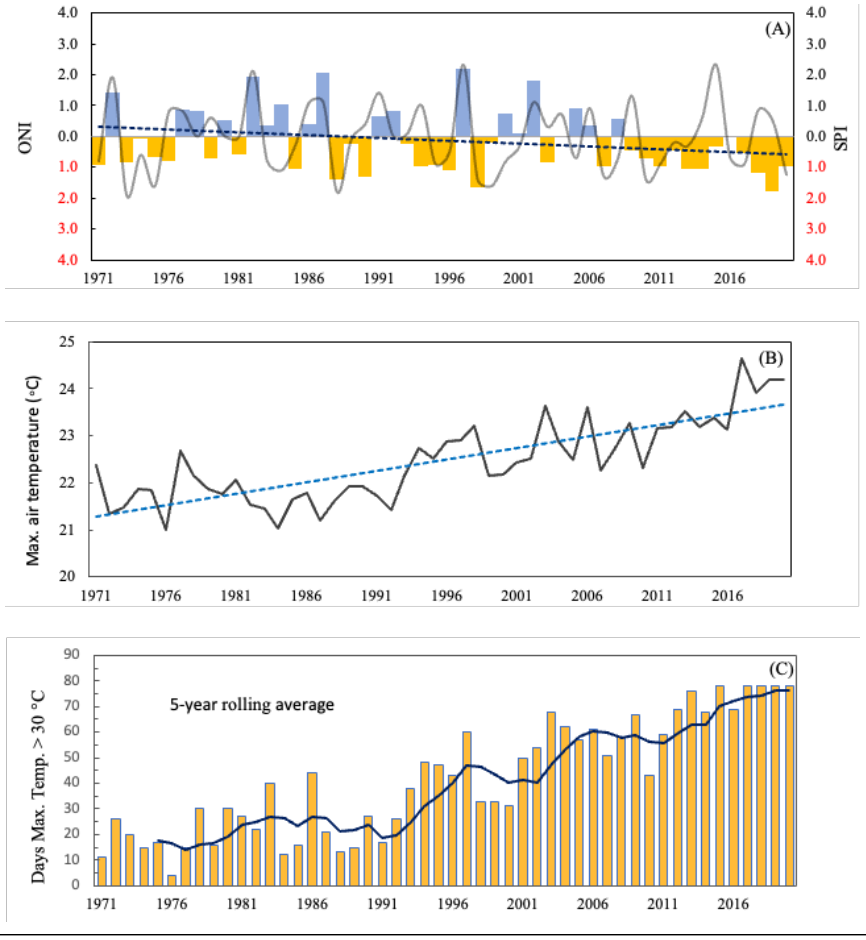
Source: data aggregated and processed from DGA.

changes in the Pacific and anthropogenic climate change (Boisier et al., 2016; Garreaud et al., 2020).

Chile (Falvey & Garreaud, 2009). Our analysis of annual maximum average temperature records from 1971 to 2020 showed a statistically significant increase in temperature in all stations (Table 1). From 1971, the regional maximum temperature in the Aconcagua Basin increased by 2.0 C° or 0.37 degrees per decade. However, most of this increase has occurred since 2000 (Figure 1). During the present drought period (2010-2020), the annual maximum average temperature was 23.8 °C, 2.2 °C warmer than the previous base trend (1970-2000) of 21.6 °C.

The intensity of the current drought is strongly correlated with warmer temperatures, which has been suggested as a driver of extreme global hydroclimatic events due to human-induced greenhouse gas emissions (Rodell & Li, 2023; Williams et al., 2022). The total number of days with extreme temperatures above 30°C has substantially increased from 184 days (1971-1980) to 774 days during the drought (2010-2020) (Figure 1). The data analysis confirms a warming trend in the Aconcagua watershed. Average maximum temperatures have increased, and the number of days with extreme temperatures above 30°C has tripled since 1965. High temperatures have exacerbated the hydric deficit by increasing evaporation and evapotranspiration, leading to water loss from soils, crops, and reservoirs and making the drought more severe (Center for Climate and Resilience Research, 2019). Temperature plays a crucial role in the hydrological regime of the Aconcagua because it controls snow accumulation and snowmelt (Pellicciotti

Figure 1. Time series of (bars) regional precipitation variability and (line) the Oceanic Niño Index (ONI) anomalies for the Niño 3.4 region (1971 to 2020). Precipitation records are expressed as Standardized Precipitation Index (SPI) values. Positive SPI values indicate above-median precipitation (i.e., wet conditions), while negative values indicate below-median precipitation (i.e., dry conditions). An ONI index of +0.5 or higher indicates El Niño conditions (increased precipitation), and an index of -0.5 or lower indicates La Niña conditions (dry conditions) (a). Regional average maximum temperature trend (1971 to 2020) (b). Number of days with maximum temperatures above 30 °C from 1971 to 2020 and 5-year rolling average at the Vilcuya hydroclimatic Station (32°51' S, 70°28' W; 1,100 m) (c)



Source: data aggregated and processed from DGA.

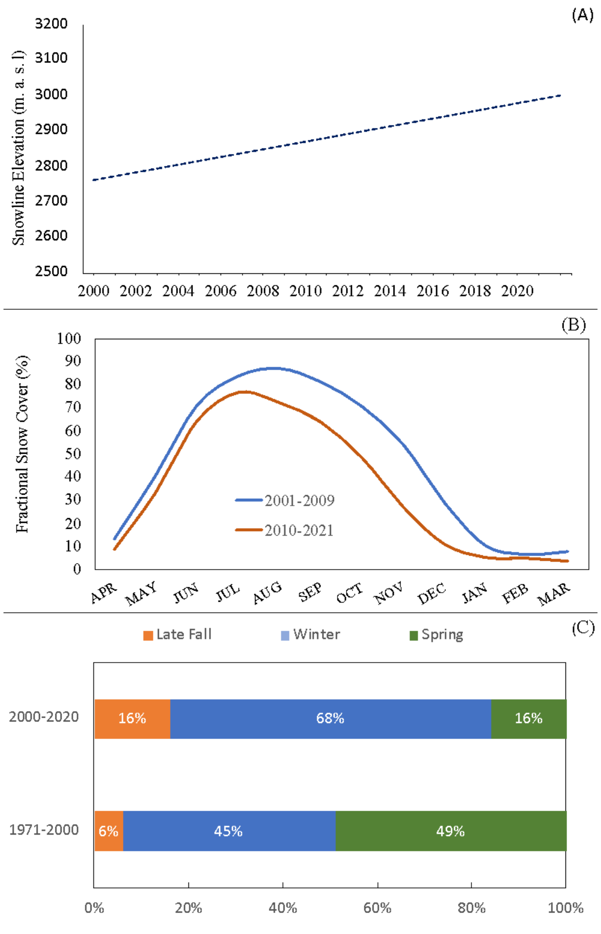
et al., 2007). Warmer conditions in the upper basin of the Aconcagua reduce the storage of water as snow, leading to decreased runoff and water scarcity.

Peak snow coverage in the Aconcagua occurs during the winter months from June through September (Saavedra et al., 2018). The elevation of the snowline decreases during winter to approximately 2,200 m. About 57%, equivalent to 979 km2, of the basin's total area lies above 2,200 m, making it the potential snowfall-receiving area. However, warmer temperatures during spring and summer cause the snowline to ascend to about 4,500 m, leading to snow and ice melt and increasing streamflow.

Based on MODIS data (2001-2020), the average annual elevation of the snowline in the Aconcagua River has risen from approximately 3,700 m in 2001 to about 4,000 m in 2016. This increase aligns with the rise in the equilibrium line altitude (ELA) of glaciers and the 0°C isotherm in the Chilean Andes (Carrasco et al., 2005; 2008). Specifically, the average winter elevation of the snowline, critical for snow accumulation, has experienced a rise of around 200 m in the last 20 years, increasing from approximately 2,760 m in 2000 to about 3,000 m in 2021 (Figure 2). This upward shift in the snowline diminishes the snow cover area available for snow accumulation, reducing streamflow during the summer months (Carrasco et al., 2005).

The winter snow coverage in the upper basin area has decreased by approximately 10%. Due to the drought, there has been a shift in the monthly snow coverage, resulting in earlier snowmelt in the spring. This can be seen in the descending curve during spring, which indicates the increasing speed of seasonal snowpack melt since 2010 (Figure 2). At the end of the spring (in December), only about 11% of the upper basin area was covered with snow during the current drought, compared to 29% during the previous decade (2001-2009). This highlights the effects of the warming trend on the snowpack, which serves as a seasonal and temporary water source. As temperatures rise, the snowpack melts earlier in the spring, reducing water availability later in the summer.

Figure 2. Evolution of the lower limit of the snowline during winter (June, July, and August averages) from January 2000 to January 2021(MODIS data) (a). Daily fraction of snow cover in the upper Aconcagua River basin compared to the base period 2001-2009 and 2010-2021 (b). Evolution of the seasonal distribution of the Maximum Snow Water Equivalent (MSWE) comparing the base period 1971-2000 to the drought 2010-2020 in the upper Aconcagua basin, at the Portillo Hydroclimatic Station (32°50' S, 70°06' W; 3,000 m) (c)



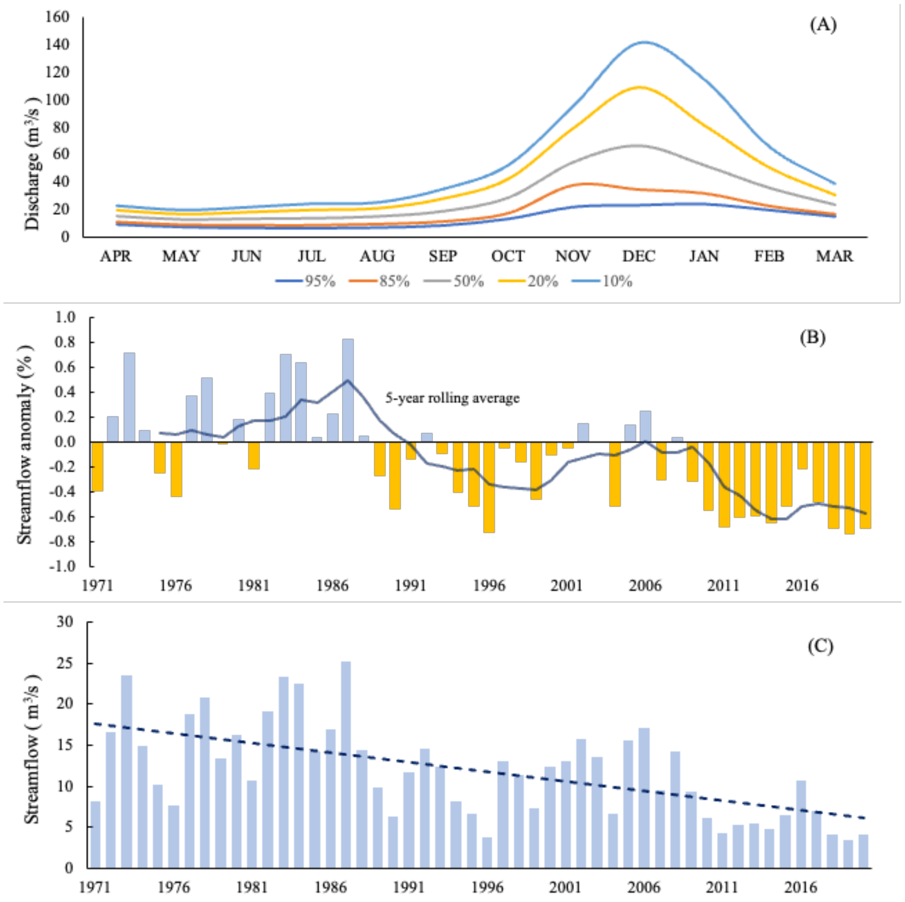
Source: data aggregated and processed from DGA.

Maximum Snow Water Equivalent (MSWE) data shows a statistically significant downward trend in the upper Aconcagua Basin (Table 1). Since the onset of the drought in 2010, the yearly MSWE value has averaged only 294 mm, a 60% deficit from the historical average between 1970 and 2000, which was 727 mm (Table 1). Winter snowpack has been below the historical average every year since 2007, resulting in a cumulative deficit of 41%. Peak MSWE during the spring months has averaged only 16% during the drought, compared to almost 49% during the base period of 1971-2000 (Figure 2). During the same period, peak MSWE during winter months has increased from 45% to 68% (Figure 2). Previously, a significant amount of the snowpack remained throughout the spring months. However, under the current dry period, the snowpack melts quickly during the early spring months, leading to a fast reduction in the snowpack and an early end to the snow season. The significant decrease of the snowpack in the upper Aconcagua Basin during the drought indicates a reduction in summer flows when water demands are higher.

As rainfall decreases during a drought, the water levels of rivers and reservoirs are driven down, reducing water availability. Additionally, prolonged droughts can also cause a decrease in groundwater recharge, resulting in declining groundwater availability. Studies have shown that droughts in the Andes Mountains have reduced surface water flows and decreased groundwater recharge, affecting water availability for human consumption and irrigation (Vuille et al., 2008). The variability of the Aconcagua River's streamflow is strongly influenced by ENSO (Oertel et al. 2020). During the warm phase of ENSO events (El Niño), there is an increase in winter precipitation, resulting in wet years with higher-than-average streamflow. However, the impact of the cold phase of ENSO events (La Niña) on streamflow remains unclear. Generally, La Niña leads to drier-than-normal winter conditions in central Chile and lower-than-average streamflow (Escobar & Aceituno, 1998; Masiokas et al., 2006; Montecinos & Aceituno, 2003; Quintana & Aceituno, 2012; Waylen & Caviedes, 1990). Historical discharge records indicate high annual variability, with streamflow peaks occurring during the summer and lower streamflow in winter. The monthly average discharge in summer is about 22.7 m3/s, dropping to approximately six m3/s during winter (Figure 3).

Historical annual discharge data analysis indicates significant downward trends at all gauging stations in the Aconcagua Basin (Table 1). Since 1989, the regional annual discharge average has been consistently below normal, with only a few exceptions (Figure 3). During the current drought, all gauging stations in the Aconcagua watershed experienced discharge reductions of 33-87% (Table 1), leading to lower-than-normal regional flows. The combination of warmer average temperatures, lower precipitation, and snowpack loss has reduced discharge, causing extreme water shortages in the Aconcagua River basin.

Figure 3. The hydrological regime of the Aconcagua with different monthly exceedance probabilities at the Chacabuquito gaging station (32°85' S, 70°51' W, 950 m) (a). Yearly regional trend of discharge anomalies from 1971 to 2020 (b) and declining discharge over the same period (c)



Source: data aggregated and processed from DGA.

A shrinking water supply

Water scarcity is when renewable freshwater resources are insufficient to meet local demand (Taylor, 2009). A commonly used indicator for measuring water stress is the 1000 m3 capita−1 year−1 threshold for water scarcity (Falkenmark, 1989). The Aconcagua Basin, home to 576,000 inhabitants, is already in a water-scarce semi-arid zone (INE, 2018). The water availability in the basin is approximately 980 m3 per capita−1 year (Fundación Amulén, 2019). Under normal conditions, the Aconcagua Basin can supply an annual gross hydric demand for approximately 2,666 million m3/y (82 m3/s), with agriculture and electricity generation accounting for the most significant consumptive and non-consumptive users.

However, water availability in the Aconcagua Basin is becoming insufficient as total water demand exceeds supply. Part of this problem resides in Chile's current water law, designed in 1981, which did not consider the effects of droughts on water resources. During the 1980s and 1990s, the region experienced above-average rainfall due to consecutive El Niño phases in the ENSO oscillation, leading to a period of hydrological abundance. Capitalizing on this favorable scenario, the government allocated water usage rights for 4,422 million m3/y, exceeding the long-term average resource availability (Table 2). However, since 2000, precipitation and streamflow have sharply declined in many river basins across central Chile, causing the existing water rights to exceed the resource availability in these basins. During the 2010-2022 drought, average water withdrawal dropped to 1,453 million m3/y, reflecting a -44% deficit from the pre-drought average of 2,603 million m3/y. Of this, 67% is from surface waters, while 33% comes from groundwater (Table 2) (DGA, 2020). The basin faced water shortages due to lower precipitation, reduced discharge, and higher temperatures, making it one of Chile's major water deficit regions.

The Aconcagua Basin contains an alluvial aquifer with a total of 4,777 wells (DGA, 2020). Groundwater plays a crucial role in the basin, serving as a significant water source for irrigation and fulfilling the freshwater needs of many rural communities. Over the past few decades, as surface water supplies decreased, the agricultural demand for groundwater has significantly increased, leading to the overexploitation of the aquifers. A recent study has shown that the committed demand, represented by all water rights granted, surpasses the available groundwater resources in all aquifer sections (MOP, 2015). Water withdrawals exceed the natural and induced recharge rates, posing a high risk of aquifer depletion (Table 2). During the present drought, groundwater levels have dropped by 20-30 m in numerous wells, with some running completely dry (Figure 4). Consequently, groundwater in the Aconcagua Basin has been declared a depleted resource. The government has ceased granting additional groundwater rights and has suspended permits for provisional groundwater exploitation.

In terms of freshwater for human consumption, the primary concern lies in meeting the increasing demand for freshwater, exacerbated by the projected drier climate for Central Chile, for the 576,000 inhabitants living in the Aconcagua Basin and in the growing Greater Valparaíso area, which is the country's second-largest metropolitan area (home to an additional 935,000 inhabitants). Although the Valparaíso-Viña del Mar metropolitan area is located outside the Aconcagua Basin, the Los Aromos reservoir, which relies on the Aconcagua River, is an important freshwater source for these two cities. The Valparaíso-Viña del Mar area has the second-largest urban freshwater consumption in the country; potable water consumption was 35.5 million m3/y in 2019 and is expected to increase to 37.3 million m3/y by 2030 (DGA 2020). The ongoing drought has led to significant water level deficits of approximately 50% in the Los Aromos reservoir (Figure 4). In the Valparaiso region, more than 34,000 people living in rural settlements (35% of the rural population) have been affected by severe water scarcity during the

Table 2

Water deficits caused by the drought. The first column contains the water rights granted during the 1980s-90s. The second column presents the water withdrawals during the pre-drought period (2000s). The third column depicts the reduced water withdrawals during the drought (2010-2020). The last column represents the water deficit withdrawals between the 2000s and 2010-2020

Source	Water Rights Granted (m^3/y)	Water Withdrawals 2000s (m3/y)	Water withdrawals (2010-2020) (m^3/y)	Water deficit (%)
Surfaace water	2,925.8	1,952.7	977.6	-49.94
Groundwater	1,497.2	650.9	475.2	-26.99
Total	4,423.0	2,603.6	1,452.9	-44.20

Source: data aggregated and processed from DGA (2020).

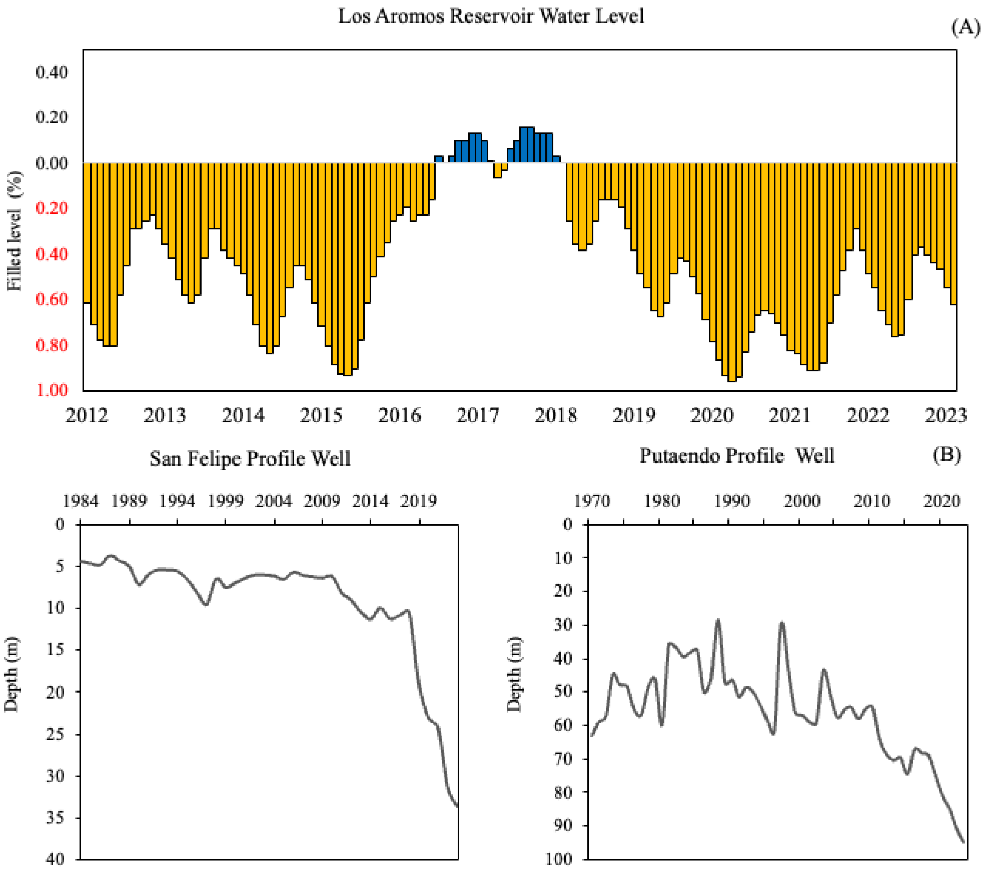
drought. Many of these rural families lack formal access to drinking water supply, and many of them currently rely on cistern trucks (specially designed vehicles for transporting freshwater) as their family wells have dried up due to extensive groundwater extraction by agribusiness (Fundación Amulén, 2019).

Socio-political factors have also contributed to exacerbating the impact of the drought on water resources, primarily due to overexploitation and mismanagement. The Chilean water model, based on private property rights over water, has promoted the concentration and speculation of water resources, leading to the overuse and depletion of aquifers and rivers (Bauer, 1998; Duran-Llacer et al., 2020; Panez-Pinto et al., 2017). Moreover, the absence of institutional capacity for water governance, regulation, and monitoring has led to a concern about water illegality. Numerous users are extracting excessive amounts of water beyond their authorized rights or without the necessary permits. Additionally, the environmental consequences of excessive water usage are not adequately evaluated and addressed. This interplay of environmental and socio-political factors has given rise to water scarcity and vulnerability in the Aconcagua Basin, highlighting the urgent need for a more integrated and sustainable water resource management approach.

Impacts and vulnerabilities of drought on agriculture

To assess the impact of the drought on agriculture, we analyzed the results of the two most recent agricultural censuses: the 2007 census representing the period before the onset of the drought and the 2021 census for the conditions after 12 years of drought. Before the drought, the total agricultural land (cultivated cropland, pastureland, and fallow land) in the Aconcagua River basin covered 143,102 hectares (1,431 km2 or 19.5% of the basin's total area). However, by 2021, the agricultural area had

Figure 4. Status of the water level in the Los Aromos reservoir during the ongoing drought. The bars indicate the reservoir's above (blue) and below (yellow) filling relative to the historical average (a). Depth of the static groundwater levels in two wells of the Aconcagua Basin (b)



Source: data aggregated and processed from DGA.

significantly contracted to only 87,661 hectares (876 km2 or 12% of the basin's area) (Table 3). During the drought, approximately 55,000 hectares of agricultural land remained unproductive, mainly due to prolonged water scarcity and reduced precipitation. This represented a significant -39% reduction in the agricultural area, with irrigated and rainfed pasturelands being the most affected, experiencing a shrinkage at -96% and -54%, respectively.

As a result of the ongoing drought, the cultivated area within the Aconcagua Basin, a subset of the total agricultural land, has seen a significant reduction of -29%, decreasing from 59,198 hectares in 2007 to 41,961 hectares in 2021. Notably, most of this affected area (98%) comprises irrigated cropland (INE, 2022). Among specific crops, those that play a vital role in food security and domestic consumption, such as legumes, vegetables, animal forage, and cereals, have witnessed the most substantial contractions (an average of -53%). In contrast, crops with a higher market value primarily destined for exports, such as temperate fruits (avocados and table grapes are the largest in the planted area), have seen more modest reductions of -17%. Interestingly, vineyards stand out as the only crop that experienced an expansion, adding 169 hectares to their growing area due to the value added in their transformation into wine and the increasing demand for this commodity. Industrial crops in the basin have seen a significant decline in their growing area (-94%), primarily due to the discontinuation of tobacco cultivation, which had a high water requirement of over 50,000 m3/ha/year. Only 30 ha are used for industrial crops to grow sunflowers to produce cooking oil (Table 3).

The land tenure system in Aconcagua is highly unequal: 160 large farms own 65% of the land, 2,600 small-family farms account for only 9% of the land, and 835 midsized farms concentrate the remaining 26% (INE, 2022). Census data reveals that the most profitable fruit and vineyard production occurs in large exploitations owned by agribusiness or medium-sized farms participating in cooperatives or with contracts with agribusiness. On the other hand, an essential segment of food commodity crops is produced by small family-owned farms (INE, 2022).

Access to water in the Aconcagua region is also characterized by inequality. Large farms and agribusiness have managed to maintain their access to scarce water due to their possession of substantial water rights or their ability to acquire additional water rights through purchases or allocations in the local water market. In contrast, small family-owned farms have experienced a gradual erosion of their water access over time due to their more precarious economic situation, which limits their capacity to adapt to a scenario of water scarcity (Zúñiga et al., 2021). Regarding this issue, a recent government study highlights the vital role of small-scale farming in enhancing the country's food sovereignty and security, given their significant contribution (about 50%) to domestic food production.

Table 3
Evolution of the agricultural land area between 2007 and 2021

Land Uses (ha) year	2007	2021	Change (ha)	Change %
Horticulture (Fruits)	38,973	32,346	-6,627	-17
Vineyards	1,079	1,248	169	16
Vegetables	8,173	2,854	-5,319	-65
Cereals	1,338	971	-367	-27
Forage Crops	6,612	3,486	-3,126	-47
Legumes	1,229	311	-918	-75
Nurseries and Seeds	1,310	715	-595	-45
Industrial Crops	485	30	-455	-94
Subtotal Cultivated Land	59,198	41,961	-17,237	-29
Irrigated Pastureland	4,976	187	-4,789	-96
Rainfed Pastureland	70,230	32,472	-37,758	-54
Temporary Fallow	8,698	13,041	4,343	50
Total Agricultural Land	143,102	87,661	-55,441	-39

Source: data aggregated and processed from INE (2007, 2021).

However, the report also points out that droughts and limited access to water continue to pose an ongoing threat to the sustainability of these farms (INDAP, 2023).

The country's water legislation and agribusiness practices significantly contribute to the inequitable allocation of this critical resource between small-family farmers and large exploitations. Chile's water code was established in 1981 under an authoritarian government, granting water rights to individuals and businesses as private property, separate from land ownership and fully marketable commodities (Hearne & Donoso, 2014). This allowed the emergence and consolidation of a robust water market in Chile, where water rights, now tradable, can generate multimillion-dollar profits for their owners. Those with sufficient financial resources can easily acquire water rights (Donoso, 2015a, 2015b, 2021). This system has amplified the concentration of water user rights in the hands of a few. At the same time, small peasant farmers and rural communities have experienced the loss of their customary water rights (Prieto, 2015; Prieto et al., 2022).

A case in point is the significant growth of fruit production for exports in the Aconcagua Basin from the late 1980s through the 2000s. Based on an NDVI analysis, there was a substantial 60% increase in agricultural land from 1989 to 2010. This expansion occurred on the valley's hillsides; 40% was developed on slopes steeper than 5°, while 35% occurred on slopes with gradients lower than 5°. Approximately half of this agricultural expansion was allocated to fruit cultivation, primarily focusing on establishing extensive avocado three plantations. Fruit production is highly lucrative, with approximately 60% of Aconcagua's fruit output designated for export (Pefaur, 2020). For example, from 1997 to 2008, the cultivated land for fruit cultivation expanded by 24%. The land area dedicated to avocado trees saw a 41% increase during the same period. Agribusiness is the main driver for the expansion in the fruit-growing area, exerting mounting pressure on water extraction in an already water-scarce region.

The new plantations employ costly irrigation systems, such as sprinklers and drip/trickle systems, relying on pumped groundwater from the valley floor to the steep hillsides. Avocado trees are water-intensive crops, demanding approximately 11,000 m3/ha/year of water in Aconcagua (Table 4). Avocado production in Aconcagua has surged from 3 million tons in 2002 to over 9 million tons in 2020 (INE 2022). Currently, the avocado-growing area accounts for 35% of the total land planted with fruits in Aconcagua, representing more than 38% of Chile's total avocado plantations (INE, 2022). Chile ranks among the top ten global producers of avocados, and its avocado exports are valued at more than 300 million dollars (Pefaur, 2020).

The expansion of large-scale fruit plantations has increased water demands, and the region's progressively drier and changing climate has exacerbated local water conflicts (Duran-Llacer et al., 2020; Muñoz et al., 2020). Avocado plantations have contributed to groundwater depletion, jeopardizing the water rights of small family farmers and rural residents who rely on groundwater extraction for their freshwater needs (Centro de Agricultura y Medio Ambiente, 2008). Since the onset of the drought in 2010, water scarcity has halted the further expansion of the fruit-growing area, and avocado orchards have experienced a decrease of 1,526 hectares, or 12% of their growing area.

Agriculture stands as the predominant water consumer in the Aconcagua Basin. To evaluate the impact of the drought on irrigation water, we analyzed the irrigation demands for various crops cultivated in the basin based on data from the 2007 and 2021 agricultural censuses. In 2007, the total irrigated area covered 64,497 hectares, requiring 816 million m3/year of water. Notably, fruits accounted for 49% of the irrigation water demand, irrigated pastures at 23%, and vegetables at 11%. By 2021, the irrigated area had decreased to 41,729 hectares, reducing total water demand by 453 million m3/year. The impact of the drought was evident, with irrigated land experiencing a substantial reduction of -35% across all crops, leading to a decrease in their respective growing areas. Water extraction for irrigation also witnessed a significant decline of -44%.

By 2021, fruits had increased their water consumption to 74.5% of the total water usage. This means that scarce water resources are used for the most profitable crops. However, their growing area decreased by -17%, from 38,973 hectares to 32,292 hectares. Three crops, avocado, table grape, and walnut, constituted 59% of the overall water consumption. The most significant decline was observed in irrigated pasturelands, which decreased from 6,000 to 181 hectares, mainly because they required the highest amount of water per hectare, reaching 31,556 m3 per year (Table 4). Irrigated pasturelands are not highly profitable crops, which may have prompted farmers to use available water in more lucrative alternatives.

Despite the reduction in fruit-growing areas and fruit growers' adoption of drip irrigation systems to cope with water scarcity, the total water consumption by fruits has not significantly decreased (Table 4). Fruit agribusinesses have managed to maintain crop production even in the

Table 4
Irrigation water demands by crops between 2007 and 2021

2007 Census Data	**Area**		**Water Requirement**	**Total Water Demand**	
Crops	**(ha)**	**%**	**(m^3/ha/y)**	**(m^3/y)**	**%**
Fruits	38,973	60.4	10,206	397,757,417	48.7
Irrigated Pastureland	6,100	9.5	31,000	189,100,000	23.2
Forage Crops	5,810	9.0	15,326	89,044,060	10.9
Vegetables	8,173	12.7	10,660	87,119,596	10.7
Cereals	1,338	2.1	11,375	15,224,300	1.9
Nurseries and Seeds	1310	2.0	8,383	10,980,253	1.3
Legumes	1,229	1.9	8,411	10,337,960	1.3
Vineyards	1,079	1.7	8,667	9,352,820	1.1
Industrial Crops	485	0.8	14,780	7,163,866	0.9
Total	**64,497**	**100**	**13,201**	**816,080,073**	**100**
2021 Census Data	**Area**		**Water Requirement**	**Total Water Demand**	
Crops	**(ha)**	**%**	**(m^3/ha/y)**	**(m^3/y)**	**%**
Fruits					
Avocado	11,18	26.8	11,265	125,976,495	27.8
Table Grape	8,901	21.3	8,472	75,409,272	16.6
Walnut	4,593	11.0	14,747	67,732,971	14.9
Other	7,615	18.2	9,024	68,714,029	15.2
Subtotal Fruits	32,292	77.39	10,877	337,832,767	74.5
Forage Crops	3,294	7.9	15,326	50,483,844	11.1
Vegetables	2,814	6.7	10,660	29,997,240	6.6
Vineyards	1,238	3.0	8,667	10,729,746	2.4
Cereals	868	2.1	11,375	9,873,500	2.2
Nurseries and Seeds	708	1.7	8,383	5,935,164	1.3
Irrigated pastureland	181	0.4	31,556	5,711,636	1.3
Legumes	306	0.7	8,411	2,573,766	0.6
Industrial crops	28	0.1	14,780	413,840	0.1
Total	**41,729**	**100**	**13,337**	**453,551,503**	**100**

Source: data aggregated and processed from INE (2007, 2022) and DGA (2007).

face of a shrinking water supply by employing strategies such as increasing plant density. For instance, avocado growers have substantially raised the plant density per hectare, from 362 trees in 2002 to 747 trees in 2020 (CIREN-ODEPA, 2002, 2020).

Discussion

A warming and drying river basin

Since 2010, the Aconcagua River Basin in Chile has faced severe water scarcity due to a prolonged drought, marked by a 40% decline in regional precipitation (Diaz et al., 2020; Oertel et al., 2020). This ongoing drought, characterized by below-normal precipitation over extended periods, has been influenced by El Niño and La Niña cycles, which typically drive interannual precipitation variability (Wu et al., 2008). Historically, El Niño events increase rainfall, while La Niña events lead to drier conditions (Quintana & Aceituno, 2012). However, the current drought, which began with the El Niño phase in 2009 and persisted through subsequent El Niño events, has lasted over thirteen years, longer than usual dry periods. This prolonged drought correlates more closely with global warming and other climate indicators than with the El Niño Southern Oscillation alone (Boisier et al., 2016; Cai et al., 2014).

The Aconcagua Basin has seen a significant rise in average annual maximum air temperatures, with a 0.37 °C increase per decade, intensifying the drought. Warming has contributed to decreased snowpack accumulation in the Andes, reducing downstream streamflow (Vuille et al., 2018). Warmer temperatures have accelerated the spring season snowmelt, diminishing summer water availability when irrigation demands are highest. Recent studies highlight that global warming exacerbates extreme hydroclimatic events, leading to reduced rainfall and water availability (Haile et al., 2020; Intergovernmental Panel on Climate Change, 2019; Williams et al., 2022).

The drought has led to a 59% reduction in surface water flows, affecting both human consumption and agriculture. It has also decreased groundwater recharge, further straining water resources. Climate change models predict continued reductions in precipitation and rising temperatures in central Chile, suggesting that these changes may be more than temporary (CCG-UC, 2022). Increasing evaporation rates and altered precipitation patterns due to higher temperatures are aggravating drought conditions, making water scarcity a critical issue.

In Chile, water scarcity is a significant climate change threat, particularly in the Aconcagua Basin. The drought has reduced total water runoff, but more critically, rising temperatures and a higher snowline have altered the seasonality of river flows. This change results in increased winter runoff and decreased summer runoff, which impacts water availability during crucial irrigation periods for agriculture. Since snowpack is essential for river streamflow in the Andes, these shifts pose a serious threat to water supplies (Gonzáles-Reyes et al., 2017; Masiokas et al., 2006).

Water scarcity in the Aconcagua Basin

The Aconcagua Basin faces a formidable challenge - it is situated within a water-scarce semi-arid zone, where water availability consistently falls below the threshold for water scarcity. This water scarcity is evidenced by a progressive decline in precipitation and streamflow observed since the 2000s. Mountains are a crucial source of freshwater in the dry Andes of South America, as they originate the region's rivers (Beniston & Stoffel, 2014; Wang et al., 2023). Diminished snowpack levels in the Andes have contributed to water shortages and hydrological droughts, reducing downstream water availability. Winter snowpacks store water, which is gradually released during spring and summer as it melts. If the snowpack is below normal levels, less water is available for downstream irrigation, drinking, and hydropower generation. Recent studies show that snow cover in the Andes has been decreasing due to climatic changes, leading to less water availability during the dry season and causing regional droughts (Vuille et al., 2018). Thus, monitoring long-term changes in snow cover in the Andes is crucial to assess the impact of droughts on water availability. Consequently, the drought period from 2010 to 2022 has experienced a pronounced water withdrawal deficit. The decrease in surface water availability is further amplified by excessive withdrawal rates, particularly for agricultural irrigation. Notably, groundwater levels have also been severely impacted, with some wells experiencing drops of 20-30 meters during the drought. This water shortage situation has tangible effects, directly affecting the growing population in the Aconcagua Basin and the Greater Valparaíso, where freshwater access is becoming increasingly precarious.

The regulatory framework adds complexity to this crisis. The existing water law in Chile, crafted in 1981, did not anticipate the impact of prolonged droughts on water resources. Consequently, water rights were allocated without accounting for the long-term average resource availability. The private property-based water rights model has inadvertently led to the concentration and speculation of water resources, exacerbating the overuse and depletion of aquifers and rivers. Furthermore, insufficient institutional capacity for effective water governance, regulation, and monitoring has paved the way for water illegality and the inadequate assessment of environmental consequences (Bauer, 2005, 2015).

The repercussions of water scarcity reverberate throughout the region, with significant impacts on access to water and people's livelihoods, particularly in rural areas. The Los Aromos reservoir, a vital source of freshwater for major cities, has faced substantial water level deficits. The crisis is deeply personal in rural communities, with many families confronting severe water scarcity. Some have turned to cistern trucks as their wells dried up due to aggressive groundwater extraction by agribusinesses. This shows that while hydrological regulation systems can buffer deficits during dry years by storing water during wet periods, their efficacy dwindles during prolonged drought cycles.

In summation, the critical water scarcity and dwindling water supply in the Aconcagua Basin are the outcomes of an intricate interplay among climate change-induced droughts, the excessive use of surface and groundwater resources, and the shortcomings of existing water governance. This situation presents a substantial challenge to the region's sustainable management and availability of water resources. Addressing this water crisis demands an immediate shift toward integrated and sustainable approaches to water resources management and governance, an imperative to secure the basin's water resources for the present and the future.

Agriculture

Due to the ongoing drought, the Aconcagua Basin faces an agricultural emergency due to water deficits. The main impact of the drought has been a contraction of the agricultural growing area caused by declining water resources. The most substantial contractions occurred in vital crops for domestic food security, such as legumes, vegetables, animal forage, and cereals, with a reduction of -53%. In contrast, export crops, like avocados, table grapes, and walnuts, saw more modest reductions of -17%. This change reflects the economic rationalization that agribusiness has implemented due to water scarcity: irrigation water has been allocated to high-value commodities such as fruits and diverted from low-value crops such as cereals, vegetables, and forage.

In the Aconcagua Basin, the agricultural landscape is characterized by two distinct groups: large agribusinesses focusing on fruit cultivation for exports and family farmers and medium-sized farms growing traditional crops for domestic consumption. The former partially relies on groundwater for irrigation, while the latter depends more on surface water. This difference in water resource utilization stems from the accessibility of groundwater withdrawal technology, which is more readily available to large agribusinesses, and its extraction is more decentralized. Due to substantial water rights, large farms and agribusinesses have maintained their access to scarce water resources, securing a competitive advantage in the water market. On the other hand, small family-owned farms have faced challenges as their limited economic capacity makes it difficult to compete for water allocations. Consequently, they have experienced a gradual erosion of their water access. The government has played a role in exacerbating this situation by imposing more water restrictions on surface water distribution and encouraging groundwater use. Furthermore, with its resources, the fruit sector has modernized irrigation systems, with approximately 97% of the fruit-growing area relying on efficient irrigation systems. In contrast, around 46% of the total irrigated land planted with vegetables, cereals, and forage crops still utilizes wasteful and outdated irrigation techniques (MINAGRI, 2016).

Given that agriculture currently consumes 74% of the available freshwater in the basin, this sector holds the most significant potential for improvement, as it exhibits the lowest levels of efficiency (Meza et al., 2020). Addressing this challenge, the broad adoption of improved irrigation efficiency systems by small-scale farms could enhance water availability (Ahmad et al., 2014). To tackle the projected drier and warmer climate in the Aconcagua Basin, a potential crop adaptation strategy for arid environments could involve incorporating crops better suited to the new ecological characteristics of the region (Zuñiga et al., 2021). Examples of such crops include jojoba (Simmondsia chinensis), pistachio, and lúcuma (Pouteria lucuma). These crops are more resilient to the drying climate conditions and could offer viable alternatives for farmers in the region (CIREN, 2020).

The drought has significantly impacted agriculture in the Aconcagua Basin, significantly reducing irrigated land. The current water consumption for agricultural purposes, particularly in climate change, is unsustainable. The unyielding extraction of water by large agribusinesses has exacerbated the impact of the drought in central Chile, magnifying existing inequalities and tensions concerning access to both land and water (Acuña & Tironi, 2022). Consequently, this situation poses a significant threat to food security and the viability of small-scale farming while highlighting the need for more equitable water management policies in the basin.

Conclusion

The Aconcagua Basin, nestled within a water-scarce semi-arid zone, confronts a dire water crisis shaped by multifaceted challenges. Driven by a confluence of factors, including overexploitation of surface and groundwater, climate change-induced droughts, and inadequacies in water governance, the basin's water use is unsustainable. The situation is precarious, with water availability already beneath the scarcity threshold and agricultural demand surpassing supply capacity.

The drought's relentless impact since 2010 casts a long shadow over central Chile. The past three decades have witnessed elevated temperatures, precipitation deficits, and reduced river flows across the Aconcagua River basin. Upper regions and valleys have borne the brunt of decreased precipitation, resulting in more than 50%

declines in discharge rates and acute shortages, particularly during dry summer months. Escalating air temperatures and altered snowpack dynamics further strain water resources, significantly impacting the region's rivers.

The surge in fruit tree cultivation before the drought, demanding substantial water resources, compounded the pre-existing challenges. This agricultural expansion, particularly in high-evapotranspiration foothill areas, intensified water needs. The growth of lucrative fruit plantations, prominently avocados and table grapes, amplified water demands, further depleting groundwater. While benefiting export-driven fruit production, this expansion heightened tensions, squeezing out smaller farmers reliant on groundwater.

Industry, mining, and urban sectors place additional demands on already stretched resources, challenging sustainability. Inadequate water management practices and a lack of water-saving culture exacerbate the situation. This ominous trajectory mandates urgent attention to water resource planning and adaptation, necessitating comprehensive strategies to secure water for industries, agriculture, and communities.

The Aconcagua River Basin's ordeal exemplifies the impact of a warming, drying climate, amplifying the severity of drought conditions and reverberating across water resources, agriculture, and local communities. Confronting this intricate crisis mandates an understanding of natural and human-induced dynamics, informing robust strategies to mitigate the prolonged effects of drought. Meeting the challenges of water scarcity demands holistic and sustainable water management approaches to safeguard the environment and the livelihoods that rely on these vital resources.

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