Assessment of Multivariate Drought Impacts on Agriculture in Central Chile for the Enhancement of Sustainable Adaptation

Alina Leticia Zárate

ABSTRACT

Over the past decade, Chile has suffered under "Mega-drought" conditions placing significant pressure on agricultural production. In response to the crisis, the Chilean government has moved to promote sustainable agricultural practices to increase agricultural resilience in a changing climate. This research focuses on multivariate drought impacts on Chile's most productive agricultural regions, the Región Metropolitana de Santiago and the Región O'Higgins, to spatially characterize priority areas for sustainable adaptation based on overall vulnerability to drought. To address this topic, I posed the following: (1) How have meteorological conditions, streamflow levels, and vegetation conditions in agricultural areas changed from non-drought years (2000-2009) to drought years (2010-2020)? (2) Based on meteorological, streamflow, and vegetation condition factors, which agricultural areas are most susceptible to drought conditions and where should Chilean sustainable agricultural development be focused? The Palmer Drought Severity Index, the Standardized Streamflow Index, and the Vegetation Condition Index were used to calculate changes in meteorological, hydrological, and agricultural drought severity respectively from 2000-2020 derived from the Catchment Attributes and Meteorology for Large Scale Studies, Chile Dataset and Landsat 5, 7 ETM+, and 8 satellite imagery. Index values were compared by running a suitability analysis in ArcGIS Pro. Overall, high vulnerability agriculture is located primarily in the Región Metropolitana de Santiago and did not correspond to areas identified by the Chilean government's Ministry of Public Works as facing severe drought. This research improves our understanding of combining drought indices to determine agricultural vulnerability and inform the implementation of sustainable adaptation in Chile.

KEYWORDS

remote sensing, PDSI, VCI, SSI, GIS

INTRODUCTION

One of the most significant threats of climate change is the increasing frequency and severity of drought and its impact on modern agriculture (Dubey et al. 2020). In recent global analyses, rapid global warming has been found to increase global aridity and exacerbate the effects of drought events, a trend that is projected to continue under modeled 1.5 and 2℃ warming scenarios (Dai 2011, Xu et al. 2019, AghaKouchak et al. 2021). Increased drought events globally are expected to have significant consequences including the overexploitation of freshwater resources such as groundwater, species extinction, ecological damage, and conflicts for water access (Srinivasan et al. 2012, Diffenbaugh et al. 2015). The future impacts of drought on agriculture and global food production are of considerable concern as recent studies have connected drought to reductions in environmental health and soil nutrient retention, decreased crop yields, increased pest and disease pressure, and higher flood risks (Turral 2011, Chang and Bonnette 2016, Madadgar et al. 2017, Pathak et al. 2018, Kuwayama et al. 2019, Peña-Guerrero et al. 2020). In light of these significant challenges, mitigation of the environmental impacts of modern agricultural practices is urgently required to protect global food security under evolving climate change conditions.

Agriculture's particular vulnerability to increased drought severity has led to the implementation of numerous adaptations to improve agricultural resilience and mitigate its impact on limited natural resources. Adaptive agricultural strategies vary widely and can include practices from polyculture, intercropping, and conservation tillage to crop breeding, climate-smart water technologies, and precision agriculture (Iglesias and Garrote 2015, Maskey et al. 2016, Dubey et al. 2020, Shahzad et al. 2021, Bwambale et al. 2022) and the application of agricultural adaptations also depend greatly on the agricultural, political, and economic contexts. Agricultural adaptation in Australia, for example, has included the implementation of canopy management initiatives, alterations to crop sequences, and the diversification of crop and livestock varieties (Anwar et al. 2013). Alternatively, China has based its agricultural adaptation on water management strategies, dedicating its resources to enhancing hydroelectric projects to improve water allocation and expanding its water storage capacity (Li and Geng 2013). Finally, California's agricultural adaptation has incorporated both sustainable agriculture and water management strategies including expanded use of groundwater, temporary water transfers among water uses, fallowing farmland, and altering cropping patterns and crop types (Medellín-Azuara et al. 2016, Chang and Bonnette 2016, Morris and Bucini 2016). Although many countries have made significant progress in adapting their agricultural production practices, many others, particularly developing countries, face challenges of how to facilitate this transition to more sustainable practices within their agricultural sectors with limited natural and economic resources.

Agricultural production is critical for economic growth and reducing poverty in Latin America, a reality that is being increasingly undermined by climate changes (Lopez Feldman and Cortes 2016, Mahlknecht et al. 2020). In Chile, the impacts of climate change have been particularly pronounced as the country has suffered severe drought conditions for 13 consecutive years beginning with a period of extreme dryness termed a “mega-drought” from 2010-2015 and lasting to the present day (Garreaud et al. 2017a, FAO 2021). Under existing and projected climate change conditions, snowpack, precipitation, and streamflow levels are expected to decrease resulting in significant water scarcity and changing water properties (i.e. salinity, pH, surface temperatures) that will negatively impact the productivity and crop yield of Chile’s irrigated agricultural system (Meza et al. 2012, Novoa et al. 2019, Muñoz et al. 2020, Peña-Guerrero et al. 2020). These drought impacts have been felt directly by Chilean farmers leading many to adopt mitigation strategies such as irrigation improvements, different crop types, and adjustments to cropping activities (Roco et al. 2017, Zúñiga et al. 2021). In 2022, Chile’s Minister of Agriculture, Esteban Valenzuela, announced new plans to diversify and strengthen the sustainability of the country’s agricultural system in the midst of severe drought by promoting family and smallholder agriculture as well as reducing consumption of water and other natural resources by prioritizing irrigation and technology adoption. The overarching goal of this plan is to increase agricultural production system sustainability, increase food sovereignty and security, and promote territorial justice in rural areas (IICA 2022).

A comprehensive understanding of drought is required to properly understand and implement drought mitigation strategies in the agricultural sector. Drought is typically classified and analyzed in four broad categories: (1) Meteorological drought, (2) Hydrological drought, (3) Agricultural drought, and (4) Socio-economic drought which are broadly defined as a deficit in precipitation, a deficit in water storage and groundwater, a deficit in soil moisture, and a deficit in water-dependent economic goods and products respectively (Wilhite and Glantz 1985, AghaKouchak et al. 2021, Altemus Cullen 2023). Drought severity is measured by a wide variety of drought indices that use combinations of remotely sensed and in-situ data to assess the characteristics and severity of drought on various temporal and spatial scales around the world (Keyantash and Dracup 2002, Zargar et al. 2011). Although much research has been conducted on Chile's drought and its impact on agriculture in recent years (Zambrano et al. 2016, Roco et al. 2017, Garreaud et al. 2017b, Novoa et al. 2019, Muñoz et al. 2020), these studies have focused primarily on single variable drought analyses to assess drought severity, thereby failing to address the multiple variables that contribute to drought conditions or apply these to spatial assessments of vulnerability that can be used to inform sustainable agricultural development in a changing climate.

In this study I ask, can a multivariate drought analysis be used to inform the implementation of the Chilean Ministry of Agriculture's plan for sustainable agricultural development in Chile's Región Metropolitana and Región O'Higgins to address the impacts of drought? To answer this I pose the following sub-questions: 1) How have meteorological, streamflow, and vegetation conditions changed from non-drought years (2000-2009) to drought years (2010-2020)? 2) Based on meteorological, hydrological, and vegetative factors, which agricultural areas within the study site are most susceptible to drought conditions and where should Chile's plan for sustainable agricultural development be prioritized? To answer these questions, I used the Palmer Drought Severity Index (PDSI), the Standardized Streamflow Index (SSI), and the Vegetation Condition Index (VCI) to calculate changes in meteorological, hydrological, and agricultural drought severity respectively from 2000-2020. The multivariate drought severity analyses were conducted using precipitation, evapotranspiration, and streamflow data provided by the Catchment Attributes and Meteorology for Large Sample Studies, Chile Dataset and vegetation condition data derived from remotely sensed Landsat 5, Landsat 7 ETM+, and Landsat 8 satellite imagery. I hypothesize that meteorological, hydrological, and agricultural drought severity will increase overall from 2000-2020 but will not be uniformly distributed within the study site. The multivariate distribution and classification of drought severity according to the indices used in this study will determine which areas are most affected by and vulnerable to drought impacts, informing where the Chilean Ministry of Agriculture's plan for sustainable agricultural development should be focused.

METHODS

Study site

Central Chile is a semi-arid area that is home to 10 million people with nearly 40% of Chileans living in the greater Santiago area. It is also the country's most productive agricultural area, hosting the majority of Chile's wine and fresh fruit production (OECD 2019). Out of 42 watersheds and river basins identified within the Región Metropolitana (33.48°S and 70.62°W) and the Región O'Higgins (34.58°S and 71.00°W), I focused on the 14 watersheds that house the majority of agricultural production (Figure 1).

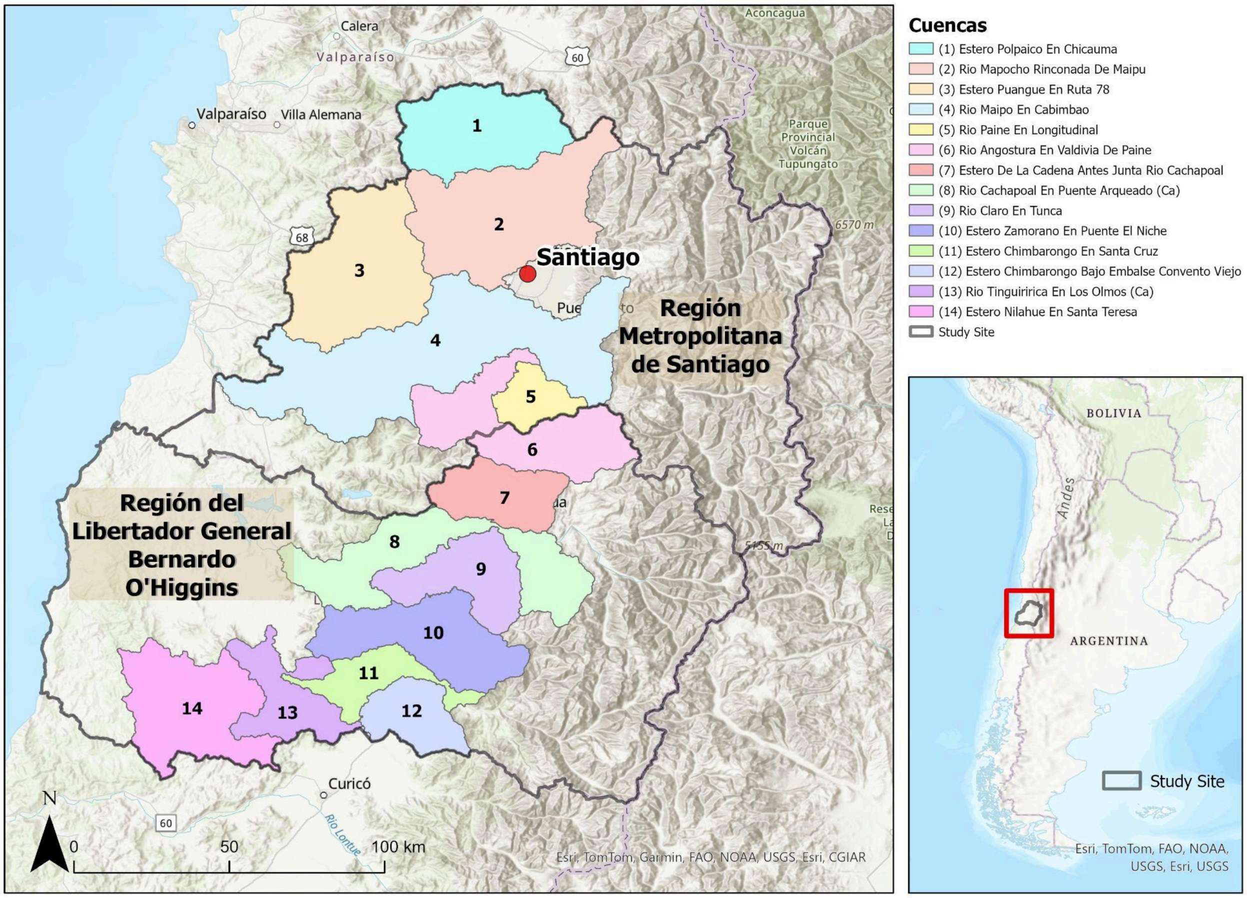


Figure 1. Study Site: Región Metropolitana de Santiago and Región del Libertador General Bernardo O'Higgins and location of associated cuencas (river basins) (Alvarez-Garreton et al. 2018).

Since 2010, Chile has experienced an uninterrupted sequence of dry years that have been termed a "Mega-Drought" and which have had significant impacts on water availability and vegetation health with environmental, social, and economic effects (Garreaud et al. 2019). The pressures created by mega-drought have been particularly acute in Central Chile where competing urban and rural water needs have resulted in decreased crop yields in agricultural irrigation districts and increased water prices for inhabitants of Chile's urban centers (Aldunce et al. 2017). Given these significant issues and the seemingly unending nature of the drought in Chile, the Chilean Ministry of Agriculture has put forth new strategies to reduce water usage and mitigate drought impacts within Chile's agricultural sector and beyond (IICA 2022, Instituto de Desarrollo Agropecuario 2023). As a result, Chile serves as a prime case for studying the prospects of geospatial drought analyses to identify agricultural vulnerability and sustainable adaptation potential.

Data and methodology

Data collection

I used a combination of satellite and field data to assess multivariate drought within the study region. I acquired and analyzed Landsat 5, Landsat 7 ETM+, and Landsat 8 time-series data at 30 m spatial resolution from 2000 to 2020 in Google Earth Engine (v7.3.1) to assess vegetation conditions within the selected watersheds. Alternatively, I used monthly average precipitation, potential evapotranspiration, and streamflow data at the catchment scale from the Catchment Attributes and Meteorology for Large Scale Studies, Chile Dataset (CAMELS-CL) focusing on the subset of 14 watersheds (Figure 1) to assess drought severity and streamflow changes (Alvarez-Garreton et al. 2018). I analyzed this data in RStudio (2023.12.0+369) and visualized it using ArcGIS Pro (Esri 3.0.3).

Calculation of standardized drought indices

Palmer drought severity index. Meteorological drought is determined by the degree of dryness in an area based on atmospheric causes and is generally measured using precipitation levels and surface temperature (Kallis 2008). The Palmer Drought Severity Index (PDSI) is commonly used to estimate meteorological drought over long periods of time by using readily available precipitation and potential evapotranspiration data at a particular location to provide a standardized index ranging from -10 (dry) to +10 (wet) (Table1) (Palmer 1965, Keyantash and Dracup 2002, Altemus Cullen 2023).

Table 1. Drought classes based on PDSI values.

PDSI values	Class
Above 4.00	Extremely Wet
3.00 to 3.99	Very Wet
2.00 to 2.99	Moderately Wet
1.00 to 1.99	Slightly Wet
0.50 to 0.99	Incipient Wet Spell
–0.49 to 0.49	Normal
–0.99 to –0.50	Incipient Dry Spell
–1.99 to –1.00	Mild Drought
–2.99 to –2.00	Moderate Drought
–3.99 to –3.00	Severe Drought
Below –4.00	Extreme Drought

To calculate meteorological drought in agricultural areas within the Metropolitana and O'Higgins regions, I used monthly precipitation and potential evapotranspiration values from 2000-2020 from the CAMELS-CL dataset. I used the scPDSI package (v 0.1.3) in RStudio (2023.12.0+369) to calculate the monthly PDSI over the 20-year period for each catchment (Alvarez-Garreton et al. 2018). I visualized the monthly changes in meteorological drought severity for each watershed in a time-series graph for each study region. Additionally, the difference in average pre-drought and drought PDSI was calculated by calculating the average PDSI value in the 10 years prior to the drought (2000-2009) and subtracting it from the average PDSI value in the 10 years of drought (2010-2020). I displayed these results geospatially in ArcGIS Pro (Esri 2.8) at the catchment scale.

Standardized streamflow index. Hydrological drought focuses on abnormal streamflow, groundwater, and surface water deficits resulting from reductions in precipitation (Kallis 2008). This type of drought has been used to refer to the inability of natural water resources to meet human water demands (Altemus Cullen 2023). There are multiple indices that are used to calculate hydrological drought including the Standardized Streamflow Index (SSI) which assesses the duration and intensity of hydrological drought for a particular river basin (Peña-Guerrero et al. 2020). SSI can be calculated to categorize hydrological drought using the same process for calculating the Standardized Precipitation Index (SPI) in which precipitation data is replaced with streamflow data (Table 2) (Shamshirband et al. 2020).

Table 2. Drought classes based on SSI values.

SSI values	Class
Above 2.00	Extremely Wet
1.50 to 1.99	Very Wet
1.00 to 1.49	Moderately Wet
–0.99 to 0.99	Normal
–1.00 to –1.49	Moderate Drought
–1.50 to –1.99	Severe Drought
Below –2.00	Extreme Drought

To calculate hydrological drought in agricultural areas within the study site, I used the CAMELS-CL database to determine catchment boundaries within the Metropolitana and O'Higgins regions and the monthly streamflow levels within each catchment and used the SPEI Package (v 1.8.1) in RStudio (R 4.3.2) to calculate SSI on a 1-month timescale from 2000-2019 (Alvarez-Garreton et al. 2018). I visualized the monthly changes in hydrological drought severity for each watershed in a time-series graph for each study region. Additionally, the difference in average pre-drought and drought SSI was determined by calculating the average SSI value in the 10 years prior to the drought (2000-2009) and subtracting it from the average SSI value in the 9 years of drought (2010-2019). The adjusted dates of data analysis are based on the availability of streamflow data within the CAMELS-CL dataset. I displayed these results geospatially in ArcGIS Pro (Esri 3.0.3) at the catchment scale.

Vegetation condition index. Agricultural drought refers to the impact of meteorological drought on agricultural cultivation, land use decision, and crop health, which can be calculated using a variety of metrics including soil moisture, evapotranspiration rates, surface temperature, and changes in crop yields (Humphreys 1931, Rosenberg 1980, Bakker 2000, Altemus Cullen 2023). A commonly used index to analyze agricultural drought is the Vegetation Condition Index (VCI). VCI uses Normalized Difference Vegetation Index (NDVI) values which quantifies vegetation greenness and is used to assess plant health. This index can be used to compare overall vegetation health during drought years with vegetation health during non-drought years by comparing current NDVI to NDVI values observed in the same period in previous years (Landsat Missions 2023).

NDVI values are calculated using the following equation:

$$NDVI = \frac{NIR - RED}{NIR + RED}$$

where RED and NIR represent red and near-infrared bands respectively. The NDVI values are then used in the following equation to determine VCI over a specified period of time:

$$VCI = 100 * \frac{NDVI - NDVI_{min}}{NDVI_{max} - NDVI_{min}}$$

where $NDVI_{min}$ and $NDVI_{max}$ are the multi-year absolute minimum and maximum NDVI for a specific pixel (Kogan 1990). VCI values are expressed as a percentage with low values indicating poor vegetation condition and high values indicating good vegetation health which are associated with a range of drought classifications (Table 3) (Bhuiyan et al. 2006, Zambrano et al. 2016).

Table 3. Drought classes based on VCI values.

VCI values (%)	Class
< 10	Extreme Drought
< 20	Severe Drought
< 30	Moderate Drought
< 40	Mild Drought
≥ 40	No Drought

To calculate agricultural drought in the study site, I consolidated Landsat 5, Landsat 7 ETM+, and Landsat 8 satellite images at 30 m resolution in Google Earth Engine (v7.3.1) to enhance data continuity and analysis. In order to account for bias in VCI calculations over the long 2000-2020 time period, I used the wettest pre-drought years (2000-2005) to calculate the $NDVI_{min}$ and $NDVI_{max}$ values and the driest drought years (2010-2015) to calculate the mean NDVI value. In both cases, I included satellite imagery of only the major harvest months (January, February, and March) when crops would be at their peak growth to calculate the NDVI values. I then ran the VCI analysis to calculate changes in vegetation health and displayed them spatially in Google Earth Engine (v7.3.1) using a red-yellow-green continuous visualization color palette.

Agricultural vulnerability and sustainable development analyses

Suitability analysis. A suitability analysis is a geographic-based process that allows sites within an area of study to be qualified, compared, and ranked based on a defined criteria. I conducted a suitability analysis to combine the contributions of meteorological, agricultural, and hydrological drought to agricultural vulnerability, defined as susceptibility to change under drought conditions, within the Metropolitana and O'Higgins regions. Agricultural areas are identified as having high vulnerability if they have been significantly impacted by all three drought types and as having low vulnerability if they have been minimally impacted by the three drought types relative to other areas within the study site. Based on the vulnerability results, I then classified the watersheds in terms of priority for sustainable adaptation interventions by the Chilean Ministry of Agriculture.

To conduct the suitability analysis, I imported the PDSI, VCI, and SSI values into ArcGIS Pro (Esri 2.8) and constructed a map to display the overlapping drought impacts within the study site. I ran a suitability analysis in which the values of the three indices were reclassified into categories of High Vulnerability, Moderate Vulnerability, and Low Vulnerability and were each given an equal weight of 0.33 (Table 4). The results were displayed and classified using a choropleth map.

Table 4. Suitability Analysis criteria, criteria scores, and weights.

Drought Type	Criteria	Criteria Scores (Vulnerability)			Weight
		3 (High)	2 (Moderate)	1 (Low)	
Meteorological	PDSI	-2.00 to -2.50	-1.50 to -1.99	-1.00 to -1.49	0.33
Hydrological	SSI	-1.00 to -1.50	-0.50 to -0.99	0 to -0.49	0.33
Agricultural	VCI	0 to 40	41 to 75	75 to 100	0.33

Sensitivity analysis. I conducted a sensitivity analysis to measure the accuracy of a model output and provide information about the level of error the model produces. This analysis can be conducted by performing additional suitability analyses in which the weights of the input variables are reassigned to determine how different inputs affect the outputs of the analysis or by comparing the results of the model to real-world classifications (Malczewski 2004). I elected to conduct the sensitivity analysis by comparing the results of the study to areas that have been classified by the Chilean government as having surface and groundwater rights fully allocated or, in other words, being in socio-economic drought (DGA 2020).

To conduct the sensitivity analysis, I used the Chilean government's Declaraciones de Agotamiento de Aguas Superficiales [Declarations of Surface Water Depletion] for comparison. I mapped the classifications of extreme drought in ArcGIS Pro (Esri 3.0.3) and compared them to the suitability analysis outputs (DGA 2020). Given that government data is classified at the catchment scale, it was expected that the majority of agricultural areas identified in this study as High Vulnerability would be located within the catchments specified as being depleted of surface water.

RESULTS

Meteorological drought severity

I assessed the meteorological drought severity for the 14 watersheds in the Región Metropolitana and Región O'Higgins over the 20 year period from 2000-2020. Based on the average monthly PDSI values for each region, I found that both regions followed a negative PDSI trend over the 20 year period and experienced extended periods of meteorological drought conditions beginning in 2008 and lasting to 2020 (Figure 2a, Figure 2b). In the Región Metropolitana, the average PDSI remained overwhelmingly negative from 2010-2015 reaching the PDSI classification of "Severe Drought" in December 2013. From August 2015 to April 2016, the Región Metropolitana experienced a wet spell and reached an unprecedented PDSI value of 6.9 in April 2016 indicating extremely wet conditions which were followed by extremely dry conditions from 2018 to 2020 reaching an all-time low -4.8 average PDSI value in November 2019 (Figure 2a). The Región O'Higgins followed a similar pattern to the Región Metropolitana with consistently negative PDSI values from 2010-2015 and a few short wet periods, particularly from August 2015 to April 2016, followed by a dry period. April 2016 would record an all-time high PDSI value of 5.6 and November 2019 would record an all-time low PDSI value of -3.8 mirroring the trends of the Región Metropolitana although slightly less extreme (Figure 2b).

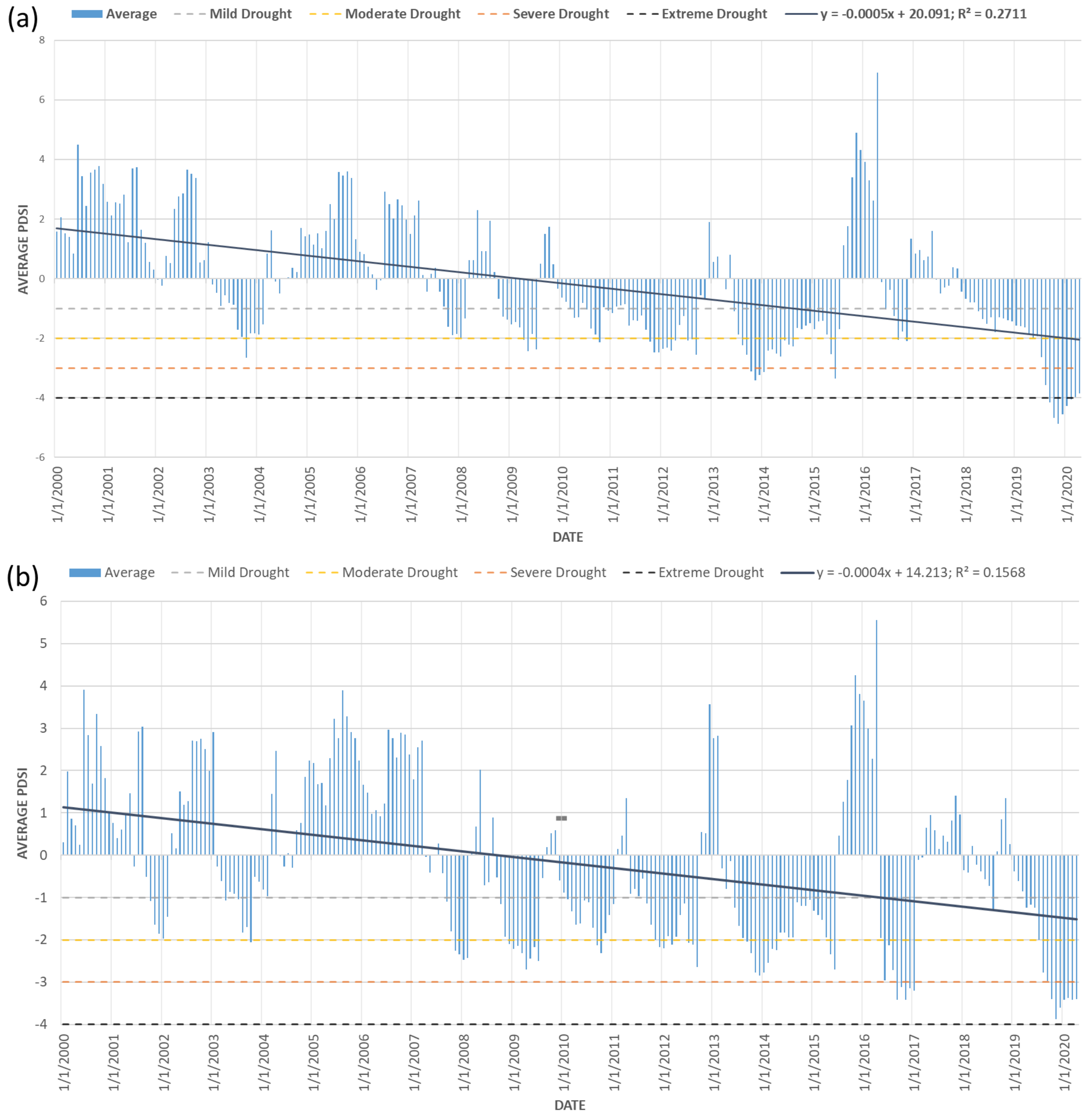


Figure 2. Average monthly PDSI values from 2000-2020. (a) Región Metropolitana de Santiago watersheds and (b) Región del Libertador General Bernardo O'Higgins watersheds

On a watershed level, I calculated the difference in average PDSI from pre-drought years (2000-2009) and drought years (2010-2020). I found that all watersheds in both the Región

Metropolitana and Región O'Higgins had a positive average PDSI value in pre-drought years ranging from 0.3 to 1.1 and a negative average PDSI value in drought years ranging from -1.2 to -2.3. In general, the Región Metropolitana experienced a more dramatic difference in PDSI values from pre-drought years to drought years with all watersheds indicating a difference greater than -2.0 PDSI. The Rio Mapocho Rinconada del Maipo watershed represented the most extreme change with a difference in PDSI of -2.4 (Figure 3). Conversely, the Región O'Higgins experienced more measured differences in PDSI values from pre-drought years to drought years of between -1.1 to -1.9 (Figure 3).

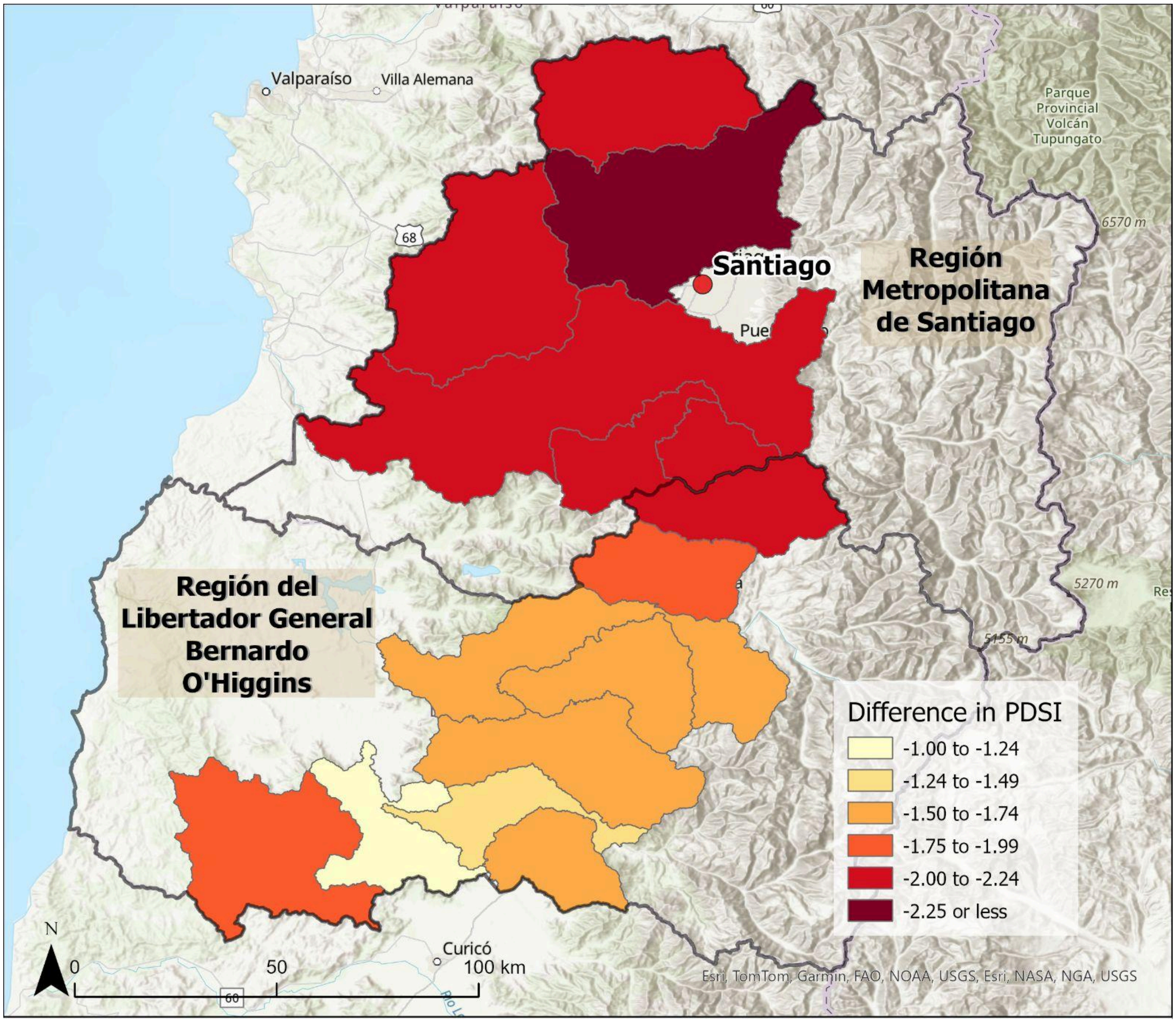
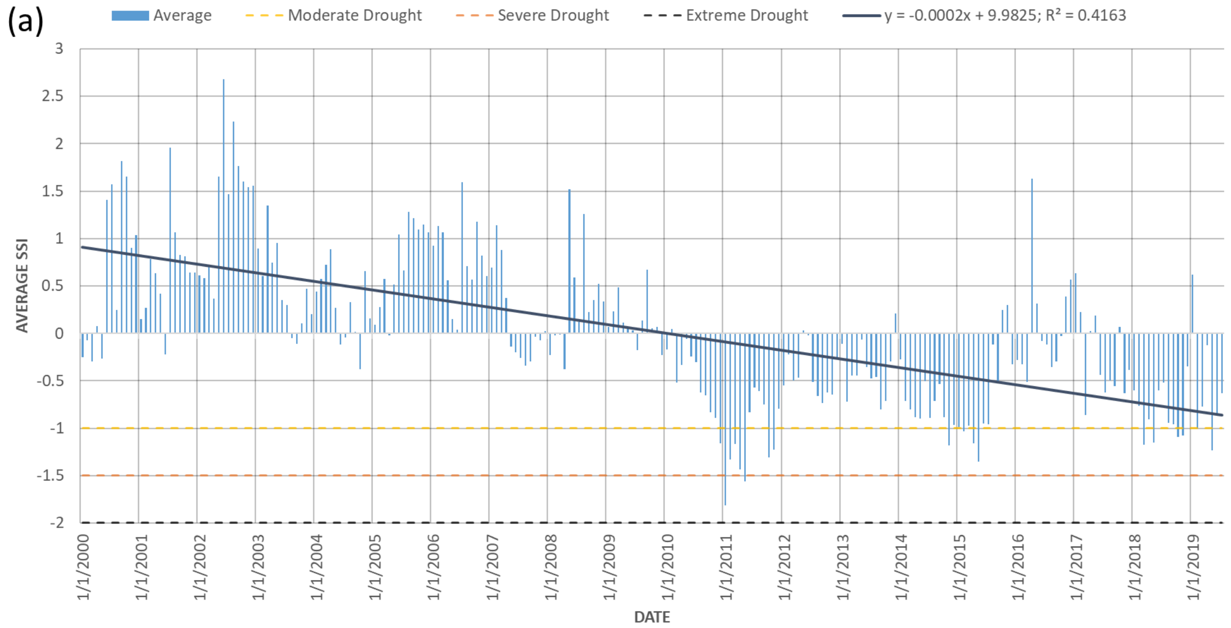


Figure 3. Difference in average pre-drought (2000-2009) and drought (2010-2020) PDSI values per watershed in the Región Metropolitana de Santiago and Región del Libertador General Bernardo O'Higgins.

Hydrological drought severity

Similar to the meteorological drought analysis, I assessed hydrological drought severity for the 14 watersheds in the Región Metropolitana and Región O'Higgins from 2000-2019 and found, based on monthly average SSI, that all watersheds followed a negative trend over the 19 year period experienced extended periods of hydrological drought conditions beginning in 2010 and lasting to 2019 (Figure 4a, Figure 4b). In the Región Metropolitana, I found that the average monthly SSI values were consistently negative beginning in 2010 with the majority of SSI values recorded between -0.5 and -1.5 between 2010 and 2019. A slight variability between positive and negative SSI values was identified in early 2016 and early 2017. Additionally, the SSI classification of "Severe Drought" was recorded in January 2011 in the region with an all-time low SSI value of -1.8 (Figure 4a). Alternatively, through analysis of watersheds in the Región O'Higgins I also found consistently negative average monthly SSI values beginning in 2010 with slightly more variation in the ranges of SSI values. This also consisted of more interspersed months with positive SSI values including a wet period from the end of 2015 to early 2018. The Región O'Higgins reached the SSI classification of "Severe Drought" and an all-time low SSI value of -1.6 in October 2013 (Figure 4b).



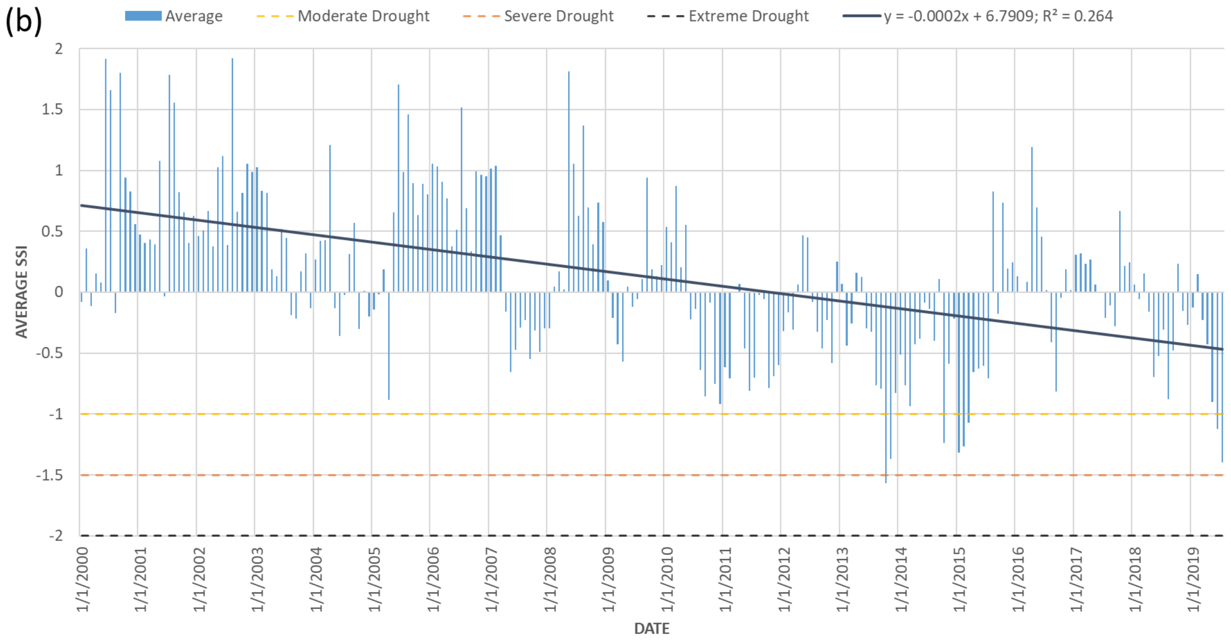


Figure 4. Average monthly SSI values from 2000-2019. (a) Región Metropolitana de Santiago watersheds and (b) Región del Libertador General Bernardo O'Higgins watersheds

To assess hydrological drought severity on a watershed level, I calculated the difference in average SSI from pre-drought years (2000-2009) and drought years (2010-2019). I found that all watersheds in both the Región Metropolitana and Región O'Higgins had a positive average SSI value in pre-drought years ranging from 0.2 to 0.6. Average SSI values in drought years for watersheds in the Región Metropolitana were also consistently negative ranging from -0.2 to -0.7 while average SSI values in drought years for watersheds in the Región O'Higgins had a wider range from 0.1 to -0.6. Sufficient data was not available for the Estero Polpaico en Chicauma, Rio Paine En Longitudinal, and Estero Chimbarongo Bajo Embalse Convento Viejo watersheds. In general, watersheds in the Región Metropolitana experienced a greater change in SSI values from pre-drought years to drought years with differences in average SSI ranging from -0.5 to -1.3. Conversely, the Región O'Higgins experienced a wider range of difference in average SSI values from pre-drought years to drought years of between -0.1 to -1.3. The Río Angostura En Valdivia de Paine watershed, which sits in both the Región Metropolitana and Región O'Higgins, represented the most extreme difference in SSI of -1.3 (Figure 5).

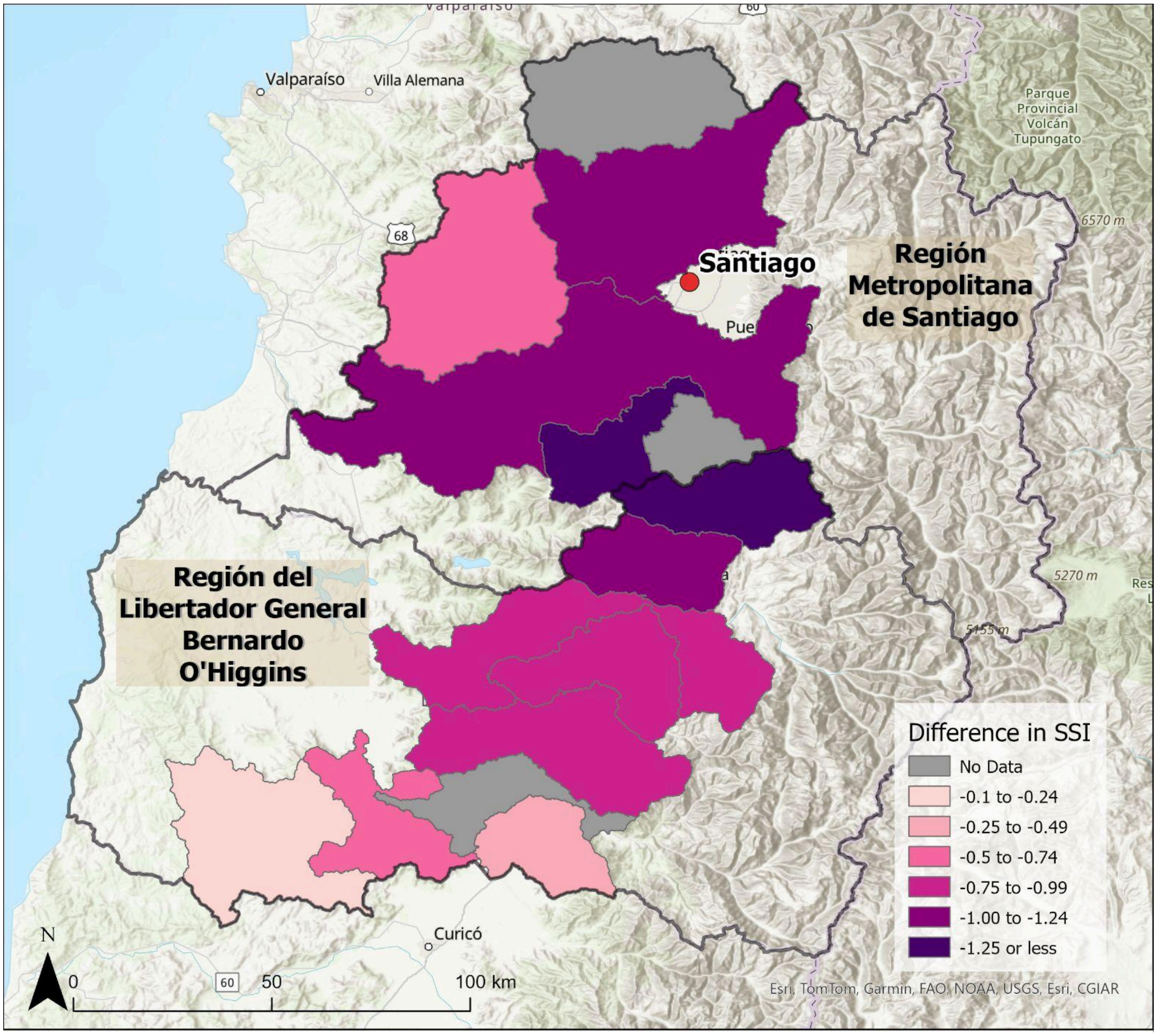


Figure 5. Difference in average pre-drought (2000-2009) and drought (2010-2019) SSI values per watershed in the Región Metropolitana de Santiago and Región del Libertador General Bernardo O'Higgins.

Agricultural drought severity

I assessed the agricultural drought severity of the 14 watersheds where agricultural production is concentrated in the Región Metropolitana and Región O'Higgins by comparing the NDVI values of the wettest pre-drought period (2000-2005) to the NDVI values of the driest drought period (2010-2015) in a VCI analysis. I found a mixed distribution of VCI values with all watersheds exhibiting VCI values ranging from 0 to 100 (Figure 6). Despite this, watersheds in the Región Metropolitana appeared to a greater concentration of areas with lower VCI values

(0-40) represented in red and orange while watersheds in the southern Región O'Higgins appeared to have a greater concentration of areas with high VCI values (70-100) indicated in dark green (Figure 6). The majority of areas in all watersheds had a moderate VCI value (50-70) indicated by yellow and light green (Figure 6).

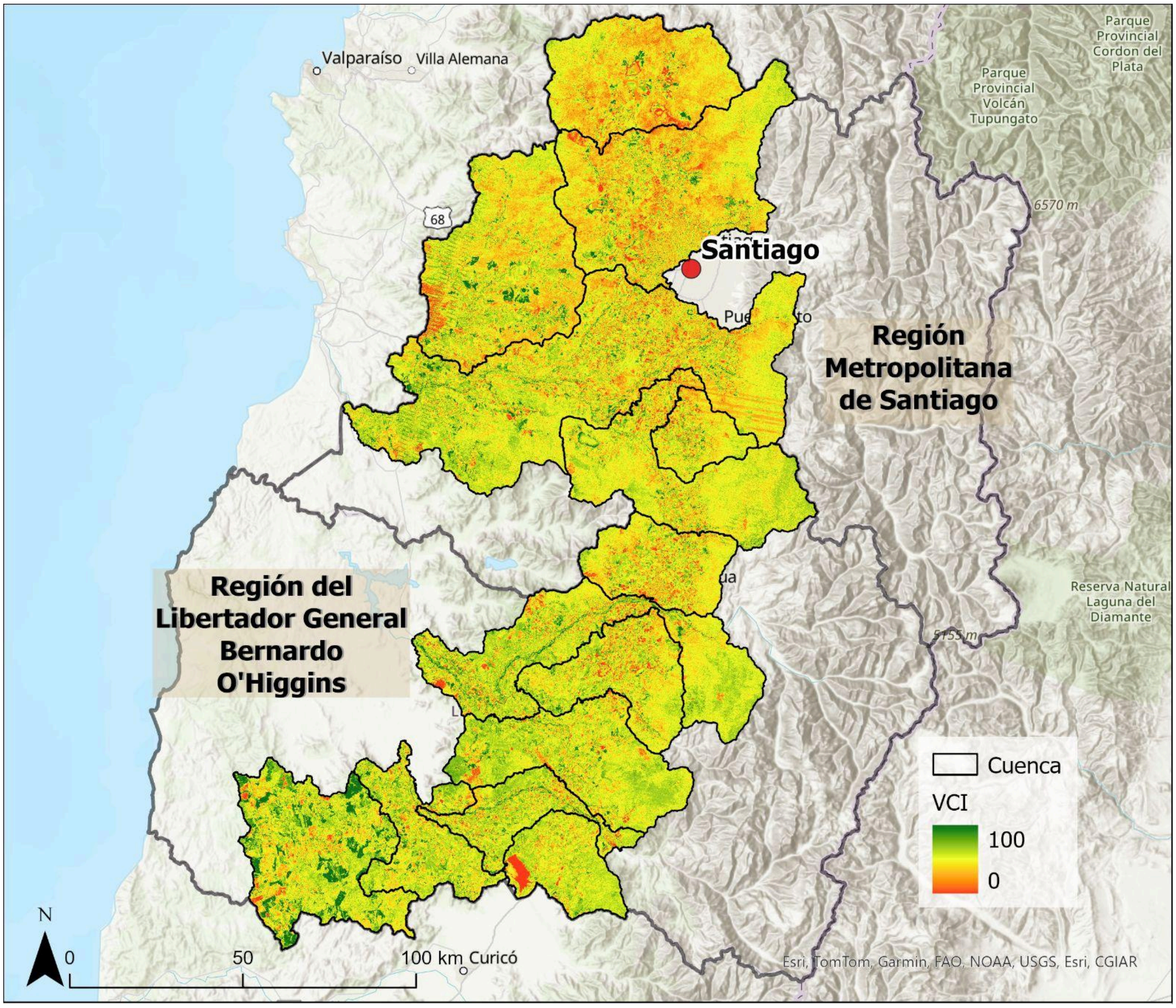


Figure 6. Vegetation Condition Index of watersheds in the Región Metropolitana de Santiago and Región del Libertador General Bernardo O'Higgins.

Multivariate drought vulnerability

To determine overall multivariate drought vulnerability, I conducted a suitability analysis that provided a combined assessment of meteorological, hydrological, and agricultural drought severity. From the analysis, I found that drought vulnerability was not evenly distributed within the study site. The analysis identified higher vulnerability in the northern river basins of the Región Metropolitana with the Río Maipo, Río Mapocho, and Río Angostura watersheds demonstrating the highest levels of vulnerability with vulnerability scores ranging from 2.31 to 2.97 (Figure 7). Conversely, I found that vulnerability decreased moving southward as the southernmost river basins in the Región O'Higgins, i.e. Estero Chimbarongo Bajo, Estero Chimbarongo En Santa Cruz, and Río Tinguiririca, demonstrated the lowest levels of vulnerability with scores ranging from 0.99 to 1.98 (Figure 7). Five watersheds within the study site (i.e. Río Tinguiririca, Estero Chimbarongo En Santa Cruz, Estero Chimbarongo Bajo, Río Cachapoal, and Río Mapocho) were declared as Depleted of Surface Waters by the Chilean Ministry of Public Works (DGA 2020). These watersheds spanned the entire study site and did not correspond to any particular vulnerability classification (Figure 7).

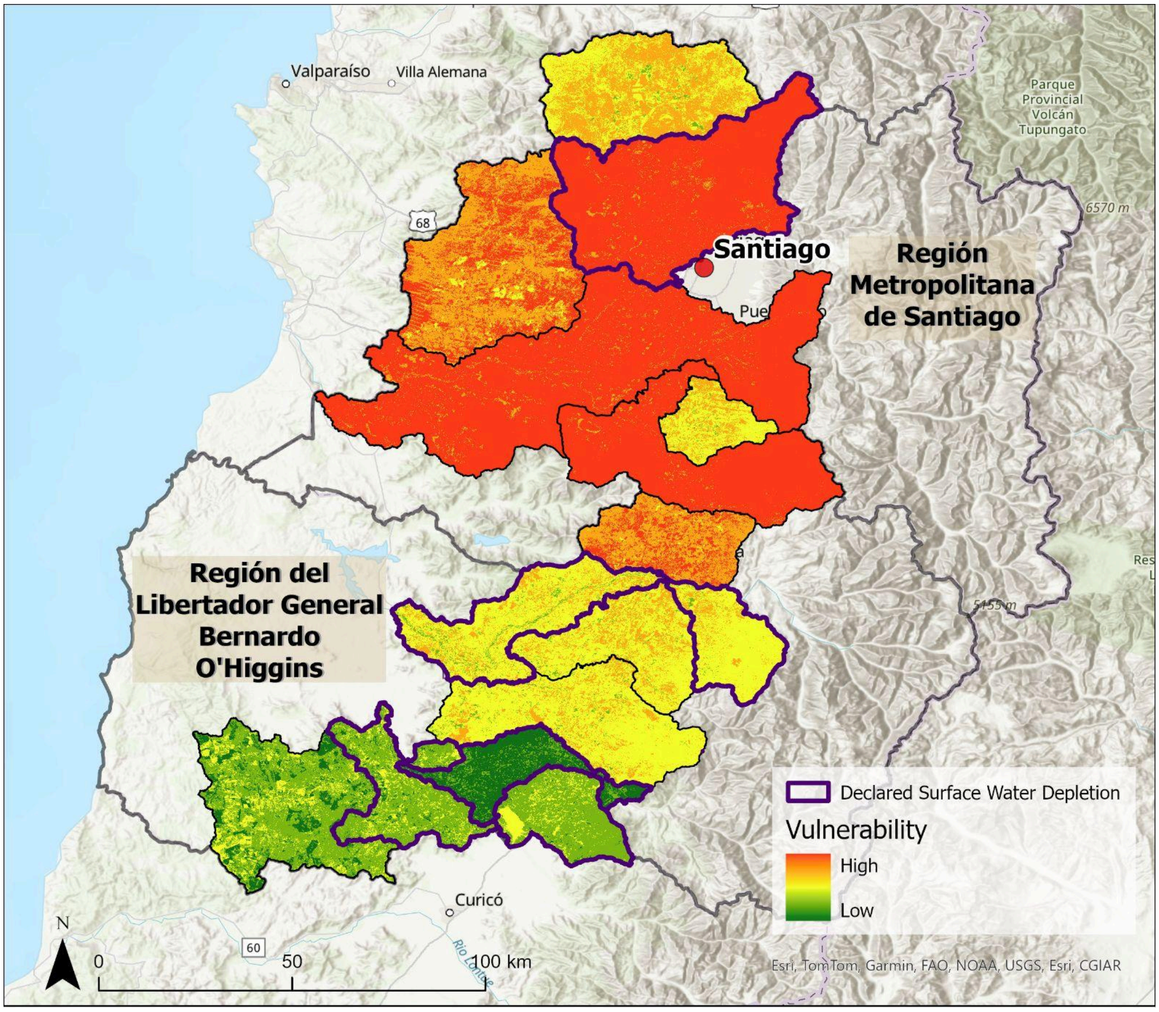


Figure 7. Multivariate drought vulnerability analysis with areas classified as Declared Surface Water Depletion by the Chilean government identified.

DISCUSSION

I used drought indices and a suitability analysis to determine the overlying impacts of meteorological, streamflow, and vegetation conditions in Central Chile for the purpose of classifying varying levels of vulnerability to drought impacts. I then distinguished areas for prioritization in the Chilean Ministry of Agriculture's plan for sustainable agricultural development according to their level of vulnerability to drought. I found that drought impacts according to the PDSI, SSI, and VCI calculations were not uniformly distributed within the study site. Rather, I found a progressive change in vulnerability from north to south with higher levels of vulnerability in northern watersheds and lower levels of vulnerability in southern watersheds. The greatest agricultural vulnerability occurred in the northern watersheds in the Región Metropolitana, particularly in watersheds adjacent to the city of Santiago. Conversely, the southernmost watersheds in the Región O'Higgins experienced the lowest agricultural vulnerability. Results from this study introduce a novel multivariate drought analysis and application for sustainable adaptation not previously reported in the literature.

Multivariate drought impacts

Meteorological and hydrological drought severity followed similar trends with average PDSI and SSI values decreasing, indicating drier conditions, for all watersheds within the study site over the 20 year period from 2000-2020. These results are consistent with related studies that have found that natural and anthropogenic contributions to Chile's megadrought beginning in 2010 (i.e. ENSO events and anthropogenic forcing) have reduced precipitation levels leading to severe water shortages and negative trends in streamflow within Central Chile (Garreaud et al. 2019, Oertel et al. 2020, Muñoz et al. 2020, Sangüesa et al. 2023). The fact that meteorological drought in both the Región Metropolitana and Región O'Higgins, indicated by negative PDSI values, was found to start in late 2007 while hydrological drought both regions, indicated by negative SSI values, was found to start in early 2010 is also consistent with other studies assessing hydrological drought responses to meteorological drought as reduced snowpack and precipitation levels often have a delayed impact on river water discharge and streamflow levels (Lorenzo-Lacruz et al. 2013, Peña-Guerrero et al. 2020) Additionally, the watersheds considered to be most severely affected by drought were consistent for both meteorological and hydrological drought analyses as watersheds in the Región Metropolitana demonstrated both more extreme average monthly PDSI and SSI values (Figure 2a, Figure 4a) and greater differences in average pre-drought and drought PDSI and SSI values indicating greater susceptibility to drought conditions (Figure 3, Figure 5). The watersheds directly adjacent to the capital city of Santiago (i.e. Río Mapocho Rinconada de Maipú, Río Maipo en Cabimbao, Río Angostura en Valdivia de Paine) exhibited the greatest changes in meteorological and hydrological drought severity between non-drought and drought years with a change in PDSI of -2.00 to -2.50 (Figure 3) and a change in SSI of -1.00 to -1.30 (Figure 5). The fact that the most drastic changes in PDSI and SSI values were observed in watersheds adjacent to large urban centers suggests that water allocation practices may also contribute to a watershed's overall drought vulnerability either by dictating water flows or over-allocating existing water resources during severe water shortages caused by meteorological and hydrological drought (Barría et al. 2021).

Alternatively, agricultural drought severity, measured by VCI, was fairly variable across all watersheds in the study site with a slightly greater concentration of low VCI values (20-40) in the Región Metropolitana and a slightly greater concentration of high VCI values (70-90) in the southern Región O'Higgins areas (Figure 6). NDVI and VCI are useful indicators of the spatial variability of agricultural drought that incorporate climatic and anthropogenic impacts on vegetation health, particularly in semi-arid regions where water is a limiting factor to vegetation growth (Peters et al. 2002, Dalezios et al. 2014, Bento et al. 2018). The results of the agricultural drought severity analysis are consistent with Garreaud et al. (2017b) which found that overall vegetation productivity decreased during the 2010-2015 drought period. The concentration of lower VCI values in the northern watersheds is consistent with the hydrological and meteorological drought severity analyses conducted in this study as vegetation condition responds rapidly to rainfall deficit in studies of other regions in Chile (Zambrano et al. 2016).

Agricultural vulnerability and adaptation prioritization

Agricultural vulnerability was determined by conducting a suitability analysis in which meteorological, hydrological, and agricultural drought analyses were assigned equal weights. The overall vulnerability followed a progressive change from north to south in which the level of vulnerability decreased with latitude. Consequently, the Río Mapocho Rinconada de Maipú, Río Maipo en Cabimbao, and Río Angostura en Valdivia de Paine watersheds exhibited the highest levels of vulnerability (2.32 - 2.98) while the Estero Nilahue en Santa Teresa, Río Tinguiririca en Los Olmos, Estero Chimbarongo en Santa Cruz, and Estero Chimbarongo Bajo watersheds exhibited the lowest levels of vulnerability (0.99 - 1.98) (Figure 7). The spatial distribution of this vulnerability is consistent with other studies that have identified agricultural areas within the Maipo river basin, a large river basin that accounts for the majority of the Región Metropolitana, as extremely vulnerable to drought as changing meteorological and hydrological conditions within the basin have been found to severely impact agricultural production (Meza et al. 2012, Peña-Guerrero et al. 2020).

This result supports the conclusion that watersheds in the Región Metropolitana should be prioritized in the Chilean Ministry of Agriculture's plan for sustainable agricultural development. Additionally, the concentration of high vulnerability areas around large urban centers suggests that water allocation practices may play an important role in agricultural vulnerability as rural and urban areas compete for increasingly scarce water resources (Barría et al. 2021). Therefore, irrigation improvements to increase the efficiency of water usage in agriculture and water management system reforms will be critical to combating agricultural vulnerability in the area as Chile's current water allocation system is based on private tradable water rights that often serve to undermine efforts to prevent water shortages (Roco et al. 2017, Budds 2020).

Although the distribution of drought vulnerability within the study site was consistent with meteorological and hydrological drought severity trends and the consequences of competing water needs between rural and urban areas, the results were not consistent with the Chilean government's classifications of socio-economic drought. I expected that the Chilean government's Declaraciones de Agotamiento de Aguas Superficiales [Declarations of Scarcity of Surface Waters] would align with the most vulnerable watersheds identified through my suitability analysis. Rather, based on public records, I found that five watersheds within the study site, Estero Chimbarongo, Rio Cachapoal, Rio Mapocho, and Rio Tinguiririca, had been given the surface water scarcity classification (DGA 1983a, 1983b, 1999, 2016). The fact that all watersheds identified had been classified prior to the start of the Chilean megadrought in 2010 except for the Rio Cachapoal watershed, which was classified in 2016, suggest that the classifications are out of date and do not reflect contemporary drought patterns in the study site.

Remote sensing model considerations

Remote sensing technologies and associated indices such as PDSI, SSI, and VCI are increasingly used to assess drought conditions in the Andes region (Altemus Cullen 2023). However, each index has associated limitations as a result of the variables that the index incorporates and the assumptions that the index makes along with data availability and accuracy. PDSI, for example, considered a more comprehensive drought index than precipitation-only indices that do not account for evapotranspiration and soil moisture, but the index largely fails to account for human water balance impacts such as water storage and irrigation (Zargar et al. 2011, Ejaz et al. 2023). SSI, on the other hand, focuses solely on streamflow levels and is, therefore, limited by the availability and accuracy of streamflow data captured from in situ gauges while NDVI and VCI data is much more accessible due to remote sensing technologies but is ultimately limited by the quality and resolution of the satellite imagery (Zargar et al. 2011). Consequently, the use of multiple drought indicators together provides a multivariate perspective that can enhance drought classification and assessment (Hao and Singh 2015). In this study, hydrological, meteorological, and agricultural drought were measured and combined to assess vulnerability within the study site. Each drought index was given an equal weight suggesting that all three drought types contribute equally to vulnerability. However, different weight combinations would likely contribute to different vulnerability classification outcomes (Malczewski 2004).

The methodology and results of this study support the potential of remote sensing technologies to inform sustainable agricultural development and water management strategies (Sheffield et al. 2018, Acharya and Lee 2019). The use of multivariate drought assessments to characterize drought in a particular region can inform policy makers on how to best allocate resources for adaptation and sustainable development and should be applied in other research contexts in other regions of the world (Hao and Singh 2015). Finally, the results of this study indicate that future studies employing multivariate drought analysis methods should incorporate, apart from meteorological, hydrological, and agricultural drought assessments, a more robust assessment of socio-economic drought, which refers to socio-economic and legal-political structures that limit the ability of a water system to meet societal needs, as an important factor of analysis to consider when assessing agricultural vulnerability to drought conditions (Lopez Feldman and Cortes 2016, Zúñiga et al. 2021, Altemus Cullen 2023).

Conclusion and broader implications

This study assessed the spatial distribution of vulnerability to drought using remote sensing technologies to compare the meteorological, hydrological, and agricultural conditions of 14 watersheds in Central Chile pre-megadrought (2000-2009) and during the Chilean megadrought (2010-2020). The multivariate drought analysis indicated that regions most vulnerable to drought conditions are located primarily in the Región Metropolitana in watersheds adjacent to the city of Santiago and, therefore, should be prioritized in the Chilean Ministry of Agriculture's plan for sustainable agricultural adaptation and development (IICA 2022). These results also indicate that conflicting water needs between rural and urban areas play a critical role in overall agricultural vulnerability in Central Chile and that improved water management systems will be required to ensure the long term agricultural resilience to drought conditions in the region (Barría et al. 2021).

The methodology and findings of this study present a novel approach to not only assessing multivariate drought conditions using remote sensing technologies, but also determining agricultural vulnerability using multiple drought indices. The results of this study are useful for both researchers and policymakers seeking to understand agricultural vulnerability in Central Chile and can inform agricultural adaptation and drought management strategies in the study region. Finally, similar methodological approaches can be applied to other agricultural regions around the world to not only assess vulnerability to drought but inform drought mitigation and sustainable agricultural development efforts.

ACKNOWLEDGEMENTS

Thank you to my faculty mentor Iryna Dronova and graduate student mentor Kate Altemus Cullen for your support and guidance on this project over the past year. Thank you to

Pasadena City College's GIS Certificate Program and my professors Brennan Wallace and Hector Agredano for giving me a foundation in how to use GIS technologies and supporting my research goals. Special thanks and my sincerest gratitude to Patina Mendez for your tremendous support, unwavering positivity, and persistent encouragement over these past two and a half years. Lastly, thank you to my parents Eloy Zárate and Senya Lubisich for your love and support and for encouraging me to pursue this type of research despite knowing absolutely nothing about it. And thank you to my siblings Ashley Hernandez, Bahia Zárate, Eloy A. Zárate, and Alaia Zárate for putting up with my work and for always believing in me.

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