The effects of multi-dimensional drought on land cover change and vegetation productivity in continental Chile

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**Abstract**

The north-central region of Chile has been the focus of research studies due to the persistent decrease in water supply, which is impacting the hydrological system and vegetation development. This persistent period of water scarcity has been defined as a mega-drought. The aim of our study is to evaluate the interaction of drought, land cover change, and vegetation productivity over continental Chile. We used drought indices for atmospheric evaporative demand (AED), water supply, and soil moisture from short-term (1, 3, 6 months) to long-term (12, 24, 36 months) time scales. We derived the drought indices using monthly ERA5-Land reanalysis data spanning from 1981 to 2023. We utilized the Moderate-Resolution Imaging Spectroradiometer (MODIS) datasets to derive information on annual land cover and monthly vegetation productivity. Our results showed that from south to north, Chile has a declining trend in water supply, and across the whole country, there is an increase in AED. These trends are stronger at longer time scales. The trend in vegetation productivity in the north-central area is affecting, to a higher degree, shrubland and savanna, followed by croplands and forests. The drought explains about 30% of the change in land cover type across Chile for forest, grassland, shrubland, and savanna. The increase in AED is the main driver of the change in land cover, followed by a reduction in precipitation and soil moisture. The change in vegetation productivity has been severe in the north-central part of the country for all land cover types, particularly savanna, shrubland, and croplands. The anomaly in soil moisture over the past 12 months (SSI-12) is the main variable explaining these changes, followed by anomalies in cumulated precipitation over one to two years (SPI-12 and SPI-24). Our results provide insightful information that would help in developing adaptation measures for ecosystems in Chile to cope with climate change and drought.

# 1. Introduction

Drought is often classified as meteorological when there is a decrease in precipitation below the mean average of several years (more than 30 years), hydrological when these anomalies last for long periods (months to years) and affect water systems, and agricultural when the deficit impacts plant health anomalies and leads to decreased productivity (Wilhite and Glantz 1985). However, it is important to note that drought is also influenced by human activities, which were not considered in the definitions. Thus, Van Loon et al. (2016) and Amir AghaKouchak et al. (2021) have given an updated definition of drought for the Anthropocene, suggesting that it should be considered the feedback of humans’ decisions and activities that drives the anthropogenic drought. Simultaneously, drought leads to heightened tree mortality and induces alterations in land cover and land use, ultimately affecting ecosystems (Crausbay et al. 2017). Even though many ecological studies have misinterpreted how to characterize drought, for example, sometimes considering “dry” conditions as “drought” (Slette et al. 2019). Then, Crausbay et al. (2017) proposed the ecological drought definition as “an episodic deficit in water availability that drives ecosystems beyond thresholds of vulnerability, impacts ecosystem services, and triggers feedback in natural and/or human systems.” In light of current global warming, it is crucial to study the interaction between drought and ecosystems in order to understand their feedback and impact on water security. (Bakker 2012)

Human-induced greenhouse gas emissions have increased the frequency and/or intensity of drought as a result of global warming, according to the sixth assessment report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) (Calvin et al. 2023). The evidence supporting this claim has been strengthened since AR5 (IPCC 2013). Recent studies, however, have produced contrasting findings, suggesting that drought has not exhibited a significant trend over the past forty years. (Vicente-Serrano et al. 2022; Kogan, Guo, and Yang 2020). Vicente-Serrano et al. (2022) analyzed the meteorological drought trend on a global scale, finding that only in a few regions has there been an increase in the severity of drought. Moreover, they attribute the increase in droughts over the past forty years solely to an increase in atmospheric evaporative demand (AED), which in turn enhances vegetation water demand, with important implications for agricultural and ecological droughts. Also, they state that “the increase in hydrological droughts has been primarily observed in regions with high water demand and land cover change”. Similarly, Kogan, Guo, and Yang (2020) analyzed the drought trend using vegetation health methods, finding that for the globe, hemispheres, and main grain-producing countries, drought has not expanded or intensified for the last 38 years. Further, Masson-Delmotte (2021) suggests that there is a high degree of confidence that rising temperatures will increase the extent, frequency, and severity of droughts. Also, AR6 (Calvin et al. 2023) predicts that many regions of the world will experience more severe agricultural and ecological droughts even if global warming stabilizes at 1.5°–2°C. To better evaluate the impact of drought trends on ecosystems, assessments are needed that relate meteorological and soil moisture variables to their effects on vegetation.

From 1960 to 2019, land use change has impacted around one-third of the Earth’s surface, which is four times more than previously thought (Winkler et al. 2021). Multiple studies aim to analyze and forecast changes in land cover globally (Winkler et al. 2021; Song et al. 2018) and regionally (Chamling and Bera 2020; Homer et al. 2020; Yang and Huang 2021). Some others seek to analyze the impact of land cover change on climate conditions such as temperature and precipitation (Luyssaert et al. 2014; Pitman et al. 2012). There is less research on the interaction between drought and land cover change (Chen et al. 2022; Akinyemi 2021; Peng et al. 2017). Peng et al. (2017) conducted a worldwide investigation utilizing net primary production to examine the spatial and temporal variations in vegetation productivity at global level. The study aimed to assess the influence of drought by comparing the twelve-month Standardized Precipitation Evapotranspiration Index (SPEI) and land cover change. According to their findings, drought is responsible for 37% of the decline in vegetation productivity, while water availability accounts for 55% of the variation. Chen et al. (2022) studied the trend of vegetation greenness and productivity and its relation to meteorological drought (SPEI of twelve months in December) and soil moisture at the global level. The results showed lower correlations (<0.2) for both variables. Akinyemi (2021) evaluates drought trends and land cover change using vegetation indices in Botwsana in a semi-arid climate. These studies mostly looked at how changes in land cover and vegetation productivity are related to a single drought index (SPEI) over a single time period of 12 months. SPEI takes into account the combined effect of precipitation and AED as a water balance, but it does not allow us to know the contribution of each variable on its own. Some things worth investigating in terms of land cover change and vegetation productivity are: i) How do they respond to short- to long-term meteorological and soil moisture droughts? ii) How is the drought impacting land cover changes? And iii) How do they behave in humid and arid climatic zones regarding drought? Likewise, there is a lack of understanding of how the alteration in water supply and demand is affecting land cover transformations.

For monitoring drought, the World Meteorological Organization recommends the SPI (Standardized Precipitation Index) (WMO et al. 2012). The SPI is a multi-scalar drought index that only uses precipitation to assess short- to long-term droughts. The primary cause of drought is precipitation anomalies, and temperature usually makes it worse (Luo et al. 2017). Nowadays, there is an increase in attention toward using AED separately to monitor droughts (Vicente‐Serrano et al. 2020). One reason is due to its attribution to increasing flash droughts in water-limited regions (Noguera, Vicente‐Serrano, and Domínguez‐Castro 2022). Vicente-Serrano, Beguería, and López-Moreno (2010) proposed the Standardized Precipitation Evapotranspiration Index (SPEI), which incorporated the temperature effect by subtracting AED from precipitation. SPEI allows for analysis of the combined effect of precipitation and AED. Since its formulation, it has been used worldwide for the study and monitoring of drought (Gebrechorkos et al. 2023; Liu et al. 2024). Hobbins et al. (2016) and McEvoy et al. (2016) developed the Evaporative Demand Drought Index (EDDI) to monitor droughts solely using the AED, and it has proven effective in monitoring flash droughts (H. Li et al. 2024; Ford et al. 2023). For soil moisture, several drought indices exist, such as the Soil Moisture Deficit Index (SDMI) (Narasimhan and Srinivasan 2005) and the Soil Moisture Agricultural Drought Index (SMADI) (Souza, Ribeiro Neto, and Souza 2021). Hao and AghaKouchak (2013) and A. AghaKouchak (2014) proposed the Standardized Soil Moisture Index (SSI), which has a similar formulation as the SPI, SPEI, and EDDI. Thus, there are plenty of drought indices that allow for a comprehensive assessment of drought on short- to long-term scales and that allow for the use of single variables from the earth’s water balance (e.g., precipitation, AED, soil moisture). The variation in climate variables impacts vegetation development, and unfavorable conditions such as low precipitation and high temperatures usually generate a decrease in vegetation productivity. To monitor the response of vegetation, the common practice is to use satellite data. The Normalized Difference Vegetation Index (NDVI) has been widely used as a proxy for biomass production (Camps-Valls et al. 2021; Paruelo et al. 2016; Helman et al. 2014). For Chile’s cultivated land, Zambrano et al. (2018) introduced the zcNDVI for assessing seasonal biomass production in response to drought. Using this information, we can advance our understanding of the impact of drought on ecosystems.

Chile’s diverse climatic and ecosystem types (Beck et al. 2023; Luebert and Pliscoff 2022) make it an ideal natural laboratory for studying climate and ecosystems. Additionally, the country has experienced severe drought conditions that have had significant effects on vegetation and water storage. North-central Chile has faced a persistent precipitation deficit since 2010, defined as a mega drought. (R. Garreaud et al. 2017), which has impacted the Chilean ecosystem. This megadrought was defined by the Standardized Precipitation Index (SPI) of twelve months in December having values below one standard deviation. Some studies have addressed how this drought affects single ecosystems in terms of forest development (Miranda et al. 2020; Alejandro Venegas-González et al. 2018), forest fire occurrence (Urrutia‐Jalabert et al. 2018), and crop productivity (Zambrano 2023; Zambrano et al. 2018, 2016). We found one study regarding land cover and drought in Chile. The study by Fuentes et al. (2021) evaluates water scarcity and land cover change in Chile between 29° and 39° of south latitude. Fuentes et al. (2021) used the SPEI of one month for evaluating drought, which led to misleading results. For example, they did not find a temporal trend in the SPEI but found a decreasing trend in water availability and an increase trend on AED, which in turn should have been capable of being captured with longer time scales of the SPEI. The term “megadrought” in Chile is used to describe a prolonged water shortage that lasts for several years, resulting in a permanent deficit that impacts the hydrological system (Boisier et al. 2018). Therefore, it is crucial to evaluate temporal scales that consider the cumulative impact over a period of several years. The association between drought and the environment in Chile is not well comprehended. Hence, it is imperative to acquire a more profound comprehension of the manner in which climatic and soil moisture droughts influence environmental dynamics, in order to make well-informed decisions on adaptation strategies.

Here, we analyze the multi-dimensional impacts of drought across ecosystems in continental Chile. More specifically, we aim to assess: i) short- to long-term temporal trends in multi-scalar drought indices; ii) temporal changes in land-use cover and the direction and magnitude of their relationships with trends in drought indices; and iii) the trend in vegetation productivity and its relationship with drought indices across Chilean ecosystems.

# 2. Study area

Continental Chile has diverse climate conditions with strong gradients from north to south and east to west (Aceituno et al. 2021) ([Figure 1](#fig-studyArea) a), which determines its great ecosystem diversity (Luebert and Pliscoff 2022) ([Figure 1](#fig-studyArea) c). The Andes Mountains are a main factor in climate latitudinal variation (R. D. Garreaud 2009). “Norte Grande” and “Norte Chico” predominate in an arid desert climate with hot (Bwh) and cold (Bwk) temperatures. At the south of “Norte Chico,” the climate changes to an arid steppe with cold temperatures (Bsk). In these two northern regions, the land is mostly bare, with a small surface of vegetation types such as shrubland and grassland. In the zones “Centro” and the north half of “Sur,” the main climate is Mediterranean, with warm to hot summers (Csa and Csb). Land cover in “Centro” comprises a significant amount of shrubland and savanna (50%), grassland (16%), forest (8%), and croplands (5%). An oceanic climate (Cfb) predominates in the south of “Sur” and the north of “Austral.” Those zones are high in forest and grassland. The southern part of the country has a tundra climate, and in “Austral,” it is a cold semi-arid area with an extended surface of grassland, forest, and, to a lesser extent, savanna.

**FIGURA 1**

# 3. Materials and Methods

## 3.1 Data

### 3.1.1 Gridded meteorological and vegetation data

To analyze land cover change, we use the classification scheme by the IGBP (International Geosphere-Biosphere Programme) from the product MCD12Q1 collection 6.1 from MODIS. The MCD12Q1 has a yearly frequency from 2001 to 2022 and defines 17 classes. To derive a proxy for vegetation productivity, we used the Normalized Difference Vegetation Index (NDVI) from the product MOD13A3 collection 6.1 from MODIS (Didan 2015). MOD13A3 provides vegetation indices at 1km of spatial resolution and monthly frequency. The NASA EOSDIS Land Processes Distributed Active Archive Center (LP DAAC), USGS Earth Resources Observation and Science (EROS) Center, Sioux Falls, South Dakota, provided the MOD13A3 and MCD12Q1 from the online Data Pool, accessible at https://lpdaa.usgs.gov/tools/data-pool/.

For soil moisture, water supply, and water demand variables, we used ERA5L (ECMWF Reanalysis version 5 over land) (Muñoz-Sabater et al. 2021), a reanalysis dataset that provides the evolution of atmospheric and land variables since 1950. It has a spatial resolution of 0.1° (9 km), hourly frequency, and global coverage. We selected the variables for total precipitation, maximum and minimum temperature at 2 meters, and volumetric soil water layers between 0 and 100cm of depth (layer 1 to layer 3). Table 1 shows a summary of the data and its main characteristics.

**TABLA 1**

## 3.2 Short- to long-term drought trends

### 3.2.1 Atmospheric Evaporative Demand (AED)

In order to compute the drought indices that use water demand, it is necessary to first calculate the AED. To do this, we employed the Hargreaves method (George H. Hargreaves 1994; George H. Hargreaves and Samani 1985) by applying the following equation:

where is extraterrestrial radiation; , , and are mean, maximum, and minimum temperature at 2m. For calculating we used the coordinate of the latitud of the centroid of each pixel. We chose the method of Hargreaves to estimate AED because of its simplicity, which only requires temperatures and extrarrestrial radiation. Also, it has been recommended over other methods (e.g., Penman-Monteith) when the access to climatic variables is limited (Vicente-Serrano et al. 2014).

### 3.2.2 Non-parametric calculation of drought indices

To derive the drought indices of water supply and demand, soil moisture, and vegetation (i.e., the proxy of productivity), we used the ERA5L dataset and the MODIS product, with a monthly frequency for 1981–2023 and 2000–2023, respectively. The dought indices correspond to a historical anomaly with regard to a variable (e.g., meteorological, vegetation, or soil moisture). To account for the anomaly, the common practice is to derive it following a statistical parametric methodology in which it is assumed that the statistical distribution of the data is known (Heim 2002). A wrong decision is usually the highest source of uncertainty (Laimighofer and Laaha 2022). In the case of Chile, due to its high degree of climatic variability, it is complex to choose a proper distribution without previous research. Here, we follow a non-parametric methodology for the calculation of the drought indices, in a similar manner as the framework proposed by Farahmand and AghaKouchak (2015); Hobbins et al. (2016);McEvoy et al. (2016).

For the purpose of monitoring water supply drought, we used the well-known Standardized Precipitation Index (SPI), which relies on precipitation data. To evaluate water demand, we chose the Evaporative Demand Drought Index (EDDI), developed by Hobbins et al. (2016) and McEvoy et al. (2016), which is based on the AED. The United States currently monitors drought using the EDDI (https://psl.noaa.gov/eddi/) as an experimental index. To consider the combined effect of water supply and demand, we selected the SPEI (Vicente-Serrano, Beguería, and López-Moreno 2010). For SPEI, an auxiliary variable is calculated. Soil moisture is the main driver of vegetation productivity, particularly in semi-arid regions (W. Li et al. 2022). Hence, for soil water drought, we used the SSI (Standardized Soil Moisture Index) (Hao and AghaKouchak 2013; A. AghaKouchak 2014). In our case, for the SSI, we used the average soil moisture from ERA5L at 1m depth. Finally, for the proxy of productivity, we used the zcNDVI proposed by Zambrano et al. (2018), which was derived from the monthly time series of NDVI derived from MOD13A1. All the indices are multi-scalar and can be used for the analysis of short- to long-term droughts.

To derive the drought indices, first we must calculate the sum of the variables with regard to the time scale (s). In this case, for generalization purposes, we will use , referring to variables , , , , and (Table 1). We cumulated each over the time series of values (months), and for the time scales :

The corresponds to a moving window (convolution) that sums the variable for time scales from the last month, month by month, until the first month in which it could sum for months. An inverse normal approximation (Abramowitz and Stegun 1968) obtains the empirically derived probabilities once the variable cumulates over time for the scale . Then, we used the empirical Tukey plotting position (Wilks 2011) over to derive the probabilities across a period of interest:

The drought indices , , , , and are obtained following the inverse normal approximation:

is referring to the drought index calculated for the variable (i.e., SPI, SPEI, EDDI, SSI, and zcNDVI). The values for the constats are: , , , , , and . For , W= , and for , replace with and reverse the sign of .

The drought indices were calculated for time scales of 1, 3, 6, 12, 24, and 36 months at a monthly frequency for 1981–2023 in order to be used for short- to long-term evaluation of drought. In the case of the proxy of vegetation productivity (zcNDVI), it was calculated for a time scale of six months at monthly frequency for 2000–2023. For zcNDVI, we test time scales of 1, 3, 6, and 12 months in December and their correlation with net primary production (NPP) obtained from the MOD17A3HGF product from MODIS. We choose to use six months because r-squared with NPP increases from one to six months and from six to 12 months has little improvement. The r-squared were between 0.31 for forest and 0.72 for shrubland (see supplementary material in Section S5).

### 3.2.3 Trend of drought indices

To estimate if there are significant positive or negative trends for the drought indices, we used the non-parametric test of Mann-Kendall (Kendall 1975). To determine the magnitude of the trend, we used Sen’s slope (Sen 1968). Some of the advantages of applying this methodology are that the Sen’s slope is not affected by outliers as regular regression does, and it is a non-parametric method that is not influenced by the distribution of the data. We applied Mann-Kendall to see if the trend was significant and Sen’s slope to estimate the magnitude of the trend. We did this to the six time scales from 1981 to 2023 (monthly frequency) and the indices SPI, EDDI, SPEI, and SSI. Thus, we have trends per index and time scale (24 in total). Then, we extracted the trend aggregated by macrozone and per land cover persitent macroclasses.

## 3.3 Interaction of land cover and drought

### 3.3.1 Land cover change

To analyze the land cover change, we use the IGBP scheme from the MCD12Q1 collection 6.1 from MODIS. This product has been previously used for studies of drought and land cover in Chile (Fuentes et al. 2021; Zambrano et al. 2018). From the 17 classes, we regrouped into ten macroclasses, as follows: classes 1-4 to forest, 5-7 to shrublands, 8-9 to savannas, 10 as grasslands, 11 as wetlands, 12 and 14 to croplands, 13 as urban, 15 as snow and ice, 16 as barren, and 17 to water bodies. Thus, we have a land cover raster time series with the ten macroclasses for 2001 and 2023. We validate the land cover macroclasses regarding a highly detailed (30 m of spatial resolution) land cover map made for Chile by Zhao et al. (2016) for 2013-2014. Our results showed a global accuracy of ~0.82 and a F1 score of ~0.66. Section S2 in the Supplementary Material shows the procedure for validation.

We calculated the surface occupied per land cover class into the five macrozones (“Norte Grande” to “Austral”) per year for 2001–2023. After that, we calculated the trend’s change in surface per land cover type and macroclass. We used Mann-Kendall for the significance of the trend (Kendall 1975) and Sen’s slope to calculate the magnitude (Sen 1968).

Later in this study, we will examine the variation in vegetation productivity across various land cover types and how water demand and supply, and soil moisture affect it. In order to avoid variations due to a change in the land cover type from year-to-year that will wrongly impact NDVI, we developed a persistence mask for land cover for 2001–2022. Thereby, we reduce an important source of variation on a regional scale. Therefore, we generated a raster mask for IGBP MODIS per pixel using macroclasses that remained unchanged for at least 80% of the years (2001–2022). This enabled us to identify regions where the land cover macroclasses are persistent.

### 3.3.2 Relationship between land cover and drought trends

We wanted to explore the relationship between the trend in land cover classes and the trend in the drought indices. For this purpose, in order to have more representative results, we conducted the analysis over sub-basins within continental Chile. We use 469 basins, which have a surface area between 0.0746 and  24,000 (), and a median area of 1,249 (). For each basin, we calculate the relative trend per land cover type, considering the proportion of the type relative to the total surface of the basin. Then, we extracted per basin the average trend of the drought indices SPI, SPEI, EDDI, SSI, and all their time scales 1, 3, 6, 12, 24, and 36. Also, we extracted the average trend in the proxy of vegetation productivity (zcNDVI). We wanted to analyze which drought indices and time scales have a major impact on changes in land cover type.

We have 25 predictors, including drought indices and vegetation productivity. We analyzed the 25 predictors per type of landcover, thus running six random forest models. Random forest uses multiple decision trees and allows for classification and regression. Some advantages are that it allows to find no linear relationship, reduces overfitting, and allows to derive the variable importance. We used random forests for regression and trained 1000 forests. To obtain more reliable results, we resampled by creating ten folds, running a random forest per fold, and calculating the r-squared (rsq), root mean square error (RMSE), and variable importance.

The variable importance helps for a better understanding of the relationships by finding which variable has a higher contribution to the model. We calculate the variable’s importance by permuting out-of-bag (OOB) data per tree and computing the mean standard error in the OOB. After permuting each predictor variable, we repeat the process for the resting variable. We repeated this process ten times (per fold) to obtain the performance metrics (rsq, RMSE, and variable importance).

## 3.4 Drought impacts on vegetation productivity

We analyzed the trend of vegetation productivity over the unchanged land cover macroclasses. To achieve this, we used the persistent mask of land cover macroclasses. This way, we tried to reduce the noise in the vegetation due to a change in land cover from year to year. We used the zcNDVI as a proxy of vegetation productivity. In Chile’s cultivated land, Zambrano et al. (2018) introduced the zcNDVI for assessing seasonal biomass production in relation to climate.

We examine the drought indices of water demand, water supply, and soil moisture and their correlation with vegetation productivity. The objective is to determine the impact of soil moisture and water demand and supply on vegetation productivity. We want to address three main questions: Which of the drought variables—supply, demand, or soil moisture—most helps to explain the changes in plant productivity? How do the short- to long-term time scales of the drought variable affect vegetation productivity in Chile? And finally, how strong is the relationship between the variables and the drought index? Thus, we will be able to advance in understanding how climate is affecting vegetation, considering the impact on the five land cover types: forest, cropland, grassland, savanna, and shrubland.

We conducted an analysis on the linear correlation between the indices SPI, SPEI, EDDI, and SSI over time periods of 1, 3, 6, 12, 24, and 36 months with zcNDVI. We used a method similar to that used by Meroni et al. (2017) which compared the SPI time-scales with the cumulative FAPAR (Fraction of Absorbed Photosynthetically Active Radiation). We performed a pixel-to-pixel linear correlation analysis for each index within the persistent mask of land cover macroclasses. We first compute the Pearson coefficient of correlation for each of the six time scales. A time scale is identified as the one that attains the highest correlation (p < 0.05). We then extracted the Pearson correlation coefficient corresponding to the time scales where the value peaked. As a result, for each index, we generated two raster maps: 1) containing the raster with values of the time scales and drought index that reached the maximum correlation, and 2) having the magnitude of the correlation obtained by the drought index at the time scales.

## 3.5 Software

For the downloading, processing, and analysis of the spatio-temporal data, we used the open source software for statistical computing and graphics, R (R Core Team 2023). For downloading ERA5L, we used the {ecmwfr} package (Hufkens, Stauffer, and Campitelli 2019). For processing raster data, we used {terra} (Hijmans 2023) and {stars} (Pebesma and Bivand 2023). For managing vectorial data, we used {sf} (Pebesma 2018). For the calculation of AED, we used {SPEI} (Beguería and Vicente-Serrano 2023). For mapping, we use {tmap} (Tennekes 2018). For data analysis and visualization, the suite {tidyverse} (Wickham et al. 2019) was used. For the random forest modeling, we used the {tidymodels}(Kuhn and Wickham 2020) and {ranger}(Wright and Ziegler 2017) packages.

# 4. Results

## 4.1 Short- to long-term drought trends

[Figure 2](#fig-trendDI) shows the spatial variation of the trend for the drought indices from short- to long-term scales. SPI and SPEI have a decreasing trend from “Norte Chico” to “Sur.” However, there is an increasing trend in “Austral.” The degree of the trend is stronger at higher time scales. The SSI indicates that in “Norte Grande,” there are surfaces that have increased in the soutwest part and in the northeast have decreased, and is shown for all time scales. Similar to SPI and SPEI, SSI decreases at higher time scales. EDDI showed a positive trend for the whole of continental Chile, with a higher trend toward the north and a descending gradient toward the south. The degree of trend increases at higher time scales.

**FIGURE 2**

The [Figure 3](#fig-trendDIMacro) displays the averaged aggregation per macrozone, the drought index, and the timescale. The macrozones that reached the lowest trend for SPI, SPEI, and SSI are “Norte Chico” and “Centro,” where the indices also decrease at longer time scales. Potentially explained due to the prolonged reduction in precipitation that has affected the hydrological system in Chile. At 36 months, it reaches trends between -0.03 and -0.04 (z-score) per decade for SPI, SPEI, and SSI. For “Sur,” the behavior is similar, decreasing at longer scales and having between -0.016 and -0.025 per decade for SPI, SPEI, and SSI. “Norte Grande” has the highest trend at 36 months for EDDI (0.042 per decade), and “Centro” has the lowest for SPI and SPEI. In “Norte Grande” and “Norte Chico,” which are in a semi-arid climate, it is evident that the EDDI has an effect on the difference between the SPI and SPEI index, which is not seen in the other macrozones. Contrary to the other macrozones, “Austral” showed an increase in all indices, being the highest for EDDI at 36 months (0.025) and the lowest for SSI, which shows only a minor increase in the trend.

**FIGURE 3**

## 4.2 Interaction of land cover and drought

### 4.2.1 Land cover change

For vegetation, we obtained and use hereafter five macroclasses of land cover from IGBP MODIS: forest, shrubland, savanna, grassland, and croplands. [Figure 1](#fig-studyArea)c shows the spatial distribution of the macroclasses through Chile for the year 2022. [Figure 1](#fig-studyArea)d shows the macroclasses of land cover persistance (80%) during 2021–2022, respectively (Table 2). Within continental Chile, barren land is the land cover class with the highest surface area (277,870 ). The largest type of vegetation, with 137,085 , is forest. Grassland has 74,247 , savanna 55,206 , shrubland 25,341 , and cropland 3,146 (Table 2). The macrozones with major changes for 2001–2022 were “Centro,” “Sur,” and “Austral,” with 36%, 31%, and 34% of their surface changing the type of land cover, respectively ([Figure 1](#fig-studyArea) and Table 3). [Figure 4](#fig-LCprop) shows the summary of the proportion of surface per land cover class and macrozone, derived from the persistance mask over continental Chile.

**TABLE 2**

**FIGURE 4**

From the trend analysis in Table 3, we can indicate that the “Norte Chico” shows an increase in barren land of 111 and a reduction in the class savanna of 70 . In the “Centro” and “Sur,” there are changes with an important reduction in savanna (136 to 318 ), and an increase in shrubland and grassland. Showing a change for more dense vegetation types. The area under cultivation (croplands) appears to be shifting from the “Centro” to the “Sur.” Also, there is a high increase in forest (397 ) in the “Sur,” seemingly replacing the savanna lost (Table 3).

**TABLE 3**

### 4.2.2 Relationship between drought indices and land cover change

According to Table 4, the random forest models for estimating the landcover trend from the trends in drought indices reach an r-squared between 0.32 and 0.39 for the types of forest, grassland, savanna, shrubland, and barren land. It is more likely that short- and medium-term increases in AED (EDDI-6 and EDDI-12) and short-term precipitation deficits (SPI-6 and SPEI-6) contributed to changes in grassland and bare land. The short-term increase of AED (EDDI-3 and EDDI-6) and the longer duration of the precipitation deficit (SPI-24, SPI-36, and SPEI-36) most likely contribute to the changes in shrubland. The changes in savanna are associated with a short- and long-term increase in AED and a three-year precipitation deficit (SPI-36). The increase in cumulative AED from 12 to 36 months is the strongest associated variable that contributes to changes in forests, followed by the reduction of soil moisture over six and 36 months. The supplementary material in Section S3 provides further details about the variable’s importance.

**TABLA 4**

We study the connection between the SPI, EDDI, and SSI drought indices and changes in land cover in [Figure 5](#fig-TrendsLandDrought). To do this, we compare the relative changes in land cover (in terms of the total surface area per land cover type and macrozone) over six and thirty-six months. [Figure 5](#fig-TrendsLandDrought) shows that the forest in the “Sur,” shrubland and grassland in “Centro,” barren land in “Norte Chico,” and savanna in “Austral” showed an increase in the surface of landcover associated with an increase in EDDI. Savanna in “Centro,” “Sur,” and “Norte Chico” decreases with the increase in EDDI. The SPI and SSI showed similar behavior regarding the trend in land cover type. A decrease in SPI and SSI is associated with an increase in the surface in shurubland and grassland in “Centro,” forest in “Sur,” and barren land in “Norte Chico,” as well as a decrease trend in savanna in “Norte Chico,” “Centro,” and “Sur.”

**FIGURE 5**

## 4.3 Drought impacts on vegetation productivity within land cover

### 4.3.1 Trends in vegetation productivity

The temporal variation within the macrozones is shown in [Figure 6](#fig-zcNDVI_var)b). There is a negative trend in “Norte Chico” with -0.035 and “Centro” with -0.02 per decade. Vegetation reached its lowest values for 2019-2022, with an extreme condition in early 2020 and 2022 in the “Norte Chico” and “Centro”. The “Sur” and “Austral” show a positive trend of around 0.012 and 0.016, respectively, per decade ([Figure 6](#fig-zcNDVI_var)).

**FIGURE 6**

In [Figure 6](#fig-zcNDVI_var) it is showed the spatial map of trends in zcNDVI ([Figure 6](#fig-zcNDVI_var)a). In “Norte Grande,” vegetation productivity, as per the z-index, exhibits a yearly increase of 0.027 for grassland and 0.032 for shrubland. In the “Norte Chico,” savanna has the lowest trend of -0.062, cropland -0.047, shrubland -0.042, and grassland -0.037. In “Centro,” shrubland reaches -0.07, savanna -0.031, cropland -0.024, forest -0.017, and grassland -0.005 per decade. This decrease in productivity could be associated either with a reduction in vegetation surface, a decrease in biomass, or browning.

### 4.3.2 Correlation between vegetation productivity and drought indices

[Figure 7](#fig-corTimeScale) shows the highest coefficient of determination (r-squared, or rsq) found in the regression analysis between zcNDVI and different drought indicators over time scales of 1, 3, 6, 12, 24, and 36 months. The spatial variation of time scales reached per index is mostly for time scales above 12 months. In the case of SSI, the predominant scales are 6 and 12 months. For all indices, to the north, the time scales are higher and diminish toward the south until the south part of “Austral,” where they increase. In [Figure 8](#fig-corPerson), the map of Pearson correlation values (r) is shown. The EDDI reached correlations above 0.5 between “Norte Chico” and “Sur.” The correlation changes from negative to positive toward the Andes Mountains and to the sea, just as in the northern part of “Austral.” The SPI and SPEI have similar results, with the higher values in “Norte Chico” and “Centro” being higher than 0.6. Following a similar spatial pattern as EDDI but with an opposite sign. The SSI showed to be the index that has a major spatial extension with a higher correlation. It has a similar correlation to SPI and SPEI for “Norte Chico” and “Sur,”  but has improvements for “Sur.”

**FIGURE 7**

**FIGURE 8**

In Table 5, we aggregate per macrozone and landcover the correlation analysis presented in [Figure 7](#fig-corTimeScale) and [Figure 8](#fig-corPerson). According to what is shown, forests seem to be the most resistant to drought. Showing that only “Centro” is slightly (rsq = 0.25) impacted by a 12-month soil moisture deficit (SSI-12). In the “Norte Chico” and to a lesser extent in the “Norte Grande,” it is evident that a SSI-12 with a rsq = 0.45 and a decrease in water supply (SPI-36 and SPEI-24 with rsq = 0.28 and 0.34, respectively) have an impact on grasslands. However, this type was unaffected by soil moisture, water supply, or demand in macrozones further south. The types that show to be most affected by variation in climate conditions are shrublands, savannas, and croplands. For savannas in “Norte Chico,” the SSI-12 and SPI-24 reached an rsq of 0.74 and 0.58, respectively. This value decreases to the south, but the SSI-12 is still the variable explaining more of the variation in vegetation productivity (rsq = 0.45 in “Centro” and 0.2 in “Sur”). In the case of croplands, the SPEI-12, SPI-36, and SSI-12 explain between 45% and 66% of the variability in “Norte Chico.” The type of land most impacted by climatic variation was shrubland, where soil moisture explained 59% and precipitation, 37%, in “Norte Chico” and “Centro,” with SSI-12 being the most relevant variable, then SPI-36 in “Norte Chico” and SPI-24 in “Sur.”

**TABLE 5**

# 5. Discussion

## 5.1 The main drivers of drought in Chile

Vicente-Serrano et al. (2022), in a study at the global scale of drought trends, indicates that there have not been significant trends in meteorological drought since 1950. Also, state that the increase in hidrological trend in some parts of the globe (northeast Brazil and the Mediterranean region) is related to changes in land cover and specifically to the rapidly increasing irrigated area, which consequently increases water extraction. Kogan, Guo, and Yang (2020) analyzed the agricultural drought impact globally and in the main grain producer countries, finding that “since 1980, the Earth warming has not changed the drought area or intensity.” In our study, we took into account the variation in vegetation productivity in Chile, specifically in areas without any changes in land cover, to prevent any misleading conclusions about the increase in water demand due to land cover change. Our results show a contrasting perspective. The SPI, SPEI, and SSI (water supply) showed a decrease in trends, except for the southern part, and an increase in EDDI (water demand). The trend, positive or negative, was stronger as the time scales increased. Trends in the long term (e.g., 36 months) are evidence of how human-induced climate change is affecting Chile, which seems to be due to an intense hydrological drought resulting from the persistence of the precipitation deficit. We found that there has been a significant trend in the decline of vegetation productivity (zcNDVI) since 2000 for the north-central part of the country, which has been extreme between 2020 and 2022 and has impacted natural and cultivated land. Additionally, we demonstrated that the drought, primarily due to an increase in AED, accounts for about 30% of the changes in land cover types (excluding croplands). These changes are associated with a decrease in water demand from vegetation. Moreover, the most water-demanding type, cropland, showed a decrease in the north-central region, while barren land showed an increase. The north-central part of the country primarily experienced these changes due to a higher increase in AED. Thus, we have evidence of a significant decline in water supply and an increase in AED for the north-central part of Chile, which show to be the most relevant variables for drought conditions. Some questions arise regarding what is occurring with the cultivated land. We used the unchanged land cover to ensure that an increase in surface area is not considered in the trend analysis. For croplands, it could happen that some areas have changed the types of crops for others with higher water demand, which consequently increases water demand. However, this effect should be minor compared to the decrease in water supply and increase in water demand at this scale of analysis.

This shows that the main cause of the hydrological drought in Chile was a steady drop in water supply made worse by an increase in AED, but it seems that in zones most affected by drought, the main cause is not an increase in vegetation water demand due to an intensification of cultivated land (e.g., an increase in irrigated crops). North-central Chile has experienced a decline in vegetation productivity across land cover types, which is primarily attributable to variations in water supply and soil moisture. An increase in water demand, such as an increase in the surface area of irrigated crops, could strengthen this trend. But it is out of the scope of this study. Future work should focus on the regions where the drought has been more severe and has a high proportion of irrigated crops to get insight on the real impact of irrigation on those zones.

## 5.2 Land cover sensitivity to drought

We analyzed two main impacts of drought on land cover. First, the attribution of drought to the change in surface area per land cover type. Drought accounts for about 30% of the surface change per land cover type, with the exception of croplands. The main variables associated with these changes are the increase in AED and, in second place, the decrease in precipitation. Second, we analyzed the time series of drought indices and vegetation productivity per land cover type. In this case, the most important variables that had an impact on zcNDVI were the soil moisture deficit, followed by the precipitation deficit, and in third place, AED.

In a study in the Yangtze River Basin in China, Jiang et al. (2020) analyzed the impact of drought on vegetation using the SPEI and the Enahanced Vegetation Index (EVI). They found that cropland was more sensitive to drought than grassland, showing that cropland responds strongly to short- and medium-term drought (< SPEI-6). In our case, the SPEI-12 was the one that most impacted the croplands in “Norte Chico” and “Centro.” In general, most studies show that croplands are most sensitive to short-term drought (< SPI-6) (Zambrano et al. 2016; Potopová et al. 2015; Dai et al. 2020; Rhee, Im, and Carbone 2010). Short-term precipitation deficits impact soil water, and thus less water is available for plant growth. However, we found that in “Norte Chico,” an SPI-36 and SPEI-12 had a higher impact, which are associated with hydrological drought (long-term), and in “Centro,” an SPI-12 and SPEI-12. Thus, we attribute this impact to the hydrological drought that has decreased groundwater storage (Taucare et al. 2024), which in turn is impacted by long-term deficits, and consequently, the vegetation is more dependent on groundwater. In “Sur” and “Austral,” the correlations between drought indices and vegetation productivity decrease, as do the time scales that reach the maximum r-squared. The possible reason for this is that the most resistant types, forest and grassland, predominate south of “Centro.” Also, drought episodes have been less frequent and intense. The drought episodes have had a lower impact on water availability for vegetation.

According to Senf et al. (2020), severe drought conditions in Europe are a significant cause of tree mortality. However, we discovered that forests, as the most resilient land cover class to drought, experience less variation in drought indices. Supporting this is Fathi-Taperasht et al. (2022), who asserts that Indian forests are the most drought-resistant and recover rapidly. Similarly, the work of Wu et al. (2024), who analyzed vegetation loss and recovery in response to meteorological drought in the humid subtropical Pearl River basin in China, indicates that forests showed higher drought resistance. Using Vegetation Optical Depth (VOD), kNDVI, and EVI, Xiao et al. (2023) tests the resistance of ecosystems and finds that ecosystems with more forests are better able to handle severe droughts than croplands. They attribute the difference to a deeper rooting depth for trees, a higher water storage capacity, and different water use strategies between forest and cropland (Xiao et al. 2023). In contrast, A. Venegas-González et al. (2023), who studied Cryptocarya alba and Beilschmiedia miersii (both from the Lauraceae family) that live in sclerophyllous forests in Chile, found that the trees’ overall growth had slowed down. This could mean that the natural dynamics of their forests have changed. They attributed it to the cumulative effects of the unprecedented drought (i.e., hydrological drought).

Thus, we attribute that forest to being the most resistant to drought, due to the fact that most of the species comprising it are highly resilient to water scarcity compared to the other land cover classes. Nonetheless, if we want to go deep in our analysis, we should use earth observation data that is able to capture a higher level of detail. For example, when we used MOD13A3 with a 1km spatial resolution to measure vegetation condition, it took the average condition of 1 square kilometer. Then, to use remote sensing to look at how a certain type of forest (like sclerophyllous forest) changes in response to drought on a local level, we should use operational products with higher spatial resolutions, like those from Landsat or Sentinel. This will let us do a more thorough analysis.

## 5.3 Vegetation productivity and drought.

We found that the 12-month soil moisture deficit most affects the productivity of vegetation in all land cover types along Chile. The main external factors that affect biomass production by vegetation are actual evapotranspiration and soil moisture, and the rate of ET in turn depends on the availability of water storage in the root zone. Thus, soil moisture plays a key role in land carbon uptake and, consequently, in the production of biomass (Humphrey et al. 2021). Moreover, Zhang et al. (2022) indicate there is a bidirectional causality between soil moisture and vegetation productivity. Lastly, some studies have redefined agricultural drought as soil moisture drought from a hydrological perspective (Van Loon et al. 2016; Samaniego et al. 2018). Even though soil moisture is the external factor most determinant of vegetation biomass, there are multiple internal factors, such as species, physiological characteristics, and plant hydraulics, that would affect vegetation productivity. Because of that, we believe that agricultural drought, referring to the drought that impacts vegetation productivity, is the most proper term, as originally defined by Wilhite and Glantz (1985).

The study results showed that the soil moisture-based drought index (SSI) was better at explaining vegetation productivity across land cover macroclasses than meteorological drought indices like SPI, SPEI, and EDDI. In the early growing season and especially in irrigated rather than rainfed croplands, soil moisture has better skills than SPI and SPEI for estimating gross primary production (GPP). This according to Chatterjee et al. (2022) evaluation of the SPI and SPEI and their correlation with GPP in the CONUS. Also, Zhou et al. (2021) indicate that the monthly scaled Standardized Water Deficit Index (SWDI) can accurately show the effects of agricultural drought in most of China. Nicolai-Shaw et al. (2017) also looked at the time-lag between the SWDI and the Vegetation Condition Index (VCI). They found that there was little to no time-lag in croplands but a greater time-lag in forests.

In our case, there is strong spatial variability throughout Chile and between classes, mainly attributable to climate heterogeneity, hydrological status, or vegetation resistance to water scarcity. The semi-arid “Norte Chico” and the Mediterranean “Centro” were where SSI had the best performance. In Chile, medium-term deficits of 12 months are more relevant in the response of vegetation, which decreases to the south, and in the case of croplands, they seem to react in a shorter time, with six months (SSI-6) in “Centro.” This variation for croplands could be related to the fact that in “Norte Chico,” the majority of crops are irrigated, but to the south there is a higher proportion of rainfed agriculture, which is most dependent on the short-term availability of water. Rather, in the “Norte Chico,” the orchards are more dependent on the storage of water in dams of groundwater reservoirs, which are affected by long-term drought (e.g., SPI-36).

## 5.4 Drought information to aid in adaptation

Different climate components, such as evaporative water demand, water supply, soil moisture, and their impact on vegetation, should be considered when evaluating the multi-dimensional nature of drought. For a better understanding of the propagation of drought (Van Loon et al., 2012) from meteorological to hydrological drought, we should consider the climatic response at different time scales, ranging from short to long. Furthermore, we must make this information publicly available and update it frequently to aid in the development of adaptation policies. The drought observatory for agriculture and biodiversity of Chile (ODES) shares this information aggregated for multiple administrative and hydrological units across Chile (https://odes-chile.org/app/unidades), with the goal of helping to prepare for future climatic conditions.

# 6. Conclusion

There is a trend toward decreasing water supply (SPI, SPEI, and SSI) in most of Chile; just in the southern part, there is an increase. The trend is most strong in the north-central zone. The whole country showed an increase in water demand (AED). The magnitude of the trend increases over longer time scales, which is evidence that the deficit is impacting the hydrological system in Chile. The trend in vegetation productivity in the north-central area is affecting, to a higher degree, shrubland and savanna, followed by croplands and forests. The most important changes in land cover are the increase of forest in “Sur” and shrubland and grassland in “Centro;” and the increase of savanna in “Centro” and “Sur.”.

The drought explains about 30% of the change in land cover type across Chile for forest, grassland, shrubland, and savanna. There is no evidence of an effect of drought on the change in cropland surface area. The increase in AED is the main driver of the change in land cover, followed by a reduction in precipitation and soil moisture. The drought time scales vary regarding the land cover type.

The change in vegetation productivity has been severe in the north-central part of the country for all land cover types, particularly savanna, shrubland, and croplands. The anomaly in soil moisture over the past 12 months is the main variable explaining these changes, followed by anomalies in cumulated precipitation over one to two years. The variation in AED seems to intensify the drought impact on vegetation productivity.

The results of this study provide insightful information that would help in developing adaptation measures for ecosystems in Chile to cope with climate change and drought.

# 7. Acknowledgment

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# References