Assessment of drought in continental Chile for 1981–2023 by climate variables of water supply and demand, soil moisture, and vegetation

Francisco Zambrano and Iongel Duran-Llacer

Abstract

A persistent drought is impacting Chile. It affects the hydrological system and vegetation development. Research studies have focused on the central part of the country. This is due to a persistent period of water scarcity. This scarcity has been found to be a megadrought. This megadrought was defined by the Standardized Precipitation Index (SPI) of twelve months in December. The SPI only considers precipitation as a drought indicator. It does not account for atmospheric evaporative demand (AED), soil moisture, or their combined vegetation productivity. We present a developing database (DDS4Chl) of drought indices for continental Chile since 1981. The indices measure water demand, supply and its impact on vegetation. We derived the SPI for water demand. We also derived the Evaporative Demand Drought Index (EDDI) for water supply. The Standardized Precipitation Evapotranspiration Index (SPEI) shows the combined effect of AED and precipitation. We estimate the standardized anomaly of cumulative soil moisture at one meter (zcSM) and the standardized anomaly of cumulative NDVI (zcNDVI) to show the impact of water demand and supply. We present the historical linear trend of the drought indices in continental Chile. Also we calculated the temporal correlation between the indices of water supply and demand, and soil moisture with the zcNDVI (proxy of vegetation productivity). The dought index for soil moisture acummulated at 12 months (zcSM-12) showed to be the best predictor of vegetation productivity around continental Chile.

Index Terms— drought, Chile, water supply, water demand, soil moisture

I. Introduction

The sixth assessment report (AR6) of the IPCC [1] indicates that human-induced greenhouse gas emissions have increased the frequency and/or intensity of some weather and climate extremes, and the evidence has been strengthened since AR5 [2]. There is high confidence that increasing global warming can expand the land area affected by increasing drought frequency and severity [3]. Climate change enhance atmospheric evaporative demand (AED) and modified precipitation patterns. Thus, to monitor drought, we must consider the water supply and demand. We must also consider its impact on vegetation productivity.

Chile has been facing a persistent rainfall deficit for more than a decade [4], which has impacted vegetation development [5] and the hydrological system [6]. Current drought conditions have affected crop productivity [7], [8], forest development [9], [10], forest fire occurrence [11], land cover change [12], water supply in watersheds [13], and have had economic impacts [14]. In 2019–2020, the drought severity reached an extreme condition in Central Chile (30–34°S) not seen for at least 40 years, and the evidence indicates that the impact is transversal to the land cover classes of forest, grassland, and cropland [5]. The prolonged lack of precipitation in Central Chile is producing changes in ecosystem dynamics that must be studied.

To evaluate meteorological drought (i.e., water supply), the World Meteorological Organization (WMO; [15];[16]) recommends the Standardized Precipitation Index (SPI; [17]), a multiscalar drought index that allows to monitor precipitation deficits from short- to long-term. Following the same approach, [18] incorporates into the SPI the effect of temperature through the use of potential evapotranspiration, thus proposing the SPEI (Standardized Precipitation Evapotranspiration Index). Similarly, to evaluate solely the evaporative demand driven by temperature, [19] and [20] came up with the Evaporative Demand Drought Index (EDDI). To assess the impact of water supply and demand on vegetation, Zambrano (2018) proposed the zcNDVI. This is a standardized anomaly of the cumulative Normalized Difference Vegetation Index (NDVI). It's similar to the SPI, SPEI, and EDDI. The zcNDVI could be accumulated over the growing season or any period (e.g., months). It results in a multiscalar drought index. Several drought indices exist for soil moisture. These include the Soil Moisture Deficit Index (SDMI), a normalized index [21], and the Soil Moisture Agricultural Drought Index (SMADI) [22]. SMADI is a normalized index that uses vegetation, land surface temperature, and a vegetation condition index (VCI, [23]).

We evaluated the trend of the drought indices SPI, SPEI, EDDI, and zcSM; and their relation to vegetation productivity. Our goal is to assess the impact on vegetation of the climate variables of water demand and supply and soil moisture.

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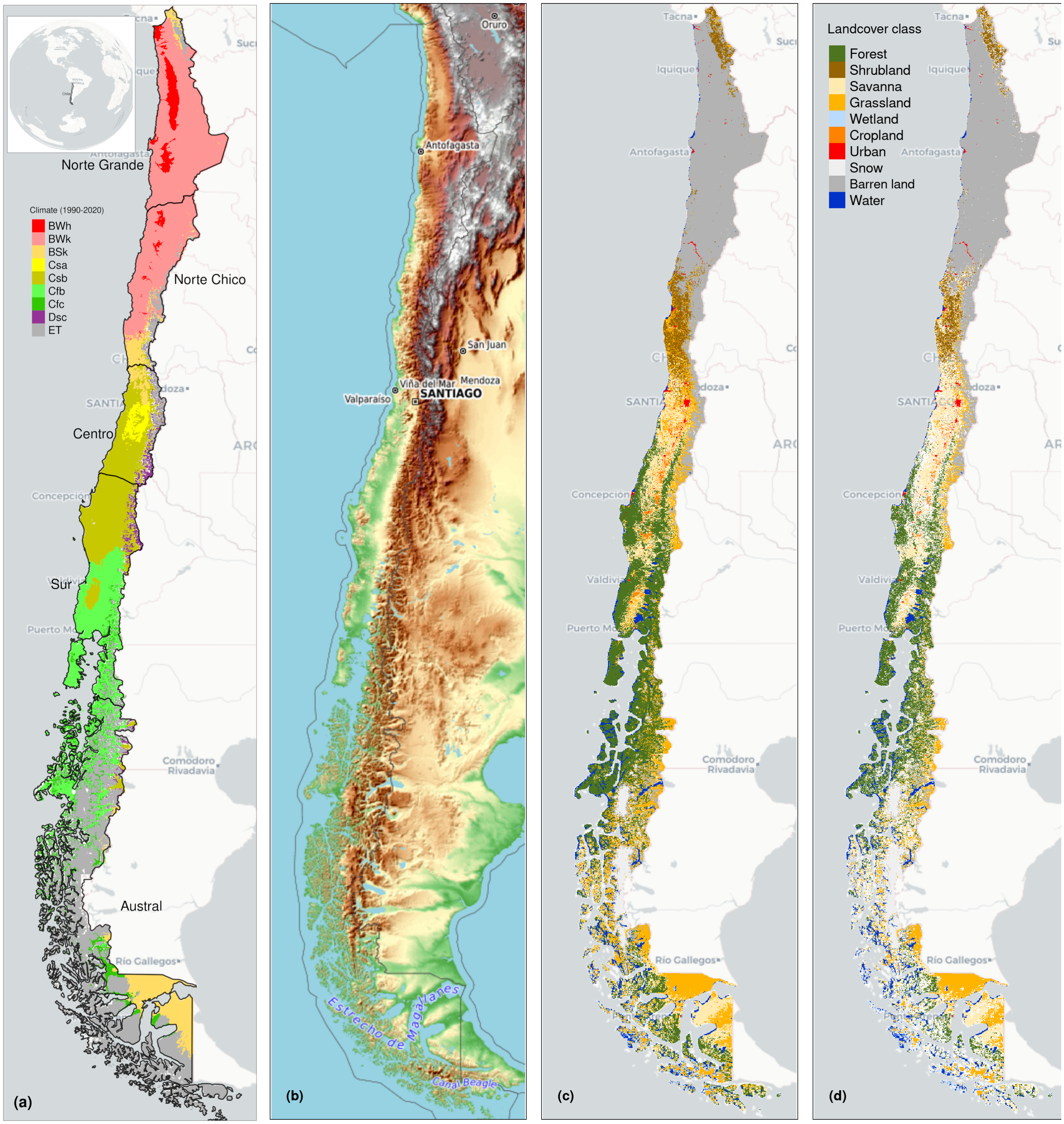

Fig. 1: (a) Chile with the Koppen-Geiger climate classes and the five macrozones “Norte Grande”, “Norte Chico”, “Centro”, “Sur”, and “Austral”. (b) Topography reference map. (c) Land cover classes for 2022. (d) Persistent land cover classes (> 80%) for 2001-2022

II. Methods

A. Study area

Continental Chile has at least seven major climatic types. They range from low desert in the north to alpine tundra and glaciers in the east and southeast. The south has an Oceanic climate and central Chile has a Mediterranean climate [24]. For the analysis, continental Chile was also divided into five zones according to a latitudinal gradient: “Norte Grande”, “Norte Chico”, “Zona Central”, “Zona Sur”, and “Zona Asutral”. (Fig. 1)

B. Data

1) Earth observation data: For water supply and demand variabes, we used ERA5-Land [25], a reanalys dataset wich provides the evolution of land variables since 1950. It has a spatial resolution of 0.1°, hourly frequency and global coverage.

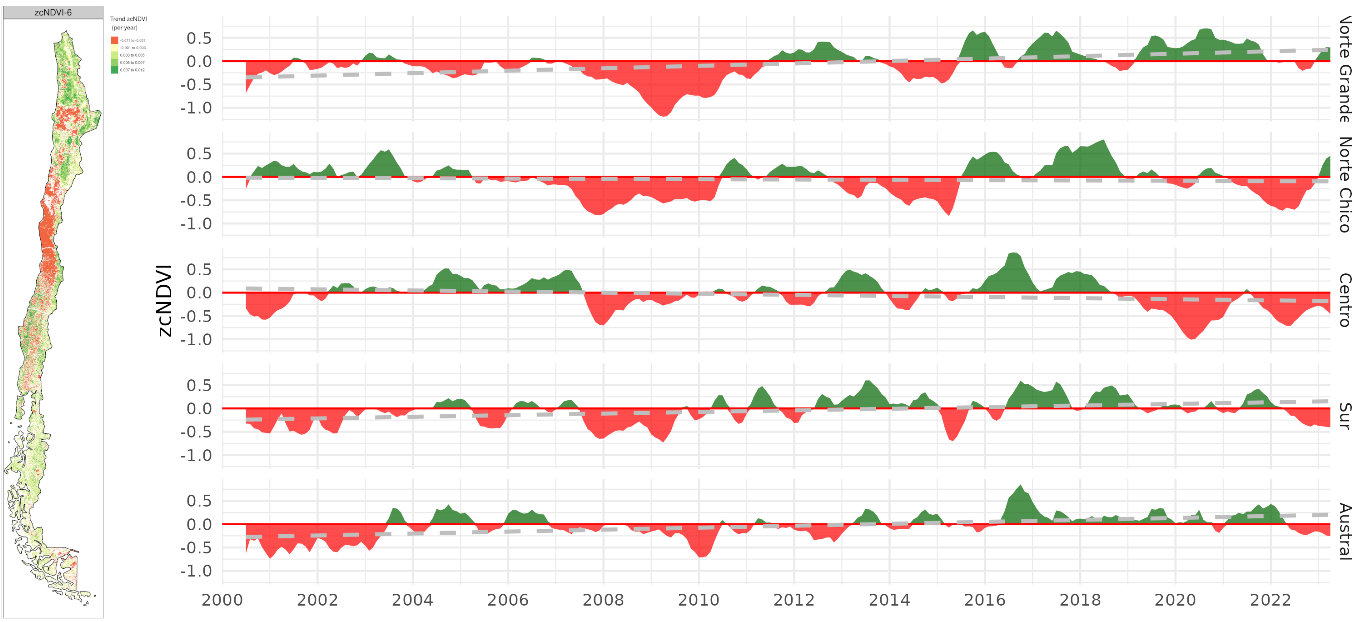

Fig. 2: (a) Map of the linear trend of the index zcNDVI-6 for 2001–2023. Greener colors indicate a positive trend and an increase in vegetation development; reder colors correspond to a negative trend and a decrease in vegetation development. (b) Temporal variation of zcNDVI-6 aggregated at macrozone level within continental Chile. Each horizontal panel corresponds to a macrozone from 'Norte Grande' to 'Zona Asutral'.

We selected the variables for total precipitation, 2 meters temperature, and volumetric soil water layers between 0 and 100cm of depth (layer 1 to layer 3).

To derive a proxy of vegetation productivity, we used the product MOD13A3 collection 6.1 from MODIS [26]. It provides vegetation indices (NDVI and EVI) at 1km of spatial resolution and monthly frequency.

C. Drought indices

We used a non-parametric method for the procedure of normalization and derivation of the standardized anomaly (drought indices). This method obtains empirically derived probabilities using an inverse normal approximation [19]. We derived the SPI, SPEI, EDDI, zcSM, and zcNDVI drought indices. We calculate all aggregations at 1, 3, 6, 12, 24, and 36 months, except for zcNDVI, which is calculated at 6 months.

D. Correlation and trend analysis

For all the pixels, we apply the following procedure: i) First, we calculated the linear trend per drought index and time scale for 1981–2023 (SPI, SPEI, EDDI, zcSM) and 2001–2023 (zcNDVI). ii) Second, over all the pixels, we used the zcNDVI as a proxy of vegetation productivity and analyzed its correlation with the drought indices SPI, SPEI, EDDI, and zcSM. We selected the time scales per index that reached the maximum coefficient of determination, and then we extracted the Pearson correlation for those time scales. The goal is to identify which climate variable has the most significant impact on vegetation development. Also, identify if it is a short- or long-term effect of the climate variable on vegetation.

III. Results

Regarding vegetation productivity, there is a negative trend on zcNDVI in the central part of the country ("Norte Chico" and "Zona Central") (Fig. 2). Indicating either a reduction of vegetation surface, biomass, or status. It reached its lowest values during the year 2020, mostly on the "Zona Central." There are other negative trends in small areas in "Norte Grande" and "zona asutral."

Analyzing the water supply in the macrozones "Norte Chico," "central," and "sur," the SPI shows a decreasing trend that increases at longer time scales due to the prolonged reduction in precipitation. It reaches a trend of -0.056 (z-score) per decade (Fig. 3) for time scales of 36 months. In the case of water demand, we analyze the EDDI. It shows a positive trend, caused by an increase in AED. The trend on EDDI reaches a maximum of 0.053 per decade in the macrozones "Norte Grande" and "Norte Chico" (Fig. 4). The behavior is similar to SPI, having close trends with opposite signs. Nevertheless, the spatial patterns are different. The maximum trend for SPI-36 is in "Norte Chico" and "Zona Central." For EDDI-36, the maximum trend is from "northe grande" to "Zona Central."

The correlation between zcNDVI-6 and drought indices shows that time scales higher than six months are predominant over continental Chile in explaining vegetation variability (Fig. 5). Pearson correlations between 0.6 and 0.9 are concentrated in the "Norte Chico" and "Zona Central" for SPI and SPEI. Soil moisture reached a correlation of 0.6–0.9 that extended north and south with respect to SPI (Fig. 6).

IV. Conlusion

The vegetation productivity shows a high negative trend in the "Norte Chico" and "Zona Central" of continental Chile. This trend is in the primary case related to long-term precipitation decreases, which in the secondary case could be explained by the increase in AED. The dought index for soil moisture (zcSM) derived from ERA5-Land showed to be the best predictor of vegetation productivity around continental Chile.

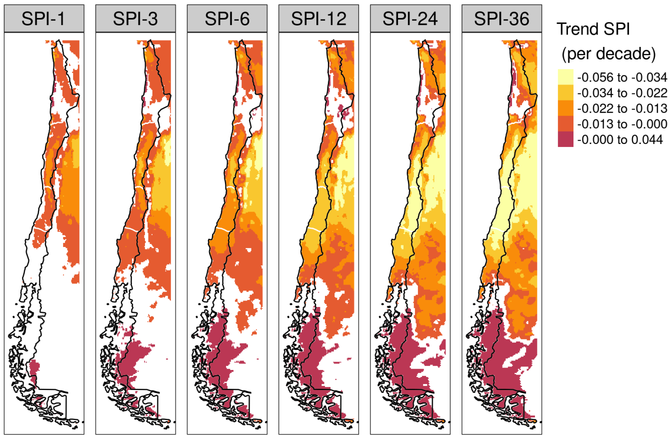

Fig. 3: Linear trend of the SPI at time scales of 1, 3, 6, 12, 24, and 36 months for 1981-2023

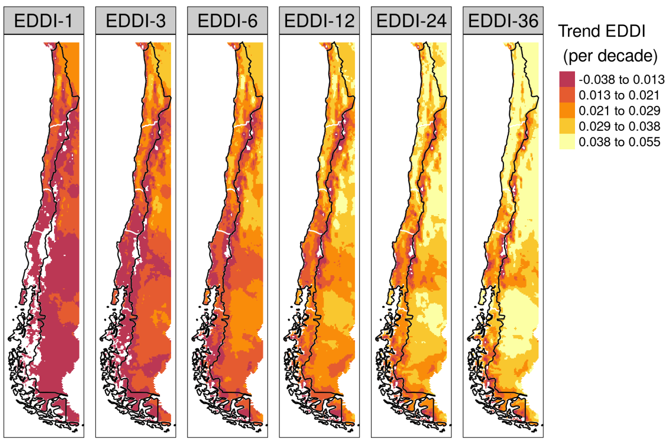

Fig. 4: Linear trend of the EDDI at time scales of 1, 3, 6, 12, 24, and 36 months for 1981-2023

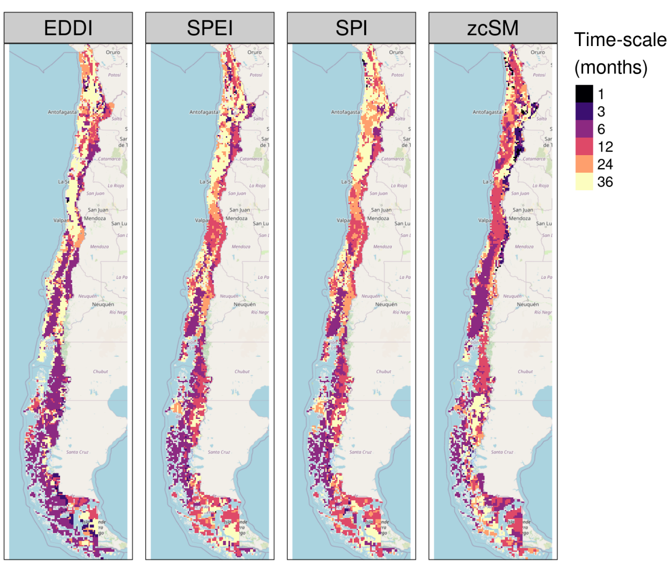

Fig. 5: Time scales per drought index that reach the maximum coefficient of determination

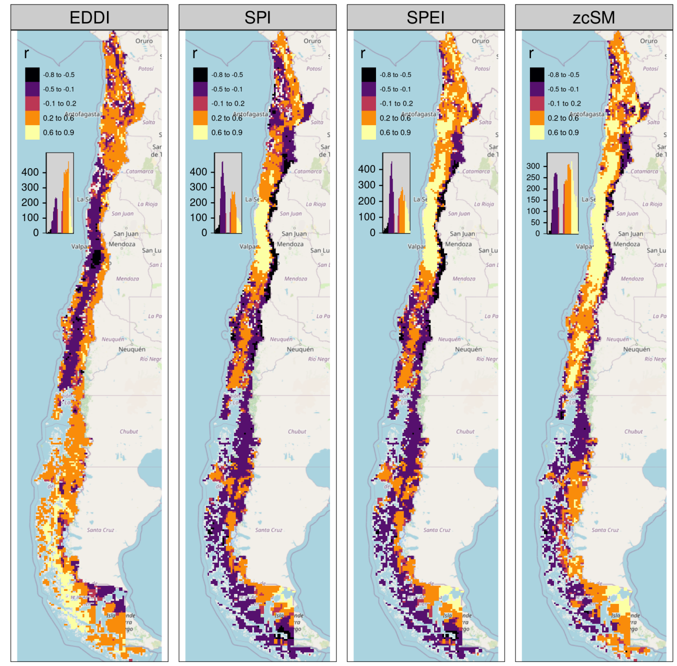

Fig. 6: Pearson correlation value for the time scales and drought index that reach the maximum coefficient of determination

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