

Assessment of drought impact over land cover in continental Chile by the analysis of water supply and demand from the ERA5-Land and MODIS

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Abstract

Human-induced greenhouse gas emissions have increased the frequency and/or intensity of weather and climate extremes. Central Chile has been affected by a persistent drought which is impacting the hydrological system and vegetation development. The region has been the focus of research studies due to the diminishing water supply, this persistent period of water scarcity has been defined as a “mega drought”. Nevertheless, our results evidence that the water deficit has expanded beyond. Our goal is to analyze the impact of drought, measured by drought indices of water supply/demand and vegetation status, in the LULCC (land use land cover change) over continental Chile. For the analysis, continental Chile was divided into five zones according to a latitudinal gradient: “Norte Grande”, “Norte Chico”, “Zona Central”, “Zona Sur”, and “Zona Austral”. We used monthly climatic re-analysis variables for precipitation, temperature and soil moisture for 1981-2023 from ERA5-Land; and MODIS (Moderate-Resolution Imaging Spectroradiometer) product MCD12Q1 for land cover for 2001-2021, and the NDVI vegetation index from product MOD13A2 collection 6.1 for 2000-2023, both from collection 6.1. We estimated atmospheric evaporative demand (AED) by combining the Hargreaves-Samani equation with the ERA5-Land temperature. We derived the drought indices SPI (Standardized Precipitation Index), SPEI (Standardized Precipitation Evapotranspiration Index), EDDI (Evaporative Demand Drought Index), zcSM (standardized anomaly of cumulative soil moisture), and the zcNDVI (standardized anomaly of cumulative NDVI). These indices were calculated for time scales of 1, 3, 6, 12, 24, and 36 months, except for zcNDVI (1, 3, and 6 months). We analyzed the temporal correlation of SPI, SPEI, EDDI, and zcSM with zcNDVI to have insights into the impact of water supply and demand on vegetation. Our results showed that LULCC had an increasing trend of 412 [km²yr⁻¹] of forest expansion in the “Zona Sur”, together with a decreasing trend of 24 [km²yr⁻¹] of cropland contraction in the “Zona Central” meanwhile the “Zona Sur” showed an increase of 31 [km²yr⁻¹], and a contraction of 80 [km²yr⁻¹] of bare soil in the “Zona Austral”. The EDDI was the less correlated index for the five macro zones and the five types of land cover, showing that the temperature in Chile has little impact on vegetation. Higher r-squared values, between 0.5 and 0.8, were obtained at “Norte Chico” and “Zona Central” for the land cover types of savanna, shrubland, grassland, and croplands for the indices SPEI and zcSM at time scales of 12 and 24 months. The forest type reaches a r-squared of ~0.5 for zcSM of 12 months. The results indicate that the “Norte Chico” and “Zona Central” are the most sensitive regions to water supply deficits longer than a year, potentially explained by a low capacity of water storage in those zones that should be further investigated.

Keywords: drought, land cover change, satellite

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1. 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]. Furthermore, drought increases tree mortality and triggers changes in land cover and, consequently, land use, thus impacting ecosystems [4]. Nevertheless, there is a lack of understanding of how the alteration in water supply and demand is affecting land cover transformations.

Precipitation is the primary driver of drought and is intensified by temperature [5]. Drought impacts soil moisture, hydrological regimes, and vegetation productivity. Initially, drought was commonly classified as meteorological, hydrological, and agricultural [6]. Lately, [7] and [8] 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. Even though it has been argued that those definitions do not fully address the ecological dimensions of drought, [4] 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”*. Moreover, many ecological studies have misinterpreted how to characterize drought, for example, sometimes considering “dry” conditions as “drought” [9]. On the other hand, the AR6 [1] states that even if global warming is stabilized at 1.5°–2°C, many parts of the world will be impacted by more severe agricultural and ecological droughts. Then, there is a challenge in conducting drought research, especially to evaluate its impact on ecosystems.

Chile has been facing a persistent rainfall deficit for more than a decade [10], which has impacted vegetation development [11] and the hydrological system [12]. Current drought conditions have affected crop productivity [13, 14], forest development [15, 16], forest fire occurrence [17], land cover change [18], water supply in watersheds [19], and have had economic impacts [20]. 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 [11]. The prolonged lack of precipitation in Central Chile is producing changes in ecosystem dynamics that must be studied.

For the spatiotemporal assessment of drought impact (i.e., by water supply and demand) on land cover changes, we need climatic reliable variables such as precipitation, temperature, soil moisture, land cover, and vegetation status. For developing countries like Chile, the weather networks present several disadvantages, such as gaps, a short history, and low-quality data. Reanalysis data, as the ERA5-Land (ERA5L) [21] provides hourly climatic information (precipitation, temperature, and soil moisture) without gaps since 1950 with global extension. ERA5L has already been used for drought assessment using the Standardized Precipitation-Evapotranspiration Index (SPEI) [22] and for flash drought [23] by analyzing soil moisture and evapotranspiration. On the other hand, satellite remote sensing [24, 25] is the primary method to evaluate how drought impacts vegetation dynamics. Vegetation drought indices (VDI) are commonly used as proxies of productivity [26, 27], which can be derived from the MODIS (Moderate-Resolution Imaging Spectroradiometer). Besides, land use and land cover (LULC) change can be driven by drought [28, 29]. To analyze these changes, multiple LULC products exist [30], one of those that provides time series since 2001 is the MCD12Q1 [31] from MODIS. The variation in water supply and demand is finally reflected in the total water storage (TWS). The TWS can be retrieved by the Gravity Recovery and Climate Experiment (GRACE), which allows analyzing water availability changes at coarse resolution [32, 33]. We can use climatic reanalysis (ERA5L) and vegetation data (MODIS) to derive drought indices of supply (i.e., precipitation) and demand (i.e., temperature) and thus evaluate the impact of drought on LULC changes. Further, the TWS can be assessed with regard to the changes in water supply and demand to gain insight into the impact on water storage.

To evaluate meteorological drought (i.e., water supply), the World Meteorological Organization (WMO; [34]) recommends the Standardized Precipitation Index (SPI; [35]), a multiscale drought index that allows to monitor precipitation deficits from short- to long-term. Following the same approach, [36] 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, [37] and [38] came up with the Evaporative Demand Drought Index (EDDI). For vegetation, in a similar manner as the SPI, SPEI and EDDI; [14] proposed the zcNDVI, a standardized anomaly of the cumulative Normalized Difference Vegetation Index (NDVI), which could be accumulated over the growing season or any period (e.g., months), resulting in a multiscalar drought index. For soil moisture, several drought indices exist, such as the Soil Moisture Deficit Index (SDMI) a normalized index [39] and the Soil Moisture Agricultural Drought Index (SMADI) [40] which is a normalized index using vegetation, land surface temperature, and a vegetation condition index (VCI, [41]). From TWS, we can estimate the standardized terrestrial water storage index (STI) [42], a standardized anomaly that follows the methodology of the SPI, SPEI, EDDI, and zcNDVI. Thereby, we have drought indices for water supply, demand, and storage, which can help to make a comprehensive assessment of drought.

In this research, we aim to analyze the impact of drought on different types of land cover classes in continental Chile by combining environmental variables such as biomass productivity, and water demand and supply gathered from earth observation products. The specific objectives of the study are: i) to calculate multi-scalar drought indices for water demand and supply for 1981–2023; ii) to evaluate LULC change for 2001–2021 and its relation to drought indices; iii) to analyze the relationship of a proxy of biomass (zcNDVI) with drought indices; and iv) to assess if the observed changes in the drought indices are linked to the TWS.

2. Study area

3. Materials and Methods

3.1. Data

3.1.1. Earth observation data

3.1.2. in-situ data

3.2. Drought indices for water demand and supply

3.3. Analysis of a biomass proxy with drought indices of supply and demand

3.4. LULC change for 2001-2021 and its relation with water supply and demand

! [Proportion of land cover class from the persistent land cover for 2001-2021 (>80%) per macrozone.

3.5. Total water storage and drought indices

Terrestrial Water Storage (TWS) is defined as the total amount of water stored on land that includes any natural or artificial water bodies, such as groundwater, soil moisture, rivers, lakes, snowpack, ice, and biomass water [43, 44]. TWS changes evidence the effects of multiple water fluxes on the hydrological cycle [44]. These are reflected in the temporal variation of observations of the Earth’s gravitational field [45, 46] and, in recent decades, the twin Gravity Recovery and Climate Experiment (GRACE) satellites and their Follow-On mission (GRACE-FO) have provided valuable results on globally distributed TWS anomalies [47, 48]. The GRACE mission was launched in March 2002 and was operational until October 2017 [49]. Then its GRACE Follow-On successor was launched in May 2018 [50, 51]. The information provided by these satellites is used to construct monthly maps of the Earth’s average gravity field, providing details of the movement of water masses or water mass anomaly estimates relative to the long-term average gravity field [43, 52].

In this study, RL06.1_V3 GRACE mascon (mass concentration) monthly solutions were used, which are provided by the Jet Propulsion Laboratory (JPL-M, <https://grace.jpl.nasa.gov>). Each GRACE Tellus monthly grid at 0.5 degrees represents the deviation of surface mass for that month relative to a reference time average (2004-2009 baseline), which is subtracted from all other monthly grids to provide terrestrial water storage anomalies (TWSA) [49, 51]. This JPL-M version of the data employs a Coastal Resolution Improvement (CRI) filter that reduces signal leakage errors across coastlines [? ?]. Although the mascon

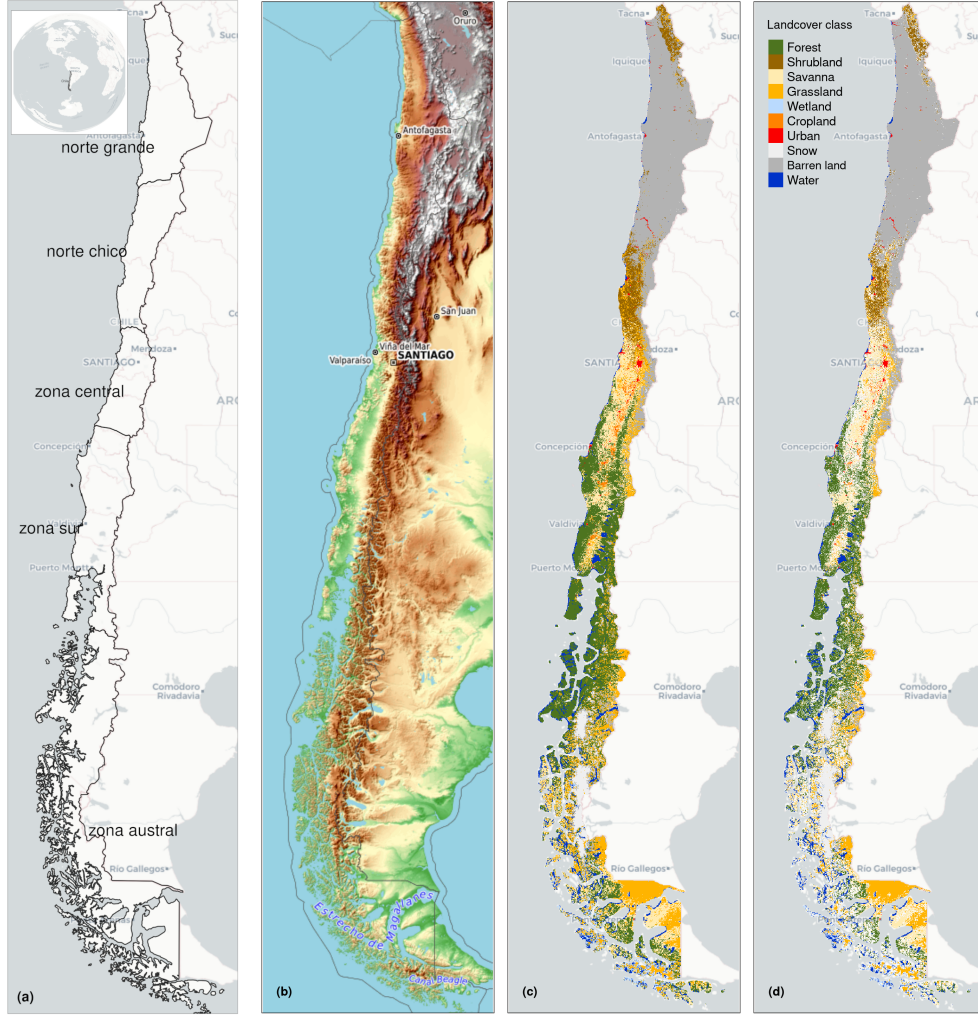


Figure 1: (a) Chile and the five zones “norte grande”, “norte chico”, “zona central”, “zona sur”, and “zona austral”. (b) Topography reference map. (c) Land cover classes for 2021. (d) Persistent land cover classes (> 80%) for 2001-2021.

solutions greatly reduced leakage errors, a gain factor, which is used to enhance the spatial resolution, was applied to the dataset as recommended for hydrological studies [49, 51]. The water storage and height anomalies are given in Equivalent Water Height or Thickness units (EWH, cm) [46], and their temporal resolution monthly is from April 2002 to May 2023.

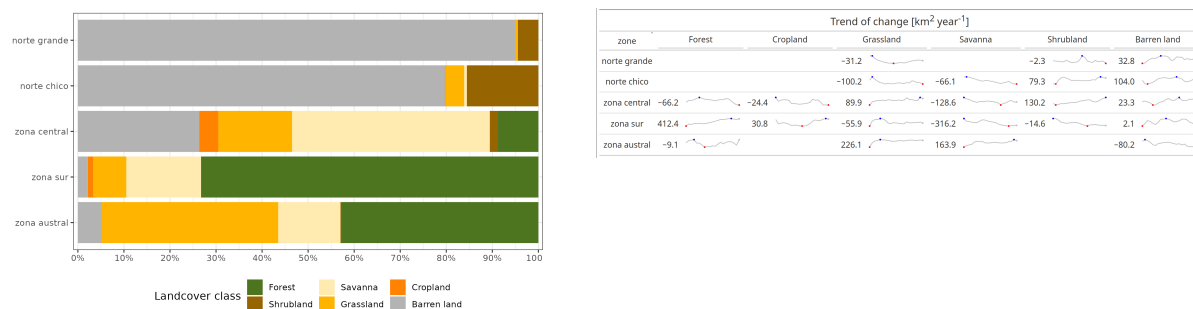


Figure 2: Proportion of land cover class from the persistent land cover for 2001-2021 (>80%) per macrozone. The table on the left shows the linear change trend next to time-series plot of surface, per land cover class (IGBP MCD12Q1.006) for 2001-2021 through the five zones on continental Chile. Blue dots on the plots indicate the maximum and red dots minimum surface reach.

3.6. Validation of ERA5-Land variables

4. Results

4.1. Drought indices for water demand and supply

4.2. Biomass proxy with drought indices of supply and demand

4.3. LULC change for 2001-2021 and its relation with water supply and demand

4.4. Total water storage (TWS) and drought indices

4.5. Validation of ERA5-Land variables

5. Discussion

6. Conclusion

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