

¹ Assessment of drought impact over land cover in continental Chile by the
² analysis of water supply and demand from ERA5-Land and MODIS

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⁴ **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.

⁵ **Keywords:** drought, land cover change, satellite

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6 **1. Introduction**

7 The sixth assessment report (AR6) of the IPCC [1] indicates that human-induced greenhouse gas emissions
8 have increased the frequency and/or intensity of some weather and climate extremes, and the evidence has
9 been strengthened since AR5 [2]. There is high confidence that increasing global warming can expand the
10 land area affected by increasing drought frequency and severity [3]. Furthermore, drought increases tree
11 mortality and triggers changes in land cover and, consequently, land use, thus impacting ecosystems [4].
12 Nevertheless, there is a lack of understanding of how the alteration in water supply and demand is affecting
13 land cover transformations.

14 Precipitation is the primary driver of drought and is intensified by temperature [5]. Drought impacts soil
15 moisture, hydrological regimes, and vegetation productivity. Initially, drought was commonly classified as
16 meteorological, hydrological, and agricultural [6]. Lately, [7] and [8] have given an updated definition of
17 drought for the Anthropocene, suggesting that it should be considered the feedback of humans' decisions
18 and activities that drives the anthropogenic drought. Even though it has been argued that those definitions
19 do not fully address the ecological dimensions of drought. [4] proposed the ecological drought definition as
20 "*an episodic deficit in water availability that drives ecosystems beyond thresholds of vulnerability, impacts*
21 *ecosystem services, and triggers feedback in natural and/or human systems*". Moreover, many ecological
22 studies have misinterpreted how to characterize drought, for example, sometimes considering "dry" condi-
23 tions as "drought" [9]. On the other hand, the AR6 [1] states that even if global warming is stabilized at
24 1.5°–2°C, many parts of the world will be impacted by more severe agricultural and ecological droughts.
25 Then, there is a challenge in conducting drought research, especially to evaluate its impact on ecosystems.

26 Chile has been facing a persistent rainfall deficit for more than a decade [10], which has impacted vegeta-
27 tion development [11] and the hydrological system [12]. Current drought conditions have affected crop
28 productivity [13, 14], forest development [15, 16], forest fire occurrence [17], land cover change [18], water
29 supply in watersheds [19], and have had economic impacts [20]. In 2019–2020, the drought severity reached
30 an extreme condition in Central Chile (30–34°S) not seen for at least 40 years, and the evidence indicates
31 that the impact is transversal to the land cover classes of forest, grassland, and cropland [11]. The prolonged
32 lack of precipitation in Central Chile is producing changes in ecosystem dynamics that must be studied.

33 For the spatiotemporal assessment of drought impact (i.e., by water supply and demand) on land cover
34 changes, we need climatic reliable variables such as precipitation, temperature, soil moisture, land cover, and
35 vegetation status. For developing countries like Chile, the weather networks present several disadvantages,
36 such as gaps, a short history, and low-quality data. Reanalysis data, as the ERA5-Land (ERA5L) [21]
37 provides hourly climatic information (precipitation, temperature, and soil moisture) without gaps since
38 1950 with global extension. ERA5L has already been used for drought assessment using the Standardized
39 Precipitation-Evapotranspiration Index (SPEI) [22] and for flash drought [23] by analyzing soil moisture
40 and evapotranspiration. On the other hand, satellite remote sensing [24, 25] is the primary method to
41 evaluate how drought impacts vegetation dynamics. Vegetation drought indices (VDI) are commonly used
42 as proxies of productivity [26, 27], which can be derived from the MODIS (Moderate-Resolution Imaging
43 Spectroradiometer). Besides, land use and land cover (LULC) change can be driven by drought [28, 29]. To
44 analyze these changes, multiple LULC products exist [30], one of those that provides time series since 2001
45 is the MCD12Q1 [31] from MODIS. The variation in water supply and demand is finally reflected in the
46 total water storage (TWS). The TWS can be retrieved by the Gravity Recovery and Climate Experiment
47 (GRACE), which allows analyzing water availability changes at coarse resolution [32, 33]. We can use climatic
48 reanalysis (ERA5L) and vegetation data (MODIS) to derive drought indices of supply (i.e., precipitation)
49 and demand (i.e., temperature) and thus evaluate the impact of drought on LULC changes. Further, the
50 TWS can be assessed with regard to the changes in water supply and demand to gain insight into the impact
51 on water storage.

52 To evaluate meteorological drought (i.e., water supply), the World Meteorological Organization (WMO;
53 [34]) recommends the Standardized Precipitation Index (SPI; [35]), a multiscalar drought index that allows
54 to monitor precipitation deficits from short- to long-term. Following the same approach, [36] incorporates

55 into the SPI the effect of temperature through the use of potential evapotranspiration, thus proposing the
56 SPEI (Standardized Precipitation Evapotranspiration Index). Similarly, to evaluate solely the evaporative
57 demand driven by temperature, [37] and [38] came up with the Evaporative Demand Drought Index (EDDI).
58 For vegetation, in a similar manner as the SPI, SPEI and EDDI; [14] proposed the zcNDVI, a standardized
59 anomaly of the cumulative Normalized Difference Vegetation Index (NDVI), which could be accumulated
60 over the growing season or any period (e.g., months), resulting in a multiscalar drought index. For soil
61 moisture, several drought indices exist, such as the Soil Moisture Deficit Index (SDMI) a normalized index
62 [39] and the Soil Moisture Agricultural Drought Index (SMADI) [40] which is a normalized index using
63 vegetation, land surface temperature, and a vegetation condition index (VCI, [41]). From TWS, we can
64 estimate the standardized terrestrial water storage index (STI) [42], a standardized anomaly that follows
65 the methodology of the SPI, SPEI, EDDI, and zcNDVI. Thereby, we have drought indices for water supply,
66 demand, and storage, which can help to make a comprehensive assessment of drought.

67 In this research, we present the dataset DDS4Chl, which provides climate variables and drought indices
68 of water demand and supply and vegetation productivity for continental Chile since 1981 at a monthly
69 frequency. Those were gathered from the earth observation products ERA5-Land and MODIS. Then, we
70 used DDS4Chl to analyze the impact of drought on different types of land cover classes in continental Chile.
71 The specific objectives of the study are: i) to analyze the trend on multi-scalar drought indices for water
72 demand and supply, soil moisture, and vegetation productivity for 1981–2023/2001–2023; ii) to evaluate
73 LULC change for 2001–2021 and its relation to drought indices; iii) to analyze the relationship of a proxy
74 of vegetation productivity (zcNDVI) with drought indices of water demand and supply and soil moisture;
75 and iv) to assess if the observed changes in the drought indices are linked to TWS.

76 2. Study area

77 3. Materials and Methods

78 3.1. Data

79 3.1.1. Earth observation data

80 For water supply and demand variables, we used ERA5-Land [43], a reanalysis dataset which provides the
81 evolution of land variables since 1950. It has a spatial resolution of 0.1°, hourly frequency and global
82 coverage. We selected the variables for total precipitation, 2 meters temperature, and volumetric soil water
83 layers between 0 and 100cm of depth (layer 1 to layer 3).

84 To derive a proxy of vegetation productivity, we used the product MOD13A3 collection 6.1 from MODIS
85 [44]. It provides vegetation indices (NDVI and EVI) at 1km of spatial resolution and monthly frequency.

86 3.1.2. in-situ data

87 3.2. Drought indices for water demand and supply, soil moisture and vegetation productivity

88 3.3. Analysis of a biomass proxy with drought indices of supply and demand

89 3.4. LULC change for 2001-2021 and its relation with water supply and demand

90 3.5. Total water storage and drought indices

91 Terrestrial Water Storage (TWS) is defined as the total amount of water stored on land that includes
92 any natural or artificial water bodies, such as groundwater, soil moisture, rivers, lakes, snowpack, ice, and
93 biomass water [45, 46]. TWS changes evidence the effects of multiple water fluxes on the hydrological cycle
94 [46]. These are reflected in the temporal variation of observations of the Earth's gravitational field [47, 48]

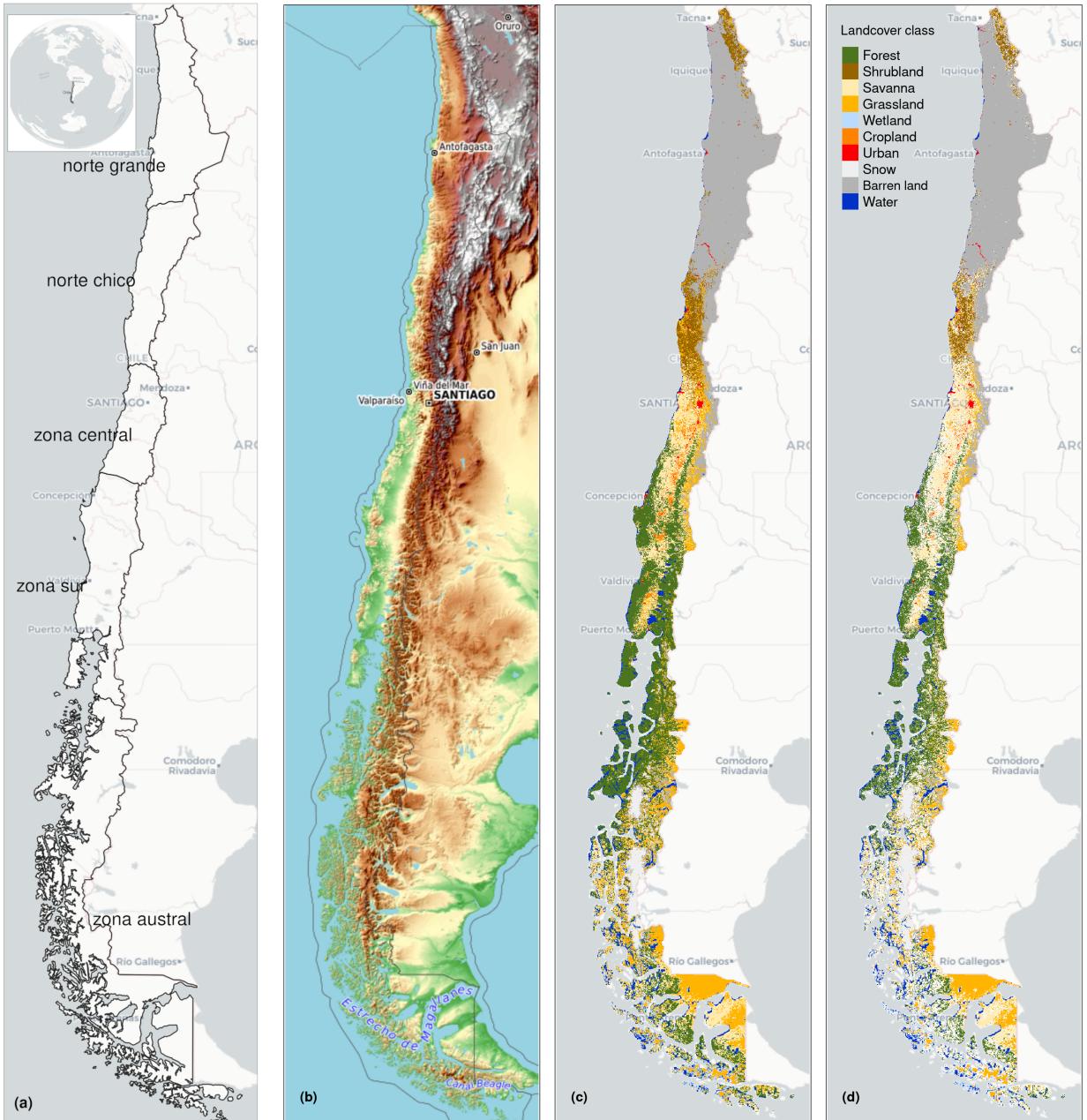


Figure 1: (a) Chile and the five zones “norte grande”, “norte chico”, “zona central”, “zona sur”, and “zona austral”. (b) Topography reference map. (c) Land cover classes for 2021. (d) Persistent land cover classes ($> 80\%$) for 2001-2021.

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 [49, 50]. The GRACE mission was launched in March 2002 and was operational until October 2017 [51]. Then its GRACE Follow-On successor was launched in May 2018 [52, 53]. 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 [45, 54].

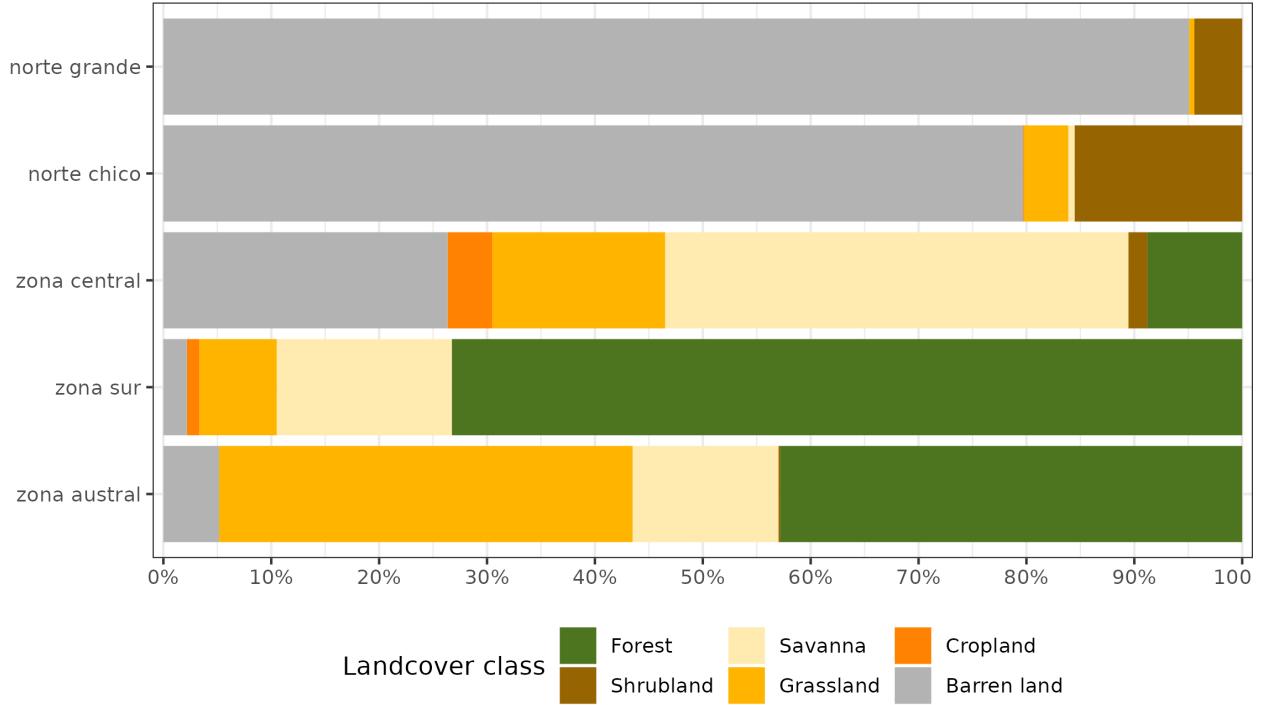


Figure 2: Proportion of land cover class from the persistent land cover for 2001-2021 (>80%) per macrozone

Table 1: Value of linear change trend next to time-series plot of surface, per landcover class (IGBP MCD12Q1.006) for 2001-2019 through Central Chile. Red dots on the plots indicate the maximum and minimum surface

zone	Trend of change [$\text{km}^2 \text{ year}^{-1}$]													
	Forest		Cropland		Grassland		Savanna		Shrubland		Barren land			
	x	y	x	y	x	y	x	y	x	y	x	y	x	y
norte grande							-31.0				-13.9		44.1	
norte chico					-98.4		-66.7		70.3		109.9			
centro	-80.3		-24.5		108.8		-136.3		132.8		23.3			
sur	392.2		34.1		-41.2		-316.2		-13.8		0.6			
austral	22.2				209.5		174.0				-84.8			

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) [51, 53]. This JPL-M version of the data employs a Coastal Resolution Improvement (CRI) filter that reduces signal leakage errors across coastlines [55, 56]. Although the mascon 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 [51, 53]. The water storage and height anomalies are given in Equivalent Water Height or Thickness units (EWH, cm) [48], and their temporal resolution monthly is from April 2002 to May 2023.

112 3.6. Validation of ERA5-Land variables

113 4. Results

114 4.1. Trend of drought indices for water demand/supply, soil moisture, and vegetation productivity

115 Regarding vegetation productivity, there is a negative trend on zcNDVI in the central part of the country
116 (“norte chico” and “zona central”) (Figure 3). Indicating either a reduction of vegetation surface, biomass,
117 or status. It reached its lowest values during the year 2020, mostly on the “zona central.” There are other
118 negative trends in small areas in “norte grande” and “zona asustral.”

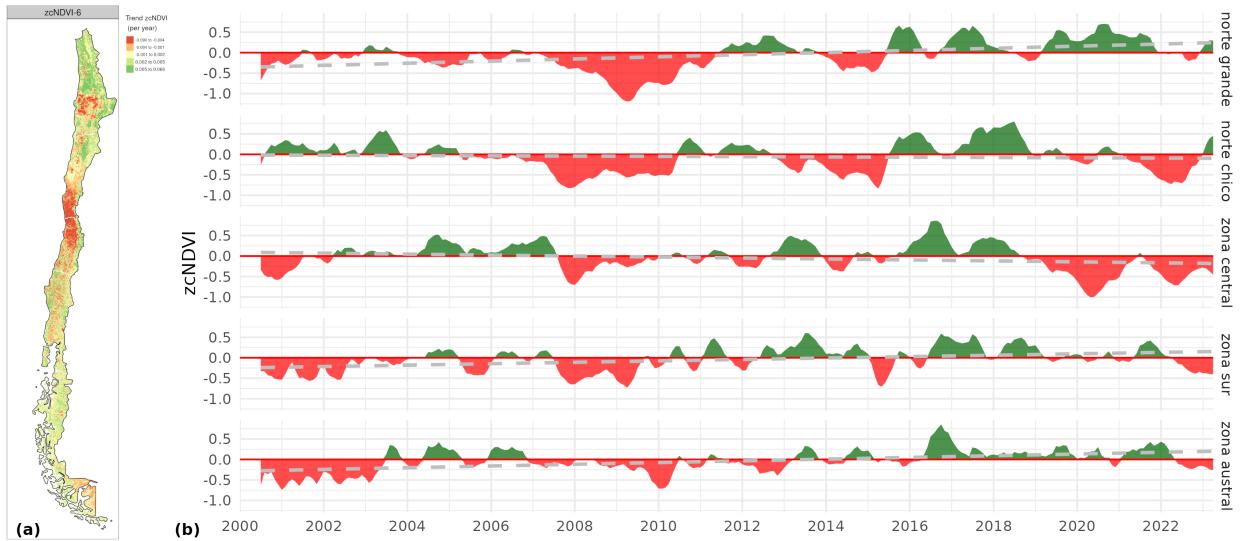


Figure 3: (a) Map of the linear trend of the index zcNDVI-6 for 2001–2023. Greener colors indicate a positive trend and an increase in vegetation development; redder colors correspond to a negative trend and a decrease in vegetation development. (b) Temporal variation of zcNDVI-6 aggregated at macrozone level within continental Chile. Each horizontal panel corresponds to a macrozone from ‘norte grande’ to ‘zona austral’.

119 Analyzing the water supply in the macrozones “norte chico,” “central,” and “sur,” the SPI shows a decreasing
120 trend that increases at longer time scales due to the prolonged reduction in precipitation. It reaches a
121 trend of -0.056 (z-score) per decade (Figure 4) for time scales of 36 months. In the case of water demand, we
122 analyze the EDDI. It shows a positive trend, caused by an increase in AED. The trend on EDDI reaches a
123 maximum of 0.053 per decade in the macrozones “norte grande” and “norte chico” (Figure 5). The behavior
124 is similar to SPI, having close trends with opposite signs. Nevertheless, the spatial patterns are different.
125 The maximum trend for SPI-36 is in “norte chico” and “zona central.” For EDDI-36, the maximum trend
126 is from “norte grande” to “zona central.”

127 The correlation between zcNDVI-6 and drought indices shows that time scales higher than six months
128 are predominant over continental Chile in explaining vegetation variability (Figure 6). Pearson correlations
129 between 0.6 and 0.9 are concentrated in the “norte chico” and “zona central” for SPI and SPEI. Soil moisture
130 reached a correlation of 0.6–0.9 that extended north and south with respect to SPI.

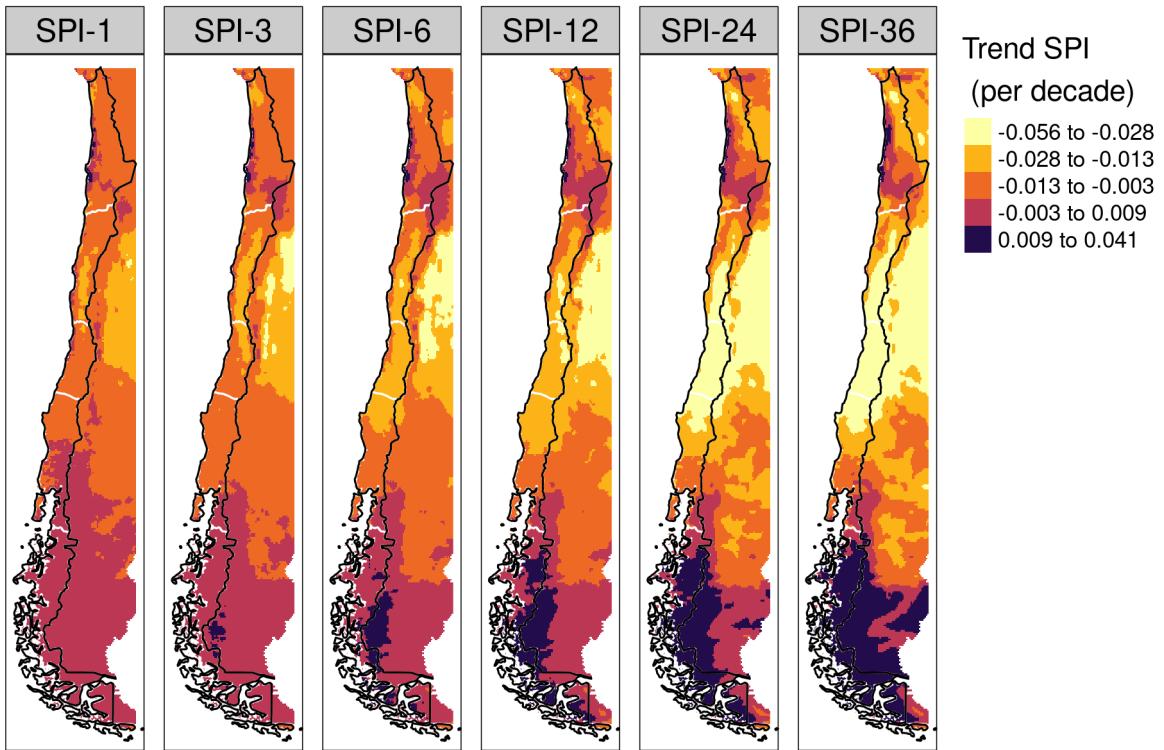


Figure 4: Linear trend of the SPI at time scales of 1, 3, 6, 12, 24, and 36 months for 1981-2023

131 4.2. *LULC change for 2001-2021 and its relation with water supply and demand*

132 4.3. *Total water storage (TWS) and drought indices*

133 4.4. *Validation of ERA5-Land variables*

134 5. Discussion

135 6. Conclusion

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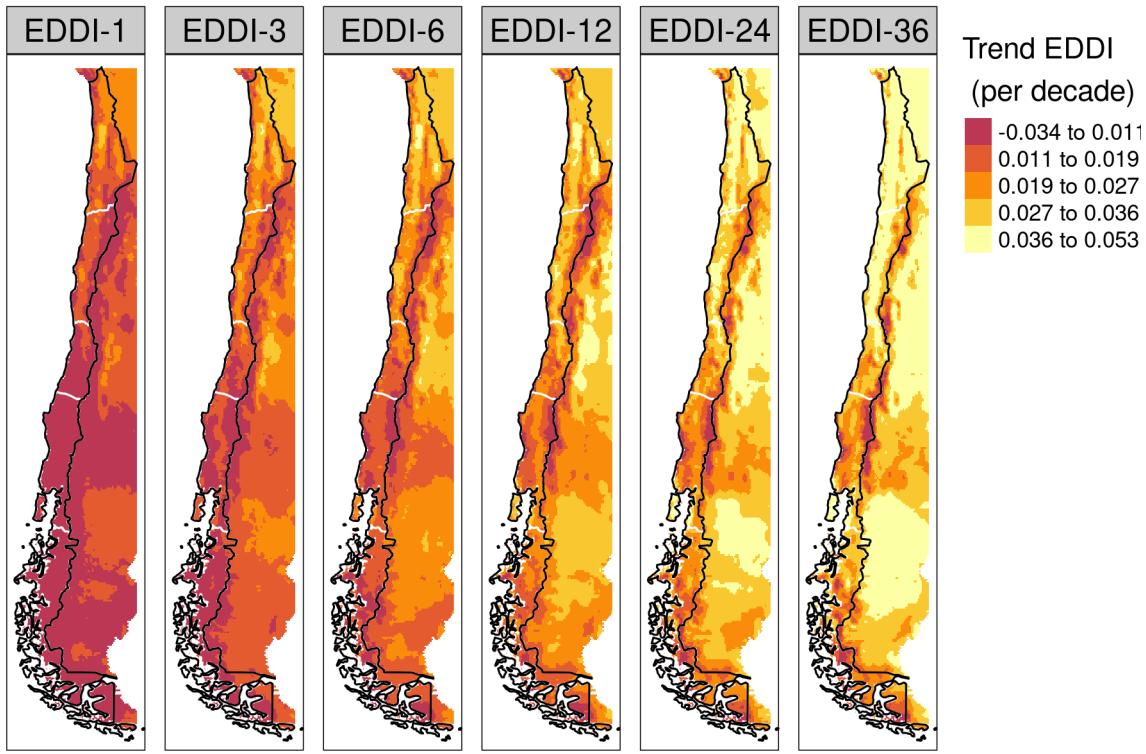


Figure 5: Linear trend of the EDDI at time scales of 1, 3, 6, 12, 24, and 36 months for 1981-2023

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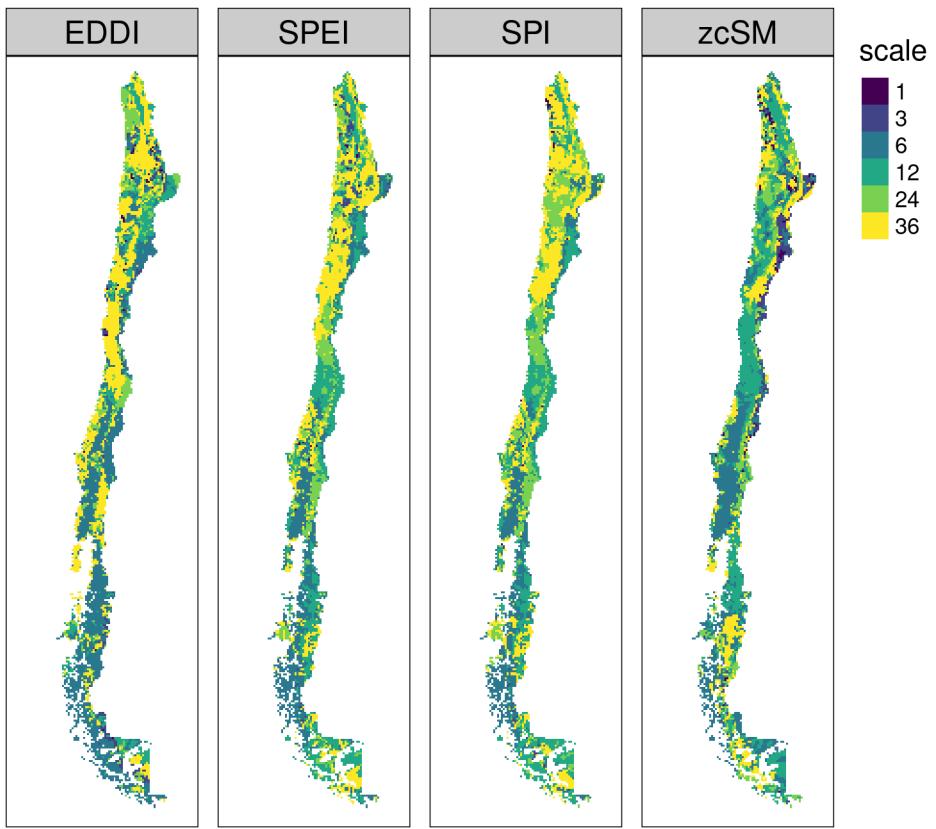


Figure 6: Time scales per drought index that reach the maximum coefficient of determination

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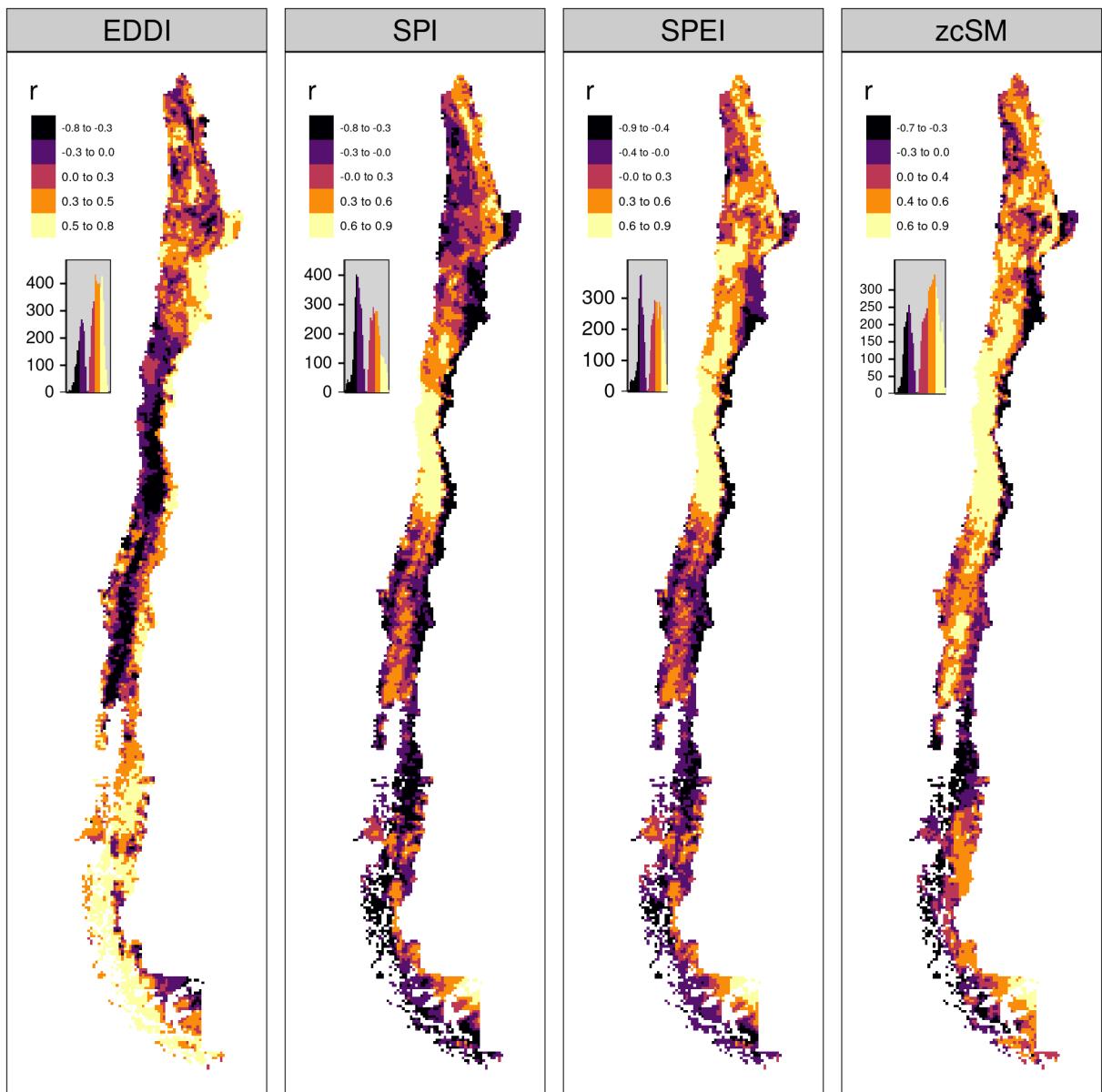


Figure 7: Pearson correlation value for the time scales and drought index that reach the maximum coefficient of determination

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