

¹ Drought indices of water demand and supply, soil moisture, vegetation, and
² its impact on LULCC in continental Chile

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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 (ERA5L); 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 ERA5L temperature. We derived the drought indices SPI (Standardized Precipitation Index), SPEI (Standardized Precipitation Evapotranspiration Index), EDDI (Evaporative Demand Drought Index), SSI (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 SSI 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 SSI at time scales of 12 and 24 months. The forest type reaches a r-squared of ~0.5 for SSI 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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¹This is the first author footnote.

6 **1. Introduction**

7 The sixth assessment report (AR6) of the IPCC (Calvin et al., 2023) indicates that human-induced green-
8 house gas emissions have increased the frequency and/or intensity of some weather and climate extremes,
9 and the evidence has been strengthened since AR5 (IPCC, 2013). There is high confidence that increasing
10 global warming can expand the land area affected by increasing drought frequency and severity (Seneviratne,
11 2021). Furthermore, drought increases tree mortality and triggers changes in land cover and, consequently,
12 land use, thus impacting ecosystems (Crausbay et al., 2017). Nevertheless, there is a lack of understanding
13 of how the alteration in water supply and demand is affecting land cover transformations.

14 Precipitation is the primary driver of drought and is intensified by temperature (Luo et al., 2017). Drought
15 impacts soil moisture, hydrological regimes, and vegetation productivity. Initially, drought was commonly
16 classified as meteorological, hydrological, and agricultural (Wilhite and Glantz, 1985). Lately, Van Loon
17 et al. (2016) and AghaKouchak et al. (2021) have given an updated definition of drought for the Anthro-
18 pocene, suggesting that it should be considered the feedback of humans' decisions and activities that drives
19 the anthropogenic drought. Even though it has been argued that those definitions do not fully address the
20 ecological dimensions of drought. Crausbay et al. (2017) proposed the ecological drought definition as "*an
21 episodic deficit in water availability that drives ecosystems beyond thresholds of vulnerability, impacts ecosys-
22 tem services, and triggers feedback in natural and/or human systems*". Moreover, many ecological studies
23 have misinterpreted how to characterize drought, for example, sometimes considering "dry" conditions as
24 "drought" (Slette et al., 2019). On the other hand, the AR6 (Calvin et al., 2023) states that even if global
25 warming is stabilized at 1.5°–2°C, many parts of the world will be impacted by more severe agricultural
26 and ecological droughts. Then, there is a challenge in conducting drought research, especially to evaluate
27 its impact on ecosystems.

28 Chile has been facing a persistent rainfall deficit for more than a decade (Garreaud et al., 2017), which
29 has impacted vegetation development (Zambrano, 2023) and the hydrological system (Boisier et al., 2018).
30 Current drought conditions have affected crop productivity (Zambrano et al., 2016, 2018), forest development
31 (Miranda et al., 2020; Venegas-González et al., 2018), forest fire occurrence (Urrutia-Jalabert et al., 2018),
32 land cover change (Fuentes et al., 2021), water supply in watersheds (Alvarez-Garreton et al., 2021), and
33 have had economic impacts (Fernández et al., 2023). In 2019–2020, the drought severity reached an extreme
34 condition in Central Chile (30–34°S) not seen for at least 40 years, and the evidence indicates that the
35 impact is transversal to the land cover classes of forest, grassland, and cropland (Zambrano, 2023). The
36 prolonged lack of precipitation in Central Chile is producing changes in ecosystem dynamics that must be
37 studied.

38 For the spatiotemporal assessment of drought impact (i.e., by water supply and demand) on land cover
39 changes, we need climatic reliable variables such as precipitation, temperature, soil moisture, land cover, and
40 vegetation status. For developing countries like Chile, the weather networks present several disadvantages,
41 such as gaps, a short history, and low-quality data. Reanalysis data, as the ERA5-Land (ERA5L) (Muñoz-
42 Sabater et al., 2021) provides hourly climatic information (precipitation, temperature, and soil moisture)
43 without gaps since 1950 with global extension. ERA5L has already been used for drought assessment using
44 the Standardized Precipitation-Evapotranspiration Index (SPEI) (Nouri, 2023) and for flash drought (Wang
45 et al., 2023) by analyzing soil moisture and evapotranspiration. On the other hand, satellite remote sensing
46 (West et al., 2019; AghaKouchak et al., 2015) is the primary method to evaluate how drought impacts
47 vegetation dynamics. Vegetation drought indices (VDI) are commonly used as proxies of productivity
48 (Paruelo et al., 2016; Schucknecht et al., 2017), which can be derived from the MODIS (Moderate-Resolution
49 Imaging Spectroradiometer). Besides, land use and land cover (LULC) change can be driven by drought
50 (Tran et al., 2019; Akinyemi, 2021). To analyze these changes, multiple LULC products exist (Grekousis
51 et al., 2015), one of those that provides time series since 2001 is the MCD12Q1 (Friedl and Sulla-Menashe,
52 2019) from MODIS. The variation in water supply and demand is finally reflected in the total water storage
53 (TWS). The TWS can be retrieved by the Gravity Recovery and Climate Experiment (GRACE), which
54 allows analyzing water availability changes at coarse resolution (Ahmed et al., 2014; Ma et al., 2017). We

55 can use climatic reanalysis (ERA5L) and vegetation data (MODIS) to derive drought indices of supply (i.e.,
56 precipitation) and demand (i.e., temperature) and thus evaluate the impact of drought on LULC changes.
57 Further, the TWS can be assessed with regard to the changes in water supply and demand to gain insight
58 into the impact on water storage.

59 To evaluate meteorological drought (i.e., water supply), the World Meteorological Organization (WMO;
60 [WMO et al. \(2012\)](#)) recommends the Standardized Precipitation Index (SPI; [McKee et al. \(1993\)](#)), a multiscalar
61 drought index that allows to monitor precipitation deficits from short- to long-term. Following the
62 same approach, [Vicente-Serrano et al. \(2010\)](#) incorporates into the SPI the effect of temperature through
63 the use of potential evapotranspiration, thus proposing the SPEI (Standardized Precipitation Evapotran-
64 spiration Index). Similarly, to evaluate solely the evaporative demand driven by temperature, [Hobbins](#)
65 [et al. \(2016\)](#) and [McEvoy et al. \(2016\)](#) came up with the Evaporative Demand Drought Index (EDDI). For
66 vegetation, in a similar manner as the SPI, SPEI and EDDI, [Zambrano et al. \(2018\)](#) proposed the zcNDVI,
67 a standardized anomaly of the cumulative Normalized Difference Vegetation Index (NDVI), which could
68 be accumulated over the growing season or any period (e.g., months), resulting in a multiscalar drought
69 index. For soil moisture, several drought indices exist, such as the Soil Moisture Deficit Index (SDMI)
70 a normalized index ([Narasimhan and Srinivasan, 2005](#)) and the Soil Moisture Agricultural Drought Index
71 (SMADI) ([Souza et al., 2021](#)) which is a normalized index using vegetation, land surface temperature, and a
72 vegetation condition index (VCI, ([Kogan, 1995](#))). From TWS, we can estimate the standardized terrestrial
73 water storage index (STI) ([Cui et al., 2021](#)), a standardized anomaly that follows the methodology of the
74 SPI, SPEI, EDDI, and zcNDVI. Thereby, we have drought indices for water supply, demand, and storage,
75 which can help to make a comprehensive assessment of drought.

76 In this research, we present the raster dataset DDS4Chl, which provides climate variables and drought
77 indices of water demand and supply and vegetation productivity for continental Chile since 1981 at a
78 monthly frequency. Those were gathered from the earth observation products ERA5L and MODIS. Then,
79 we used DDS4Chl to analyze the impact of drought on different types of land cover classes in continental
80 Chile. The specific objectives of the study are: i) to analyze the trend on multi-scalar drought indices
81 for water demand and supply, soil moisture, and vegetation productivity for 1981–2023/2001–2023; ii) to
82 evaluate LULC change for 2001–2021 and its relation to drought indices; iii) to analyze the relationship of
83 a proxy of vegetation productivity (zcNDVI) with drought indices of water demand and supply and soil
84 moisture; and iv) to assess if the observed changes in the drought indices are linked to TWS.

85 2. Study area

86 Continental Chile has a diverse climate condition from north to south and east to west ([Aceituno et al.,](#)
87 [2021](#)) ([Figure 1](#)), which determines its great ecosystem diversity ([Figure 2](#)). The Andes Mountains are a
88 main factor in latitudinal variation ([Garreaud, 2009](#)). To describe the climate and ecosystem of Chile, we
89 use the Koppen-Geiger release by [Beck et al. \(2023\)](#) and the landcover type persistance of 80% of times
90 for 2001–2022, from the IGBP classification scheme ([Friedl and Sulla-Menashe, 2019](#)) (see [Section 3.4](#)).
91 “Norte Grande” and “Norte Chico” predominate in an arid desert climate with hot (Bwh) and cold (Bwk)
92 temperatures. At the south of “Norte Chico,” the climate changes to an arid steppe with cold temperatures
93 (Bsk). Mainly, the land is barren, with a minor surface of vegetation types such as shrubland and grassland.
94 In the zones “Centro” and the north half of “Sur,” the main climate is Mediterranean, with warmer to hot
95 summers (Csa and Csb). In “Centro,” there is a major proportion (~50%) of Chilean matorral (shrubland
96 and savanna, ([Fuentes et al., 2021](#))), followed by grassland (~16%), forest (8%), and croplands (5%). The
97 south part of “Sur” and the north part of “Austral” are dominated by an Oceanic climate (Cfb). Those zones
98 are high in forest and grassland. The southern part of the country has a tundra climate, and in Patagonia,
99 it is a cold semi-arid area with an extended surface of grassland, forest, and, to a lesser extent, savanna.

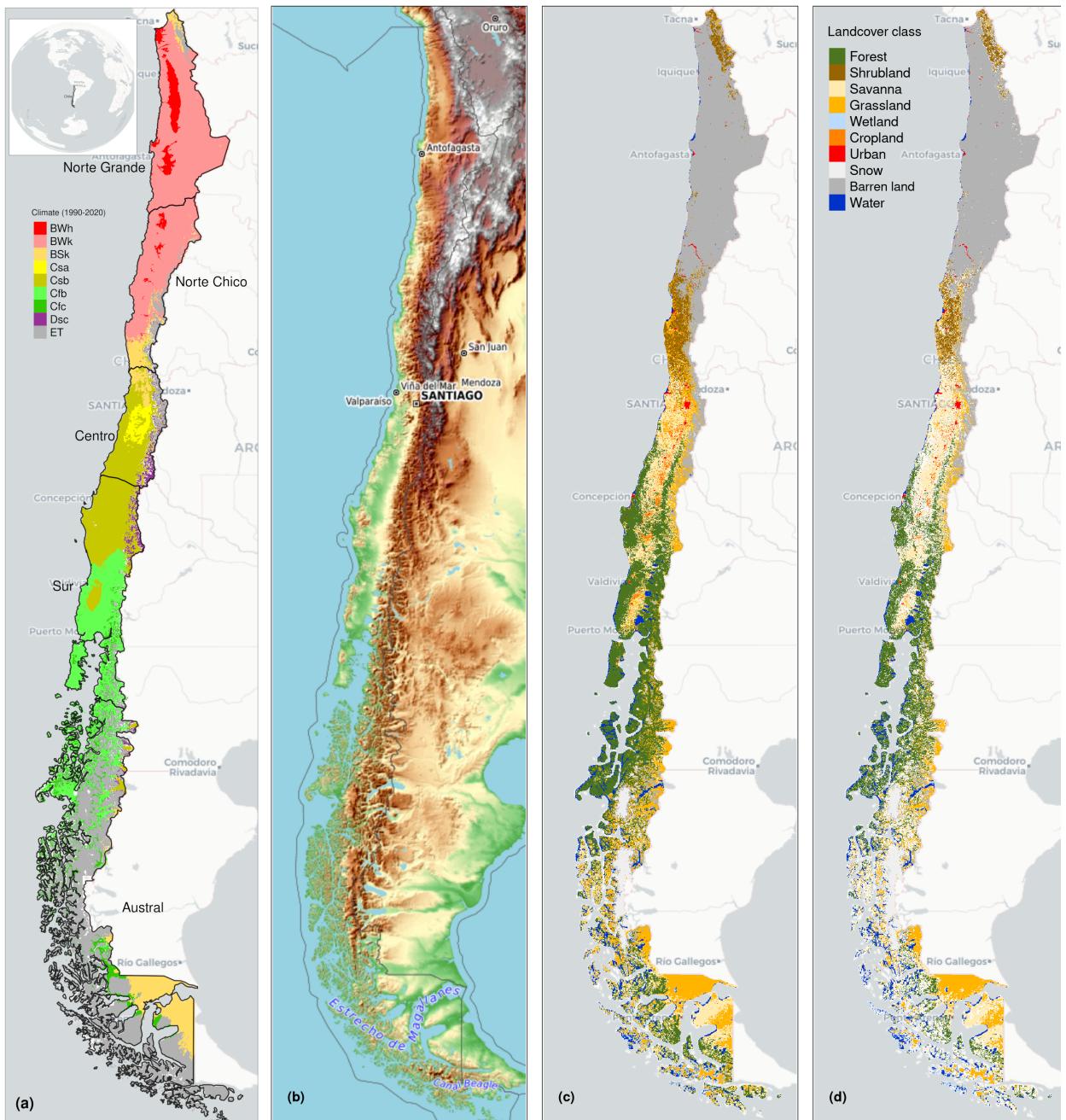


Figure 1: (a) Chile with the Koppen-Geiger climate classes and the five macrozones “Norte Grande”, “Norte Chico”, “Centro”, “Sur”, and “Austral”. (b) Topography reference map. (c) Land cover classes for 2022. (d) Persistent land cover classes (> 80%) for 2001-2022

100 3. Materials and Methods

101 3.1. Software and packages used

102 For the downloading, processing, and analysis of the spatio-temporal data, we used the open source software
 103 for statistical computing and graphics, R ([R Core Team, 2023](#)). For downloading ERA5L, we used the

¹⁰⁴ `{ecmwfr}` package (Hufkens et al., 2019). For processing raster data, we used `{terra}` (Hijmans, 2023) and
¹⁰⁵ `{stars}` (Pebesma and Bivand, 2023). For managing vectorial data, we used `{sf}` (Pebesma, 2018). For
¹⁰⁶ the calculation of AED, we used `{SPEI}` (Beguería and Vicente-Serrano, 2023).

¹⁰⁷ 3.2. Data

¹⁰⁸ 3.2.1. Earth observation data

¹⁰⁹ For water supply and demand variables, we used ERA5L (Muñoz-Sabater et al., 2021), a reanalys dataset
¹¹⁰ that provides the evolution of land variables since 1950. It has a spatial resolution of 0.1°, hourly frequency,
¹¹¹ and global coverage. We selected the variables for total precipitation, 2 meter temperature maximum and
¹¹² minimum, and volumetric soil water layers between 0 and 100cm of depth (layer 1 to layer 3). The data
¹¹³ was downloaded using the Copernicus Climate Data Store (CDS) Application Program Interface (API)
¹¹⁴ implemented in `{ecmfwr}` (Hufkens et al., 2019).

¹¹⁵ To derive a proxy of vegetation productivity, we used the product MOD13A3 collection 6.1 from MODIS
¹¹⁶ (Didan, 2015). It provides vegetation indices (NDVI and EVI) at 1km of spatial resolution and monthly
¹¹⁷ frequency. The MOD13A3.061 and MCD12Q1.061 were retrieved from the online Data Pool, courtesy of
¹¹⁸ the NASA EOSDIS Land Processes Distributed Active Archive Center (LP DAAC), USGS Earth Resources
¹¹⁹ Observation and Science (EROS) Center, Sioux Falls, South Dakota, <https://lpdaac.usgs.gov/tools/data-pool/>.

Table 1: Description of the earth observation data used

Product	Sub-product	Variable	Spatial Resolution	Period	Units	Short Name
ERA5L		Precipitation	0.1°	1981-2023	mm	P
		Maximum temperature			°C	T _{max}
		Minimum temperature			°C	T _{min}
		Volumetric Soil Water Content at 1m			m3/m3	SM
ERA5L*	MOD13A3.061	Atmospheric Evaporative Demand	0.1°	1981-2023	mm	AED
		Normalized Difference Vegetation Index			1 km	NDVI
MODIS	MCD12Q1.061	Landcover IGBP scheme		2001-2022		Landcover

*Derived from ERA5L with Eq. 1.

¹²¹ 3.2.2. *in-situ* data

¹²² POR COMPLETAR

¹²³ 3.2.3. Validation of ERA5L variables

¹²⁴ POR COMPLETAR

¹²⁵ 3.3. Drought Indices

¹²⁶ 3.3.1. Atmospheric Evaporative Demand (AED)

¹²⁷ For the indices EDDI and SPEI that use water demand, first we have to calculate the AED. For this, we
¹²⁸ used the method of Hargreaves (Hargreaves, 1994; Hargreaves and Samani, 1985):

$$AED = 0.0023 \cdot Ra \cdot (T + 17.8) \cdot (T_{max} - T_{min})^{0.5} \quad (1)$$

129 where Ra ($MJ\ m^2\ day^{-1}$) is extraterrestrial radiation; T , T_{max} , and T_{min} are mean, maximum, and
 130 minimum temperature ($^{\circ}C$). We calculate the centroid coordinates per pixel and use the latitude to estimate
 131 Ra .

132 We chose the method of Hargreaves to estimate AED because of its simplicity, which only requires tem-
 133 peratures and extrarrestrial radiation. Also, it has been recommended over other methods when the use of
 134 several climatic variables is limited (Vicente-Serrano et al., 2014).

135 3.3.2. Non-parametric calculation of drought indices

136 We derived the drought indices of water supply and demand, soil moisture from the ERA5L dataset, and
 137 vegetation from the MODIS product, all at monthly frequency.

138 To evaluate water demand, we chose the *EDDI* (Hobbins et al., 2016; McEvoy et al., 2016) index, which
 139 uses the *AED*. For supply, we used the index recommended by the World Meteorological Organization
 140 (WMO) for monitoring drought, the *SPI* (McKee et al., 1993). We calculated the *SPEI*, which used a
 141 balance between P and *AED*, in this case, an auxiliary variable $D = P - AED$ is used. In this study,
 142 we used the *SSI* (standardized soil moisture index at 1 m) (Hao and AghaKouchak, 2013; AghaKouchak,
 143 2014), which uses soil moisture at 1m depth. Finally, for the proxy of productivity, *zcNDVI*, we used the
 144 NDVI. Before using the NDVI, it was smoothed using a locally-weighted polynomial regression, following
 145 the procedure described in Zambrano et al. (2018) and Zambrano et al. (2016).

146 All the indices are multi-scalar and were calculated for time scales of 1, 3, 6, 12, 24, and 36 months, except
 147 for *zcNDVI*, which was calculated for 6 months. The goal is to be able to evaluate short- and long-term
 148 droughts in water demand and supply and soil moisture. This is particularly important for central Chile
 149 because it has suffered from a prolonged decrease in precipitation for more than 12 years (Garreaud et al.,
 150 2020; Boisier et al., 2018; Garreaud et al., 2017).

151 To calculate the drought indices, first we must calculate the accumulation of the variable. In this case, for
 152 generalization purposes, we will use V , referring to P , *AED*, D , *NDVI*, and *SM* (Table 1). We cumulated
 153 each V over the time series of n values, and for the time scales s :

$$154 \quad A_{si} = \sum_{i=n-s-i+2}^{n-i+1} V_i \quad \forall i \geq n-s+1 \quad (2)$$

155 It corresponds to a moving window (convolution) that sums the variable for s starting for the last month
 156 n until the month, which could sum for s months ($n-s+1$). Once the variable is cumulated over time
 157 for the scale s , we used a nonparametric approach following Hobbins et al. (2016) to derive the drought
 158 indices. Thus, the empirically derived probabilities are obtained through an inverse normal approximation
 159 (Abramowitz and Stegun, 1968). Then, we used the empirical Tukey plotting position (Wilks, 2011) over
 A_i to derive the $P(A_i)$ probabilities across a period of interest:

$$160 \quad P(A_i) = \frac{i - 0.33}{n + 0.33'} \quad (3)$$

161 The drought indices *SPI*, *SPEI*, *EDDI*, *SSI*, and *zcNDVI* are obtained following the inverse normal
 approximation:

$$162 \quad DI(A_i) = W - \frac{C_0 + C_1 \cdot W + c_2 \cdot W^2}{1 + d_1 \cdot W + d_2 \cdot W^2 + d_3 \cdot W^3} \quad (4)$$

163 DI is referring to the drought index calculated for the variable V . The values for the constats are:
 $C_0 = 2.515517$, $C_1 = 0.802853$, $C_2 = 0.010328$, $d_1 = 1.432788$, $d_2 = 0.189269$, and $d_3 = 0.001308$. For

¹⁶⁴ $P(A) \leq 0.5$, $W = \sqrt{-2 \cdot \ln(P(A_i))}$, and for $P(A_i) > 0.5$, replace $P(A_i)$ with $1 - P(A_i)$ and reverse the sign
¹⁶⁵ of $DI(A_i)$.

¹⁶⁶ *3.4. LULC change for 2001-2022 and its relation with water supply and demand, and soil moisture*

¹⁶⁷ *3.4.1. Landcover macroclases and validation*

¹⁶⁸ To analyze the LULCC, we use the IGBP scheme from the MCD12Q1 collection 6.1 from MODIS. This
¹⁶⁹ product has a yearly frequency from 2001 to 2022. The IGBP defines 17 classes; from these, we regrouped
¹⁷⁰ into ten macroclasses, as follows: classes 1-4 to forest, 5-7 to shrublands, 8-9 to savannas, 10 as grasslands,
¹⁷¹ 11 as wetlands, 12 and 14 to croplands, 13 as urban, 15 as snow and ice, 16 as barren, and 17 to water
¹⁷² bodies. Thus, we have a landcover raster time-series with the ten classes for 2001 and 2023.

¹⁷³ To validate the landcover obtained, we compare the macroclasses with the ones of a more detailed landcover
¹⁷⁴ map made by [Zhao et al. \(2016\)](#) for Chile with samples acquired in the years 2013–2014 (LCChile). The
¹⁷⁵ later has a spatial resolution of 30 m and three levels of defined classes; from those, we used level 1, which
¹⁷⁶ fits with the macroclasses landcover. We chose the years 2013 (IGBP2013) and 2014 (IGBP2014) from
¹⁷⁷ landcover macrolcasses to validate with LCChile.

¹⁷⁸ We follow the next procedure:

- ¹⁷⁹ i) resampled LCChile to the spatial resolution (500m) of the landcover macroclasses using the nearest
¹⁸⁰ neighbor method,
- ¹⁸¹ ii) took a random sample of 1000 points within continental Chile and extracted the classes that fell within
¹⁸² each point for LCChile, IGBP2013, and IGBP2014; we considered the point extracted from LCChile
¹⁸³ as the truth and the values as the other two years as prediction
- ¹⁸⁴ iii) calculate a confusion matrix with the classes extracted in the 1000 poitns for LCChile, IGBP2013, and
¹⁸⁵ IGBP2014. Calculate the performance metrics of accuracy and F1.

$$\text{Accuracy} = \frac{TP + TN}{TP + TN + FP + FN} = \frac{\text{correct classifications}}{\text{all classifications}}$$

$$F1 = \frac{2 \cdot TP}{2 \cdot TP + FP + FN}$$

¹⁸⁶ where TP and FN refer to true positive and false negative, correctly classified classes; TN and FP to true
¹⁸⁷ negative and false positive, wrongly classified classes.

¹⁸⁹ *3.4.2. Landcover persistence mask 2001-2022*

¹⁹⁰ The time series of NDVI is affected by climatic conditions, vegetation development, seasonality, and changes
¹⁹¹ in vegetation type. In this study, we want to analyze the variation in vegetation productivity in different
¹⁹² landcover types and how it is affected by water demand, water supply, and soil moisture. In order to avoid
¹⁹³ changes due to a change in the landcover type, that will wrongly impact NDVI. We will develop a persistence
¹⁹⁴ mask for landcover for 2001–2023. Thereby, we reduce an important source of variation on a regional scale.

¹⁹⁵ Thus, we calculated a raster mask for IGBP MODIS considering the macroclasses that remain without
¹⁹⁶ change for more than 80% of the years (2001–2022) per pixel, which allows us to identify the areas with no
¹⁹⁷ landcover change for the macroclasses.

198 3.4.3. Landcover trend and drought indices

199 We calculated the surface occupied per landcover class into the five macrozones (“Norte Grande” to “Austral”) per year for 2001–2023. After that, we calculated the trend’s change in surface; we used the Sen’s
200 slope (Sen, 1968) based on Mann-Kendall (Kendall, 1975). This way, we obtain a matrix of trends of 5 x
201 5 (macrozones x landcover). The aim is to later explore if the trend in landcover classes is associated with
202 a trend in the drought indices. For this, we will use the techniques of regression and regularization of Lasso
203 (Tibshirani et al., 2010) and Ridge (Hoerl and Kennard, 1970). Also, we will test random forests for this
204 purpose (Ho, 1995). We will choose the trend of landcover surface per macroclass and macrozone as the
205 response variable and the trend of the drought indices (SPI, SPEI, EDDI, and SSI for time scales 1, 3, 6,
206 12, 24, and 36 months) as the predictor variables. With this analysis, we expect to gather insights regarding
207 whether there is a pattern of climatic influence along Chile or if what is happening in Central Chile has to
208 do with more localized climatic conditions.
209

210 3.5. Trend of drought indices for water demand and supply, soil moisture, and vegetation productivity

211 3.5.1. Mann-Kendall and Sen’s slope

212 To estimate if there are significant positive or negative trends for the drought indices, we used the non-
213 parametric test of Mann-Kendall (Kendall, 1975). To determine the magnitude of the trend, we used Sen’s
214 slope (Sen, 1968). Some of the advantages of applying this methodology are that the Sen’s slope is not
215 affected by outliers as regular regression does, and it is a non-parametric method that is not affected by the
216 distribution of the data. We applied both to the six time scales from 1981 to 2023 (monthly frequency) and
217 the indices SPI, EDDI, SPEI, and SSI. In the case of zcNDVI (six months) was for 2000 to 2023. Thus,
218 we have 31 trends. Also, we extracted the trend aggregated by macrozone and landcover class, obtaining a
219 table of 31x5x5 (drought indices trends x macrozone x landcover class). We will use this data in Section 3.4
220 to analyze if there is a strong relationship between the trends of drought indices and land cover surface
221 within continental Chile.

222 3.5.2. Trend in vegetation productivity without landcover change

223 Vicente-Serrano et al. (2022) made a global analysis of the drought’s severity trend using SPI, SPEI, and
224 the Standardized Evapotranspiration Deficit Index (SEDI; Vicente-Serrano et al. (2018)) to evaluate AED.
225 They indicate that the increase in hydrological drought has been due to anthropogenic effects rather than
226 climate change. This is because the global increase in AED did not explain the change in the spatial pattern
227 of the hydrological drought. Also, they state that “*the increase in hydrological droughts has been primarily
228 observed in regions with high water demand and land cover change*”. We will contrast this hypothesis with
229 what is occurring in Chile. To achieve this, we will use the landcover class type that remains more than
230 80% of types for 2001–2022 to evaluate the trend on zcNDVI and use this as a mask where there are low
231 changes.

232 3.6. Impact for water supply and demand, and soil moisture in vegetation productivity within landcover types

233 The aim of this section is to analyze the drought indices of water demand and supply and soil moisture
234 against vegetation to address: i) if short- or long-term time scales are most important in impacting vegetation
235 through Chile; and ii) the strength of the correlation for the variable and the time scale. Then, we will
236 summarize for each landcover class and macrozone. Thus, we will be able to advance in understanding how
237 climate is affecting vegetation, considering the impact on the five macroclasses: forest, cropland, grassland,
238 savanna, and shrubland.

239 To assess how water demand and supply and soil moisture are related to vegetation productivity (zcNDVI),
240 we analyze the linear correlation between the indices SPI, SPEI, EDDI, and SSI for 1, 3, 6, 12, 24, and
241 36-month time scales against zcNDVI. We followed a similar approach to that used by Meroni et al. (2017)

242 when using the SPI for meteorological drought against the cumulative FAPAR (Fraction of Absorbed Photo-
 243 synthetically Active Radiation) as a proxy for vegetation productivity. We made a pixel-to-pixel linear
 244 correlation analysis per index. First, we calculate the Pearson coefficient of correlation for the six time scales
 245 and let the time scale that reaches the maximum correlation be significant ($p < 0.05$). Then, we extracted
 246 the Pearson correlation value corresponding to the time scales that reached the maximum value. Thus, we
 247 derived two raster maps per index, the first with the time scales and the second with the correlation value.

248 4. Results

249 4.1. Data

250 4.1.1. Validation of ERA5L variables

251 4.2. LULC change for 2001-2022 and its relation with water supply and demand, and soil moisture

252 4.2.1. Landcover macroclasses and validation

253 The validation of IGBP2013 and IGBP2014 with LCChile reached similar metrics of performance, having
 254 an accuracy of 0.82 and a F1 score of 0.66 (see SS1).

255 4.2.2. Landcover persistence mask 2001-2022

256 The macrozones with major LULCC for 2001-2022 were “Centro”, “Sur”, and “Austral” with 36%, 31%,
 257 and 34%, respectively (Figure 1 and Table 2)

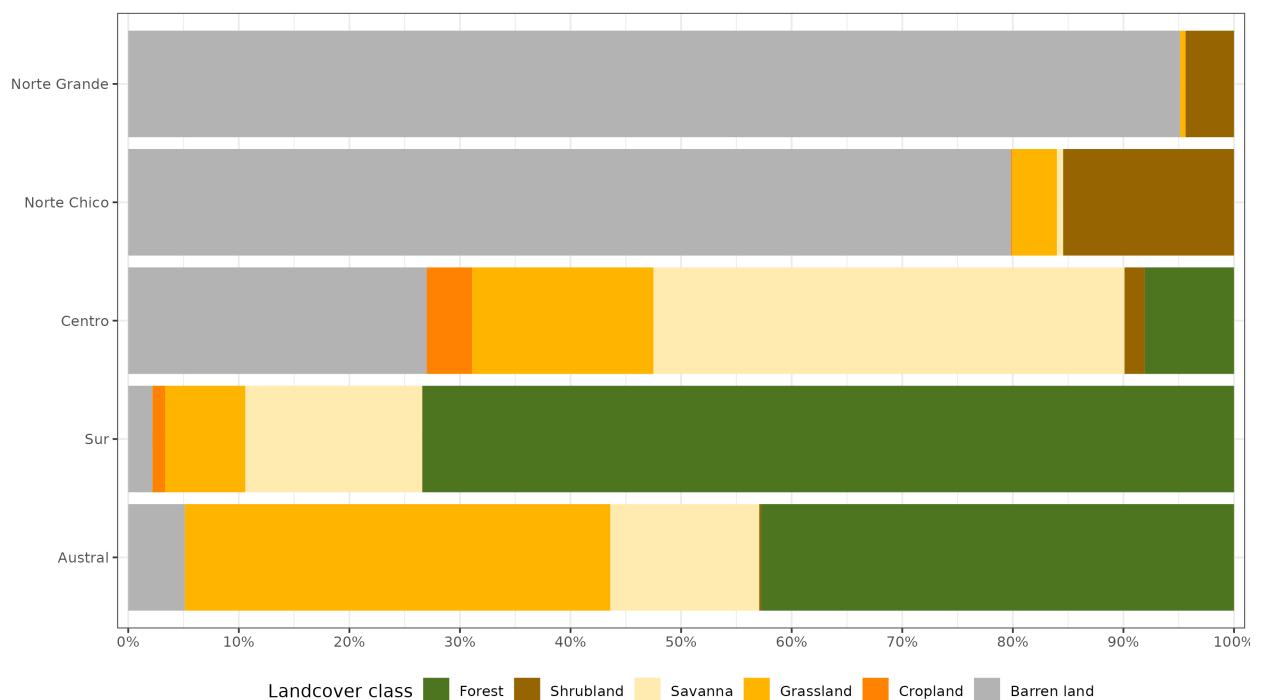
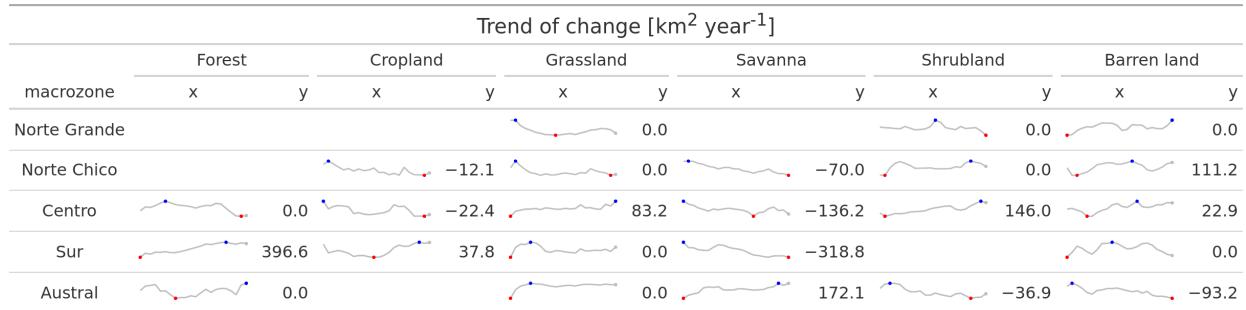


Figure 2: Proportion of land cover class from the persistent land cover for 2001-2022 (>80%) per macrozone

258 Figure 2 shows the summary of the proportion of surface per landcover class and macrozone, derived from
 259 the mask over continental Chile.

260 4.2.3. Landcover trend and drought indices

Table 2: The value of Sen’s slope trend next to the time-series plot of surface per landcover class (IGBP MCD12Q1.016) for 2001–2022 through Central Chile. Values of zero indicate that there was not a significant trend. Red dots on the plots indicate the maximum and minimum values of surface.



261 The “Norte Chico” shows an increase in barrend land of $111 \text{ km}^2 \text{year}^{-1}$ and a reduction in the class savanna
 262 $-70 \text{ km}^2 \text{year}^{-1}$. In the “Centro” and “Sur” there are changes in the Chilean matorral, with an important
 263 reduction in savanna (-136 to $-318 \text{ km}^2 \text{yr}^{-1}$), and an increase in shrubland and grassland. Showing a change
 264 for more dense vegetation types. It appears to be a change from the surface occupied by cropland from the
 265 “Centro” to the “Sur.” Also, there is a high increase in forest ($397 \text{ km}^2 \text{yr}^{-1}$) in the “Sur,” replacing the
 266 savanna lost.

267 4.3. Trend of drought indices for water demand and supply, soil moisture, and vegetation productivity

268 Regarding vegetation productivity aggregated through the macrozones in the five landcover macroclasses.
 269 In “Norte Grande” there is a increase trend of 0.02 (z-index) per decade, related with types of grassland
 270 and shrubland. There is a negative trend in “Norte Chico” with -0.04 and “Centro” with -0.02 per decade.
 271 In the “Norte Chico,” savanna (-0.05) has the lowest trend, and the rest of the types are around -0.04. In
 272 “Centro,” shrubland reaches -0.06, followed by grassland with -0.05, and croplands and savanna have ~ 0.01
 273 per decade. This could be associated either with a reduction in vegetation surface, a decrease in biomass,
 274 or browning (Miranda et al., 2023). Vegetation reached its lowest values since the year 2019, reaching an
 275 extreme condition in early 2020 and 2022 in the “Norte Chico” and Centro” (Mega Drought). The “Sur”
 276 and “Austral” show a positive trend of around 0.016 per decade (Figure 3). The area most affected by a
 277 negative trend in vegetation seems to be associated with the Chilean matorral (Fuentes et al., 2021), despite
 278 the croplands being as severely impacted by drought as native vegetation does in “Norte Chico.”

279 Analyzing the water supply, the macrozones that have the lowest trend are “Norte Chico” and “Centro,”
 280 where the SPI, SPEI, and SSI show that it decreases at longer time scales due to the prolonged reduction in
 281 precipitation. At 36 months, it reaches trends between -0.03 and -0.04 (z-score) per decade for SPI, SPEI,
 282 and SSI (Figure 4). For “Sur,” the behavior is similar, decreasing at longer scales and having between -0.016
 283 and -0.025 per decade for SPI, SPEI, and SSI. On the other hand, all macrozones show an increase in the
 284 trend in all the drought indices, with “Norte Grande” having the highest at 36 months (0.042 per decade).
 285 Because of this, the SPEI (which uses AED) reached its lowest value in “Norte Grande,” with -0.03 at 36
 286 months. Despite the other macrozones, “Austral” showed an increase in all indices, being the highest for
 287 EDDI at 36 months (0.025) and the lowest for SSI, which shows only a minor increase in the trend (Figure 4).

288 4.4. Impact for water supply and demand, and soil moisture in vegetation productivity

289 According to what is shown in Figure 5, Figure 6, and Table 3, forest seems to be the most resistant
 290 type to drought. Showing that only “Centro” is slightly ($\text{rsq} = 0.25$) impacted by a 12-month soil moisture
 291 deficit (SSI-12). Grasslands are shown to be impacted by a SSI-12 with a $\text{rsq} = 0.45$ and by a decrease in

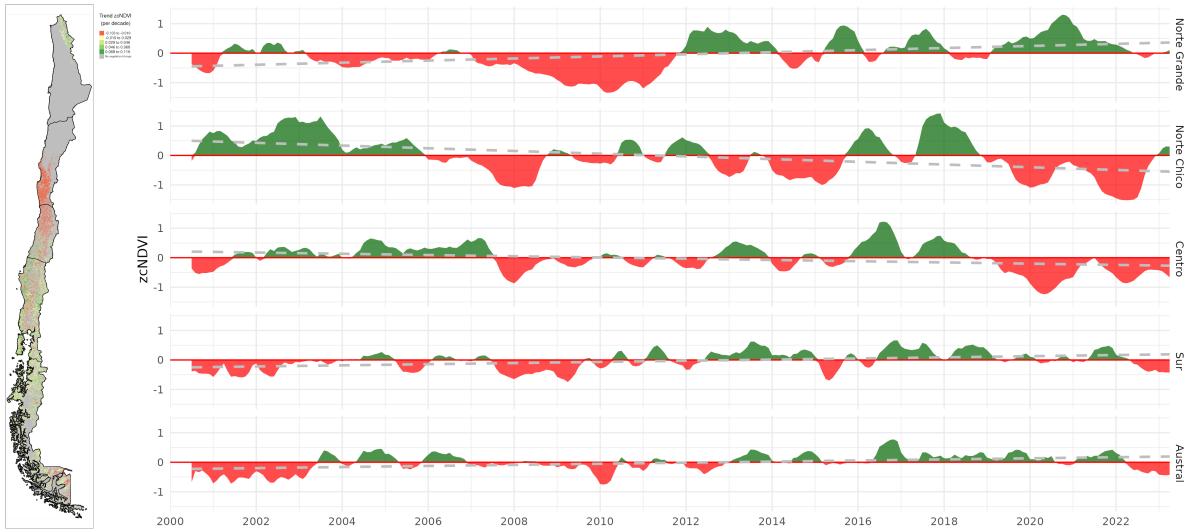
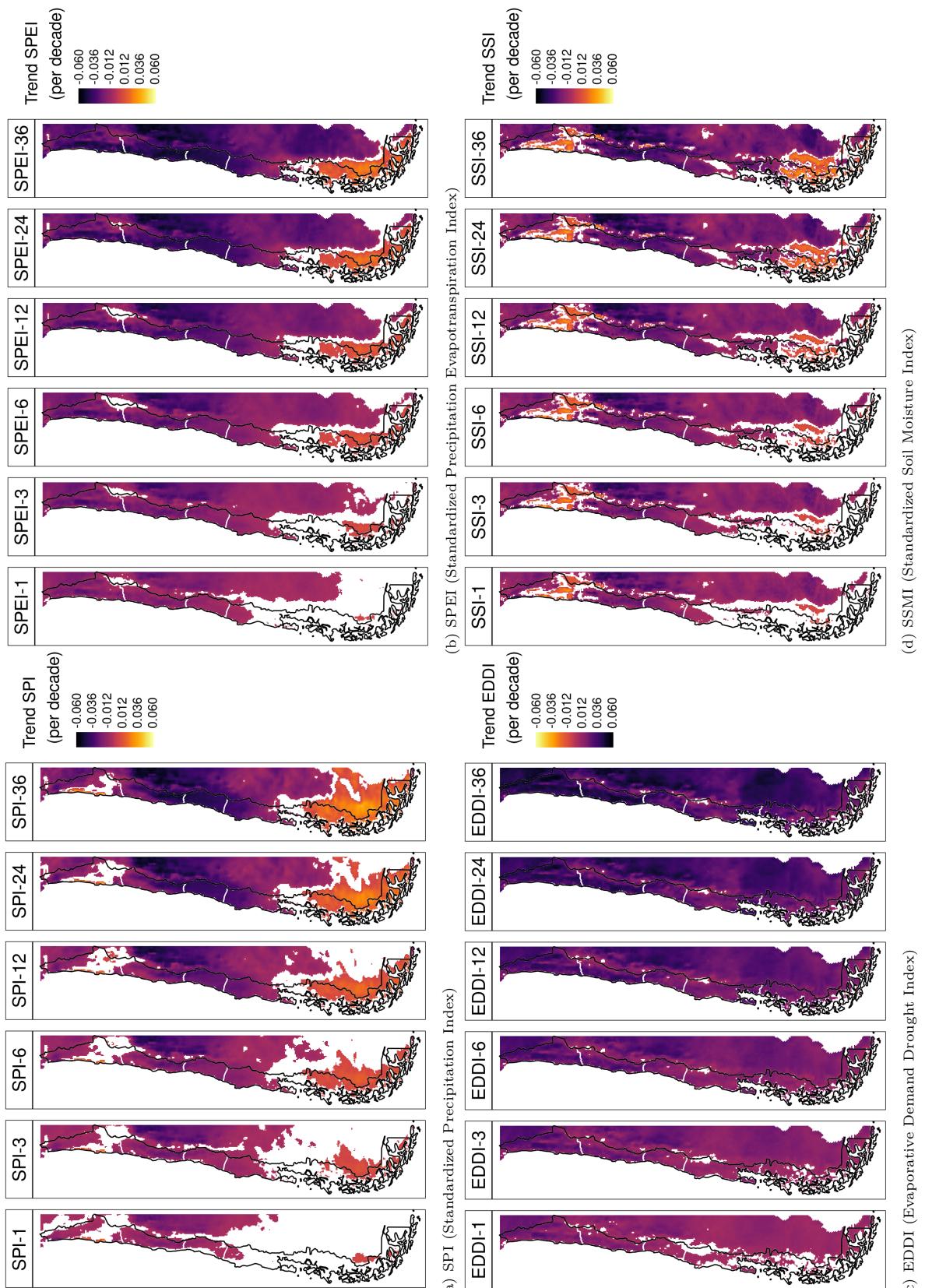


Figure 3: (a) Map of the linear trend of the index zcNDVI-6 for 2001–2023. Greener colors indicate a positive trend; redder colors correspond to a negative trend and a decrease in vegetation productivity. Grey colors indicate either no vegetation or a change in landcover type for 2001–2022. (b) Temporal variation of zcNDVI-6 aggregated at macrozone level within continental Chile. Each horizontal panel corresponds to a macrozone from ‘Norte Grande’ to ‘Austral’.

water supply (SPI-36 and SPEI-24 with $rsq = 0.28$ and 0.34 , respectively) in the “Norte Chico” and to a lesser degree in the “Norte Grande.” But, in further south macrozones, this type was not affected by water demand, water supply, or soil moisture. 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 “Norte Chico.” The most affected type by climatic variation was shrubland, where in “Norte Chico” and “Centro” soil moisture explained 59% and precipitation, 37% , with SSI-12 being the most relevant variable, followed by SPI-36 in “Norte Chico” and SPI-24 in “Sur.”

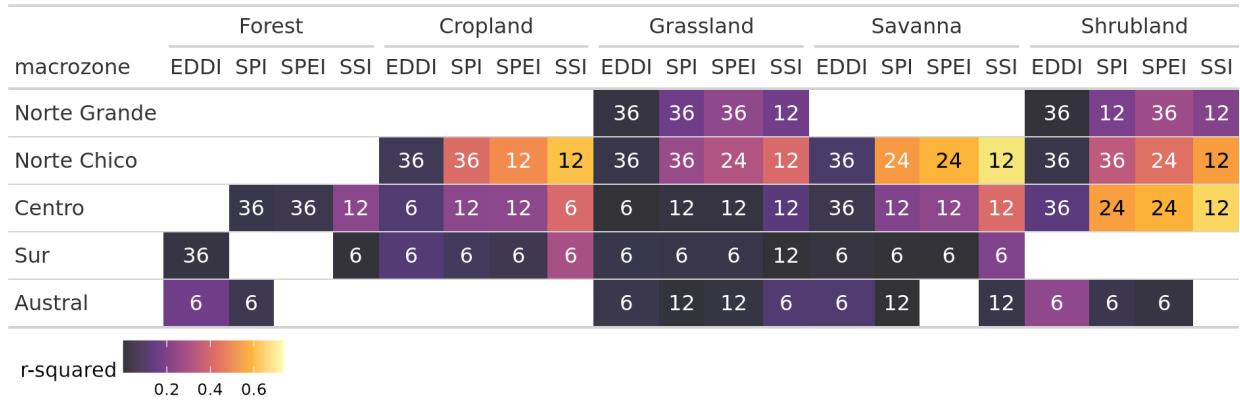


(c) EDDI (Evaporative Demand Drought Index)

(d) SSMI (Standardized Soil Moisture Index)

Figure 4: Linear trend of the drought index (*) at time scales of 1, 3, 6, 12, 24, and 36 months for 1981-2023

Table 3: Summary per landcover macroclass and macrozone regarding the correlation between zcNDVI with the drought indices EDDI, SPI, SPEI, and SSI for time scales of 1, 3, 6, 12, 24, and 36. The numbers in each cell indicate the time scale that reached the maximum correlation for the landcover and macrozone, and the color indicates the strength of the r-squared obtained with the index and the time scale.



302 5. Discussion

303 1.- Respecto a lo que indica [Vicente-Serrano et al. \(2018\)](#), de que el aumento en la tendencia en severidad
 304 de la sequía (hidrológica) tiene que ver más con un aumento de la demanda de agua (LULCC) que a una
 305 tendencia en las condiciones climáticas (SPI-12).

306 2.- Sobre los tipos de landcover más afectados por los indicadores de sequía. Asociación con el matorral
 307 chileno ([Fuentes et al., 2021](#)). Diferencia entre el Norte Chico y Centro y lo que pasa hacia el sur.

308 3. Como podrían servir estos resultados para desarrollar un predictor de sequía basado.

309 4.- Qué se podría hacer mejor en futuras investigaciones del tema.

310 5.- Sequía, aridez, water scarcity ([Van Loon and Van Lanen, 2013](#)) Si puede utilizar el mapa y proyección
 311 climática de Koppen_Geiger ([Beck et al., 2023](#)) para dirigir esta discusión

312 6. Conclusion

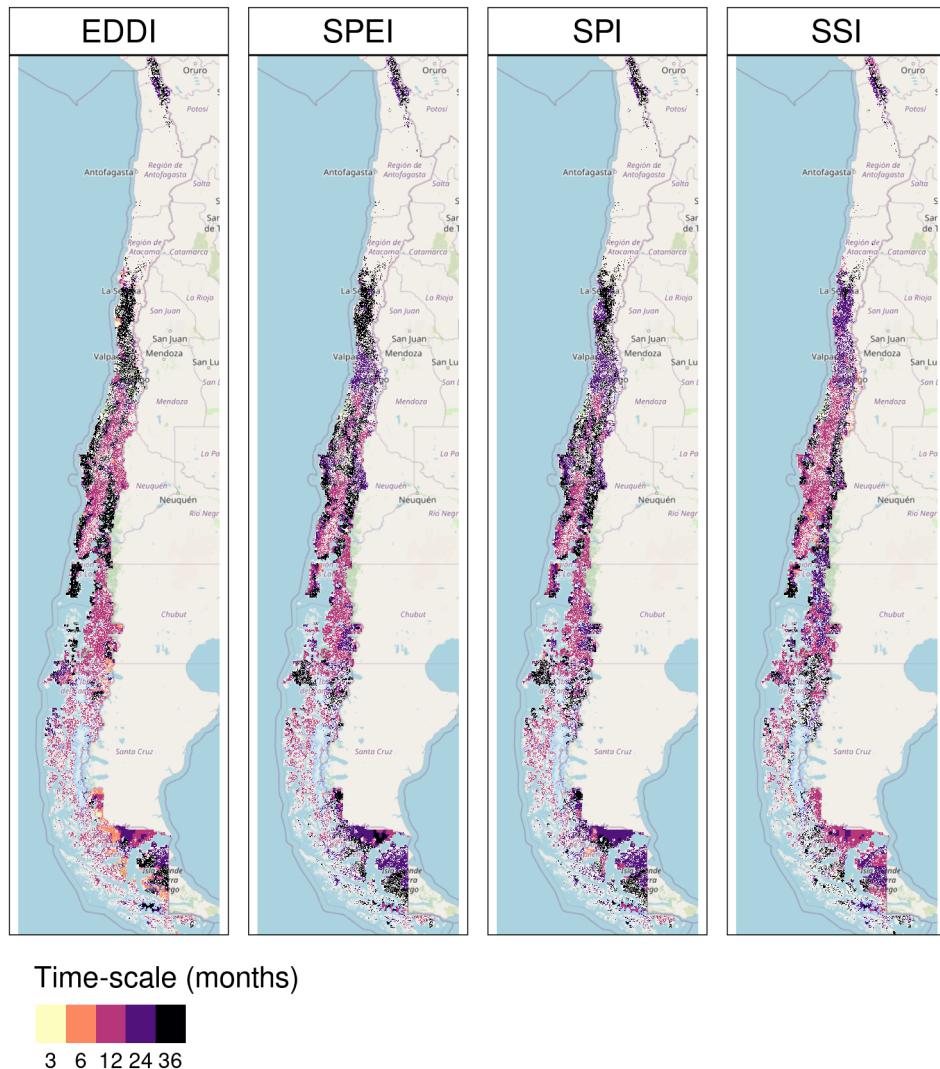


Figure 5: Time scales per drought index that reach the maximum coefficient of determination

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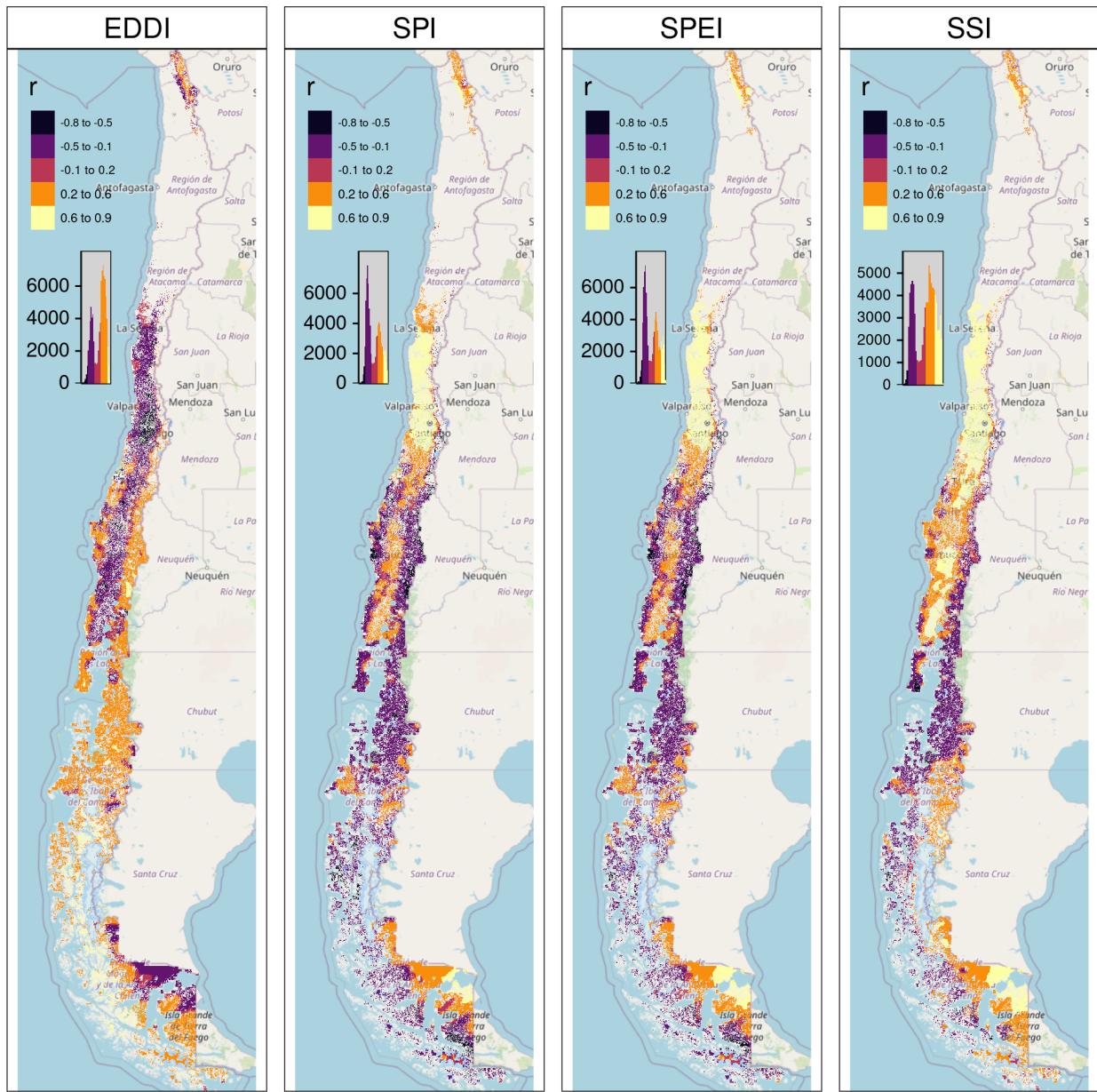


Figure 6: Pearson correlation value for the time scales and drought index that reach the maximum coefficient of determination

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