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

Francisco Zambrano[a,1,*]

[a] *Universidad Mayor, Hémera Centro de Observación de la Tierra, Facultad de Ciencias, Escuela de Ingeniería en Medio Ambiente y Sustentabilidad, Santiago, Chile, 7500994*

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

*Corresponding author
Email address: francisco.zambrano@umayor.cl (Francisco Zambrano)

[1] This is the first author footnote.

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

2. Study area

Continetal Chile has a diverse climate condition from north to south and east to west [43] (Figure 1), which determines its great ecosystem diversity (Figure 2). The Andes Mountains are a main factor in latitudinal variation [44]. To describe the climate and ecosystem of Chile, we use the Koppen-Geiger release by [45] and the landcover type persistance of 80% of times for 2001–2022, from the IGBP classification scheme [31]. "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). Mainly, the land is barren, with a minor 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 warmer to hot summers (Csa and Csb). In "Centro," there is a major proportion (~50%) of chilean matorral (shrubland and savanna), followed by grassland (~16%), forest (8%), and croplands (5%). The south part of "Centro" and the north part of "Austral" are dominated by an Oceanic climate (Cfb). Those zones are high in forest and grassland. The southern part of the country has a tundra climate, and in Patagonia, it is a cold semi-arid area with an extended surface of grassland.

3. Materials and Methods

3.1. Data

3.1.1. Earth observation data

For water supply and demand variabes, we used ERA5-Land [21], 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. 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 [46]. It provides vegetation indices (NDVI and EVI) at 1km of spatial resolution and monthly frequency.

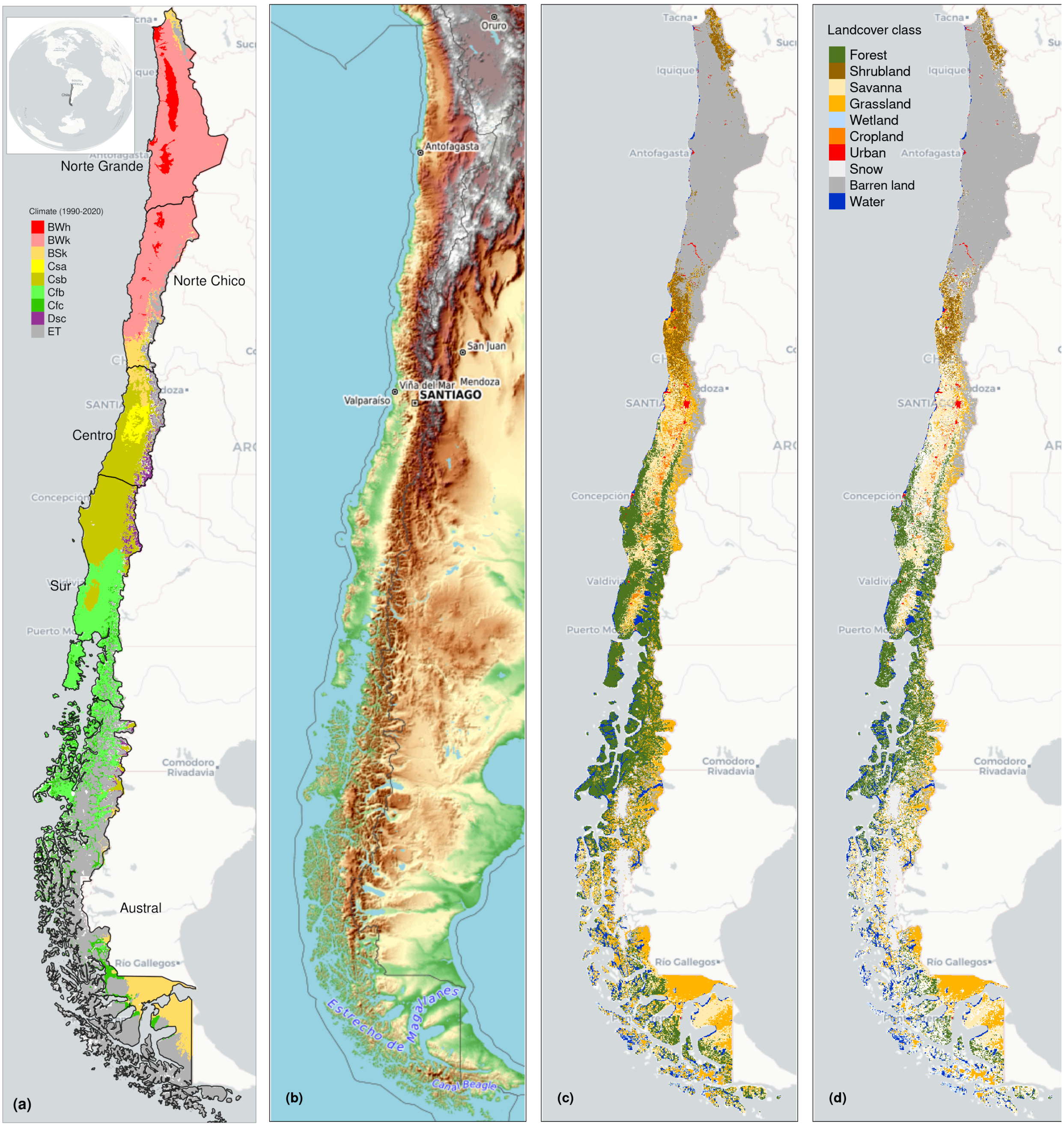

Figure 1: (a) Chile with the Koppen-Geiger climate classes and the five macrozones “Norte Grande”, “Norte Chico”, “Centro”, “Sur”, and “Austral”. (b) Topography reference map. (c) Land cover classes for 2022. (d) Persistent land cover classes (> 80%) for 2001-2022

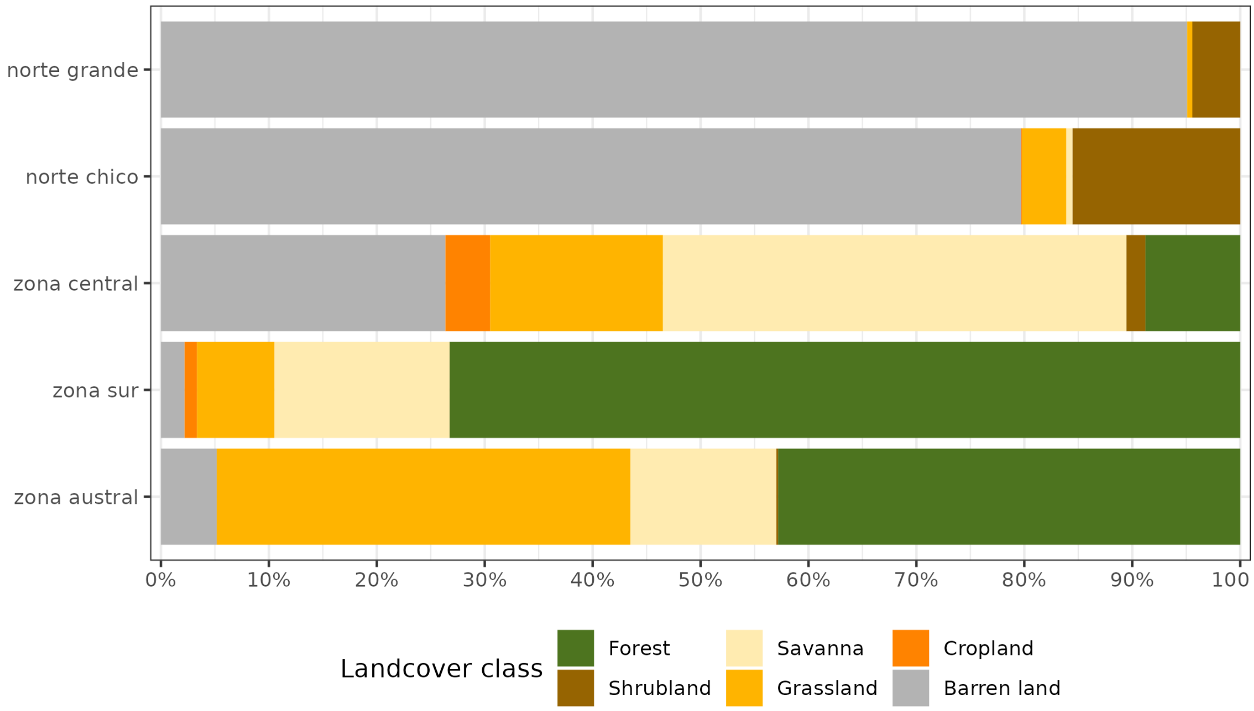

Figure 2: Proportion of land cover class from the persistent land cover for 2001-2021 (>80%) per macrozone

3.1.2. in-situ data

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

3.3. Impact fof water supply and demand, and soil moisture in vegetation productivity within landcover types

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

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 [47, 48]. TWS changes evidence the effects of multiple water fluxes on the hydrological cycle [48]. These are reflected in the temporal variation of observations of the Earth's gravitational field [49, 50] 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 [51, 52]. The GRACE mission was launched in March 2002 and was operational until October 2017 [53]. Then its GRACE Follow-On successor was launched in May 2018 [54, 55]. 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 [47, 56].

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) [53, 55]. This JPL-M version of the data employs a Coastal Resolution Improvement (CRI) filter that reduces signal leakage errors across coastlines [57, 58]. 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 [53, 55]. The water storage and height anomalies are given in Equivalent Water Height or Thickness units (EWH, cm) [50], and their temporal resolution monthly is from April 2002 to May 2023.

3.6. Validation of ERA5-Land variables

4. Results

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

Regarding vegetation productivity, there is a negative trend on zcNDVI in the central part of the country ("norte chico" and "zona central") (Figure 3). 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."

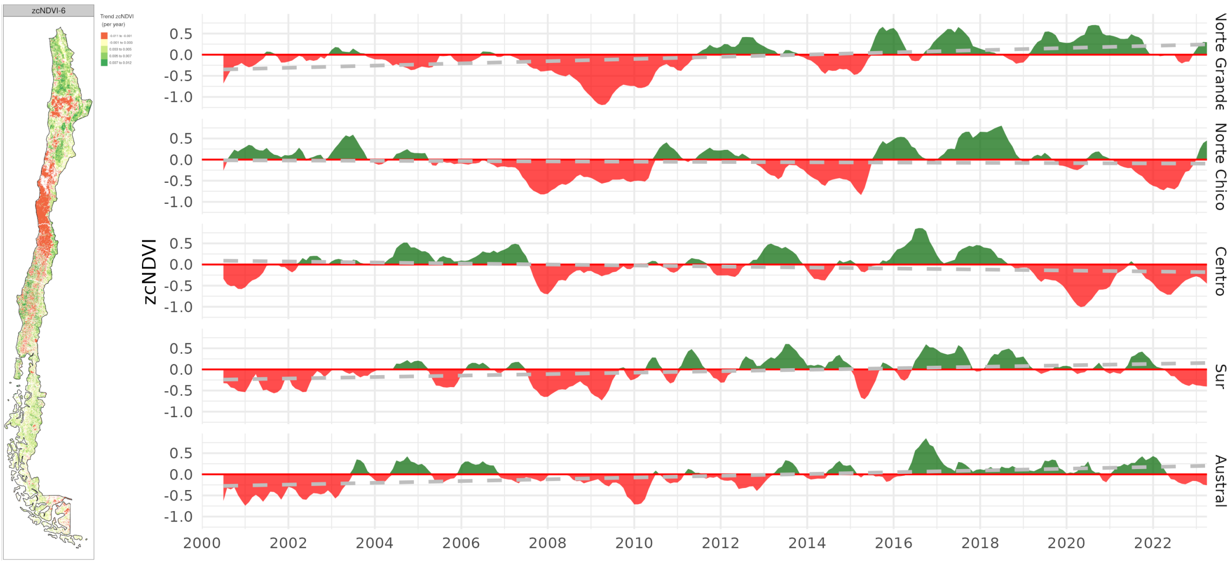

Figure 3: (a) Map of the linear trend of the index zcNDVI-6 for 2001–2023. Greener colors indicate a positive trend and an increase in vegetation development; reder colors correspond to a negative trend and a decrease in vegetation development. (b) Temporal variation of zcNDVI-6 aggregated at macrozone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

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 (Figure 4) 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" (Figure 5). 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 (Figure 6). 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.

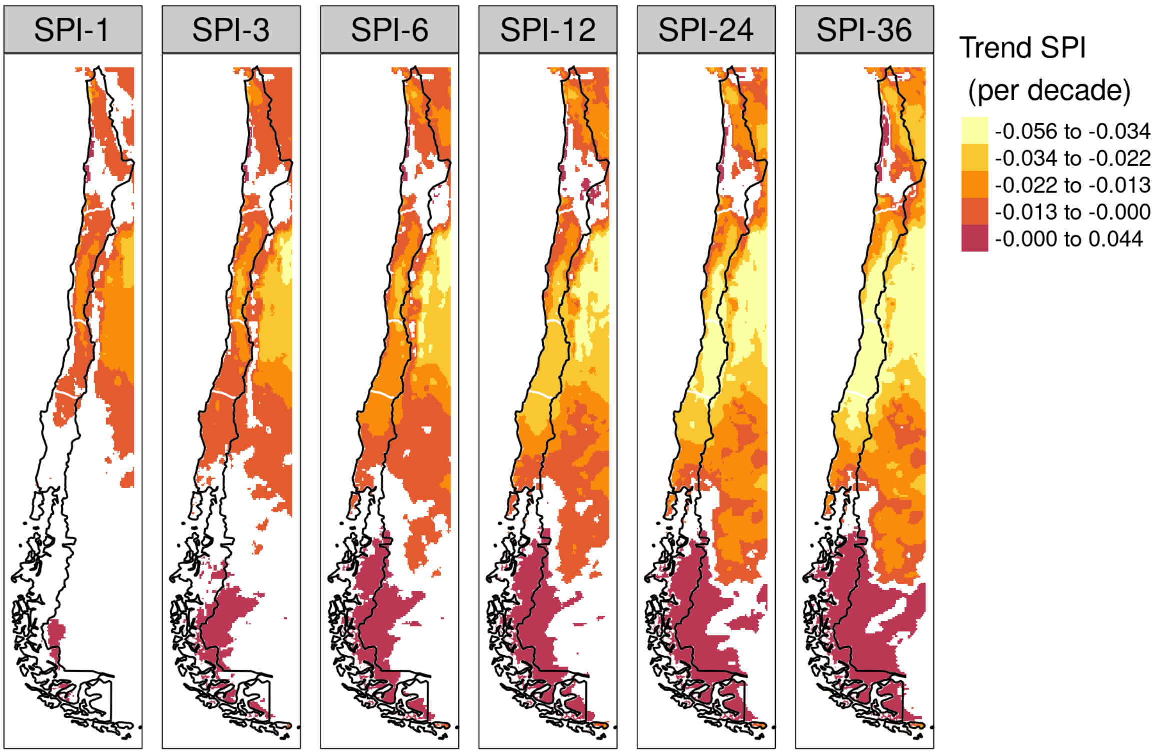

Figure 4: Linear trend of the SPI at time scales of 1, 3, 6, 12, 24, and 36 months for 1981-2023

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

Trend of change [km^2 year^{-1}]												
	Forest		Cropland		Grassland		Savanna		Shrubland		Barren land	
zone	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

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

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

4.4. Total water storage (TWS) and drought indices

4.5. Validation of ERA5-Land variables

5. Discussion

6. Conclusion

References

[1] K. Calvin, D. Dasgupta, G. Krinner, A. Mukherji, P. W. Thorne, C. Trisos, J. Romero, P. Aldunce, K. Barrett, G. Blanco, W. W. Cheung, S. Connors, F. Denton, A. Diongue-Niang, D. Dodman, M. Garschagen, O. Geden, B. Hayward, C. Jones,

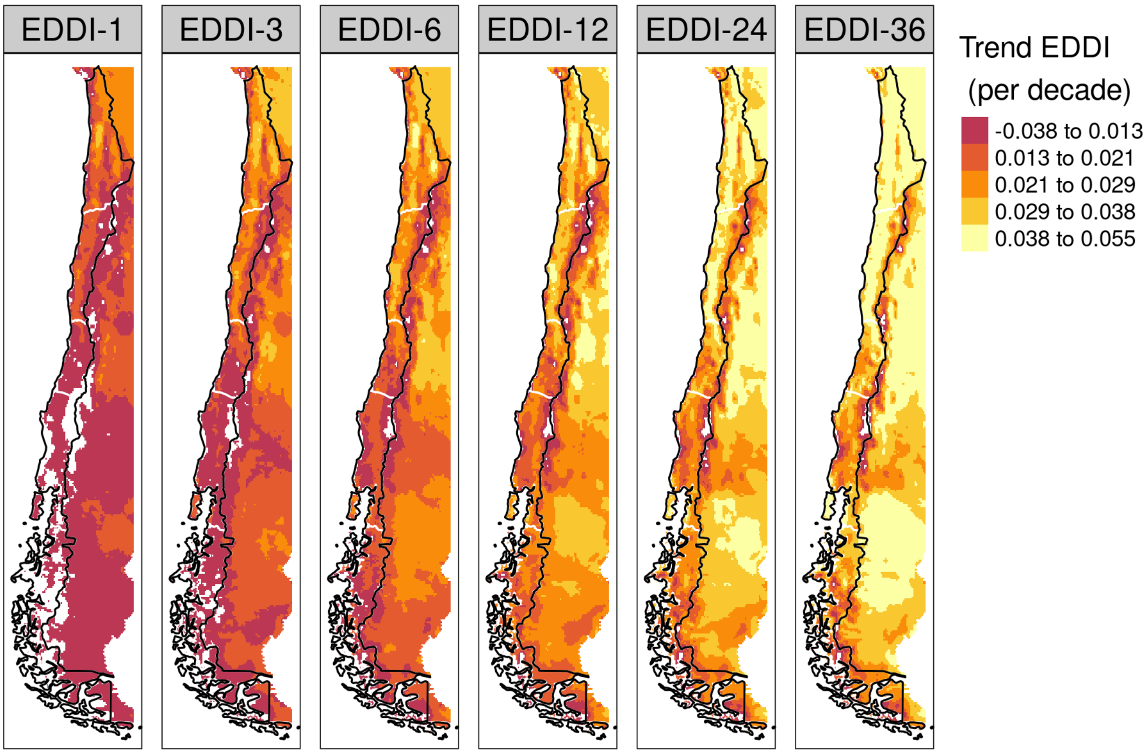

Figure 5: Linear trend of the EDDI at time scales of 1, 3, 6, 12, 24, and 36 months for 1981-2023

Table 2

	Forest				Cropland				Grassland				Savanna				Shrubland			
macro	eddi	spi	spei	zcsm	eddi	spi	spei	zcsm	eddi	spi	spei	zcsm	eddi	spi	spei	zcsm	eddi	spi	spei	zcsm
norte grande									36	36	36	12	36	36	36	24	36	12	36	12
norte chico					36	36	12	12	36	36	24	12	36	24	24	12	36	36	24	12
centro		36	36	12	6	12	12	6	6	12	12	12	36	12	12	12	36	24	24	12
sur	36			6	6	6	6	6	6	6	6	12	6	6	6	6	6	12	12	24
austral	6	6			6	12	12	12	6	12	12	6	6	12		12	6	6	6	

r-squared 0.2 0.4 0.6

F. Jotzo, T. Krug, R. Lasco, Y.-Y. Lee, V. Masson-Delmotte, M. Meinshausen, K. Mintenbeck, A. Mokssit, F. E. Otto, M. Pathak, A. Pirani, E. Poloczanska, H.-O. Pörtner, A. Revi, D. C. Roberts, J. Roy, A. C. Ruane, J. Skea, P. R. Shukla, R. Slade, A. Slangen, Y. Sokona, A. A. Sörensson, M. Tignor, D. Van Vuuren, Y.-M. Wei, H. Winkler, P. Zhai, Z. Zommers, J.-C. Hourcade, F. X. Johnson, S. Pachauri, N. P. Simpson, C. Singh, A. Thomas, E. Totin, P. Arias, M. Bustamante, I. Elgizouli, G. Flato, M. Howden, C. Méndez-Vallejo, J. J. Pereira, R. Pichs-Madruga, S. K. Rose, Y. Saheb, R. Sánchez Rodríguez, D. Ürge Vorsatz, C. Xiao, N. Yassaa, A. Alegría, K. Armour, B. Bednar-Friedl, K. Blok, G. Cissé, F. Dentener, S. Eriksen, E. Fischer, G. Garner, C. Guivarch, M. Haasnoot, G. Hansen, M. Hauser, E. Hawkins, T. Hermans, R. Kopp, N. Leprince-Ringuet, J. Lewis, D. Ley, C. Ludden, L. Niamir, Z. Nicholls, S. Some, S. Szopa, B. Trewin, K.-I. Van Der Wijst, G. Winter, M. Witting, A. Birt, M. Ha, J. Romero, J. Kim, E. F. Haites, Y. Jung, R. Stavins, A. Birt, M. Ha, D. J. A. Orendain, L. Ignon, S. Park, Y. Park, A. Reisinger, D. Cammaramo, A. Fischlin, J. S. Fuglestvedt, G. Hansen, C. Ludden, V. Masson-Delmotte, J. R. Matthews, K. Mintenbeck, A. Pirani, E. Poloczanska, N. Leprince-Ringuet, C. Péan, IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I,

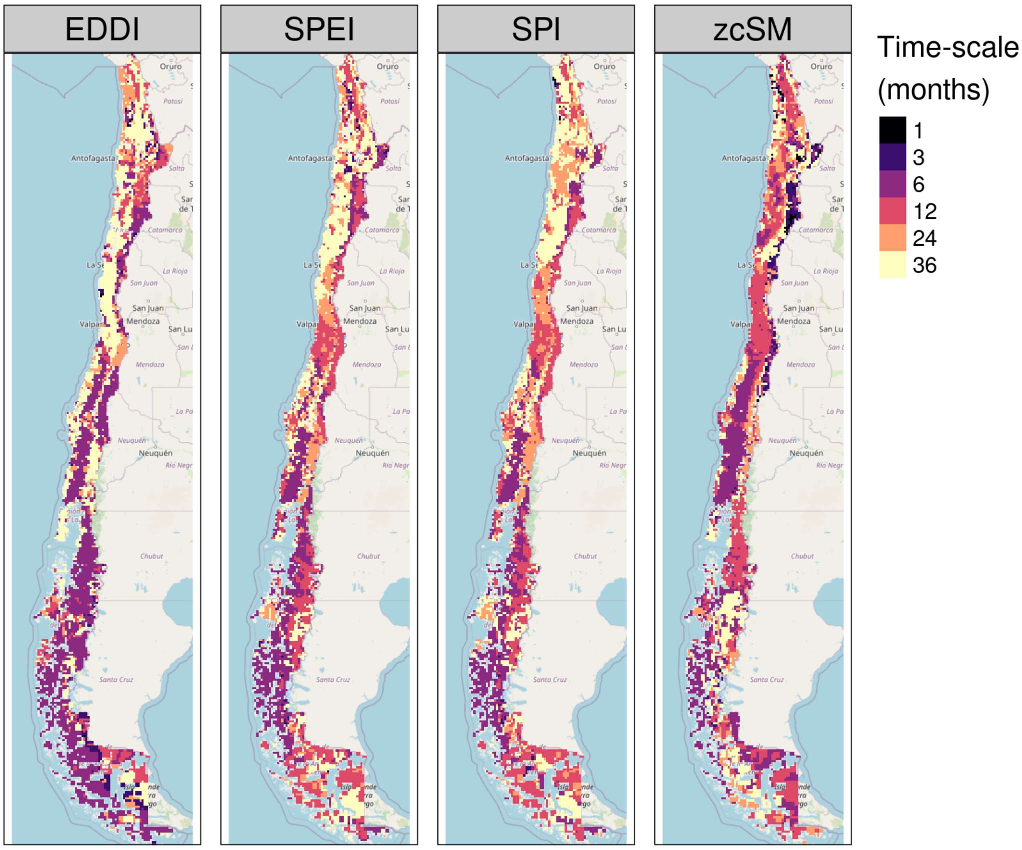

Figure 6: Time scales per drought index that reach the maximum coefficient of determination

II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland., Tech. rep., Intergovernmental Panel on Climate Change (IPCC) (Jul. 2023).
URL https://www.ipcc.ch/report/ar6/syr/

[2] IPCC, Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK; New York, USA, 2013. doi:10.1017/CBO9781107415324.
URL www.climatechange2013.org

[3] X. a. A. M. a. B. W. a. D. C. a. L. A. a. G. S. a. I. I. a. K. J. a. L. S. a. O. F. a. P. I. a. S. M. a. V.-S. S. a. W. M. a. Z. . M.-D. B. a. V. a. O. Seneviratne, S and Zhang, Weather and Climate Extreme Events in a Changing Climate, Cambridge University Press. In Press., 2021, publication Title: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.

[4] S. D. Crausbay, A. R. Ramirez, S. L. Carter, M. S. Cross, K. R. Hall, D. J. Bathke, J. L. Betancourt, S. Colt, A. E. Cravens, M. S. Dalton, J. B. Dunham, L. E. Hay, M. J. Hayes, J. McEvoy, C. A. McNutt, M. A. Moritz, K. H. Nislow, N. Raheem, T. Sanford, Defining Ecological Drought for the Twenty-First Century, Bulletin of the American Meteorological Society 98 (12) (2017) 2543–2550, publisher: American Meteorological Society. doi:10.1175/BAMS-D-16-0292.1.
URL https://journals.ametsoc.org/view/journals/bams/98/12/bams-d-16-0292.1.xml

[5] L. Luo, D. Apps, S. Arcand, H. Xu, M. Pan, M. Hoerling, Contribution of temperature and precipitation anomalies to the California drought during 2012–2015, Geophysical Research Letters 44 (7) (2017) 3184–3192. doi:10.1002/2016GL072027.
URL https://agupubs.onlinelibrary.wiley.com/doi/10.1002/2016GL072027

[6] D. A. Wilhite, M. H. Glantz, Understanding: The drought phenomenon: The role of definitions, Water International 10 (3) (1985) 111–120. doi:10.1080/02508068508686328.
URL http://dx.doi.org/10.1080/02508068508686328

[7] A. F. Van Loon, T. Gleeson, J. Clark, A. I. Van Dijk, K. Stahl, J. Hannaford, G. Di Baldassarre, A. J. Teuling, L. M. Tallaksen, R. Uijlenhoet, D. M. Hannah, J. Sheffield, M. Svoboda, B. Verbeiren, T. Wagener, S. Rangecroft, N. Wanders, H. A. Van Lanen, Drought in the Anthropocene, Nature Geoscience 9 (2) (2016) 89–91. doi:10.1038/ngeo2646.

[8] A. AghaKouchak, A. Mirchi, K. Madani, G. Di Baldassarre, A. Nazemi, A. Alborzi, H. Anjileli, M. Azarderakhsh, F. Chi-

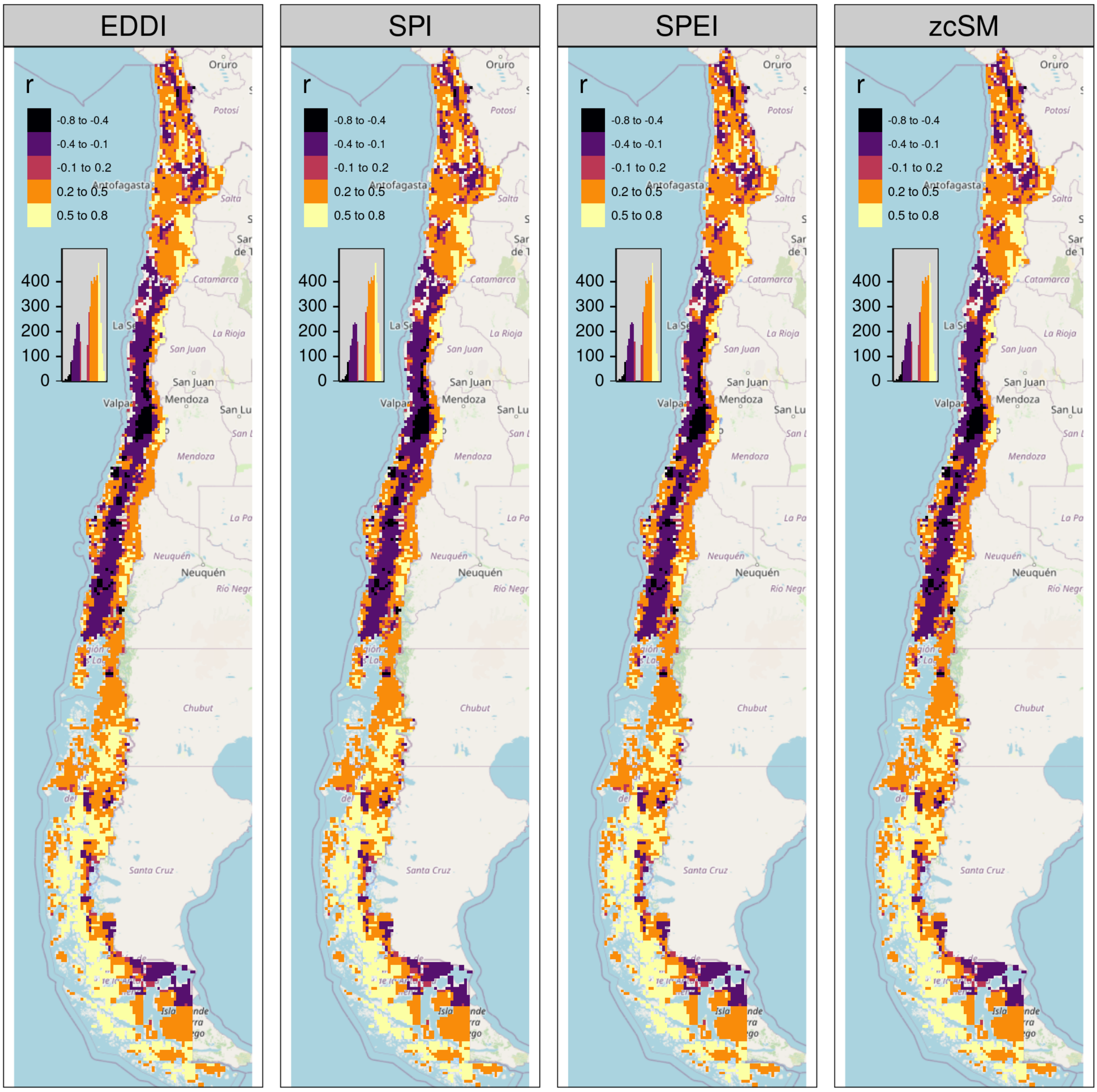

Figure 7: Pearson correlation value for the time scales and drought index that reach the maximum coefficient of determination

ang, E. Hassanzadeh, L. S. Huning, I. Mallakpour, A. Martinez, O. Mazdiyasni, H. Moftakhari, H. Norouzi, M. Sadegh, D. Sadeqi, A. F. Van Loon, N. Wanders, Anthropogenic Drought: Definition, Challenges, and Opportunities, Reviews of Geophysics 59 (2) (2021) e2019RG000683. doi:10.1029/2019RG000683.
URL https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2019RG000683

[9] I. J. Slette, A. K. Post, M. Awad, T. Even, A. Punzalan, S. Williams, M. D. Smith, A. K. Knapp, How ecologists define drought, and why we should do better, Global Change Biology 25 (10) (2019) 3193–3200. doi:10.1111/gcb.14747.
URL https://onlinelibrary.wiley.com/doi/10.1111/gcb.14747

[10] R. Garreaud, C. Alvarez-Garreton, J. Barichivich, J. P. Boisier, D. Christie, M. Galleguillos, C. LeQuesne, J. McPhee, M. Zambrano-Bigiarini, The 2010-2015 mega drought in Central Chile: Impacts on regional hydroclimate and vegetation, Hydrology and Earth System Sciences Discussions 2017 (2017) 1–37. doi:10.5194/hess-2017-191.
URL http://www.hydrol-earth-syst-sci-discuss.net/hess-2017-191/

[11] F. Zambrano, Four decades of satellite data for agricultural drought monitoring throughout the growing season in Central

Chile, in: R. M. Vijay P. Singh Deepak Jhajharia, R. Kumar (Eds.), Integrated Drought Management, Two Volume Set, CRC Press, 2023, p. 28.

[12] J. P. Boisier, C. Alvarez-Garreton, R. R. Cordero, A. Damiani, L. Gallardo, R. D. Garreaud, F. Lambert, C. Ramallo, M. Rojas, R. Rondanelli, Anthropogenic drying in central-southern Chile evidenced by long-term observations and climate model simulations, Elementa 6 (1) (2018) 74. doi:10.1525/elementa.328.
URL https://www.elementascience.org/article/10.1525/elementa.328/

[13] F. Zambrano, M. Lillo-Saavedra, K. Verbist, O. Lagos, Sixteen years of agricultural drought assessment of the biobío region in chile using a 250 m resolution vegetation condition index (VCI), Remote Sensing 8 (6) (2016) 1–20, publisher: Multidisciplinary Digital Publishing Institute. doi:10.3390/rs8060530.
URL http://www.mdpi.com/2072-4292/8/6/530

[14] F. Zambrano, A. Vrieling, A. Nelson, M. Meroni, T. Tadesse, Prediction of drought-induced reduction of agricultural productivity in Chile from MODIS, rainfall estimates, and climate oscillation indices, Remote Sensing of Environment 219 (2018) 15–30, publisher: Elsevier. doi:10.1016/j.rse.2018.10.006.
URL https://www.sciencedirect.com/science/article/pii/S0034425718304541

[15] A. Miranda, A. Lara, A. Altamirano, C. Di Bella, M. E. González, J. Julio Camarero, Forest browning trends in response to drought in a highly threatened mediterranean landscape of South America, Ecological Indicators 115 (2020) 106401. doi:10.1016/j.ecolind.2020.106401.
URL https://linkinghub.elsevier.com/retrieve/pii/S1470160X20303381

[16] A. Venegas-González, F. R. Juñent, A. G. Gutiérrez, M. T. Filho, Recent radial growth decline in response to increased drought conditions in the northernmost Nothofagus populations from South America, Forest Ecology and Management 409 (2018) 94–104. doi:10.1016/j.foreco.2017.11.006.
URL https://linkinghub.elsevier.com/retrieve/pii/S0378112717313993

[17] R. Urrutia-Jalabert, M. E. González, . González-Reyes, A. Lara, R. Garreaud, Climate variability and forest fires in central and south-central Chile, Ecosphere 9 (4) (2018) e02171. doi:10.1002/ecs2.2171.
URL https://esajournals.onlinelibrary.wiley.com/doi/10.1002/ecs2.2171

[18] I. Fuentes, R. Fuster, D. Avilés, W. Vervoort, Water scarcity in central Chile: the effect of climate and land cover changes on hydrologic resources, Hydrological Sciences Journal 66 (6) (2021) 1028–1044. doi:10.1080/02626667.2021.1903475.
URL https://www.tandfonline.com/doi/full/10.1080/02626667.2021.1903475

[19] C. Alvarez-Garreton, J. P. Boisier, R. Garreaud, J. Seibert, M. Vis, Progressive water deficits during multiyear droughts in basins with long hydrological memory in Chile, Hydrology and Earth System Sciences 25 (1) (2021) 429–446. doi:10.5194/hess-25-429-2021.
URL https://hess.copernicus.org/articles/25/429/2021/

[20] F. J. Fernández, F. Vásquez-Lavín, R. D. Ponce, R. Garreaud, F. Hernández, O. Link, F. Zambrano, M. Hanemann, The economics impacts of long-run droughts: Challenges, gaps, and way forward, Journal of Environmental Management 344 (2023) 118726. doi:10.1016/j.jenvman.2023.118726.
URL https://linkinghub.elsevier.com/retrieve/pii/S0301479723015141

[21] J. Muñoz-Sabater, E. Dutra, A. Agustí-Panareda, C. Albergel, G. Arduini, G. Balsamo, S. Boussetta, M. Choulga, S. Harrigan, H. Hersbach, B. Martens, D. G. Miralles, M. Piles, N. J. Rodríguez-Fernández, E. Zsoter, C. Buontempo, J.-N. Thépaut, ERA5-Land: a state-of-the-art global reanalysis dataset for land applications, Earth System Science Data 13 (9) (2021) 4349–4383. doi:10.5194/essd-13-4349-2021.
URL https://essd.copernicus.org/articles/13/4349/2021/

[22] M. Nouri, Drought Assessment Using Gridded Data Sources in Data-Poor Areas with Different Aridity Conditions, Water Resources Management 37 (11) (2023) 4327–4343. doi:10.1007/s11269-023-03555-4.
URL https://link.springer.com/10.1007/s11269-023-03555-4

[23] M. Wang, L. Menzel, S. Jiang, L. Ren, C.-Y. Xu, H. Cui, Evaluation of flash drought under the impact of heat wave events in southwestern Germany, Science of The Total Environment 904 (2023) 166815. doi:10.1016/j.scitotenv.2023.166815.
URL https://linkinghub.elsevier.com/retrieve/pii/S0048969723054402

[24] H. West, N. Quinn, M. Horswell, Remote sensing for drought monitoring \& impact assessment: Progress, past challenges and future opportunities, Remote Sensing of Environment 232, publisher: Elsevier Inc. (Oct. 2019). doi:10.1016/j.rse.2019.111291.

[25] A. AghaKouchak, A. Farahmand, F. S. Melton, J. Teixeira, M. C. Anderson, B. D. Wardlow, C. R. Hain, Remote sensing of drought: Progress, challenges and opportunities, Reviews of Geophysics 53 (2) (2015) 452–480. doi:10.1002/2014RG000456.
URL http://dx.doi.org/10.1002/2014RG000456.

[26] J. M. Paruelo, M. Texeira, L. Staiano, M. Mastrángelo, L. Amdan, F. Gallego, An integrative index of Ecosystem Services provision based on remotely sensed data, Ecological Indicators 71 (2016) 145–154, publisher: Elsevier. doi:10.1016/J.ECOLIND.2016.06.054.
URL https://www.sciencedirect.com/science/article/pii/S1470160X16303843

[27] A. Schucknecht, M. Meroni, F. Kayitakire, A. Boureima, A. Schucknecht, M. Meroni, F. Kayitakire, A. Boureima, Phenology-Based Biomass Estimation to Support Rangeland Management in Semi-Arid Environments, Remote Sensing 9 (5) (2017) 463, publisher: Multidisciplinary Digital Publishing Institute. doi:10.3390/rs9050463.
URL http://www.mdpi.com/2072-4292/9/5/463

[28] H. T. Tran, J. B. Campbell, R. H. Wynne, Y. Shao, S. V. Phan, Drought and Human Impacts on Land Use and Land Cover Change in a Vietnamese Coastal Area, Remote Sensing 2019, Vol. 11, Page 333 11 (3) (2019) 333, publisher: Multidisciplinary Digital Publishing Institute. doi:10.3390/RS11030333.

URL https://www.mdpi.com/2072-4292/11/3/333/htm

[29] F. O. Akinyemi, Vegetation Trends, Drought Severity and Land Use-Land Cover Change during the Growing Season in Semi-Arid Contexts, Remote Sensing 2021, Vol. 13, Page 836 13 (5) (2021) 836, publisher: Multidisciplinary Digital Publishing Institute. doi:10.3390/RS13050836.
URL https://www.mdpi.com/2072-4292/13/5/836/htm

[30] G. Grekousis, G. Mountrakis, M. Kavouras, An overview of 21 global and 43 regional land-cover mapping products, International Journal of Remote Sensing 36 (21) (2015) 5309–5335. doi:10.1080/01431161.2015.1093195.
URL https://www.tandfonline.com/doi/full/10.1080/01431161.2015.1093195

[31] M. Friedl, D. Sulla-Menashe, MCD12Q1 MODIS/Terra+Aqua Land Cover Type Yearly L3 Global 500m SIN Grid V006 [Data set]. NASA EOSDIS Land Processes DAAC (2019). doi:10.5067/MODIS/MCD12Q1.006.

[32] M. Ahmed, M. Sultan, J. Wahr, E. Yan, The use of GRACE data to monitor natural and anthropogenic induced variations in water availability across Africa, Earth-Science Reviews 136 (2014) 289–300, publisher: Elsevier. doi:10.1016/J.EARSCIREV.2014.05.009.

[33] S. Ma, Q. Wu, J. Wang, S. Zhang, Temporal Evolution of Regional Drought Detected from GRACE TWSA and CCI SM in Yunnan Province, China, Remote Sensing 2017, Vol. 9, Page 1124 9 (11) (2017) 1124, publisher: Multidisciplinary Digital Publishing Institute. doi:10.3390/RS9111124.
URL https://www.mdpi.com/2072-4292/9/11/1124/htm

[34] WMO, M. Svoboda, M. Hayes, D. A. Wood, Standardized Precipitation Index User Guide, WMO, Geneva, 2012, series Title: WMO Publication Title: WMO-No. 1090 © Issue: 1090.
URL http://library.wmo.int/opac/index.php?lvl=notice_display&id=13682

[35] T. B. Mckee, N. J. Doesken, J. Kleist, The relationship of drought frequency and duration to time scales. In: Proceedings of the Ninth Conference on Applied Climatology., American Metereological Society (Boston) (1993) 179–184.

[36] S. M. Vicente-Serrano, S. Beguería, J. I. López-Moreno, A multiscalar drought index sensitive to global warming: The standardized precipitation evapotranspiration index, Journal of Climate 23 (7) (2010) 1696–1718. doi:10.1175/2009JCLI2909.1.
URL http://dx.doi.org/10.1175/2009JCLI2909.1

[37] M. T. Hobbins, A. Wood, D. J. McEvoy, J. L. Huntington, C. Morton, M. Anderson, C. Hain, The Evaporative Demand Drought Index. Part I: Linking Drought Evolution to Variations in Evaporative Demand, Journal of Hydrometeorology 17 (6) (2016) 1745–1761. doi:10.1175/JHM-D-15-0121.1.
URL http://journals.ametsoc.org/doi/10.1175/JHM-D-15-0121.1

[38] D. J. McEvoy, J. L. Huntington, M. T. Hobbins, A. Wood, C. Morton, M. Anderson, C. Hain, The Evaporative Demand Drought Index. Part II: CONUS-Wide Assessment against Common Drought Indicators, Journal of Hydrometeorology 17 (6) (2016) 1763–1779. doi:10.1175/JHM-D-15-0122.1.
URL http://journals.ametsoc.org/doi/10.1175/JHM-D-15-0122.1

[39] B. Narasimhan, R. Srinivasan, Development and evaluation of Soil Moisture Deficit Index (SMDI) and Evapotranspiration Deficit Index (ETDI) for agricultural drought monitoring, Agricultural and Forest Meteorology 133 (1-4) (2005) 69–88. doi:10.1016/j.agrformet.2005.07.012.
URL https://linkinghub.elsevier.com/retrieve/pii/S0168192305001565

[40] A. G. S. S. Souza, A. Ribeiro Neto, L. L. D. Souza, Soil moisture-based index for agricultural drought assessment: SMADI application in Pernambuco State-Brazil, Remote Sensing of Environment 252 (2021) 112124. doi:10.1016/j.rse.2020.112124.
URL https://linkinghub.elsevier.com/retrieve/pii/S0034425720304971

[41] F. N. Kogan, Application of vegetation index and brightness temperature for drought detection, Advances in Space Research 15 (11) (1995) 91–100. doi:10.1016/0273-1177(95)00079-T.

[42] A. Cui, J. Li, Q. Zhou, R. Zhu, H. Liu, G. Wu, Q. Li, Use of a multiscalar GRACE-based standardized terrestrial water storage index for assessing global hydrological droughts, Journal of Hydrology 603 (2021) 126871. doi:10.1016/j.jhydrol.2021.126871.
URL https://linkinghub.elsevier.com/retrieve/pii/S0022169421009215

[43] P. Aceituno, J. P. Boisier, R. Garreaud, R. Rondanelli, J. A. Rutllant, Climate and Weather in Chile, in: B. Fernández, J. Gironás (Eds.), Water Resources of Chile, Vol. 8, Springer International Publishing, Cham, 2021, pp. 7–29.
URL http://link.springer.com/10.1007/978-3-030-56901-3_2

[44] R. D. Garreaud, The Andes climate and weather, Advances in Geosciences 22 (2009) 3–11. doi:10.5194/adgeo-22-3-2009.
URL https://adgeo.copernicus.org/articles/22/3/2009/

[45] H. E. Beck, T. R. McVicar, N. Vergopolan, A. Berg, N. J. Lutsko, A. Dufour, Z. Zeng, X. Jiang, A. I. J. M. van Dijk, D. G. Miralles, High-resolution (1 km) Köppen-Geiger maps for 1901–2099 based on constrained CMIP6 projections, Scientific Data 10 (1) (Oct. 2023). doi:10.1038/s41597-023-02549-6.
URL http://dx.doi.org/10.1038/s41597-023-02549-6

[46] K. Didan, MOD13Q1 MODIS/Terra Vegetation Indices 16-Day L3 Global 250m SIN Grid V006, Tech. rep., NASA EOSDIS Land Processes DAAC (2015). doi:http://dx.doi.org/10.5067/MODIS/MOD13Q1.006.

[47] V. Humphrey, M. Rodell, A. Eicker, Using Satellite-Based Terrestrial Water Storage Data: A Review, Surveys in Geophysics 44 (5) (2023) 1489–1517. doi:10.1007/s10712-022-09754-9.
URL https://link.springer.com/10.1007/s10712-022-09754-9

[48] S. Deng, Y. Liu, W. Zhang, A Comprehensive Evaluation of GRACE-Like Terrestrial Water Storage (TWS) Reconstruction Products at an Interannual Scale During 1981–2019, Water Resources Research 59 (3) (2023) e2022WR034381. doi:10.1029/2022WR034381.

URL https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2022WR034381

[49] R. Abolafia-Rosenzweig, M. Pan, J. Zeng, B. Livneh, Remotely sensed ensembles of the terrestrial water budget over major global river basins: An assessment of three closure techniques, Remote Sensing of Environment 252 (2021) 112191. doi:10.1016/j.rse.2020.112191.
URL https://linkinghub.elsevier.com/retrieve/pii/S0034425720305642

[50] F. Sabzehee, A. Amiri-Simkooei, S. Iran-Pour, B. Vishwakarma, R. Kerachian, Enhancing spatial resolution of GRACE-derived groundwater storage anomalies in Urmia catchment using machine learning downscaling methods, Journal of Environmental Management 330 (2023) 117180. doi:10.1016/j.jenvman.2022.117180.
URL https://linkinghub.elsevier.com/retrieve/pii/S0301479722027530

[51] B. D. Tapley, M. M. Watkins, F. Flechtner, C. Reigber, S. Bettadpur, M. Rodell, I. Sasgen, J. S. Famiglietti, F. W. Landerer, D. P. Chambers, J. T. Reager, A. S. Gardner, H. Save, E. R. Ivins, S. C. Swenson, C. Boening, C. Dahle, D. N. Wiese, H. Dobslaw, M. E. Tamisiea, I. Velicogna, Contributions of GRACE to understanding climate change, Nature Climate Change 9 (5) (2019) 358–369. doi:10.1038/s41558-019-0456-2.
URL https://www.nature.com/articles/s41558-019-0456-2

[52] V. Ferreira, B. Yong, H. Montecino, C. E. Ndehedehe, K. Seitz, H. Kutterer, K. Yang, Estimating GRACE terrestrial water storage anomaly using an improved point mass solution, Scientific Data 10 (1) (2023) 234. doi:10.1038/s41597-023-02122-1.
URL https://www.nature.com/articles/s41597-023-02122-1

[53] M. Ramjeawon, M. Demlie, M. Toucher, Analyses of groundwater storage change using GRACE satellite data in the Usutu-Mhlatuze drainage region, north-eastern South Africa, Journal of Hydrology: Regional Studies 42 (2022) 101118. doi:10.1016/j.ejrh.2022.101118.
URL https://linkinghub.elsevier.com/retrieve/pii/S2214581822001318

[54] F. W. Landerer, F. M. Flechtner, H. Save, F. H. Webb, T. Bandikova, W. I. Bertiger, S. V. Bettadpur, S. H. Byun, C. Dahle, H. Dobslaw, E. Fahnestock, N. Harvey, Z. Kang, G. L. H. Kruizinga, B. D. Loomis, C. McCullough, M. Murböck, P. Nagel, M. Paik, N. Pie, S. Poole, D. Strekalov, M. E. Tamisiea, F. Wang, M. M. Watkins, H. Wen, D. N. Wiese, D. Yuan, Extending the Global Mass Change Data Record: GRACE Follow-On Instrument and Science Data Performance, Geophysical Research Letters 47 (12) (2020) e2020GL088306. doi:10.1029/2020GL088306.
URL https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2020GL088306

[55] W. Yin, S. Yang, L. Hu, S. Tian, X. Wang, R. Zhao, P. Li, Improving understanding of spatiotemporal water storage changes over China based on multiple datasets, Journal of Hydrology 612 (2022) 128098. doi:10.1016/j.jhydrol.2022.128098.
URL https://linkinghub.elsevier.com/retrieve/pii/S0022169422006734

[56] J. Wahr, S. Swenson, V. Zlotnicki, I. Velicogna, Time-variable gravity from GRACE: First results: TIME-VARIABLE GRAVITY FROM GRACE, Geophysical Research Letters 31 (11) (2004) n/a–n/a. doi:10.1029/2004GL019779.
URL http://doi.wiley.com/10.1029/2004GL019779

[57] NASA Jet Propulsion Laboratory (JPL) Tellus, JPL GRACE Mascon Ocean, Ice, and Hydrology Equivalent Water Height Release 06 Coastal Resolution Improvement (CRI) Filtered Version 1.0 (2018). doi:10.5067/TEMSC-3MJC6.
URL https://podaac.jpl.nasa.gov/dataset/TELLUS_GRACE_MASCON_CRI_GRID_RL06_V1

[58] D. N. Wiese, F. W. Landerer, M. M. Watkins, Quantifying and reducing leakage errors in the JPL RL05M GRACE mascon solution, Water Resources Research 52 (9) (2016) 7490–7502. doi:10.1002/2016WR019344.
URL https://agupubs.onlinelibrary.wiley.com/doi/10.1002/2016WR019344