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

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2023-10-09

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.

# Introduction

The sixth assessment report (AR6) of the IPCC (Calvin et al. 2023) 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 (IPCC 2013). There is high confidence that increasing global warming can expand the land area affected by increasing drought frequency and severity (Seneviratne 2021). Furthermore, drought increases tree mortality and triggers changes in land cover and, consequently, land use, thus impacting ecosystems (Crausbay et al. 2017). 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 (Luo et al. 2017). Drought impacts soil moisture, hydrological regimes, and vegetation productivity. Initially, drought was commonly classified as meteorological, hydrological, and agricultural (Wilhite and Glantz 1985). Lately, Van Loon et al. (2016) and Amir AghaKouchak et al. (2021) 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. Crausbay et al. (2017) 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” (Slette et al. 2019). On the other hand, the AR6 (Calvin et al. 2023) 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 (Garreaud et al. 2017), which has impacted vegetation development (Zambrano 2023) and the hydrological system (Boisier et al. 2018). Current drought conditions have affected crop productivity (Zambrano et al. 2016, 2018), forest development (Miranda et al. 2020; Venegas-González et al. 2018), forest fire occurrence (Urrutia‐Jalabert et al. 2018), land cover change (Fuentes et al. 2021), water supply in watersheds (Alvarez-Garreton et al. 2021), and have had economic impacts (Fernández et al. 2023). 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 (Zambrano 2023). 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) (Muñoz-Sabater et al. 2021) 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) (Nouri 2023) and for flash drought (Wang et al. 2023) by analyzing soil mositure and evapotranspiration. On the other hand, satellite remote sensing (West, Quinn, and Horswell 2019; A. AghaKouchak et al. 2015) is the primary method to evaluate how drought impacts vegetation dynamics. Vegetation drought indices (VDI) are commonly used as proxies of productivity (Paruelo et al. 2016; Schucknecht et al. 2017), which can be derived from the MODIS (Moderate-Resolution Imaging Spectroradiometer). Besides, land use and land cover (LULC) change can be driven by drought (Tran et al. 2019; Akinyemi 2021). To analyze these changes, multiple LULC products exist (Grekousis, Mountrakis, and Kavouras 2015), one of those that provides time series since 2001 is the MCD12Q1 (Friedl and Sulla-Menashe 2019) 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 (Ahmed et al. 2014; Ma et al. 2017). 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; WMO et al. (2012)) recommends the Standardized Precipitation Index (SPI; (**Mckee1993?**)), a multiscalar drought index that allows to monitor precipitation deficits from short- to long-term. Following the same approach, Vicente-Serrano, Beguería, and López-Moreno (2010) 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, Hobbins et al. (2016) and McEvoy et al. (2016) came up with the Evaporative Demand Drought Index (EDDI). For vegetation, in a similar manner as the SPI, SPEI and EDDI;  Zambrano et al. (2018) 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 (Narasimhan and Srinivasan 2005) and the Soil Moisture Agricultural Drought Index (SMADI) (Souza, Ribeiro Neto, and Souza 2021) which is a normalized index using vegetation, land surface temperature, and a vegetation condition index (VCI, (Kogan 1995)). From TWS, we can estimate the standardized terrestrial water storage index (STI) (Cui et al. 2021), a standardized anomaly that follows the methodology of the SPI, SPEI, EDDI, and zcNDVI. Thereby, we have drought indices for water supply, demand, and storage, which can help to make a comprehensive assessment of drought.

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

# Study area

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| (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. |

# Materials and Methods

## Data

### Earth observation data

### in-situ data

## Drought indices for water demand and supply

## Analysis of a biomass proxy with drought indices of supply and demand

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

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

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| |  |  | | --- | --- | |  |  |   Figure 1: Proportion of land cover class from the persistent land cover for 2001-2021 (>80%) per macrozone. The table on the left shows the linear change trend next to time-series plot of surface, per land cover class (IGBP MCD12Q1.006) for 2001-2021 through the fives zones on continental Chile. Blue dots on the plots indicate the maximum and red dots minimum surface reach. |

## 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 (Humphrey, Rodell, and Eicker 2023; Deng, Liu, and Zhang 2023). TWS changes evidence the effects of multiple water fluxes on the hydrological cycle (Deng, Liu, and Zhang 2023). These are reflected in the temporal variation of observations of the Earth’s gravitational field (Abolafia-Rosenzweig et al. 2021; Sabzehee et al. 2023) 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 (Tapley et al. 2019; Ferreira et al. 2023). The GRACE mission was launched in March 2002 and was operational until October 2017 (Ramjeawon, Demlie, and Toucher 2022). Then its GRACE Follow-On successor was launched in May 2018 (Landerer et al. 2020; Yin et al. 2022). 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 (Humphrey, Rodell, and Eicker 2023; Wahr et al. 2004).

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) (Ramjeawon, Demlie, and Toucher 2022; Yin et al. 2022). This JPL-M version of the data employs a Coastal Resolution Improvement (CRI) filter that reduces signal leakage errors across coastlines (**Wiese2019?**; **Wiese2016?**). 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 (Ramjeawon, Demlie, and Toucher 2022; Yin et al. 2022). The water storage and height anomalies are given in Equivalent Water Height or Thickness units (EWH, cm) (Sabzehee et al. 2023), and their temporal resolution monthly is from April 2002 to May 2023.

## Validation of ERA5-Land variables

# Results

## Drought indices for water demand and supply

## Biomass proxy with drought indices of supply and demand

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

## Total water storage (TWS) and drought indices

## Validation of ERA5-Land variables

# Discussion

# Conclusion

# References

Abolafia-Rosenzweig, R., M. Pan, J. L. Zeng, and B. Livneh. 2021. “Remotely Sensed Ensembles of the Terrestrial Water Budget over Major Global River Basins: An Assessment of Three Closure Techniques.” *Remote Sensing of Environment* 252 (January): 112191. <https://doi.org/10.1016/j.rse.2020.112191>.

AghaKouchak, A., A. Farahmand, F. S. Melton, J. Teixeira, M. C. Anderson, B. D. Wardlow, and C. R. Hain. 2015. “Remote Sensing of Drought: Progress, Challenges and Opportunities.” *Reviews of Geophysics* 53 (2): 452–80. <https://doi.org/10.1002/2014RG000456>.

AghaKouchak, Amir, Ali Mirchi, Kaveh Madani, Giuliano Di Baldassarre, Ali Nazemi, Aneseh Alborzi, Hassan Anjileli, et al. 2021. “Anthropogenic Drought: Definition, Challenges, and Opportunities.” *Reviews of Geophysics* 59 (2): e2019RG000683. <https://doi.org/10.1029/2019RG000683>.

Ahmed, Mohamed, Mohamed Sultan, John Wahr, and Eugene Yan. 2014. “The Use of GRACE Data to Monitor Natural and Anthropogenic Induced Variations in Water Availability Across Africa.” *Earth-Science Reviews* 136 (September): 289–300. <https://doi.org/10.1016/J.EARSCIREV.2014.05.009>.

Akinyemi, Felicia O. 2021. “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): 836. <https://doi.org/10.3390/RS13050836>.

Alvarez-Garreton, Camila, Juan Pablo Boisier, René Garreaud, Jan Seibert, and Marc Vis. 2021. “Progressive Water Deficits During Multiyear Droughts in Basins with Long Hydrological Memory in Chile.” *Hydrology and Earth System Sciences* 25 (1): 429–46. <https://doi.org/10.5194/hess-25-429-2021>.

Boisier, Juan P., Camila Alvarez-Garreton, Raúl R. Cordero, Alessandro Damiani, Laura Gallardo, René D. Garreaud, Fabrice Lambert, Cinthya Ramallo, Maisa Rojas, and Roberto Rondanelli. 2018. “Anthropogenic Drying in Central-Southern Chile Evidenced by Long-Term Observations and Climate Model Simulations.” *Elementa* 6 (1): 74. <https://doi.org/10.1525/elementa.328>.

Calvin, Katherine, Dipak Dasgupta, Gerhard Krinner, Aditi Mukherji, Peter W. Thorne, Christopher Trisos, José Romero, et al. 2023. “IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, 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.” Intergovernmental Panel on Climate Change (IPCC). <https://www.ipcc.ch/report/ar6/syr/>.

Crausbay, Shelley D., Aaron R. Ramirez, Shawn L. Carter, Molly S. Cross, Kimberly R. Hall, Deborah J. Bathke, Julio L. Betancourt, et al. 2017. “Defining Ecological Drought for the Twenty-First Century.” *Bulletin of the American Meteorological Society* 98 (12): 2543–50. <https://doi.org/10.1175/BAMS-D-16-0292.1>.

Cui, Aihong, Jianfeng Li, Qiming Zhou, Ruoxin Zhu, Huizeng Liu, Guofeng Wu, and Qingquan Li. 2021. “Use of a Multiscalar GRACE-Based Standardized Terrestrial Water Storage Index for Assessing Global Hydrological Droughts.” *Journal of Hydrology* 603 (December): 126871. <https://doi.org/10.1016/j.jhydrol.2021.126871>.

Deng, Shanshan, Yuxin Liu, and Wenxi Zhang. 2023. “A Comprehensive Evaluation of GRACE‐Like Terrestrial Water Storage (TWS) Reconstruction Products at an Interannual Scale During 1981–2019.” *Water Resources Research* 59 (3): e2022WR034381. <https://doi.org/10.1029/2022WR034381>.

Fernández, Francisco J., Felipe Vásquez-Lavín, Roberto D. Ponce, René Garreaud, Francisco Hernández, Oscar Link, Francisco Zambrano, and Michael Hanemann. 2023. “The Economics Impacts of Long-Run Droughts: Challenges, Gaps, and Way Forward.” *Journal of Environmental Management* 344 (October): 118726. <https://doi.org/10.1016/j.jenvman.2023.118726>.

Ferreira, Vagner, Bin Yong, Henry Montecino, Christopher E. Ndehedehe, Kurt Seitz, Hansjörg Kutterer, and Kun Yang. 2023. “Estimating GRACE Terrestrial Water Storage Anomaly Using an Improved Point Mass Solution.” *Scientific Data* 10 (1): 234. <https://doi.org/10.1038/s41597-023-02122-1>.

Friedl, M, and D Sulla-Menashe. 2019. “MCD12Q1 MODIS/Terra+Aqua Land Cover Type Yearly L3 Global 500m SIN Grid V006 [Data Set]. NASA EOSDIS Land Processes DAAC.” <https://doi.org/10.5067/MODIS/MCD12Q1.006>.

Fuentes, Ignacio, Rodrigo Fuster, David Avilés, and Willem Vervoort. 2021. “Water Scarcity in Central Chile: The Effect of Climate and Land Cover Changes on Hydrologic Resources.” *Hydrological Sciences Journal* 66 (6): 1028–44. <https://doi.org/10.1080/02626667.2021.1903475>.

Garreaud, René, Camila Alvarez-Garreton, Jonathan Barichivich, Juan Pablo Boisier, Duncan Christie, Mauricio Galleguillos, Carlos LeQuesne, James McPhee, and Mauricio Zambrano-Bigiarini. 2017. “The 2010-2015 Mega Drought in Central Chile: Impacts on Regional Hydroclimate and Vegetation.” *Hydrology and Earth System Sciences Discussions* 2017: 1–37. <https://doi.org/10.5194/hess-2017-191>.

Grekousis, George, Giorgos Mountrakis, and Marinos Kavouras. 2015. “An Overview of 21 Global and 43 Regional Land-Cover Mapping Products.” *International Journal of Remote Sensing* 36 (21): 5309–35. <https://doi.org/10.1080/01431161.2015.1093195>.

Hobbins, Michael T., Andrew Wood, Daniel J. McEvoy, Justin L. Huntington, Charles Morton, Martha Anderson, and Christopher Hain. 2016. “The Evaporative Demand Drought Index. Part I: Linking Drought Evolution to Variations in Evaporative Demand.” *Journal of Hydrometeorology* 17 (6): 1745–61. <https://doi.org/10.1175/JHM-D-15-0121.1>.

Humphrey, Vincent, Matthew Rodell, and Annette Eicker. 2023. “Using Satellite-Based Terrestrial Water Storage Data: A Review.” *Surveys in Geophysics* 44 (5): 1489–1517. <https://doi.org/10.1007/s10712-022-09754-9>.

IPCC. 2013. *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, UK; New York, USA: Cambridge University Press. <https://doi.org/10.1017/CBO9781107415324>.

Kogan, F. N. 1995. “Application of Vegetation Index and Brightness Temperature for Drought Detection.” *Advances in Space Research* 15 (11): 91–100. <https://doi.org/10.1016/0273-1177(95)00079-T>.

Landerer, Felix W., Frank M. Flechtner, Himanshu Save, Frank H. Webb, Tamara Bandikova, William I. Bertiger, Srinivas V. Bettadpur, et al. 2020. “Extending the Global Mass Change Data Record: GRACE Follow‐On Instrument and Science Data Performance.” *Geophysical Research Letters* 47 (12): e2020GL088306. <https://doi.org/10.1029/2020GL088306>.

Luo, Lifeng, Deanna Apps, Samuel Arcand, Huating Xu, Ming Pan, and Martin Hoerling. 2017. “Contribution of Temperature and Precipitation Anomalies to the California Drought During 2012–2015.” *Geophysical Research Letters* 44 (7): 3184–92. <https://doi.org/10.1002/2016GL072027>.

Ma, Siyu, Qianxin Wu, Jie Wang, and Shiqiang Zhang. 2017. “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): 1124. <https://doi.org/10.3390/RS9111124>.

McEvoy, Daniel J., Justin L. Huntington, Michael T. Hobbins, Andrew Wood, Charles Morton, Martha Anderson, and Christopher Hain. 2016. “The Evaporative Demand Drought Index. Part II: CONUS-Wide Assessment Against Common Drought Indicators.” *Journal of Hydrometeorology* 17 (6): 1763–79. <https://doi.org/10.1175/JHM-D-15-0122.1>.

Miranda, Alejandro, Antonio Lara, Adison Altamirano, Carlos Di Bella, Mauro E. González, and Jesus Julio Camarero. 2020. “Forest Browning Trends in Response to Drought in a Highly Threatened Mediterranean Landscape of South America.” *Ecological Indicators* 115 (August): 106401. <https://doi.org/10.1016/j.ecolind.2020.106401>.

Muñoz-Sabater, Joaquín, Emanuel Dutra, Anna Agustí-Panareda, Clément Albergel, Gabriele Arduini, Gianpaolo Balsamo, Souhail Boussetta, et al. 2021. “ERA5-Land: A State-of-the-Art Global Reanalysis Dataset for Land Applications.” *Earth System Science Data* 13 (9): 4349–83. <https://doi.org/10.5194/essd-13-4349-2021>.

Narasimhan, B., and R. Srinivasan. 2005. “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): 69–88. <https://doi.org/10.1016/j.agrformet.2005.07.012>.

Nouri, Milad. 2023. “Drought Assessment Using Gridded Data Sources in Data-Poor Areas with Different Aridity Conditions.” *Water Resources Management* 37 (11): 4327–43. <https://doi.org/10.1007/s11269-023-03555-4>.

Paruelo, José M., Marcos Texeira, Luciana Staiano, Matías Mastrángelo, Laura Amdan, and Federico Gallego. 2016. “An Integrative Index of Ecosystem Services Provision Based on Remotely Sensed Data.” *Ecological Indicators* 71 (December): 145–54. <https://doi.org/10.1016/J.ECOLIND.2016.06.054>.

Ramjeawon, Manish, Molla Demlie, and Michele Toucher. 2022. “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 (August): 101118. <https://doi.org/10.1016/j.ejrh.2022.101118>.

Sabzehee, F., A. R. Amiri-Simkooei, S. Iran-Pour, B. D. Vishwakarma, and R. Kerachian. 2023. “Enhancing Spatial Resolution of GRACE-Derived Groundwater Storage Anomalies in Urmia Catchment Using Machine Learning Downscaling Methods.” *Journal of Environmental Management* 330 (March): 117180. <https://doi.org/10.1016/j.jenvman.2022.117180>.

Schucknecht, Anne, Michele Meroni, Francois Kayitakire, Amadou Boureima, Anne Schucknecht, Michele Meroni, Francois Kayitakire, and Amadou Boureima. 2017. “Phenology-Based Biomass Estimation to Support Rangeland Management in Semi-Arid Environments.” *Remote Sensing* 9 (5): 463. <https://doi.org/10.3390/rs9050463>.

Seneviratne, X and Adnan, S and Zhang. 2021. *Weather and Climate Extreme Events in a Changing Climate*. Edited by P. Zhai Masson-Delmotte V., C. Péan A. Pirani S. L. Connors, and T. K. Maycock Lonnoy J. B. R. Matthews. Cambridge University Press. In Press.

Slette, Ingrid J., Alison K. Post, Mai Awad, Trevor Even, Arianna Punzalan, Sere Williams, Melinda D. Smith, and Alan K. Knapp. 2019. “How Ecologists Define Drought, and Why We Should Do Better.” *Global Change Biology* 25 (10): 3193–3200. <https://doi.org/10.1111/gcb.14747>.

Souza, Alzira Gabrielle Soares Saraiva, Alfredo Ribeiro Neto, and Laio Lucas De Souza. 2021. “Soil Moisture-Based Index for Agricultural Drought Assessment: SMADI Application in Pernambuco State-Brazil.” *Remote Sensing of Environment* 252 (January): 112124. <https://doi.org/10.1016/j.rse.2020.112124>.

Tapley, Byron D., Michael M. Watkins, Frank Flechtner, Christoph Reigber, Srinivas Bettadpur, Matthew Rodell, Ingo Sasgen, et al. 2019. “Contributions of GRACE to Understanding Climate Change.” *Nature Climate Change* 9 (5): 358–69. <https://doi.org/10.1038/s41558-019-0456-2>.

Tran, Hoa Thi, James B. Campbell, Randolph H. Wynne, Yang Shao, and Son Viet Phan. 2019. “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): 333. <https://doi.org/10.3390/RS11030333>.

Urrutia‐Jalabert, Rocío, Mauro E. González, Álvaro González‐Reyes, Antonio Lara, and René Garreaud. 2018. “Climate Variability and Forest Fires in Central and South‐central Chile.” *Ecosphere* 9 (4): e02171. <https://doi.org/10.1002/ecs2.2171>.

Van Loon, Anne F., Tom Gleeson, Julian Clark, Albert I. J. M. Van Dijk, Kerstin Stahl, Jamie Hannaford, Giuliano Di Baldassarre, et al. 2016. “Drought in the Anthropocene.” *Nature Geoscience* 9 (2): 89–91. <https://doi.org/10.1038/ngeo2646>.

Venegas-González, Alejandro, Fidel Roig Juñent, Alvaro G. Gutiérrez, and Mario Tomazello Filho. 2018. “Recent Radial Growth Decline in Response to Increased Drought Conditions in the Northernmost Nothofagus Populations from South America.” *Forest Ecology and Management* 409 (February): 94–104. <https://doi.org/10.1016/j.foreco.2017.11.006>.

Vicente-Serrano, Sergio M., Santiago Beguería, and Juan I. López-Moreno. 2010. “A Multiscalar Drought Index Sensitive to Global Warming: The Standardized Precipitation Evapotranspiration Index.” *Journal of Climate* 23 (7): 1696–1718. <https://doi.org/10.1175/2009JCLI2909.1>.

Wahr, John, Sean Swenson, Victor Zlotnicki, and Isabella Velicogna. 2004. “Time-Variable Gravity from GRACE: First Results: TIME-VARIABLE GRAVITY FROM GRACE.” *Geophysical Research Letters* 31 (11): n/a–. <https://doi.org/10.1029/2004GL019779>.

Wang, Menghao, Lucas Menzel, Shanhu Jiang, Liliang Ren, Chong-Yu Xu, and Hao Cui. 2023. “Evaluation of Flash Drought Under the Impact of Heat Wave Events in Southwestern Germany.” *Science of The Total Environment* 904 (December): 166815. <https://doi.org/10.1016/j.scitotenv.2023.166815>.

West, Harry, Nevil Quinn, and Michael Horswell. 2019. “Remote Sensing for Drought Monitoring \& Impact Assessment: Progress, Past Challenges and Future Opportunities.” *Remote Sensing of Environment* 232 (October). <https://doi.org/10.1016/j.rse.2019.111291>.

Wilhite, Donald A., and Michael H. Glantz. 1985. “Understanding: The Drought Phenomenon: The Role of Definitions.” *Water International* 10 (3): 111–20. <https://doi.org/10.1080/02508068508686328>.

WMO, Mark Svoboda, Michael Hayes, and Deborah A. Wood. 2012. *Standardized Precipitation Index User Guide*. Geneva: WMO. <http://library.wmo.int/opac/index.php?lvl=notice_display&id=13682>.

Yin, Wenjie, Shuai Yang, Litang Hu, Siyuan Tian, Xuelei Wang, Ruxin Zhao, and Peijun Li. 2022. “Improving Understanding of Spatiotemporal Water Storage Changes over China Based on Multiple Datasets.” *Journal of Hydrology* 612 (September): 128098. <https://doi.org/10.1016/j.jhydrol.2022.128098>.

Zambrano, Francisco. 2023. “Four Decades of Satellite Data for Agricultural Drought Monitoring Throughout the Growing Season in Central Chile.” In *Integrated Drought Management, Two Volume Set*, edited by Rasoul Mirabbasi Vijay P. Singh Deepak Jhajharia and Rohitashw Kumar, 28. CRC Press.

Zambrano, Francisco, Mario Lillo-Saavedra, Koen Verbist, and Octavio Lagos. 2016. “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): 1–20. <https://doi.org/10.3390/rs8060530>.

Zambrano, Francisco, Anton Vrieling, Andy Nelson, Michele Meroni, and Tsegaye Tadesse. 2018. “Prediction of Drought-Induced Reduction of Agricultural Productivity in Chile from MODIS, Rainfall Estimates, and Climate Oscillation Indices.” *Remote Sensing of Environment* 219 (December): 15–30. <https://doi.org/10.1016/j.rse.2018.10.006>.