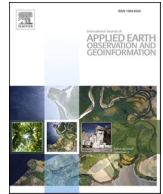




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Andean peatlands at risk? Spatiotemporal patterns of extreme NDVI anomalies, water extraction and drought severity in a large-scale mining area of Atacama, northern Chile

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ABSTRACT

In the Andes, multiple human and climatic factors threaten the conservation of bofedales, a type of high altitude peat forming wetland widely distributed in the tropical and subtropical Andes. In northern Chile, climate change and water extraction for industrial activities are among the most significant threats to these relevant socio-hydrological systems hosting indigenous pastoral communities. In this study, we present an integrated analysis of Normalized Difference Vegetation Index (NDVI) anomalies, drought severity and water rights granted to industry to provide insight on the conservation status of bofedales, historical drivers of their transformation, and current threats. Using Landsat satellite imagery from 1986 to 2018, we identify spatio-temporal NDVI changes of 442 bofedales in one of the leading copper producing regions of the world. The NDVI time series analysis over 32 growing seasons was used to detect extreme anomalies, i.e. values outside the 95 % of the reference frequency distribution, indicating periods of extreme changes in the productivity of these high Andes wetlands. To evaluate the relationship between bofedales NDVI extreme periods to drought and continued water extraction activities, we combine a climate-based multi-temporal-scale drought index (SPEI) with the geospatial latitudinal distribution of water rights granted for extractive industries in the study area. Over the time period of analysis, the total amount of granted water rights increased 465 % from 1,201 l/s recorded before 1985 to 5,584 l/s in 2018. In the areas where the highest amount of water rights are concentrated, i.e. between 21.3°S and 22.1°S, “green” bofedales (NDVI > 0.23) are practically absent. NDVI of the austral summer (JFM) was highly correlated with the severity of drought occurring during the three months of the growing season peak. While our findings show bofedal productivity is mostly influenced by precipitation and temperature of the wet season (JFM) during the study period, results also raise questions regarding possible bofedal loss occurring over the previous 80 years

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prior to the satellite record, wherein water extraction activities have significantly increased according to official records.

1. Introduction

Since the beginning of the 20th century, in the Atacama Desert of northern Chile, extractive industries have been the most critical threat to water sources' sustainability in the highlands (Yáñez & Molina 2011). In addition to water extraction activities, extreme climate events, including droughts, stress regional hydrological demands for ecosystem functioning and production purposes. In the arid Atacama region, dense vegetation and surface water are scarce, except for the occurrence of a type of peat-forming high-altitude wetlands, locally known as bofedales (ok'os or uqhu, in Aymara). Bofedales are restricted to the altitudinal belt in the Andes at elevations between 3,000 and 5,000 m.a.s.l. from southern Peru and Bolivia to northern Chile and north-eastern Argentina (Ruthsatz 2012, Squeo et al. 2006). In the western Altiplano they cover a significant area of about 510 km² (Chávez et al., 2019a).

Bofedales are key socio-hydrological systems contributing to the sustainability of mountain ecosystems across the Andes (Yager et al. 2021). They regulate water storage and flows; are rich with biodiversity, hosting a dense variety of plant and animal species (Meneses et al. 2014), and have high carbon sequestration rates which position them as an integral part of the regional and global climate system (Buytaert et al., 2011, Hribljan et al., 2015). Besides, they are vibrant sites to indigenous highland communities, who manage them for developing herding activities (Yager et al. 2019).

The formation and sustainability of bofedales depends on adequate water inputs (Caballero et al. 2002, Hribljan et al. 2015, Squeo et al. 2006, Anderson et al. 2021), which may be sourced from precipitation, groundwater, aquifers, and glacier run-off. Due to the hydrological inter-dependence of bofedales, their extreme sensitivity to climate variability and change, including variations in precipitation and temperature pose several threats to their stability (Bury et al. 2013, Cooper et al. 2015, Hribljan et al. 2015, Otto and Gibbons 2017, Zimmer et al. 2014).

Multiple climatic and human-driven factors threaten the conservation of bofedales (Castro 1997, Loza et al. 2015, Prieto et al. 2019). Among other drivers, extractive industries and climate change constitute the most significant threat to bofedales due to their direct impact on hydrological inputs. The Chilean economy depends on mining and the spatial concentration of this industry in the hyper arid Atacama Desert requires a high demand for freshwater for its production processes (Sernageomin, 2011, Romero-Toledo et al. 2017). Case-studies in northern Chile indicate the gradual disappearance of bofedales in the upper Loa River basin as a result of mining (Cavieres 1985, Villagrán and Castro 1997); the effects of water extraction in the groundwater-climate interactions in bofedales located at Pampa Lagunillas basin (Scheihing and Tröger, 2018), and the disappearance of bofedales due to mining activities and its impacts on indigenous communities (Castro 1997, Romero-Toledo et al. 2017, Prieto et al. 2019).

Across the Andes, the observed data and projected scenarios show change in regional precipitation patterns and evaporation rates, and extended dry periods are expected (Buytaert et al., 2010, Rabatel et al., 2013, Seth et al. 2010, Vuille et al. 2003). The northern Atacama Desert's highlands are among the most vulnerable areas to climate change (IPCC 2021), and thus bofedales located in this region face a critical situation, mainly due to warming scenarios in northern Chile (Mesequer-Ruiz et al. 2018, IPCC 2021), which is marked in the Altiplano (Vuille et al. 2015); the increase of dry streaks during the rainy season (Sarri-colea and Romero 2015), and changes in the spatiotemporal distribution of precipitation (Mesequer-Ruiz et al. 2019, Mesequer-Ruiz et al. 2020). Recently, Anderson et al. (2021) found that bofedales productivity is closely related to cumulative precipitation and snow persistence,

explaining the productivity of one to two upcoming growing seasons. Therefore, bofedales are sensitive to changes in water availability.

Notwithstanding the socioecological relevance of these ecosystems at different spatio-temporal scales (Yager et al. 2019, Yager et al. 2021, Cooper et al. 2015, Earle et al., 2003, Squeo et al., 2006), their accelerated degradation and current threats (Ramsar 2018, Yager et al., 2019), gaps in the current understanding of how both climate and industrial activities interact and influence the condition of bofedales and, particularly, their productivity, prevail. Several studies have analyzed the spatial and temporal transformations of bofedales productivity using satellite imagery (Baldassini et al. 2012, Meza Aliaga and Díaz Villalobos, 2014, Dangles et al. 2017, Chávez et al., 2019a, Anderson et al. 2021). On the other hand, research from the social sciences has developed rich work on the impacts of the Chilean water model and water extraction by extractive industries in the highlands. However, many studies emphasize the social dimension, and neglect consideration of "the environment" (e.g., Babidge 2016, Budds 2010, Yáñez & Molina 2011, Molina 2012, Prieto et al., 2019), a common problem in socio-environmental studies (Walker 2005). Hence, this research aims to integrate social and environmental perspectives (Lave 2014) of bofedal productivity. To achieve this goal, we study the spatio-temporal dynamics of the network of bofedales and markers of their productivity by analyzing the time series of the Normalized Difference Vegetation Index (NDVI) over four decades to identify areas experiencing/undergoing extreme productivity changes. We connect this analysis with a multi-temporal-scale drought index (Standardized Precipitation-Evapotranspiration Index, SPEI) and the spatio-temporal evolution of water rights granted for extractive industries in the study area. The SPEI is a drought index especially suited for studies of the effects of drought severity on diverse ecosystems and allows to determine the accumulated drought severity in a given time period (Labudová et al. 2017).

The following questions guide this research: Q1) how is the productivity of bofedales in the latitudinal range where most granted water rights are concentrated?; Q2) what is the relationship between SPEI and bofedales productivity at different latitudes and concentrations of granted water rights? and Q3) are extreme productivity changes of bofedales temporally or spatially related to changes in the amount of water rights or SPEI?

This research is focused on the network of bofedales located in the El Loa Province (Antofagasta Region, Northern Atacama Desert, Chile). Multiple factors make this area an important study site: it is the province with the highest concentration of large scale mining activities in Chile and in South America, among the leading copper exporting areas in the world, it is one of the most vulnerable areas to climate change in the Atacama Desert, and many indigenous communities develop agro-pastoral activities in the area. Results from this study advance our knowledge of the geospatial linkages among water status, drought severity impacts, and the socio-political relationships that are embedded in Andean mountain ecosystems studies in general and bofedales in particular. In addition, the results of this research that links bofedal distribution with socio-economic and climatic processes can provide vital information for policy and management plans at various institutional scales.

2. Study area

This research was conducted in the highland region of the Atacama Desert (a biogeographic region known as dry puna, and 3,000 m.a.s.l.), circumscribed to the el Loa Province (Region of Antofagasta, Northern Chile).¹ This area, shown in pink in Fig. 1, comprises 27.52 km² and includes a network of 442 bofedal units according to the digital inventory of Chávez et al. (2019a).

2.1. Climatic characterization

The predominant arid conditions of the Atacama Desert are explained by the influence of a sub-tropical anticyclone, known as the South Pacific High. The Andes Mountain range isolates this desert from the eastern tropical continental climate by blocking the warm and moist winds from the Amazon (Houston and Hartley, 2003, Garreaud et al. 2009). In these contrasting conditions, the divergence between these two air masses determines a particular rainfall behavior in the highlands, with high annual and seasonal variability (Romero et al., 2013, Garreaud 2000). Annual precipitation is primarily concentrated in the austral summer as a consequence of the position of an upper-level anticyclone in the southeast of the central Andes (i.e., the Bolivian High) that drives the so-called South American Monsoon (Sarricolea and Romero 2015, Sarricolea and Meseguer-Ruiz 2020). Throughout the rest of the year, precipitation is infrequent, even nonexistent. The interannual variability of rainfall is related to ENSO, with wet episodes related to La Niña (cold) phase and dry spells during the warm El Niño (warm) phase (Sarricolea and Romero 2015). During the summer season, the maximum rainfall occurs at 18° S (300 mm) and declines towards the south (500 mm at 26° S) (Meseguer-Ruiz et al. 2020). The W-E altitudinal gradient determines an increase in precipitation in this direction, with maximum penetration in the research area between 22° and 24° S (Villagrán and Castro 1997). More specifically, the study area is generally classified as a high-altitude semi-desert, with two different types of climates according to the Köppen-Geiger classification: cold semi-arid with dry winter (Bsk(w)) and tundra with dry winter (ET(w)) (Sarricolea et al. 2017).

2.2. Bofedales and productivity

Bofedales are mainly composed by cushion plants of the Juncaceae family such as *Oxychloe andina* and *Distichia muscoides*), associated with a variety of other vascular plants (e.g., *Zameioscirpus atacamensis*, *Phylloscirpus deserticola*, *Plantago tubulosa*), grasses, (e.g. *Festuca* spp., *Deyeuxia* spp., *Cortaderia atacamensis*), and aquatic species (*Mimulus* and *Ranunculus*, *Lilaeopsis macloviana*, *Triglochin striata*) (Luebert and Plissock 2006, Meneses et al. 2015, Villagrán et al. 1983, Ruthsatz 2012). While between 18 and 20° S, these ecosystems cover extended areas of the highlands, in our research area, they form only small islands or are restricted to riparian vegetation associated with rivers and ravines (Villagrán et al. 1983, CIREN 2018, Chávez et al., 2019a). Fig. 2 shows an example of a bofedal unit of the study area. However, in the recent past and according to historical records, larger areas of the altiplano in this region were covered by larger bofedales than those registered in the inventory of Chávez et al. (2019a), which considers only the period after 1986. However, we have verified their existence by reviewing the records of explorers who have extensively described the existence of bofedales and bodies of water in the area that no longer exists today (Bertrand 1885, Walcott 1925, Hanson 1926, Risopatrón 1918, Rudolph 1927). Their narratives have been corroborated by technical documents

(Cavieres 1985), botanical and ethnobotanical research (Villagrán and Castro 1997), archaeological surveys (Prieto et al. 2019), oral histories of herders (Carrasco 2011, Prieto et al. 2019), and historical aerial photos (1961–1964) provided by the Chilean Military Geographical Institute (IGM).

Due to their adaptation to the altitude and proximity to water tables, bofedales develop a high rate of plant productivity producing dense layers of organic matter (Cooper et al. 2015, Hribljan et al. 2015). Its production rate is one of the fastest among mountain peatlands and the ecosystems of the puna (Hribljan et al. 2015). The structuring species of the bofedales actively participate in the wetlands' functioning and productivity, constituting them as one of the fastest-growing mountain peatland systems (Loza et al. 2015). Bofedal productivity varies between different periods in response to climate and meteorological conditions and human-driven water availability and growing season length (Squeo et al. 2006, Cooper et al. 2015, Yager et al. 2019). The peak productivity occurs in summer which corresponds to the rainy season (Squeo et al. 2006).

2.3. Socio-economic context

Likan-antai are indigenous settlements located at different altitudinal levels of the Loa Province (to a lesser extent, there are also Quechua communities). They reside permanently in villages (Fig. 1), where agricultural activities predominate, while close to the bofedales there are small domestic units (locally known as estancias) located one or more days' walk from the central village. They are occupied seasonally for grazing around the bofedales during the summer when there is greater availability of forage due to rainfall. (Castro and Martínez 1996). Human populations have inhabited this area since the early Holocene (De Souza 2004, Núñez and Santoro 2011). Around 1,500BCE, inhabitants developed herding around the vegas, bofedales, and ravines (Núñez and Santoro 2011, Jackson and Benavente 2010). Since then, in the highlands, inhabitants have developed different occupation patterns, adaptation practices, socio-economic relations, herding (and to lesser extent agriculture) many of which rely upon and include management of the bofedales (Villagrán and Castro 1997). However, since the early 20th century, agropastoral societies have undergone substantial transformations (Castro and Martínez 1996, Gundermann, 1998, Calderón and Prieto, 2020). Among other factors, the drying up of the bofedales due to industrial water extraction in certain parts of the study area has been a determining driver of migration towards urban areas (Villagrán and Castro 1997, Prieto et al. 2019).

Starting in the second half of the 19th century, large volumes of surface and groundwater have been extracted in the Loa Province's highlands for mining activity and water supply of the main cities of our study area (Villagrán and Castro 1997, Molina 2005, Prieto et al. 2022). These activities are especially relevant in the research area, considering its leading role in the world production of copper and brine mining (e.g. potassium, lithium). These mining activities demand high water consumption for all their production phases. Chilean copper production is the largest globally (Cochilco, 2020a), in fact, the country's copper production accounted for 28 % of the world total in 2019 (Sernageomin, 2020). The Antofagasta region concentrates the most significant production of copper at the national level with 54 % of the total (Sernageomin, 2020), and is the largest consumer of water with 41 % of the total inland water used by copper mining in 2019 (Cochilco, 2020b). Several current mining projects, both in execution and planning, suggest that this scenario will not change in the short-medium term (Cochilco 2020a). Besides copper mining, the current lithium mining boom is threatening several high-altitude salt flats rich in biodiversity (García-Sanz et al. 2021, Liu et al., 2019), which share water sources with the bofedales of the area. This way, the overexploitation of water resources in the area has damaged and threatened the high altitude ecosystems in general and bofedales in particular (Cavieres 1985, Aldunate 1985, Castro 1997, Liu et al., 2019).

¹ The administrative division of Chile is divided into sixteen regions, which are the first-level administrative division. In turn, each region is divided into provinces (*provincias*). This research was conducted in El Loa province, which is part of the Antofagasta region.

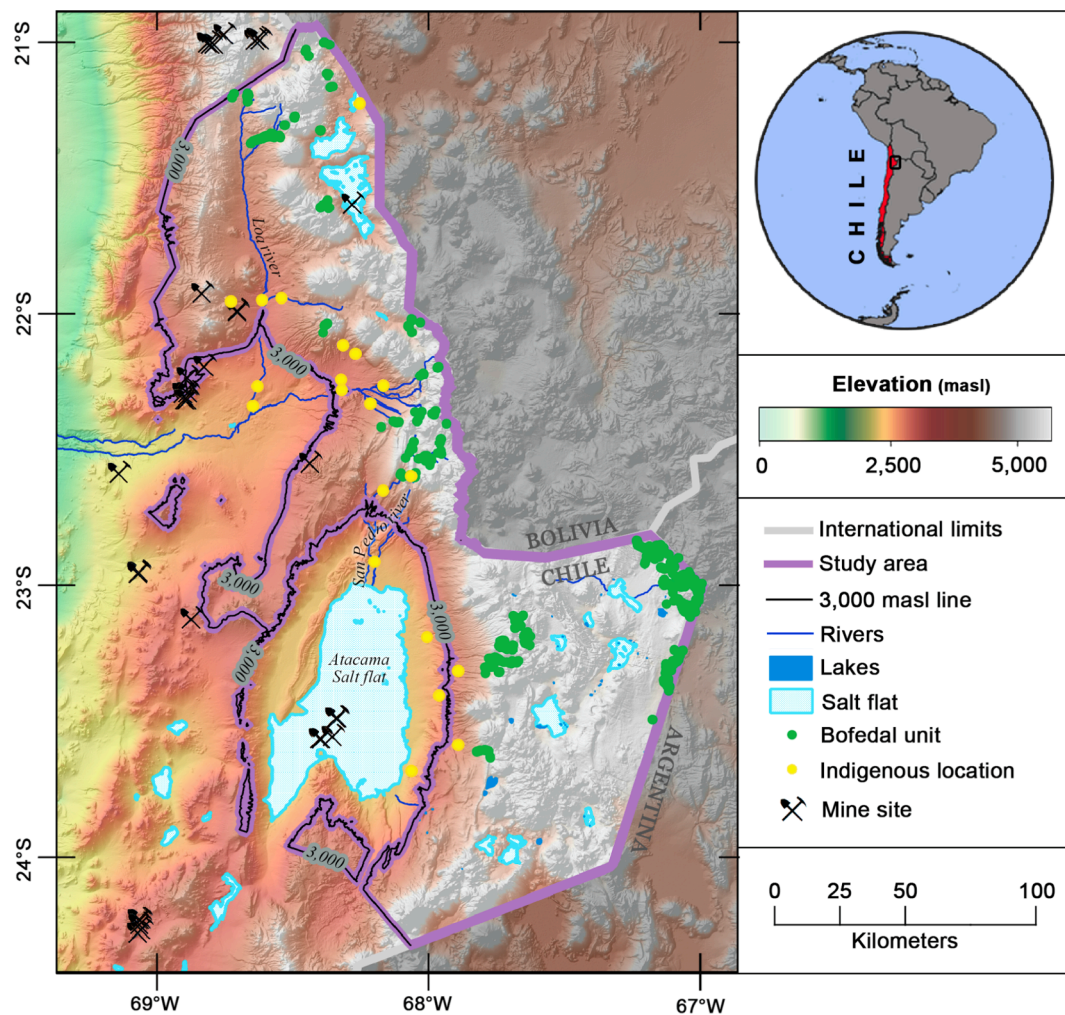


Fig. 1. The study area comprises the bofedal units of the Antofagasta Region, Northern Chile. Bofedales are located at high elevations (above 3,000 m a.s.l.). A total of 442 bofedal units were considered in this study. In this map, Bofedal units are represented by points, which correspond to the centroid of the Bofedal polygons considered in this study. More spatial detailed information can be found in the dashboard of this paper, available at https://labgrs.shinyapps.io/AEOG_peatlands

3. Methodological approach

The proposed methodological approach aims to answer the three research questions proposed in the Introduction section (Q1, Q2 and Q3) and is presented in the flowchart of Fig. 3. To answer these questions we combined three input datasets: water rights granted for mining, Landsat NDVI data of each peatland polygon, and gridded rainfall and temperature data. The following sections (3.1 to 3.3) explain in detail the methods applied to each input dataset as well as the integration of all variables (3.4).

3.1. NDVI time series and identification of years with extreme anomalies

In this study, we used Landsat imagery from 1986 to 2018 to assess the productivity of all bofedal units (polygons) at different temporal scales (long-term and annual) and to detect years with extreme productivity changes, both negative and positive. Monthly NDVI values were derived from Landsat data (Collection 1 Level 2) and included Paths/Rows: 233/074, 233/075, 233/076, 232/076, 232/077, 001/075). Collection 2 was not considered since at the date this research was conducted, it still presented technical issues and it was constantly updated. Besides, we carried out a harmonization between the different Landsat sensors using the coefficients proposed by Roy et al. (2016) for Collection 1. For each of the 442 bofedal (polygon) units identified by

Chávez et al. (2019a), we extracted the NDVI signal through the means of the median NDVI value of all 30x30 meters Landsat pixels inside each bofedal polygon per month. We calculated the average value for pixels when more than one Landsat scene was available for the same month.

To assess NDVI anomalies as “extreme”, we used the “npphen” R package (Chávez et al., 2022). This probabilistic approach allows detailed assessment of extreme events and has been applied to study vegetation disturbances in different ecosystems (e.g. Bowman et al., 2019, Decuyper et al., 2020, Estay et al., 2019, Gutiérrez et al., 2020), including desert areas (Chávez et al., 2019a, Chávez et al., 2019b). There are two important advantages of this probabilistic approach with regards to parametric approaches using curve fitting for reconstructing the phenological baseline (e.g. bi-logistic or sine functions): i) it adapts to describe any type of annual phenological behavior and ii) it calculates the frequency distribution of the phenological annual cycle, from which anomalies can be assessed in terms of how “unlikely” or “extreme” they are (Fig. 4). A practical guide to “npphen” can be found in this link <http://www.pucv.cl/uuaa/labgrs/proyectos/introduction-to-npphen-in-r>.

The first step in this method is the calculation of a phenological baseline through kernel density estimations (KDE) of the annual NDVI-time space (Fig. 4) using all available NDVI records during the reference period. In this study, we aim at detecting extreme anomalies throughout the entire time series and therefore the reference period also included the complete period of analysis (1986–2015). KDE works by averaging

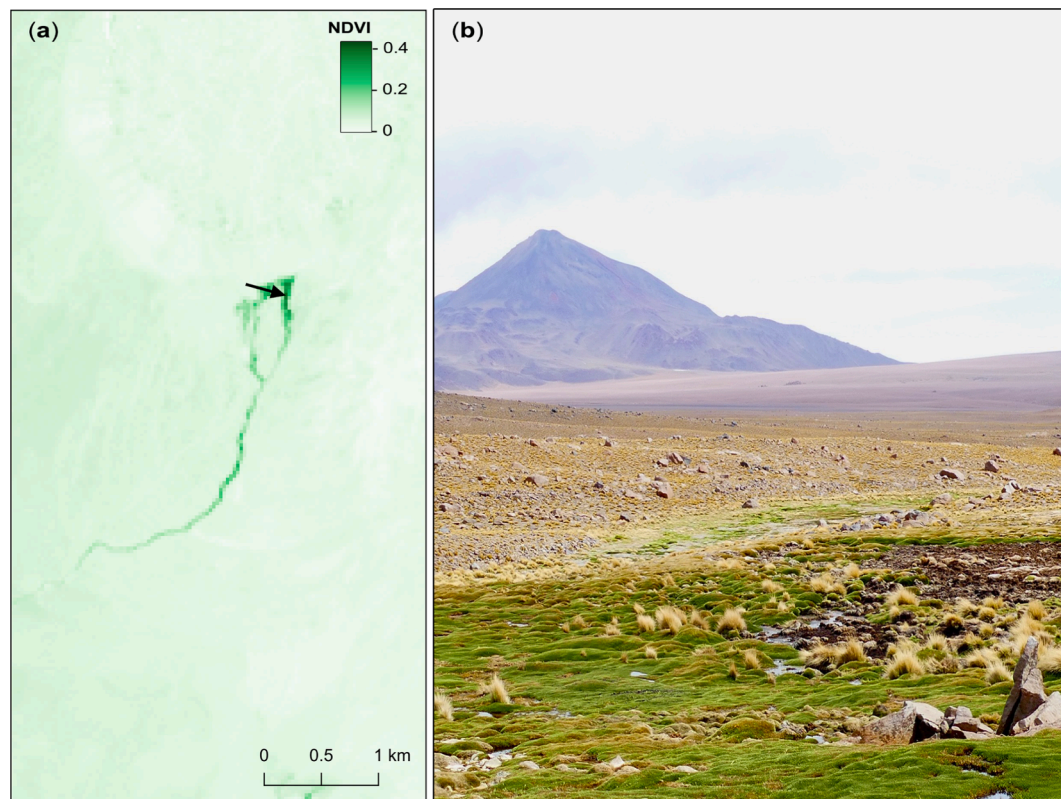


Fig. 2. Example of a bofedal unit of the study area (-22.46° , 67.95°) observed from (a) NDVI Landsat 8 image and (b) from a field photograph. The black arrow in the map shows the location and orientation of the photograph.

the heights of Gaussian kernels calculated in two dimensions (x and y) in the NDVI-time space using a two dimension bandwidth h (hx and hy). This bandwidth is variable and calculated using the multivariate plug-in selector proposed by Wand and Jones (1994). This way, the reference is set as the most frequent annual behavior (dark-red line inside the kernel in Fig. 4ab) and NDVI anomalies can be calculated as the difference between the NDVI observations and the most expected phenological curve. To evaluate how extreme these NDVI anomalies are, the position of the observed NDVI value in the kernel density space is checked (Fig. 4). In this study, we consider extreme negative or positive NDVI anomalies (Fig. 4b) when the observed NDVI value is outside the 95 % of the historical frequency distribution. This way, we aimed to identify the 2.5 % of the most extreme negative and 2.5 % of the most extreme positive years for the entire multi-decadal period of analysis. A complete description of the “npphen” approach is currently under review for publication, nevertheless, readers can refer to the following preprint for more information: Estay and Chávez (2018).

In many cases, the NDVI time series presented months without valid data (NA) (see Figure S1). To minimize NA dates, we focus on the three months Jan-Feb-March period, corresponding to the peak of the annual phenological cycle of bofedales (Figure S1), to construct composites of annual NDVI (NDVI_{JFM}) and NDVI anomalies for the 442 bofedal polygons of the study area. Please notice that in the South Hemisphere the growing season does not coincide with the calendar year. For this reason, the annual phenological cycle was set to start on July 1st, which is the day of the growing season 1 (DGS 001), and to end on June 30th of the following year (DGS 365).

3.2. Drought severity determination

We used monthly precipitation and temperature series available in the CR2MET database (<https://www.cr2.cl/datos-productos-grillados/>) over a 5-km grid for continental Chile (Boisier et al. 2018). According to

these data, we calculated the mean Standardized Precipitation Evapotranspiration Index (SPEI) values (Vicente-Serrano et al. 2010) for the entire study area, using time scales from 1 to 24 months from January 1984 to April 2018. The SPEI, among other drought indices (Balbo et al. 2019), such as Palmer Drought Severity index or SPI (Balbo et al. 2019) has been widely used to evaluate the influence of drought severity on vegetation dynamics (Albano et al. 2020, Jin et al. 2020, Luo et al. 2020). The SPEI allows us to detect the temporal window with the highest relationship with a concrete phenomenon.

3.3. Water rights

Archival research of historic water rights (WR) was conducted using the official depository of Chilean water rights or “Dirección General de Aguas” to identify both the distribution and evolution of the water rights granted to extractive industries in the study area. Official records of water rights commenced in 1905 and continue through the present. We examined data from 1905 till 2018 and looked for breaches and inconsistencies that were corrected when possible using supplemental data available from official technical reports (Figueiredo Ferraz Consultoría e Ingeniería de Proyecto, 1996, Dirección General de Aguas, 2004), data located at the Real Estate Registrar (Conservador de Bienes Raíces), court rulings, and field validation. We subtracted from the analysis the WR that are not currently exploited by industries since they do not imply effective extraction. Furthermore, we identified these former rights by reviewing the payment of fees for not using water rights, field validations, and interviews with experts and government officials. We georeferenced the data using GIS software to develop a database of the official distribution of water resources between 1905 and 2018.

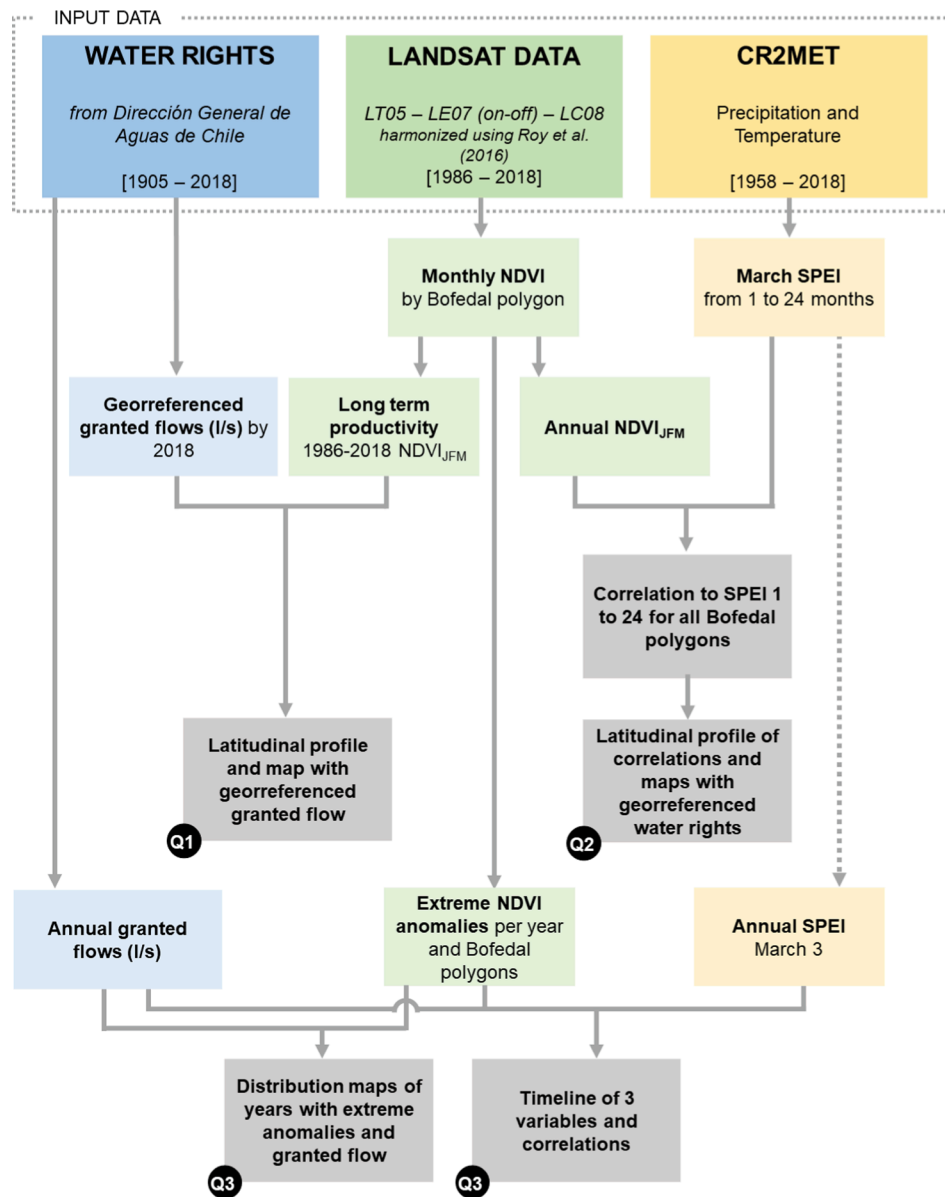


Fig. 3. Flowchart of the methods and the three research questions proposed in the introduction (Q1, Q2 and Q3).

3.4. Data integration

The three variables of interest (SPEI, NDVI, and WR) that we considered in this study have different temporal and spatial dimensions. Therefore, cannot be integrated using a single statistical approach. Bofedales productivity (NDVI_{JFM}) and anomalies were calculated on a yearly basis and for each bofedal (spatially discrete), while a single March SPEI was calculated for the entire study area but at different moving windows. The third variable, WR, are related to specific coordinates and the granted volume flow. Its only temporal feature is the year the right was granted. For this reason, the data integration of these three variables was carried out in four steps (gray boxes in Fig. 3):

i) We map the spatial location of the bofedal units disaggregated by different levels of mean annual productivity for the entire period (1986–2018) together with current (2018) granted WR. Along with the maps, we prepared latitudinal profiles of the two variables by calculating the area of bofedales at 5 different long-term NDVI_{JFM} classes and the total WR for each 0.1° of latitude of the study area.

ii) For each bofedal unit, we correlated the annual NDVI_{JFM} to the 1- to 24-months moving window March SPEI through means of the Pearson

correlation. Significant values are considered with a 95 % level. Both NDVI and SPEI follow a normal distribution. Pearson correlation is more suited in cases correlating these variables since Spearman works with rank-ordered values. We also calculated Spearman correlations (see [Supplementary material, Figure S4](#)) and temporal/spatial patterns of the results are not substantially different. We then displayed the spatial distribution of the Pearson correlation for each bofedal of the study area for each width of the SPEI moving window ([Supplementary material S3](#)) and summarized the moving windows at which significant ($P \leq 0.05$) maximum positive (green) or minimum negative (pink) Pearson correlation to annual NDVI occurred.

iii) We map the spatial location of the correlations between annual NDVI_{JFM} of single bofedales units and the different March SPEI moving windows together with the granted WR. Along with the maps, and similar to i), we prepared latitudinal profiles by calculating the area of bofedales at 8 different classes of significant correlations (4 negative and 4 positive) and the total WR for each 0.1° of latitude of the study area. The hypothesis here was that bofedales at latitudes with higher concentration of water rights had a weaker relationship to the drought conditions (SPEI at the different moving windows).

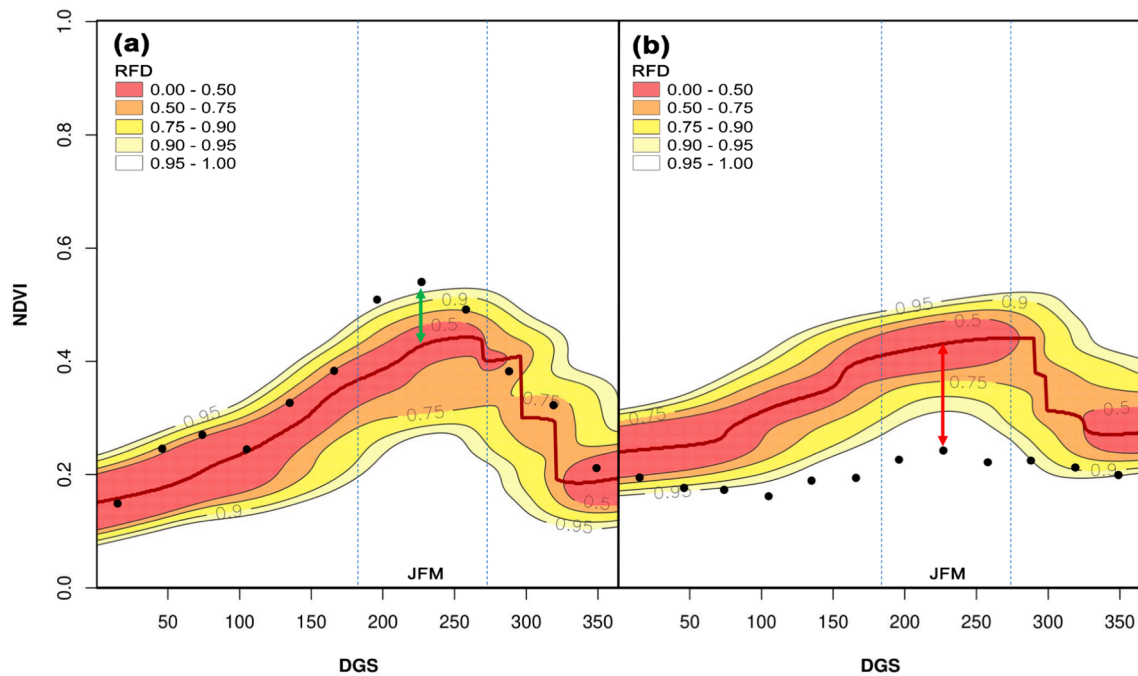


Fig. 4. Detection of years with extreme NDVI anomalies using the probabilistic “npphen” R package and austral summer (January-February-March, or JFM) Landsat NDVI records of two Bofedales units. (A) Example of a bofedal (68.07°S, 22.04°W) with an extreme positive anomaly in 2014: this year the NDVI_{JFM} records were outside the 0.95 reference frequency distribution (RFD), i.e. the positive anomalies belonged to the 2.5 % of the highest NDVI recorded in 32 years. (B) Example of a bofedal (67.19°S, 22.87°W) with an extreme negative anomaly in 2014: i.e. the negative anomalies belonged to the 2.5 % of the lowest NDVI recorded in 32 years. DGS = day of the growing season.

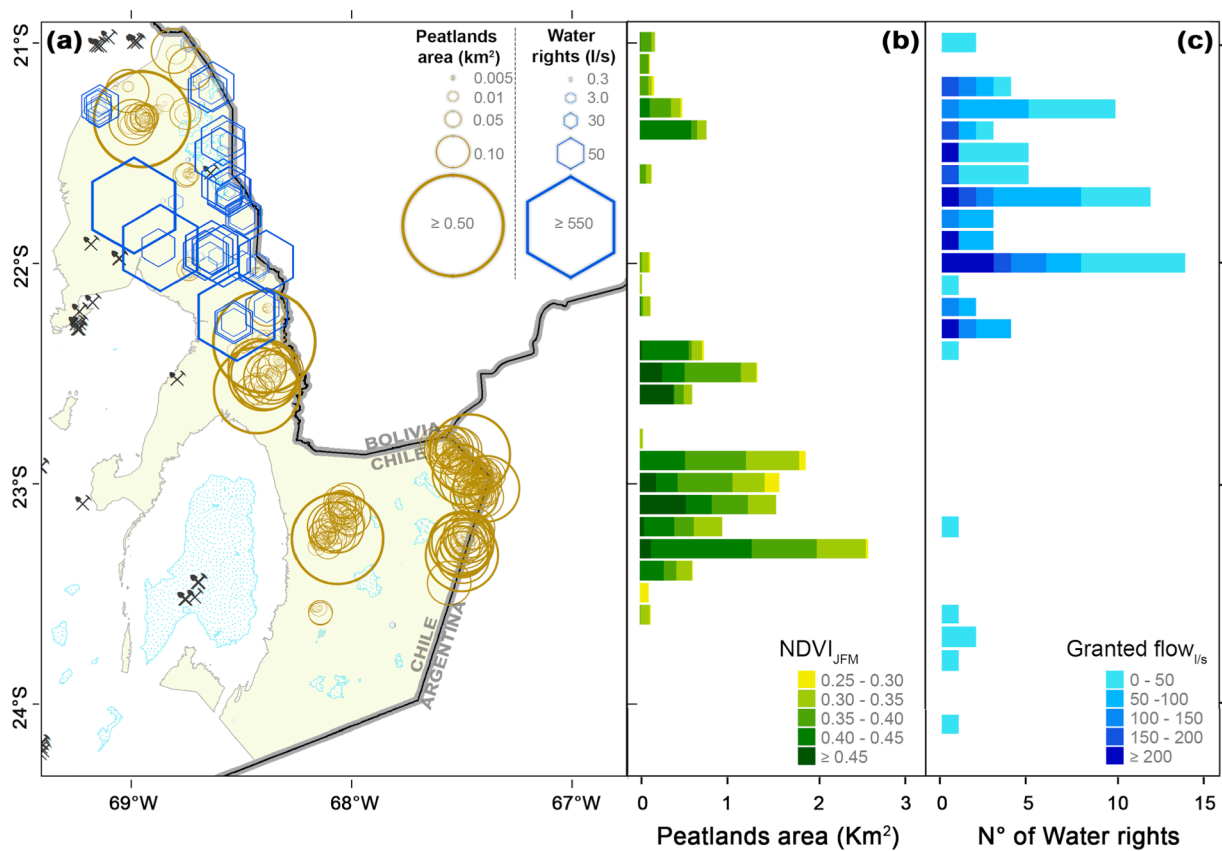


Fig. 5. Spatial distribution of bofedales and extractive water rights in the study area. **a)** Location and size (km²) of the 442 bofedal units and location and granted water rights accumulated (and active) by 2018. **b)** Latitudinal distribution of bofedales sorted by long-term productivity (1986–2018 NDVI_{JFM}). **c)** Latitudinal distribution of water rights sorted by granted flow (l/s). For latitudinal plots, each bar represents 0.1°S.

iv) We construct a yearly timeline with the total granted WR, SPEI March 3 and total area of bofedales suffering extreme positive or negative productivity anomalies. This provides a regional overview of the three variables through time. Finally, we showed specific maps of the years that concentrated more positive or negative productivity anomalies together with the WR granted that year to visually assess whether negative anomalies were spatially related to the presence or concentration of WR.

To facilitate the visual spatial assessment of the different variables, especially the annual NDVI_{JFM} time series of each of the 442 Bofedales, we developed an interactive dashboard combining graphs and maps, which is available at https://labgrs.shinyapps.io/AEOG_peatlands/. Please zoom in to the different bofedal polygons and click inside the polygon to display the NDVI_{JFM} time series.

4. Results

4.1. Spatial distribution of bofedales and water rights

Fig. 5 shows the distribution of the 442 bofedal units located in the study area together with the 75 WR officially granted by 2018 to extractive industries, equivalent to a total of 5,584 l/s. Readers can refer to the on-line dashboard available at https://labgrs.shinyapps.io/AEOG_peatlands/ for more details. WR under current use are concentrated in the north of the study area between 21°S and 22.4°S (Fig. 5-A-C), and only five are located in the southern part of the study area with granted flows of only 8.77 l/s. By contrast, bofedales are concentrated in the middle and southern part of the study area, with the main cluster of large units located between 22.9°S and 23.4°S. There are

no clear spatial trends in terms of bofedales size and productivity and units of different dimensions and NDVI_{JFM} classes can be observed in the entire latitudinal range. As noted when highlighting the limitations in the discussion section, what is remarkable is the gap with few bofedal units between 21.3°S and 22.1°S where most of the WR are located.

4.2. Spatio-temporal relationship between bofedales productivity and drought severity

From all possible SPEI time scales correlated to bofedales annual NDVI_{JFM}, we selected from 1- to 24-months previous to the March SPEI because of their higher correlations and because they should be good predictors of the bofedales Summer productivity (NDVI_{JFM}) since March is the last month of the annual NDVI growing season peak (Fig. 4 and Figure S2). Correlations to the 24 time scales for the March SPEI were calculated for each of the 442 bofedales and the results were summarized in Fig. 6 by total (km²) and relative (%) area of the bofedales with only significant positive and negative correlations. To construct the summary presented in Fig. 6A, we check at which March SPEI occurred the significant ($P \leq 0.05$) maximum positive correlation or minimum negative correlation for each bofedal unit and sum its area to the bar of that March SPEI. The results show that, considering all units of the study area, most of the bofedales have maximum positive correlations to March SPEI 1 (considering only March of each year), 2 (March and February of each year), and 3 (March, February, and January of each year). This is an indication that drought severity during the peak of the growing season (January to March) explains the most of bofedales productivity of that same year. Although minimum negative correlations also occurred for about 10 % of the total area of bofedales for March

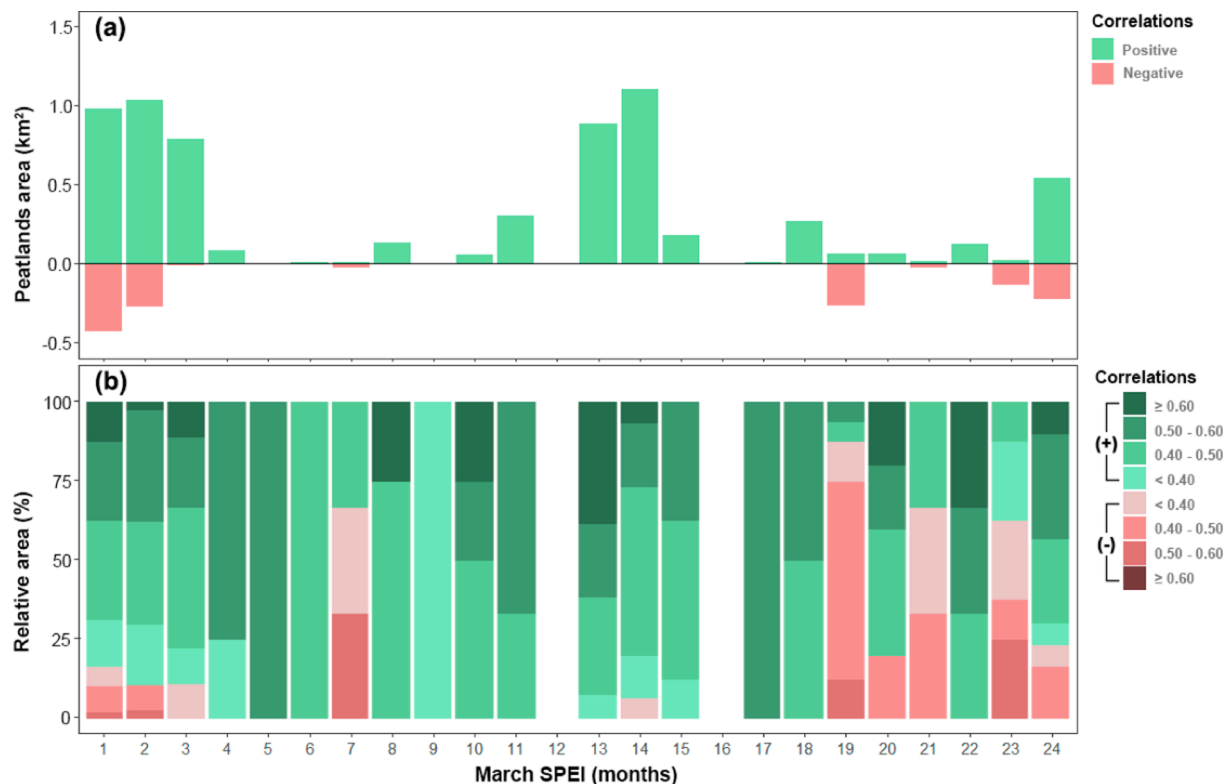


Fig. 6. Barplots summarizing the area of bofedal units with different Pearson correlation factors calculated between the regional Standardized Precipitation Evapotranspiration Index of March (March SPEI) and annual NDVI values of January-February-March (NDVI_{JFM}) of individual bofedales and for different time scales (1–24) for the March SPEI. **a)** For each window for the March SPEI, we sum the area of all bofedal polygons with significant ($P \leq 0.05$) maximum positive (green) or minimum negative (pink) Pearson correlation to NDVI_{JFM}. **b)** For each window for the March SPEI, we show the relative area of the bofedales with maximum or minimum correlation (A), but now organized by the different levels of positive (green palette) and negative (red palette) correlations. Please be aware that for some March SPEI months the area approaches zero, but it is not zero (e.g. 5, 6) while for others (12,16) is actually zero). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

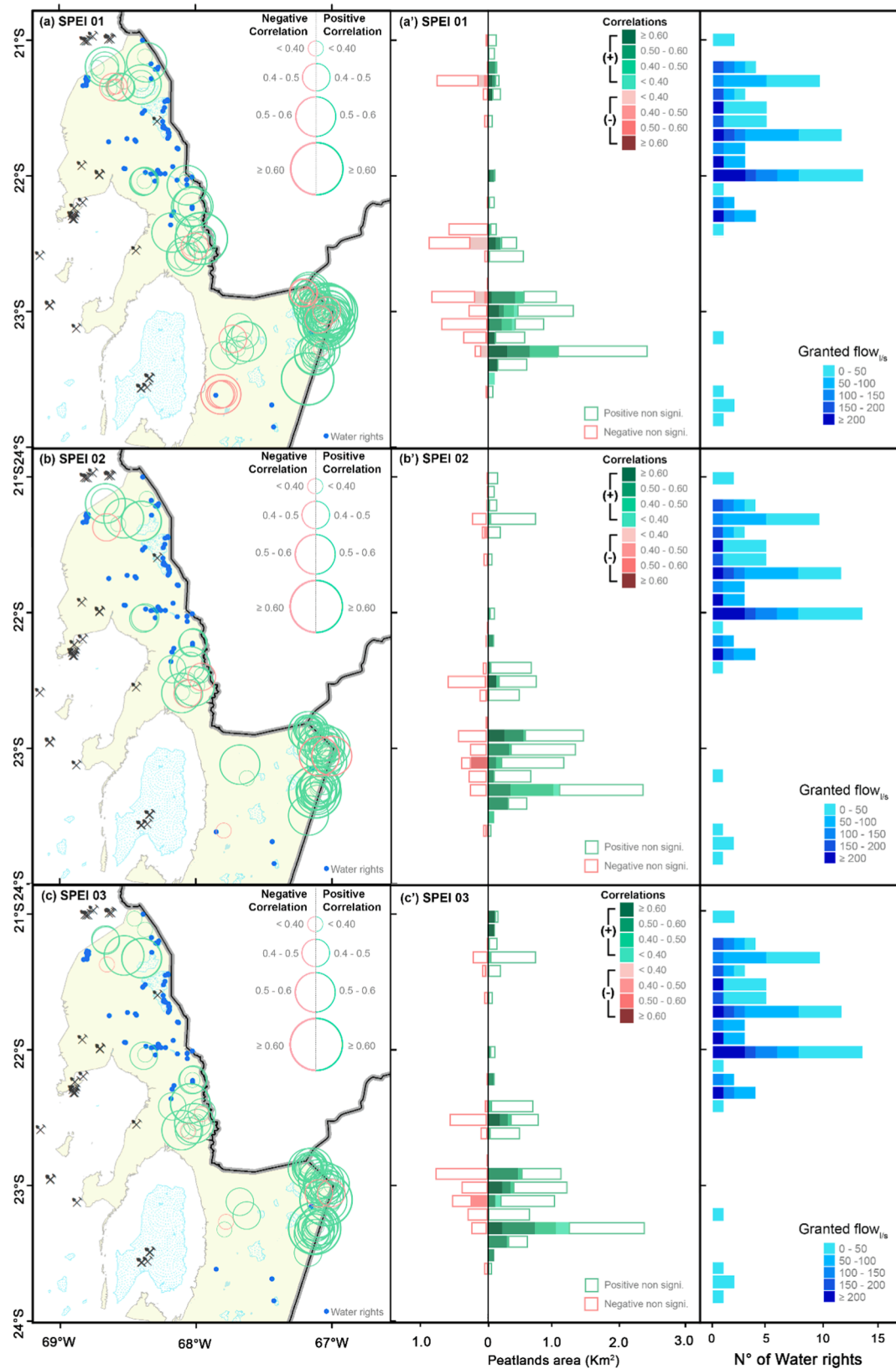


Fig. 7. Location of water rights and bofedales with different Pearson correlation between NDVI_{JFM} and SPEI March 1, 2 and 3 (a, b, c) and barplots (a', b', c') showing the area of bofedal units organized by the different levels of significant positive (green palette) and negative (red palette) correlation and by latitude (each bar represents 0.1° latitude). In supplementary material 1, the maps for the 24 SPEI March moving windows are provided. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

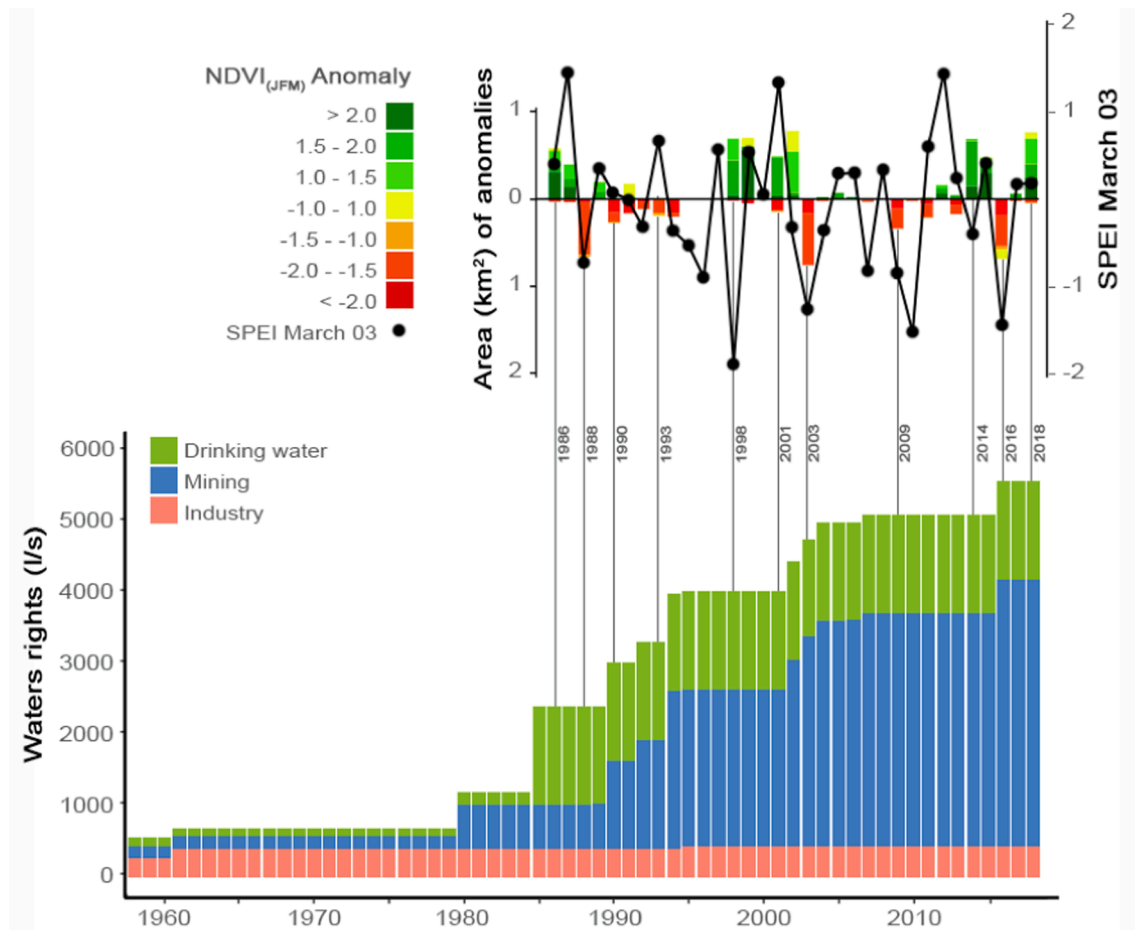


Fig. 8. Timeline showing a long record of granted water rights in the study area (1958–2018), summer drought by means of the SPEI March 3 (1986–2018) and the bofedales area showing extreme productivity anomalies, accounted by $NDVI_{JFM}$ anomalies that fall outside the 95% of the historical frequency distribution 1986–2018.

SPEI 1 and 2, i.e. going the opposite direction as droughts, it almost disappears for March SPEI 3, which is an indication that the accumulated drought of three months plays a more important role for bofedales summer productivity. This is indeed supported by the fact that about 80 % of the bofedales area with significant correlations present a correlation to March SPEI 3 larger than 0.4 (Fig. 6-B). A significant area of bofedales also has a maximum positive correlation to SPEI 13 and 14, which is an indication of the lagged influence of the drought conditions in the Summer of the previous growing season.

4.3. Spatial distribution of water rights and bofedales with different levels of correlation to drought

We display the geographical location of correlation between $NDVI_{JFM}$ of single bofedal units and the 24 different March SPEI in Figure S3 along to the location of granted WR (blue dots), while in Fig. 7 we show only the correlations to March SPEI 1, 2, and 3 (panel A), that showed large areas of maximum correlations according to Fig. 6. In Fig. 7B, we showed the latitudinal distribution of the correlations weighted by bofedales area for each of the three SPEI. Open bars represent non-significant correlations. From this figure, no clear spatial patterns can be observed from the location of different correlations between annual productivity and drought in regard to the location of water rights. Indeed, bofedales with non-significant correlations and the few bofedal units with negative correlation to SPEI are distributed along with the entire latitudinal range and not spatially related to the presence of WR. This supports that the annual productivity of the photosynthetically active bofedales of the study area over the last three decades is

mainly driven by SPEI.

4.4. Vegetation productivity of bofedales: NDVI anomalies, water rights, and drought

Fig. 8 provides an overview of major changes in annual productivity for all bofedales in the study area, the drought conditions through the years, and the increasing number of granted WR. Clear steps can be observed on the progressive increment of WR, 1985 being the most significant, going from about 1,201 l/s to 2,411 l/s. By 2018, 5,584 l/s had been granted in the study area (67 % mining, 25 % drinking water and 8 % industry). In the period from 1986 to 2018 we can observe different bofedal areas with extreme positive and negative $NDVI_{JFM}$ anomalies, which are explained to some extent by SPEI (there was a positive Pearson correlation between the area of extreme events and SPEI March 3 of 0.3 with a p-value of 0.08). For this calculation, we consider the area of extreme negative anomalies as negative values. The area of both extreme positive and negative anomalies was never larger than 1 km², which is less than 4 % of the total area covered by bofedales in our study area. Overall, only local and no regional extreme productivity changes in bofedales can be observed in the spatio-temporal framework of this study. In fact, Fig. 9 shows that the location of bofedal units with extreme anomaly years vary in location for different years, which is an indication that local rather than regional drivers would explain extreme changes in bofedales productivity dynamic.

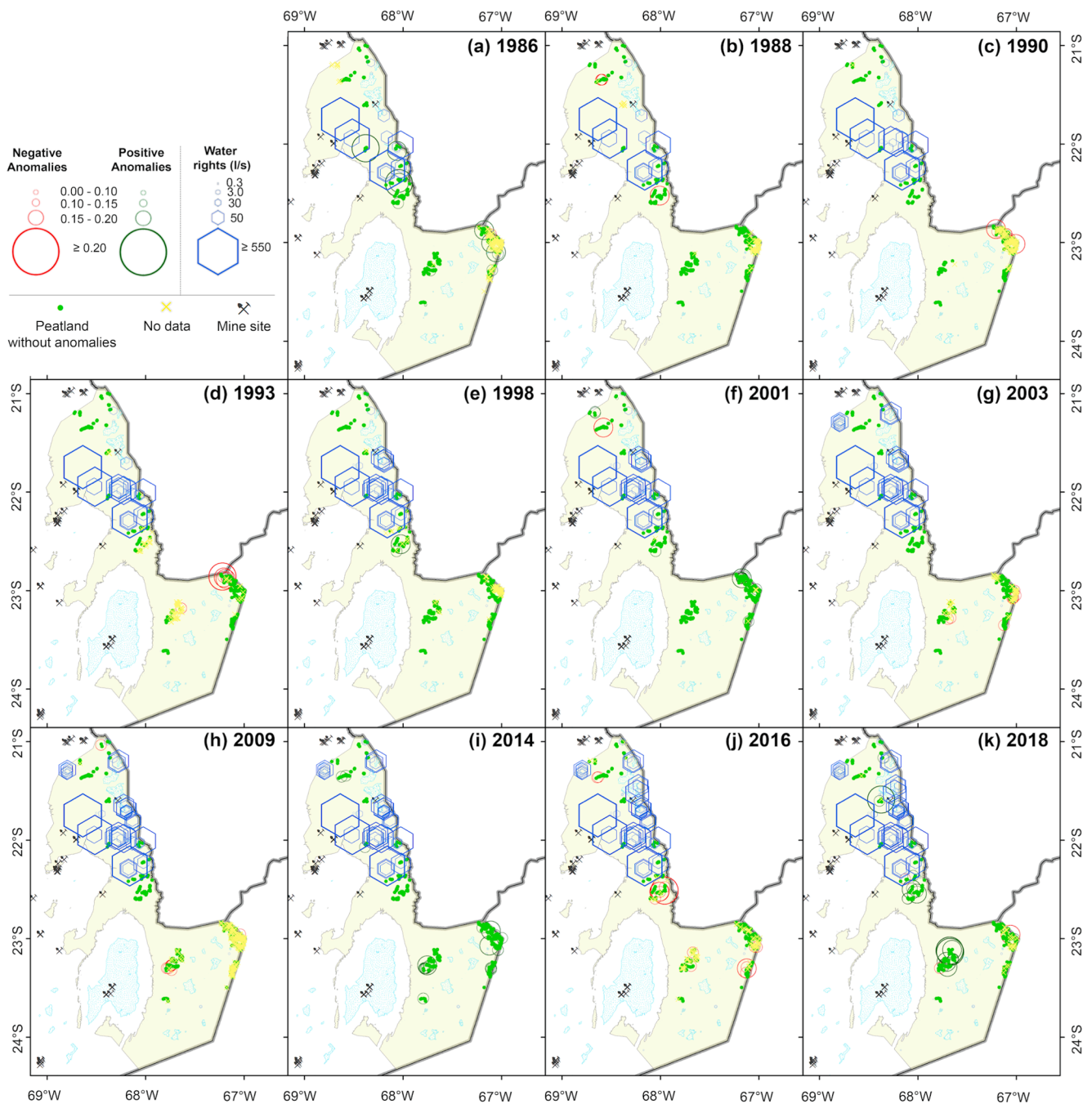


Fig. 9. Location of water rights and bofedales with extreme NDVI_{JFM} anomalies for selected years (those with larger bofedal areas of positive or negative extreme anomalies as indicated in Fig. 8).

5. Discussion

As shown in section 4.2, the highest SPEI-NDVI correlations are found for SPEI March 3, which is expected because it considers the drought severity in the growing season (Chávez et al., 2019a). Throughout the growing season, the drought sensitivity of vegetation varies depending on the phenological stage of the dominant species, reproductive stages and the high growth vegetative period being more susceptible to drought (Hahn et al. 2021). The high correlation found for SPEI March 13 and 14 suggests a lagged effect of the drought conditions of the previous year, which is in line with the findings of Anderson et al. (2021), who demonstrated that climate variables, specifically precipitation and snow persistence, from 2 years before were strongly associated with bofedales productivity. For the bofedales whose productivity

did not show good positive correlations with the SPEI 3 (March), we can hypothesize that they may be affected by snowmelt accumulated during the previous winter season. Another explanation could be that these bofedales have been punctually affected by torrential precipitation (high daily concentration) that affects the bofedal productivity (Craine et al. 2012) as runoff velocity increases, producing gully erosion (Hartman et al. 2016). We have conducted preliminary visual validation of this phenomenon in sloping and basin bofedales in the study area and further north. The SPEI cannot detect these types of extreme events since it is an index that considers only monthly precipitation values. It has also been demonstrated that the interannual precipitation variability may have negative effects in arid sites ecosystems with mean annual precipitation over 300 mm/yr, such as in the study area (Gherardi and Sala 2019).

Several indices exist for drought studies based on climatic variables

such as the Palmer Drought Severity Index, the Standardized Precipitation Index (SPI) or the SPEI, used in this study. The SPI (McKee et al., 1993) uses precipitation data and allows the determination and quantification of drought severity and has been used worldwide at different temporal and spatial scales. However, changes in climatic conditions, as it is in the Andean Altiplano, can violate the stationarity assumption of SPI, inducing erroneous interpretations (Blain et al., 2022). To overcome this problem, SPEI considers both precipitation and temperature data for its calculation and contemplates a climatic water balance at different timescales. Moreover, it includes temperature as a complementary variable to compute the potential evapotranspiration. Despite SPEI was originally calculated for each 5x5 km pixel of our study area, we used the mean SPEI considering the predominantly homogeneous orography (literally Altiplano means in Spanish “high and flat”) and has the same Koppen-Geiger climate (Sarricolea et al. 2017). Other studies have also used mean SPEI for greater areas (e.g. Turco et al. 2017), avoiding heavy raster calculations and facilitating the interpretation of the spatio-temporal patterns of correlations. This way, in this study differences in correlation for all possible temporal aggregations and time lags could be related to particular productivity conditions of the bofedal units.

Our results provide a good diagnostic of the current status of bofedales in one of the most active mining areas of Chile and South America and insights of which areas should be prioritized in monitoring efforts. These are the few bofedales units between 21.3°S and 22.1°S, where most of the WR are located, as well as the bofedales in the north (Fig. 5). Considering the individual responses of each bofedal to the interacting effects of water extraction and drought behavior, impacts on their productivity should be studied at the unit level separately. Indeed, several unique factors in each unit merit consideration through in situ studies at the individual bofedal unit level (topography, management, overgrazing, extreme events, etc.). While this research focused exclusively on changes in bofedal productivity concerning drought and water extraction, recent literature has shown in detail that local herder practices are also an essential factor in understanding the productivity behavior of these ecosystems (Yager et al. 2021). Thus, to improve our knowledge in the future, we aim to incorporate into our studies the diverse bofedal management techniques developed by herders (e.g., irrigation, burning, fencing).

Literature has shown that remote sensing techniques are helpful to understanding the transformations of bofedal productivity (García and Otto 2015, Dangles et al. 2017, Chávez et al., 2019a). Despite this potential, the fact that intensive water extraction began in the study area before the availability of satellite imagery limits us from analyzing the direct relation between bofedal productivity, precipitation and temperature behavior, and water extraction prior to 1986 (when the Landsat Thematic Mapper instrument started acquiring images for our study site on a systematic way). The digital inventory of bofedales carried out by Chávez et al. (2019a), used a base for this study, considered only “green” bofedales, i.e. with $NDVI \geq 0.23$ and, for this reason, bofedales that could have been “green” before 1986 would not be considered in this study. This situation is especially relevant given that the area with the most significant extraction of water has a reduced presence of bofedales in terms of area and productivity (Fig. 5), which shows that areas with high concentration of water rights show much less bofedal abundance. However, as mentioned above, large areas of bofedales existed prior to the study period in areas where the water rights are concentrated. For this reason, a retrospective study before 1986 would be very relevant to explain the existence of this bofedales gap. While this matter was not considered in this paper, in the near future we expect to conduct an historical retrospective study using a multi-source approach (aerial photographs, historical atlas, books and documents) to fill this gap.

6. Conclusions

This research assessed the spatio-temporal changes of bofedal plant productivity in relation to droughts and water extraction in the northern

Atacama Desert's highlands. We analyzed the time series of the NDVI over 32 growing seasons to determine areas experiencing extreme negative or positive changes in productivity. While several studies have evaluated the productivity of bofedales in the Andes using satellite imagery, this analysis is the first to research the interaction between these variables by considering a drought index and the history of water extraction by industries. We found that most bofedales positively correlate with SPEI 1, 2 and 3. This indicates that drought during the peak of the growing season explains most of the summer productivity behavior. While there are minimal negative correlations for approximately 25 % of the total bofedales area of SPEI 1, these are not observed for SPEI 2 and 3. This situation would indicate that the three-month cumulative drought has greater weight for the productivity of bofedales during the growing season. In the areas with the highest concentration of water rights, NDVI-SPEI correlations were not different from the rest of the bofedales. However, this is due to the fact that the negative effects of mining water extractions between 21.3°S and 22.1°S most likely occurred in that area prior to the availability of satellite images.

The fact that the Atacama Desert is one of the regions of the planet with the highest water demand due to mining activities, in addition to being an area highly vulnerable to climate change, demands further research to provide insights for the development of policy and management plans for water and related ecosystems. To this end, this study provides relevant information of which bofedales are currently under higher threat (21°–23.5°S) at a regional level, considering the latitudinal overlap between current “green” bofedales and active WR. In turn, the importance of these ecosystems for the region's indigenous communities makes their conservation an urgent environmental justice issue to be considered. The imminent transformation of the Chilean water management model within the current political debate opens the window for this type of consideration, mainly for the purpose of recognizing the social and environmental value of these ecosystems, which are practically absent to date.

CRediT authorship contribution statement

Roberto O. Chávez: Methodology, Formal analysis, Conceptualization, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing. **Oliver Meseguer-Ruiz:** Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing. **Matías Olea:** Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Matías Calderón-Seguel:** Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Project administration. **Karina Yager:** Conceptualization, Investigation, Writing – review & editing. **Rosa Isela Meneses:** Investigation, Writing – review & editing. **José A. Lastra:** Investigation, Writing – review & editing, Visualization. **Ignacio Núñez:** Investigation. **Pablo Sarricolea:** Investigation, Writing – review & editing. **Roberto Serrano-Notivol:** Investigation, Writing – review & editing. **Manuel Prieto:** Conceptualization, Methodology, Formal analysis, Investigation, Resources, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jag.2022.103138>.

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