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Original Article

Bofedal response to climate variability, local management, and water extraction: A case study of Chucuyo, Northern Chile

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Abstract: Andean high-altitude wetlands are important ecosystems that serve a range of social-ecological functions. In the Andes, bofedales, a specific type of peat-producing wetland, are essential for the sustainability of mountain ecosystems and indigenous pastoralist communities. The Chucuyo bofedal in northern Chile is affected by climatic variability and water extraction for agricultural uses via the Lauca canal. Herders in the local community also actively manage this wetland according to their traditional ecological knowledge to ensure permanent fodder for their animals. In this article, we analyze the annual behavior of the Chucuyo bofedal after the wet season. Based on precipitation data, extracted water flows, vegetation vigor from satellite images, and an ethnographic approach, we determined that the bofedal's productivity was negatively correlated with the amount of precipitation and positively correlated with the surface area of the wetland. However, water extraction via the Lauca channel had no significant relationship with either surface area or vegetation vigor. We identify community practices and traditional ecological knowledge as key elements in the maintenance of these ecosystems. This situation is critical in the context of an aging population and the current pattern of migration out of the region to urban areas. The results provide substantial empirical evidence for future decision-making regarding the conservation of these ecosystems.

Keywords: Atacama; Bofedales; Indigenous people; Lauca canal; Normalized Difference Vegetation Index

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1 Introduction

High-altitude Andean wetlands (locally known as Humedales Altoaninos), such as vegas, bofedales, and salt flats, provide multiple ecological and social benefits and fulfill a large number of socio-ecological functions (Garcia and Otto 2015). In particular, bofedales are a type of peat formation azonal wetland limited to elevations between 3,000 to nearly 5,000 m a.s.l. (Squeo et al. 2006). Bofedales are essential for the sustainability of mountain ecosystems (Yager et al. 2019). They are niches of biodiversity, play a role in global climate regulation, and regulate the water cycle (Buytaert et al. 2011; Garcia and Otto 2015; Dorador et al. 2013). They also fulfill important social functions (Yager et al. 2019). In the Atacama region (northern Chile, northwestern Argentina, western Bolivia, and southern Peru), bofedales have been used and managed since pre-Hispanic times by indigenous herders to ensure year-round fodder for their animals (mainly domesticated camelids: llamas, *Lama glama*, and alpacas, *Vicugna pacos*), as well as being a space of high cultural value (Palacios 1977; Orlove 1977; Lane 2014).

These ecosystems are currently at risk for several reasons. Human activities and climate change are identified as the main threats to bofedales' maintenance of their socio-ecological functions. Global climate change will affect this ecoregion in various ways. Warming trends are especially evident in Northern Chile (Meseguer-Ruiz et al. 2018), with unclear tendencies in precipitation patterns (Sarricolea et al. 2017a; Meseguer-Ruiz et al. 2020). In this context, rainfall variability expresses at both seasonal and interannual scales. A rainy season between December and March concentrates the major part of the accumulated precipitation (Sarricolea and Romero 2015), but substantial differences are evident from one year to the next (Meseguer-Ruiz et al. 2019).

Bofedales are extremely sensitive to the aforementioned impacts (Otto and Gibons 2017), expressing them by means of their productivity (Chávez et al. 2019; Anderson et al. 2021). Various studies have addressed the issue following the Normalized Difference Vegetation Index (NDVI) data according to different satellite imagery (Baldassini et al. 2012; Dangles et al. 2017; Casagranda et al. 2019; García et al. 2019). These studies show the potential of remote sensing series to observe and evaluate the evolution of these high mountain ecosystems. They also allow us to monitor their responses to environmental changes in these areas. However, there is a particular scarcity of these studies in the Chilean Altiplano.

The Chilean Altiplano is the driest area of the whole plateau, having a tundra climate with extreme weather conditions (Sarricolea et al. 2017b), but it has nevertheless been inhabited by human populations such as the Aymara since pre-Hispanic times. Since the mid-twentieth century, the indigenous Aymara communities of northern Chile have undergone important changes. These include the deruralization of their activities, as well as depeasantization, proletarianization, and the establishment of translocalized relationship networks, which include urban spaces or other places to which they have migrated (González 2007). The Aymara herding community of Chucuyo (Fig. 1) provides a good example of this phenomenon. Like other communities in the Andes, this community manages their bofedales according to their own ecological knowledge and practices for ensuing permanent fodder for their animals (White-Nockleby et al. 2021).

The water availability in this area is primarily determined by climate variability, but water in this region is highly compromised by the Lauca channel, a waterway that runs from the Lauca River to the Azapa Valley and irrigates agricultural land near the city of Arica. Its construction began in 1948, starting the water extraction of the 1960s (see details in Gonzalez et al. 2016). The effects of climate variability might be masked by the effects of water extraction from the Lauca River. Because climate variability and the Lauca channel play fundamental roles in the water availability of the Chucuyo bofedales, analyzing their relationship is essential if we are to understand how new climate scenarios may contribute to further aggravating the situation of a territory with existing problems of water scarcity caused by human interventions.

The present research seeks to determine the impacts of both the Lauca channel and climate variability on the bofedales of the Chucuyo indigenous community. To do this, we analyze the evolution of the bofedales' productivity, surface area, and precipitation variability, the flow rate of the Lauca channel, and the impacts of the community's activities in the region. The study demonstrates the importance of developing a mixed methodological approach that includes traditional ecological knowledge. This kind of approach provides an empirical basis that can inform the design and development of public policies and management plans at different scales to guarantee the conservation of these important ecosystems, and to identify the relevance of community management to guarantee these ecosystems conservation under an unfavorable climate context in other high mountain areas.

2 Study Area

The indigenous community of Chucuyo is located in the Arica y Parinacota region in northern

Chile (Fig. 1) at 4,400 m a.s.l. It is an Aymara cattle-raising locality that has inhabited these areas since pre-Hispanic times (Sitzia et al. 2019), and the community has developed the routines of everyday life within this harsh environment. In local practices, the territory is organized into hamlets or ranches (locally known as estancias) in which the main economic activity is raising camelids. This requires the community to make seasonal use of water resources and manage their bofedales.

Chucuyo is located in the Lauca River basin, which covers an area of 2,427 km². The Lauca River basin is located in the Putre commune, is a tributary of the Coipasa salt flat in the Bolivian Altiplano, and forms part of the Altiplano basins of the Arica and Parinacota region. The Lauca River is fed by the waters of the Cotacotani lagoons, which in turn feed the Parinacota bofedales, the sector in which its headwaters are located.

The Chucuyo community is part of the historic indigenous community of Parinacota, where there is a subdivision in terms of land ownership. However, water rights are collectively owned by both communities in places where the descendants of the people of Chucuyo, Parinacota, and other adjacent settlements are grouped together. Water is especially important to these communities in their daily activities. Herding, for example, is an essential activity. Herders use water as part of various local managerial practices, including irrigation, to maintain their bofedal. These practices are based on traditional ecological knowledge about the climate and its environment. Indeed, climate perception plays a fundamental role in the construction of local community knowledge, as it allows communities to plan their actions to account for the effects of climate variability.

3 Data and Methods

3.1 Mapping and Ethnographic approach

To create a description of the forms of land use of

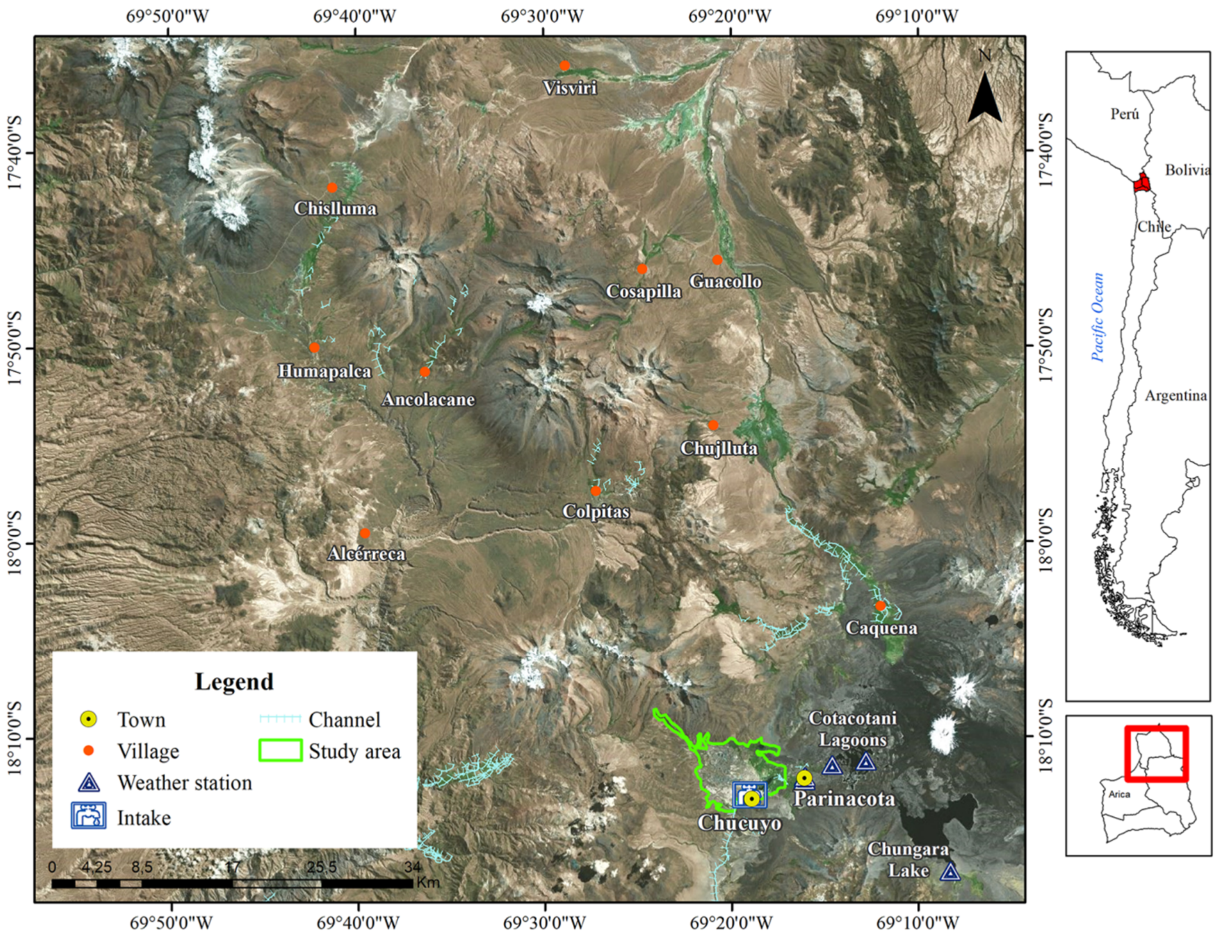

Fig. 1 Location of the indigenous community of Chucuyo, northern Chile.

the indigenous community of Chucuyo, we used as base information the cartography of the uses of the bofedales created by Castro and Bahamondes (1998). These authors explain the uses of various herding areas of the Altiplano in the Arica y Parinacota region. The territories of the communities of Visviri, Humapalca, Colpitas, Parinacota, Cosapilla, Ancolacane, Chujlluta, Guacollo, Alcerreca, Caquena, and Chislluma, among others, are cartographically represented. First, we digitalized the cartographic information using Geographic Information Systems, then we georeferenced this information with control points. Using this procedure, it was possible to generate layers describing the land use patterns. According to this, we labeled the bofedales with their respective names and measured their distribution and extension. In order to identify the bofedal corresponding to the community of Chucuyo, the same procedure was carried out, also incorporating the successional property plan of the families belonging to the locality of Chucuyo. To complement the description of land uses in the Chucuyo community, semi-structured interviews were conducted with key informants (community leaders).

3.2 Satellite, climatic, and flow data

We determined the productivity of the Chucuyo bofedal by means of the NDVI, extracted between 1987 and 2015 using satellite images corresponding to the beginning of the autumn season, when the bofedales generally show greater vegetational vigor (Chávez et al. 2019). The NDVI is calculated according to both the Near Infrared and Red bands as it follows:

$$\mathrm{NDVI} = \frac{\mathrm{NIR}_{band} - \mathrm{Red}_{band}}{\mathrm{NIR}_{band} + \mathrm{Red}_{band}} \quad (1)$$

where NIR_{band} is the Near Infrared band and Red_{band} is the Red band from the Landsat images (Rouse et al. 1974).

NDVI values range from -1 to 1. Negative values correspond to manmade structures or water surfaces, since bare soils range from 0 to 0.2 and plants between 0.2 and 1. We worked with this time period because older satellite images are not available on a continuous annual basis to build a continuous series that can later be correlated with meteorological information. We carried out the analysis using Landsat 5 and Landsat 8 satellite images, obtained from the USGS website (https://earthexplorer.usgs.gov/). To carry out the classification of the productivity ranges, we considered 14 control points as a reference in the study area. The surface area of the bofedal was also extracted from the Landsat images.

The vegetation identified as more vigorous corresponds with locations closest to surface water runoff or bodies of water, which also show darker colors on the ground and in the satellite images. The vegetation identified as of medium and low intensity was selected using the same criteria (distance from water bodies and evidence on the ground of less vegetational vigor). As a complement, control points were taken in areas with bare soils, and where there is evidence of saline deposits and dry vegetation due to the drying of water bodies. To process the satellite images, we drew a polygon that covers the entire Chucuyo bofedal. Subsequently, we developed a reclassification system to calculate the area of the bofedal by year, taking into consideration the spatial resolution of each image. To establish the limits of the Chucuyo bofedal, the area of the bofedal in the year 2013 was taken as a reference, as this was the year in the study period during which the bofedal showed its greatest extension. To measure the bofedal's behavior, we prepared a graph showing the fluctuation in its surface area, indexed to its average. Based on the fluctuation in surface area and the vigor of the vegetation, we determined which years were above and below the average area of the bofedal. To understand the variations in the productivity of the Chucuyo bofedal, we calculated the average values from each of the images we worked with.

To determine the extracted water from the Lauca channel, we used monthly values from the Bocatoma Lauca station (located at 18°12'58"S - 69°19'2"W), belonging to the Chilean General Water Directorate (hereinafter DGA, its Spanish acronym) between 1987 and 2015. We determined that there were less than 1% missing values per year in the series. We also used monthly precipitation values from the Retén Chucuyo meteorological station from the DGA (Fig. 1). We conducted data quality analysis and gap-filling using the Climatol R package (Guijarro 2016), analyzing seasonal precipitation anomalies over the 1987-2015 period. We finally related these two hydrological variables with the NDVI data of the bofedal and its surface using the Pearson correlation, assuming that all of the variables follow a normal distribution.

4 Results and Discussion

We located the territory corresponding to the historical indigenous community of Parinacota, which includes the localities of Chucuyo and Parinacota. It was also possible to locate bofedales, intermittent streams, streams that were used for grazing, permanent hamlets, temporary hamlets, crossroads, villages, apachetas, main peaks, communal hills, tutelary hills, internal and external grazing routes of the Parinacota territory, lake masses, and surface runoffs (Fig. 2).

With the information in this study, it was possible to confirm that the community is extensive in nature, meaning that the space it occupies covers extensive sectors that are far from the nuclear towns. Evidence of this can be seen in the large number of permanent and seasonal ranches, as well as the various routes and grazing circuits organized around bofedales and bodies of water, which tend to vary depending on climatic factors. The Chucuyo bofedal corresponds to the distribution shown in Fig. 3.

The Aymara herding communities have developed different strategies for managing the landscape, in particular the water resources in the bofedales (Yager et al. 2019). In the case of the indigenous community of Chucuyo, these strategies allowed community members to optimize the available resources in each season, depending on climatic variability and herd size. The work patterns and technologies of the indigenous communities are linked to the ecological cycles of the territories where they live and to their cosmovision. The Chucuyo community, for example, has developed a cycle in which activities related to cattle raising are mixed with ritual technology (Van Kessel 1998). According to the ethnographic data gathered previously, some of the ritual activities carried out by the community around water use in Chucuyo include the *Wilancha* ceremony, the *Killpa* (or *floreo de llamos*), carnivals, and community cleaning of canals. The *Wilancha* consists of a ceremony that takes place during

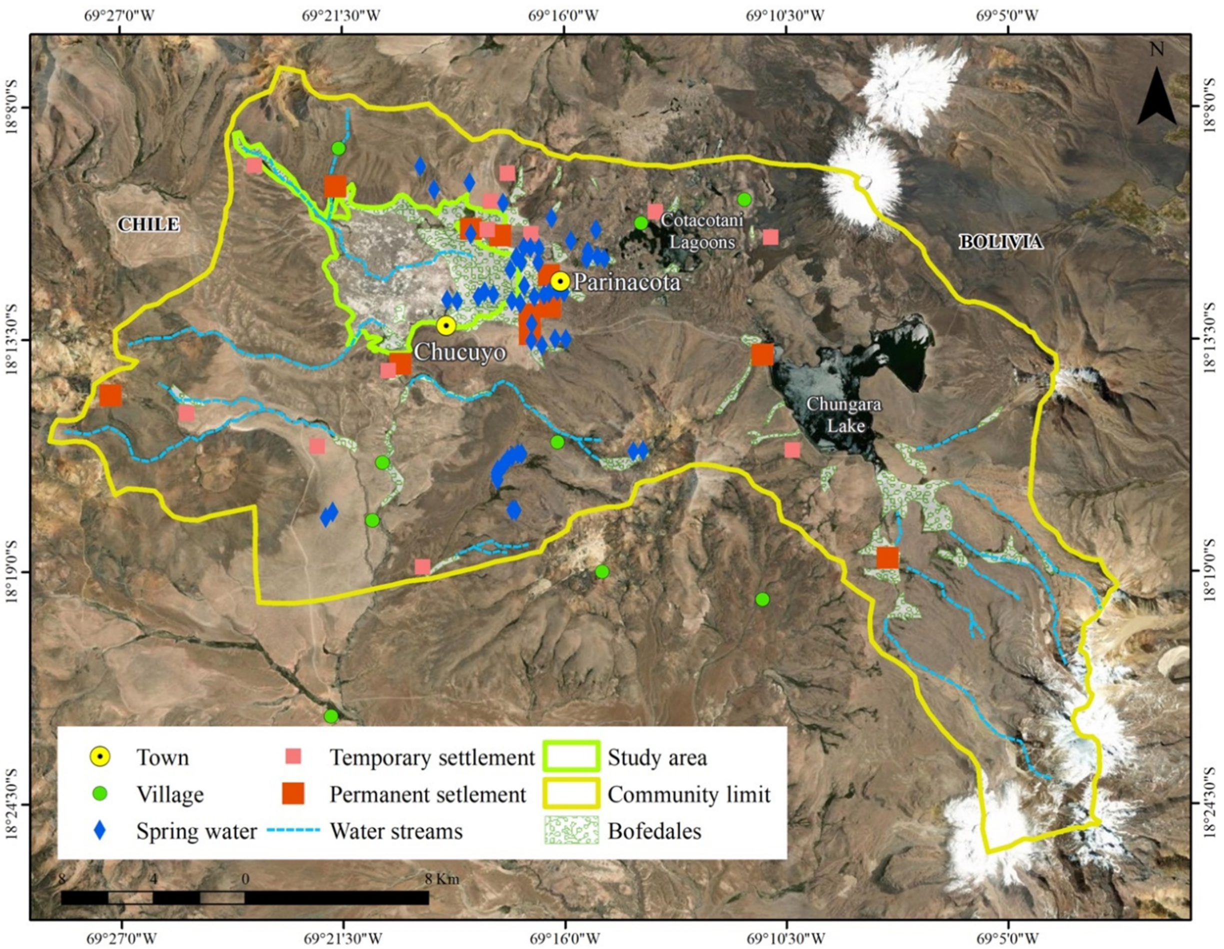

Fig. 2 Location of the Chucuyo community territory in the Arica and Parinacota Region in 2015.

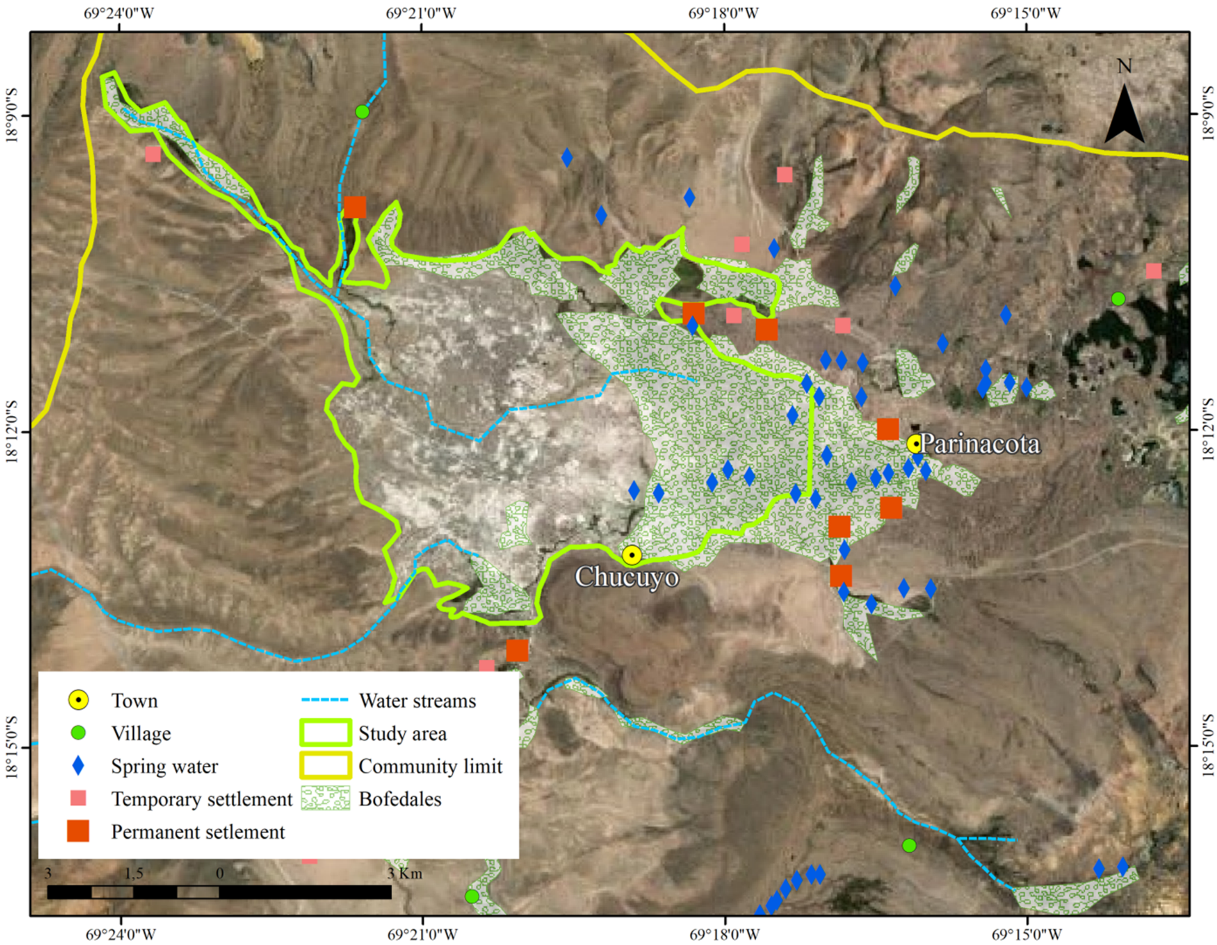

Fig. 3 Location of the Chucuyo bofedal in the Altiplano in 2015.

December, January, and part of February, in which some of the best animals are sacrificed in front of the *Payachatas*, the community's tutelary (or sacred) hills, and also in the springs in gratitude for the water they provided for the community's livestock activity. In the *Wilanchas*, the community leaders, such as *mayordomos*, *alférez* (ensign), and celebration-goers drink the blood mixed with toasted flour "to give them more energy," as an informant told us. Later, with the meat of the sacrificed animals, *huatias* (a traditional dish) were made for the community. While the *Wilancha* is a way of enacting the symbolic relationship between the community and elements of the natural environment (according to semi-structured interviews with D.H. and S.T.), as a ritual technology it also has concrete effects favoring social reproduction (Van Kessel 1998).

The *Killpa* is a celebration that takes place during January and February in which animals are branded with colored pompoms and saddled to carry loads. During the celebration, in addition to branding the animals, Chucuyo community members take advantage of the opportunity to exchange animals, as this allowed them to improve the genetic quality of the camelids they raise. The cleaning of community canals is another important activity carried out in Chucuyo, with the function of distributing the water from the bofedales. This activity was carried in November, December, and January, as these are the months in which the rainy season begins.

These ritual practices are linked to a situated perception of the climate based on everyday experiences (Orlove 2002). They are the basis of the traditional ecological knowledge from which the Chucuyo community has developed the water resource management strategies for its bofedales. With this knowledge, the community is able to identify different characteristics in the interdecadal and interannual climatic variability of its space and map how this relates to its territory. According to some leaders, during the 1980s the community experienced a long period of drought that had a negative impact on livestock activity, causing some of its members to abandon this activity and migrate to the city of Arica. According to one of the community members, “There were years of intense droughts. The worst years were in the early 80s to the 90s, when the Payachatas looked like hills — they had no snow at all”.

Community members also stated that in recent years there have been extreme levels of precipitation, corresponding to wet years. In the latter case, they pointed out that the temporal distribution of precipitation during the wet season becomes a determining factor in water availability for their bofedales. The concentration of precipitation in very short periods leads to erosive processes caused by the violent surface runoffs that are activated during these extreme events, which end up damaging the development of the bofedales.

Regarding the behavior of the Chucuyo bofedal according to the remote sensing analysis, we determined the highest and lowest values for each of the satellite images used, taking into consideration that these correspond to the months of April in the 1987 - 2015 series. From the result of both values, an annual average was calculated in order to observe the variations. The years with the highest average levels of vigor were 1992, with a value of 0.148; 2003, with a value of 0.114; 1990, with a value of 0.099; and 1995, with a value of 0.084. The years that showed a lower level of vegetation vigor were 2004 with a value of -0.123; 2012, with a value of -0.099; 1999, with a value of -0.055; and 2005, with a value of -0.041.

It should be noted that there were years in which the maximum vegetational vigor was above or equal to the values of the years with high average vegetational vigor previously mentioned (1992, 2003, 1990, and 1995); however, these also had very low minimum values that were close to the average (Table 1).

It is necessary to point that the mean NDVI may not really reflect the annual surface dynamic of the bofedal due to the negative values in bare soils of the study area, which represents a limitation to this study. Moreover, the NDVI may also not necessarily reflect the bofedal vigor because high values may be related with high presences of gramineous plants, that may reflect a degradation of the bofedal. Also, more severe droughts situations may not necessarily reflect a clear

Table 1 Temporal variation of the Chucuyo bofedal NDVI and surface area (ha)

Year	Max NDVI	Min NDVI	Mean NDVI	Surface Area
1987	0.510638	-0.428571	0.041033	38.847
1988	0.631068	-0.575000	0.028034	45.072
1989	0.603774	-0.551724	0.026025	43.134
1990	0.576923	-0.379310	0.098806	39.909
1991	0.580018	-0.489796	0.045102	41.547
1992	0.575758	-0.280081	0.147879	37.503
1993	0.494737	-0.481481	0.006628	37.458
1994	0.600021	-0.538462	0.030769	43.878
1995	0.588235	-0.419355	0.084440	39.249
1996	0.586957	-0.478261	0.054348	40.971
1997	0.562501	-0.608696	-0.023098	41.064
1998	0.553398	-0.485714	0.033842	35.205
1999	0.595962	-0.705882	-0.054961	42.351
2000	0.657658	-0.626667	0.015495	46.221
2001	0.663551	-0.680005	0.008224	45.423
2002	0.627119	-0.623529	0.001795	40.161
2003	0.560976	-0.333333	0.113821	33.801
2004	0.684211	-0.931035	-0.123412	42.075
2005	0.657658	-0.739130	-0.040736	42.717
2006	0.666667	-0.941176	0.1372545	45.774
2007	0.555556	-0.461538	0.047009	37.743
2008	0.704918	-0.714286	-0.004684	44.706
2009	0.666667	-0.818182	0.0757575	43.908
2010	0.672414	-0.555556	0.058429	32.694
2011	0.650485	-0.804878	0.077196	43.908
2012	0.519231	-0.717949	-0.099359	32.694
2013	0.457837	-0.342958	0.057439	51.915
2014	0.409969	-0.327990	0.040989	45.261
2015	0.465570	-0.343777	0.060896	51.418

loss of wetland area, as shown in other studies (Shen et al. 2021). This is reflected in particular years. For example, 1997 was one of the wettest years in all the studied period, but a reduction of the vegetational vigor in the Chuvire sector was detected. On the contrary, in 2003 and 2004, two of the driest years, we detected high vegetational vigor in all areas, despite a reduction of the bofedal surface.

The satellite image analysis showed variations in the surface area of the Chucuyo bofedal between 1987 and 2015. According to the series studied, the year that presented the greatest extension was 2013, with 51.915 ha (Fig. 4). The year in which the bofedal had the smallest area was 2012, with an extension of 32.694 ha. As a result, the average for all of the years analyzed was 41.725 ha.

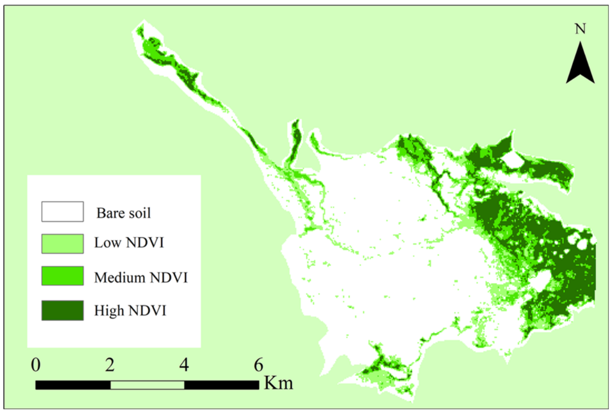

Fig. 4 NDVI values and extension of the Chucuyo bofedal in 2013.

Between 1987 and 1992, there is an almost intercalated variation of years with high and low vegetation vigor. The bofedales that showed the most marked annual variations were Rosapata, Chucuyo, Choallani, Jachumacho, and Casa Rosada. In the period between 1993 and 1998, there was a dramatic weakening of vegetational vigor and a reduction in the surface area of all of the bofedales, with Chuvire and Rosapata being the most affected sectors. In contrast to the above-mentioned period, in the series corresponding to the years 1999 to 2004, there was a marked increase in vegetational vigor in each of the bofedales. During the series corresponding to the years 2005 to 2010, the trend of bofedales with high vegetational vigor continued, except in the years 2010 and 2007, when there was a weakening of vigor in the Chuvire and Rosapata bofedales. In the series corresponding to the years 2011 to 2015, there was also a tendency to maintain a high vegetational vigor, except in 2012, when there was a dramatic weakening of vigor in Chuvire and Rosapata and a reduction in the surface area of all the bofedales (Table 2, Appendixes 1 and 2).

The accumulated annual precipitation and the total annual extracted flow show high interannual variability (Fig. 5). The precipitation variability corresponds with the results presented in Meseguer-Ruiz et al. (2019). The extracted flow by the Lauca channel also varies with no observable relationship with water availability. This is explained by the fact that the variations in water extraction depend mainly on the decisions of institutions such as the DGA and COMCA (the Azapa Channel Water Community), considering the amount of water demanded by the Azapa valley. The productive growth of the Azapa valley has conditioned the local practices of the Chucuyo community due to the pressure exerted by economic interests on the waters of the Lauca canal. The territorial inequality expressed in the distribution of water use rights is an example of how regional development policies have favored the productive

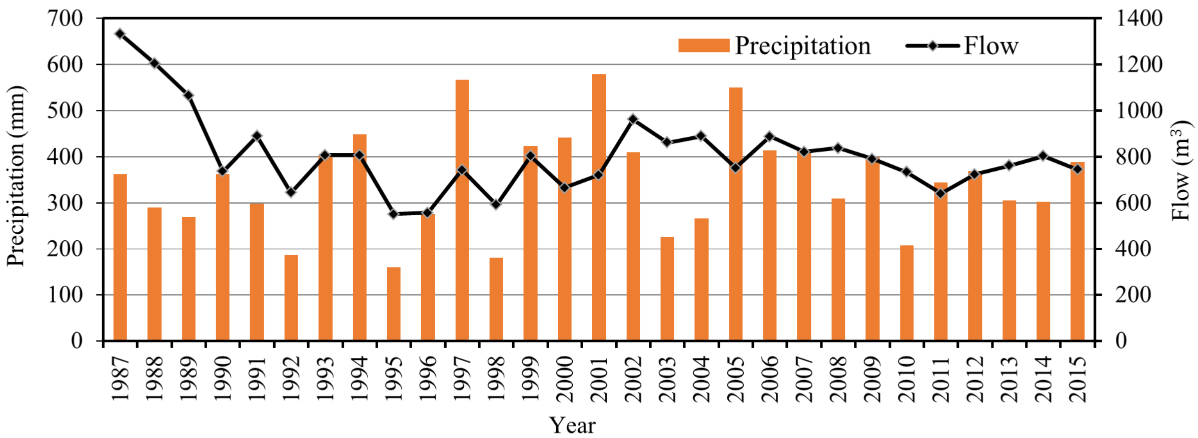

Fig. 5 Temporal variability of precipitation and flow in the above-mentioned stations between 1987 and 2015.

Table 2 Observed changes in the Chucuyo bofedal in Chile

Year	Observed changes
1987	Weakening of vegetational vigor in the Rosapata, Jachumacho, and Casa Rosada sectors.
1988	Increased vegetational vigor in the Rosapata, Chucuyo, Choallani, Jachumacho, and Casa Rosada sectors.
1989	Increased vegetational vigor in the Rosapata, Chucuyo, Choallani, Jachumacho, and Casa Rosada sectors.
1990	Weakening of vegetational vigor in the Rosapata, Choallani, Jachumacho, and Casa Rosada sectors.
1991	High vegetational vigor in Rosapata, Chuvire, and Cruzane.
1992	Weakening of vegetational vigor in the Rosapata and Chuvire sectors.
1993	Dramatic weakening of vegetational vigor and reduction of bofedal area in the Chuvire sector. Weakening of vegetational vigor in the Rosapata sector.
1994	Increased vegetational vigor in the Chuvire, Rosapata, Jachumacho, and Casa Rosada sectors.
1995	Reduction of vegetational vigor in the Rosapata sector.
1996	Reduction of vegetational vigor in the Chuvire sector.
1997	Reduction of vegetational vigor in the Chuvire sector.
1998	Reduction of vegetational vigor in all bofedal patches.
1999	Increased vegetational vigor in all bofedal areas.
2000	High vegetational vigor in all bofedal areas.
2001	High vegetational vigor in all bofedal areas.
2002	High vegetational vigor in all bofedal areas.
2003	High vegetational vigor in all bofedal areas. Reduction in the surface area of the bofedal.
2004	High vegetational vigor in all bofedal areas.
2005	High vegetational vigor in all bofedal areas.
2006	High vegetational vigor in all bofedal areas.
2007	Weakening of vegetational vigor in the Chuvire and Rosapata sectors.
2008	High vegetational vigor in all areas of the bofedal.
2009	High vegetational vigor in all areas of the bofedal.
2010	Weakening of vegetational vigor in the Chuvire and Rosapata sectors.
2011	High vegetational vigor in all areas of the bofedal.
2012	Weakening of vegetational vigor in the Chuvire and Rosapata sectors. Reduction in the surface area of all bofedal areas.
2013	Increase in the surface area of all bofedal areas. High and medium vegetational vigor in all of the bofedales.
2014	Medium and low vegetational vigor in all bofedal patches.
2015	High and medium vegetational vigor in all the bofedales.

expansion of the agricultural valleys over the local livestock-raising economies of the Altiplano.

Annual precipitation and NDVI show a negative correlation (-0.345; Table 3). According to some community reports, the bofedal not only depends on precipitation water availability, but also on groundwater recharge, which occurs in the summer periods. The distribution of rainfall allows for improvements in the vegetational vigor of the bofedal. This means that extreme precipitation events, which represent a very important amount in the total annual precipitation (Meseguer-Ruiz et al. 2019), cannot provide water to the bofedal productivity: they generate higher surface water circulation and erodibility and a lower groundwater recharge, influencing the NDVI directly (Anderson et al. 2021). The consideration of the complete year precipitation can also generate differences of only the wet season would be considered, so the bofedales productivity could show a better correlation with other indices (such as drought severity indices).

Table 3 Pearson correlations between the different variables. Significant values ($p < 0.1$) are marked with *.

	NDVI	Surface Area
Precipitation	-0.345*	0.338*
Flow	-0.120	0.081

Note: NDVI=Normalized Difference Vegetation Index.

The annual precipitation and the Chucuyo bofedal surface show a positive correlation (0.338). However, it is necessary to point out that temperature data were not integrated. Temperature affects the distribution of the vegetation cover of the bofedales due to the evapotranspiration process and the freezing burn in the typical low temperatures of the Altiplano (Meseguer-Ruiz et al. 2018).

The bofedal NDVI and surface do not show a significant correlation with the extracted flow in the Lauca channel. Hence, the influence of precipitation could be modifying this relationship (Guo et al. 2014). It is necessary to point out that the behavior of the bofedal not only depends on climatic variables, but also on the managing practices of the Andean communities (Yager et al. 2019). According to some leaders, the surface area of the bofedal depends to a large extent on the work carried out by the community to weed and open the water springs. These tasks have been changing over the last decade in their scheduling: in the past, these activities were programmed for August, after the coldest months, but now they are carried out at the end of September and October, in the spring, prior to the wet season. These practices have weakened recently because there are fewer community members, and those who still inhabit the territory belong to older age groups and are not carrying out these collective activities (Verzijl and Quispe 2013; Tapia Tosetti et al. 2018).

As part of their traditional ecological knowledge, members of the Chucuyo community recognize the interdecadal and interannual climate variability, most of which is in agreement with a statistical analysis of precipitation in the region. However, it should be noted that the daily concentration of precipitation within the wet periods becomes a relevant factor for the community, as concentrated precipitation events are not beneficial for the bofedal. The excess water produced by rainfall forms temporary lagoons that help recharge the aquifer of the Lauca River as part of a natural cycle. However, the Lauca canal intervenes to take advantage of the increase in this resource, as much of the surface runoff activated is a tributary to the main river in the stretch before the intake.

As has been widely recognized in the literature (White-Nockleby et al. 2021), the cleaning and maintenance of canals in bofedales (among other management practices, such as livestock rotation and the use of fire) have a significant effect on their size, vegetation quality and overall productivity (Yager et al. 2019). The herders clean the canals at the end of the dry season, when the wetlands are at their lowest stage of annual productivity. Through this action, they prepare for the extensive distribution of water during the wet season, when productivity increases. This makes it possible to irrigate sectors of the wetlands that do not receive surface water during the dry season. Finally, this type of action makes it possible to cope with rainfall variability. For the same reason, it has been demonstrated that changes or variations in the behavior of precipitation may not directly influence the vegetation productivity of the bofedal (Guo et al. 2014). Despite this, a reduction in annual rainfall will lead to a decrease in the bofedal's surface (Otto and Gibbons 2017). The degree of anthropic influence is such that these local practices are highly relevant for the conservation of these ecosystems. Indeed, when they are not carried out, the wetlands can experience degradation (Yager et al. 2019).

Finally, the work with cartographic information carried out by Castro and Bahamondes (1998) on the different forms of land use in the Chucuyo - Parinacota community allowed us to identify elements of the territory characteristic of the lifestyles of the indigenous Aymara cattle-raising communities. In the present research, the inclusion of this information allowed for the construction of a territorial synthesis of the community, in which sectors, areas of bofedales, and pastoral circuits are visible in places that do not currently appear to have a major use, as shown by the spaces of pastoral circuits located close to the town of Chucuyo (a space that currently appears as bare soil in the NDVI analysis). In addition, the identification of each of the bofedales by their respective local names allowed us to complement the spatial analysis exercise of the bofedal behavior, as it includes the categorization system of the community itself, who understand these entities in a systematic way.

5 Conclusions

The construction of the Lauca channel appears to have generated a negative impact on the high Andean wetlands of the indigenous community of Chucuyo, as it has diminished water availability of the sector of the Lauca River basin, but its effects cannot be quantified with the available data. This fact was determined from the collection of ethnographic information of the territory, meteorological information, fluvial information, and NDVI calculations.

The extraction of water through the Lauca channel is not consistent with an environmental rationale that has as a premise to care for the sustainability of these ecosystems: the evidence shows that more water resources were extracted from the Lauca River basin system during periods of water scarcity, which was denounced by the indigenous community at the time.

However, it is difficult to quantify the damage to the bofedal because there is no satellite information from the years prior to the construction of the Lauca Canal, which would allow the spatial reconstruction of its dimensions and vegetational vigor. Further research is necessary to determine the environmental and climatic reconstruction of these wetlands, preferably using other sources of information or evidence in the territory.

However, there is evidence that the effects of climatic variability affect the behavior of the bofedal, where precipitation plays a crucial role in the expansion or retreat of its surface and its vegetational vigor. The presence of indigenous communities in the territory also plays a significant role in the management of the bofedal, as they have local knowledge about the care of these fragile ecosystems. Maybe considering only the wet season behavior of a combined index of precipitation and temperature would show more accurate results (such a drought severity index).

In future research, it would be fruitful to analyze the daily concentration of precipitation in the summer period, as extreme rainfall events of short duration can cause erosion in the bofedales. Similarly, temperature variable could be included in the analyses, because the thermal oscillation characteristics of the Altiplano could intensify the effects of evapotranspiration at high temperatures and the freezing (burning) of bofedales in extreme cold. These data could be complemented with vegetation surveys to understand the corresponding changes in vegetation. More refined remote sensing analyses accompanied by botanical surveys would allow a better understanding of the transformation of these ecosystems. Finally, in-depth ethnographic research could help to refine our understanding of the role of traditional ecological knowledge in the socioecological transformation of these ecosystems. This last issue is not minor: it has been shown in the literature that herders are important actors in the conservation of these ecosystems. Given the importance of bofedales as carbon sinks, biodiversity niches, and water reservoirs, a high level of attention is required in territorial planning and water governance. These are especially important elements to consider in the current Chilean institutional context. The current environmental institutional framework, the mining code, and especially the water code, have favored the interests of extractive industries through free-market models (Tecklin et al. 2011; Prieto 2015). Together with historical colonial dynamics, this situation has rendered invisible the traditional practices of indigenous communities, which have also been dispossessed of their resources. This circumstance is crucial within the current political debate in Chile, where social movements aim to change a neoliberal constitution that does not recognize indigenous peoples, promotes private investments in indigenous lands, and maintains a pro-market economic model for managing natural resources.

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