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Reframing Pastoral Practices of *Bofedal* Management to Increase the Resilience of Andean Water Towers

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Across the Andes, a critical challenge for mountain socioecological systems is securing water for future generations. Pastoral communities are especially vulnerable because their livelihood practices are often unseen or perceived as a threat to natural resource conservation. In addition to the challenges of climate change, socioeconomic and political processes complicate the drivers of pasture degradation and sustainable water management. Often overlooked systems in assessments of Andean water towers are bofedales *(high-altitude peat wetlands), which are critical to supporting mountain pastoral livelihoods. While "natural" azonal mountain peatland and humid meadow development occurs across the Andes, we posit that* bofedales *are sociohydrological systems created through pastoral management practices over generations. Drawing on the results of applied research on* bofedales *across the Andes and a literature review of published papers, we present a conceptual reframing of* bofedal *typologies and change analysis, which prioritizes the role of pastoralists in interdisciplinary research and comparative assessments of land-use and land-cover change in Andean highland regions. We identified key socioecological challenges to sustainable* bofedal *management, related to herder decision-making and articulated within broader socioeconomic processes. Reframing* bofedales *as sociohydrological constructs permits the identification of actionable knowledge and the support of water conservation practices applied by pastoralists across Andean water tower regions. If Andean pastoralists are recognized as stewards of sociohydrological systems that are critical to water towers, rather than perceived as threats to natural resources,* bofedal *conservation planning may be prioritized and locally supported.*

Keywords: *pastoralism; Andes;* bofedales*; water towers; cultural landscape; irrigation; mountain sustainability; sociohydrology; alpine peatlands.*

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Introduction

Across the Andes, threats of water scarcity are recognized as diminishing water supplies compounded by the impacts of climate change and increasing water demand by human populations and extraction industries, including urbanization, agriculture, hydropower, and mining (Orlove et al 2008; Urrutia and Vuille 2009; Bury et al 2013). Due to the climatic, orographic, and ecosystem characteristics, the tropical Andean mountains are recognized as "water towers" that store and regulate hydrological assets that are critical for highland ecosystems and downstream populations (Immerzeel et al 2020). Yet, Andean water towers are among the most vulnerable features to the impacts of climate change, marked by rapid glacier loss, diminishing discharge, and increased surface temperature, which increase sociohydrological risks (Mark et al 2017). As such, there is an urgent need to identify actionable pathways to secure and extend the sustainability of regional water supplies provided by Andean water towers (McDowell et al 2019).

In the high-elevation regions of the Andean water towers, pastoral communities have managed local hydrology and mountain ecosystem resources for millennia (Capriles and Tripcevich 2016). Ethno-historical and archaeological studies have identified sophisticated sociopolitical organization regarding irrigation practices among Andean societies (Mitchell and Guillet 1994), yet few traditional practices remain intact. Many of these practices are vulnerable to loss, including pastoral management practices that remain unseen, undervalued, or even negatively perceived (Lane 2006; Verzijl and Quispe 2013). As Andean landscapes continue to rapidly transform, some irreversibly, the identification and continuation of local indigenous knowledge and practices that increase the resilience of mountain sociohydrological systems and support pastoral livelihoods are urgent pursuits (Gilles et al 2013; Valdivia et al 2013).

The observed climate data and model scenarios for the Andes show accelerating deglaciation, increases in surface temperature, and significant alterations in the seasonality and intensity of precipitation and extreme events (Buytaert et al 2010, 2011; Rabatel et al 2013). Across the high-elevation regions of the Andes, glaciers constitute a critical hydrological asset through the storage of water in snow and ice and the seasonal release of outflow to support mountain ecosystems. In addition to monitoring physical change (eg surface area and volume) in hydrological systems (eg glaciers, lakes, and rivers), it is critical to conserve the regulating function of mountain ecosystems for sustaining water systems. Such ecosystems include peatlands (ie *bofedales*) and wetlands, meadows and grasslands (ie *puna* and *paramo*), and native forests (ie *Polylepis* spp). Due to the hydrological regulation and provision of *bofedales* (Segnini et al 2013), their sustainability in mountain regions under current climate change is widely recognized as a research priority (Bury et al 2013; Otto and Gibbons 2017; Polk et al 2017). In addition to the multiple socioecosystem services provided by *bofedales*, they play a significant role in carbon cycling, having some of the highest rates of sequestration of mountain land-cover classes (Chimner and Karberg 2008; Buytaert et al 2011; Hribljan et al 2015).

Andean pastoral communities have managed *bofedales* since pre-Hispanic times (Flores-Ochoa 1977; Erickson 2000; Lane 2014; Capriles and Tripcevich 2016). In highland regions where pastoralism persists, indigenous communities (eg Aymara, Quechua, Colla, and Atacameños) depend upon and actively manage *bofedales* as a critical source of perennial green forage and water for herds of llama (*Lama glama*) and alpaca (*Vicugna pacos*), as well as nonnative cattle, sheep, horses, and goats (Browman 1989; Baied and Wheeler 1993; Villagrán and Castro 1997; Postigo et al 2008).

Interwoven with the impacts of climate change, local decision-making on pastoral management is influenced by broader socioeconomic systems and often results in outmigration, labor shortages, environmental contamination, and conflicts regarding land tenure, water access, and natural resource use (Coppock et al 2017; Figueroa-Armijos and Valdivia 2017). Once considered isolated mountain systems (Flannery et al 1989), Andean pastoral communities and mountain socioecological systems are now closely connected to production needs for globalized markets, for example, the luxury textile industry (eg vicuña and alpaca wool), international export of subsistence crops (eg quinoa), water extraction for mining (eg metals and lithium), and dam development for hydropower and urban populations. Nonproximate (ie regional or global) processes can also trigger unsustainable pastoral practices, such as increased grazing pressures, reduced pasture rotation, loss of traditional knowledge, and abandonment of communal irrigation practices. As a result, Andean pastoral management objectives, social relations, and risk management strategies have significantly changed in recent years, impacting land use, land-cover change (Coppock et al 2017), and the sustainability of *bofedal* systems (Yager et al 2019). In severe circumstances, pastoral communities experience displacement, shortages of social services, threats to economic welfare, exposure to environmental toxins, and increasing ethnic and gender inequalities.

Across the Andes, conflicts regarding water supply, demand, and allocation are palpable among pastoral communities. Viewing water management challenges through a transdisciplinary lens allows the identification, prioritization, and analysis of generalizable patterns that can facilitate a better understanding of the social, institutional, and economic activities of sociohydrological systems leading to sustainable hydrological outcomes (Brelsford et al 2020). Water management decisions are cumulative, occurring at multiple institutional scales, through which infrastructure and practices are socially and politically negotiated to affect the control of water, including quantity, quality, allocation, and flow, the sum of which produces a sociohydrological system. Similarly, we posit that *bofedales* are key sociohydrological systems that are critical to the long-term sustainability of Andean water towers. As such, an appropriate transdisciplinary research framework is needed to evaluate the sociohydrological functions of *bofedales*, their management by mountain communities, and the processes that support sustainable outcomes.

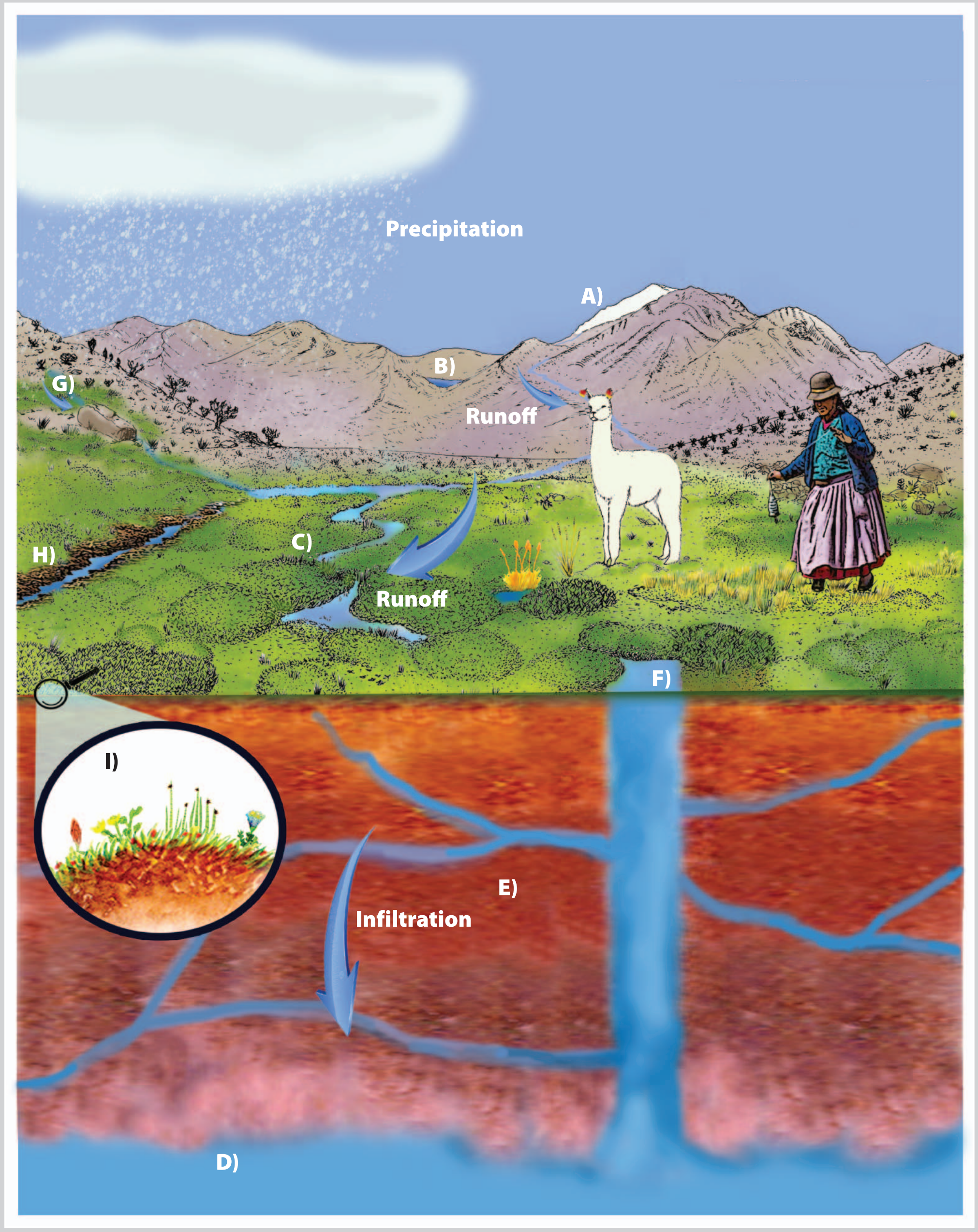
Pastoralists manage mosaics of mountain ecosystems, including *bofedales*, highland grasslands (*puna* and *paramo*), and native forests, which are all important for Andean natural resource use and conservation. A transdisciplinary research agenda producing translational knowledge on the integration of socioecological systems and practices is therefore necessary (Mathez-Stiefel et al 2017). We posit that reframing *bofedales* as sociohydrological systems is critical to secure sustainable water and forage resources for herding communities. Denaturalizing *bofedales*, in part, is necessary to understanding political and socioeconomic drivers of land-use and land-cover change, and to identifying the nested social institutions at multiple scales that influence the sustainability of *bofedales*. It is also necessary to include local stakeholders in water governance and conservation planning aimed at increasing the resilience of Andean water towers. In particular, a transdisciplinary, multiscale approach is needed to understand changing pastoral management decision-making at the microscale (eg within a herding parcel or *sayaña*), and in relation to local (eg community-level) and regional climate, political, and socioeconomic processes (eg water-extraction activities).

Background on *bofedales*

Andean water towers are best known for their towering glaciers, alpine lakes, and rivers that provide critical water supplies for mountain and downstream populations. Less visible but essential features are the mountain aquifers and natural springs, which are recharged by seasonal precipitation and snow events. Infiltration and replenishment of hydrological channels and interconnected systems are frequently dependent upon stable soils and adequate vegetation cover, including *bofedales*, which are often nestled in glacier valleys and at the bases of mountain flanks. Applying a broad natural science typology, *bofedales* are concentrated mosaics of compact cushion plants with low-growing plant assemblages associated with a network of mountain surface hydrological systems, including streams, water holes, and springs. *Bofedales* contribute to increasing water infiltration, recharge of aquifers, and slowing seasonal water runoff. As such, *bofedales* provide critical water regulation and storage for mountain socioecological systems and constitute key hydrological components of Andean water towers (Figure 1).

Commonly applied natural science descriptors for *bofedales* include mountain fens, mires, bogs, humid meadows, and alpine wetlands; importantly, each of these typologies differs in their distinct chemical, biogeographic, biotic, and hydrological properties (Lindsay 2018). While *bofedales* are

Figure 1 Schematic illustration of a *bofedal* and sociohydrological components in an Andean water tower, including precipitation, runoff, and infiltration contributing to water flow and recharge in a *bofedal*, and key landscape features: (A) glacier, (B) high-elevation lake, (C) *bofedal*, (D) aquifer, (E) organic material, (F) water hole (*ojo de agua*), (G) water spring, (H) irrigation canal, and (I) macroscale view of *bofedal* plants.



found in high-elevation alpine watersheds across the tropical Andes, there are generalizable differences from a natural science perspective in terms of their biogeographic distribution and characteristic vegetation composition.

In the arid to semiarid high-elevation regions of the tropical Central Andes, *bofedales* are azonal ecological communities occurring in the high *puna* region (at elevations of approximately 3500 to 5000 m above sea level [masl]) across Bolivia, Peru, northern Argentina, and Chile (Ruthsatz 2012; Meneses et al 2019). *Bofedales* are azonal in that they differ from the drier mountain land-cover classes due to year-round plant growth, organic soils, and provision of a constant source of water. They are otherwise termed a mountain peatland system. Through a botanical lens, *bofedales* in the central and southern *puna* regions are composed of mosaics of compact cushion plants, dominated by vascular plants from the Juncaceae family (eg *Oxychloe andina*, *Distichia* spp, *Patosia clandestina*), and commonly associated with the presence of Cyperaceae (eg *Phylloscirpus*, *Zameioscirpus*), Plantaginaceae (*Plantago tubulosa*), and Gramineae (eg *Deyeuxia* spp, *Poa* spp) (Ruthsatz 1993, 2012; Luebert and Pliscoff 2006; Meneses et al 2015, 2019). In the northern *puna–paramo* transition of the tropical Andes, including Peru, Ecuador, and Colombia, the study of *bofedales* has been applied to describe both peat-accumulating systems (Chimner and Karberg 2008) and more broadly to mountain wetland systems (Polk et al 2017; Chimner et al 2019). The *bofedales* of the *paramo* and northern humid *puna* regions of

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Ecuador and northern Peru have a higher cover of mosses in their vegetation associations (Cooper et al 2010), while the southern *puna* regions are associated with dry grasses (Cooper et al 2010, 2015; Meneses et al 2019). *Bofedales* vary in size according to their geomorphological setting and hydrological conditions (Squeo et al 2006). The water that replenishes *bofedal* systems may include contributions from surface hydrology (eg lakes and streams), springs, precipitation (including surface runoff), and glacier outflow (Polk et al 2017; Cooper et al 2019). In pastoralist communities, herein emphasized, the water is sustained by the construction of canals and waterways to redirect hydrological flow and infiltration.

From a broader social science perspective, the term "*bofedales*" is a local, vernacular description of high-elevation irrigated pastures used by indigenous Andean herding communities. Aymara and Quechua names for *bofedales* include *ok'os* or *uqhu*, and the dominant plant species are called *cachu* (*Distichia muscoides*), kunkuna (*Distichia muscoides*), and *k'uli urcu* (*Oxychloe andina*), in addition to many associated plants (eg *tiña*, *chinka*, *llachhu*, *kachu*, *waricha*, *porqu'e*) (Palacios-Ríos 1977; Canales and Tapia Núñez 1987; Villagrán and Castro 1997). Other vernacular terms used to describe humid meadows include *cienega*, *vega*, or *humedal*, which are more prevalent in midelevation Andean regions (between 3000 and 4000 masl). The latter terms differ from *bofedales* in describing areas with limited forage value that do not accumulate peat and are more often unmanaged. This is in part due to their limited occurrence in agropastoral zones, where labor investment is typically more focused on crop production. Thus, there are important biogeographical, botanical, and sociocultural differences among commonly applied *bofedal* typologies.

Conceptual framing of *bofedales*

Given the broad range of terms and characteristics, researchers must consider the use and application of *bofedal* typologies, which may directly impact land-use decisions, policy priorities, and conservation planning. The conceptual framing of *bofedales* across a spectrum from "natural" to "anthropogenic" varies among stakeholders, policymakers, and scientists and thereby confounds the multiplicity of drivers of environmental change, as well as the perceived threats to the natural resources of Andean water towers. Institutional perceptions of land-use and land-cover change—in particular, drivers of degradation, erosion, and threats to biodiversity—have often been based on a dichotomous human–nature view, resulting in misidentification of indigenous practices and blame of local land-use managers as destructive agents (Fairhead and Leach 1996; Dove 2004, 2006). Such erroneous conceptual framing by state agencies can result in decadal- to century-long systems of sociopolitical oppression of local land users that are closely tied to natural resource management policies (Blaikie 1985; Dove and Kammen 2015).

In order to evaluate the conceptual framing of "*bofedales*" in current scientific literature, we conducted a bibliographic analysis of published research on *bofedales* in Chile, Argentina, Peru, and Bolivia. The study included keyword searches of titles and abstracts using reference databases (including the Web of Science Core Collection and SciELO Citation Index) to identify published journal articles, book chapters, and conference papers focused on *bofedales*. Our search identified 119 publications, published between 1977 and 2018, which included *bofedal* terminology and common synonyms. The publications were further analyzed using a coding process based on various *bofedal* characteristics (including location, methodologies applied, discipline, role of herder management, and vegetation types). From this study, a quantitative analysis of the scope of bibliographic references was carried out to further consider the breadth of applied disciplinary views and research approaches on these Andean ecosystems (see White-Nockleby et al 2021). Many of the fundamental natural science publications on *bofedales* are appropriately dedicated to localized botanical study of these systems (eg Ruthsatz 1993, 2012), and subregional peatland distribution and change analysis (eg Izquierdo et al 2015; Dangles et al 2017; Chimner et al 2019). Researchers from the natural sciences may consider the primary drivers of *bofedal* change to be bioclimatic and environmental, for example, geological, physiographical, morphological, climatological, or biological characteristics (Earle et al 2003; Squeo et al 2006; Dangles et al 2017). From an alternative perspective, researchers may confound all Andean wetlands as *bofedales* or erroneously conceive them as ahistorical and ecological settings of social relations (Hartman 1996; Gandarillas et al 2016; Struelens et al 2017). Both approaches reproduce a binary relationship between nature and culture; *bofedales* are not a strictly uniform biogeographical entity nor are human actors (ie herders) merely passive users of these ecosystems.

Over more than a decade, we have conducted applied research on *bofedales* with local communities in Peru, Bolivia, and Chile (eg Meneses et al 2015, 2019; Prieto 2015; Yager 2015; Prieto et al 2019; Yager et al 2019), including vegetation studies, institutional analysis, ethnographic research, geospatial analysis, hydrological studies, archaeological studies, and archival research. While publications may be appropriately focused on discipline-specific topics, for example, botany (eg Meneses et al 2019) or hydrology (eg Cooper et al 2015), we recognize the value in identifying the linkages, drivers, and networks between and across systems. Interdisciplinary research on *bofedales* increasingly recognizes the critical role of local stakeholders and *bofedales* in mountain sustainability (eg Postigo et al 2008; Valdivia and Yager 2018). Furthermore, local testimonies from Andean communities recognize that water access and irrigation are critical to the sustainability of *bofedales* (Yager et al 2019). The impediment of a binary or bounded research approach may result in overlooking the imperative role that pastoralists have held over multiple generations in sustaining *bofedales* as sociohydrological systems. *Bofedales* are neither strictly "natural" nor "pristine" (Denevan 2001), but rather part of the built cultural landscape, or "landscape capital" (Erickson 2000), resulting from hundreds of years of management actions, embedded with indigenous knowledge of ecosystem linkages among climate, water, and vegetation. In this applied perspective, *bofedales* constitute fusion landscape entities and socioenvironmental encyclopedias of the ways in which cultural practices, socioeconomic institutions, and power relations impacting pastoralists have been negotiated over time under changing environmental, political, and socioeconomic influences.

Reframing *bofedal* management

Bofedales are mountain sociohydrological systems that are vital to mountain sustainability for highland and downstream communities. The built water infrastructure increases water storage, regulates outflow, slows erosion during extreme weather events, and is a critical source of water availability throughout the year, most importantly during the extended dry season or drought years (Garcia and Otto 2015). We posit that while zonal mountain peatland development occurs across the Andes, the alpine systems become a *bofedal* through intentional pastoral practices occurring over multiple generations. *Bofedal* condition reflects not only shifts in climate and environmental factors, but it also signifies change in dominant socioeconomic relationships, such as cultural knowledge, pastoral identity, community cohesion, and indigenous livelihood practices in relation to broader political and socioeconomic processes.

Pastoralists are not only tasked with herd management decisions (eg herd size, species composition, transhumant migration, and pasture rotation), but also water management decisions. Without access to healthy *bofedales*, pastoralism in the Andes would not have endured over millennia, nor would it have become integral to Andean society, including pre-Inka, colonial, and present populations. Pastoralists directly manage water to ensure adequate forage. The alpaca, in particular, is dependent upon the forage provided by *bofedales*, while the llama has a broader palate for grazing dry grasses (eg *Festuca* spp) characteristic of the *puna* (Baied and Wheeler 1993). Many Andean herding practices have transformed in the postcolonial era to include nonnative domesticates, especially in the northern Central Andes (eg Cordillera Blanca, Peru), including cattle and horses, which require supplemental forage and higher labor investments, and result in greater damage to vegetation in *bofedales* than traditional herds.

Irrigation (*irpa*) is a fundamental aspect of *bofedal* management among pastoralists (Flores-Ochoa 1977; Palacios-Ríos 1977, 1996). Traditional practices range from the use of ephemeral canals and miniature reservoirs to the installation of intricate waterways, artificial ponds, and constructed pipelines (natural and cement). The "opening" of natural water valves (eg springs or brooks) or artificial output (eg wells), and the distribution and duration of water flow are often managed according to community-based rules and regulations. The availability of labor, infrastructure, and community-scale management of irrigation practices will vary across Andean communities and linkages with municipal, state, and national agropastoral policies and markets (Guillet and Mitchell 1991; Guillet 1992).

Communities that maintain a certain level of cohesion of pastoral identity will prioritize community-scale efforts to improve and sustain their *bofedales*. This may include annual canal cleaning (eg *faena*), pasture rotation (eg *j'akas*), shared access to community grazing plots (eg *machajes*), and seeding and transplanting *bofedal* plants. Individualized water management practices may include subtle diversions of water flow and direction, using boulders, rocks, gullies, or artificially built diversions, to evenly distribute water across a *bofedal* and to direct it to areas experiencing desiccation. Traditional knowledge of local plants allows them to be used as indicators of *bofedal* health that inform irrigation needs, including soil moisture and water table level, and signals of grazing pressure that inform herd management decisions. Local pasture management may also include the application of fire, with diverse socioecological incentives, including clearing encroaching dry grasses, revitalizing tussock growth, communicating messages over long distances, or signaling land ownership in an area of dispute. Other herder practices can include the application of *abono* (camelid dung) as a natural fertilizer. Through pasture rotation or facilitated access to multiple grazing parcels, herding animals contribute to seed dispersal and fertilization through dispersion of droppings (Yager et al 2008).

In addition to the technical tasks of *bofedal* management, ritual performance is a vital practice associated with sociohydrological systems (Lansing 1991; van Kessel 1997; Prieto 2016). Andean ritual practices, often including glaciers and mountain springs, create bonds between social groups and the nonhuman world (Castro and Aldunate 2003), wherein relationships remain in *ayni* (reciprocity) through practices of *pagos* (payments), *cariño* (affection), and *respeto* (respect). Rituals to ensure water, *bofedal*, and animal health and abundance can include *despachos* (offerings), canal cleaning ceremonies, and pilgrimages to mountains peaks that are recognized as protective spirits (*apus*), corresponding to astronomical–cosmological cycles and the agropastoral calendar (Sallnow 1987).

Ethnographic testimonies indicate that a continuous supply of water is essential to maintain, improve, and extend a *bofedal* (Palacios-Ríos 1977; Yager 2015). Frequent drought conditions, or drastic reductions of water inputs, will result in *bofedal* degradation and even rapid loss. Though *bofedales* endure interannual drought conditions, dating over several millennia (eg ∼7 ky; Hribljan et al 2015), herders attest that drought conditions are more prevalent at present day, and seasonal precipitation is noncontinuous and characterized as extreme events (eg isolated downpour events that cause greater erosion and runoff). Under current climate change conditions, herders recognize that the natural water sources (eg springs and glaciers) on which they normally depend are decreasing (Orlove et al 2008; Yager 2015; Yager et al 2019). While glacier outflow may have once created the water flow to harness and supplement *bofedal* replenishment, many glaciers are past peak outflow (Mark et al 2017), and accelerated loss has resulted in disconnected, patchy, and fragmented ecosystems (Seimon et al 2017). In addition to decreasing water supplies, decline in irrigation management is often due to labor shortages resulting from outmigration (for work and education) and loss of traditional knowledge across generations (Turin and Valdivia 2011). Under current climate change, *bofedales* are already experiencing rapid desiccation, and many are vulnerable to irrevocable loss in less than a decade. When a herder is unable to manage water flow in a *bofedal*, it can rapidly decay within a few years' time, especially under drought conditions. Once the *bofedal* is disconnected from sustaining water supplies, the restoration of these systems within a single lifetime is often not feasible, as many were constructed and maintained with water inputs, both human and natural, permitting their growth over hundreds to thousands of years.

Reframing *bofedal* change

While broader national and international policy is critical to mitigating the impacts of climate change on mountain water towers, local actions are also necessary to address water sustainability. Some studies seek to identify and define critical hydrological inputs to *bofedal* sustainability, yet they continue to prioritize climatological parameters in the context of projected warming over the role of local human agency. Social processes, such as migration, loss of traditional practices, and political invisibilization of pastoral communities, also lead to system outcomes of *bofedal* degradation and loss, which often reflect larger processes of environmental injustice and dispossession. When herders migrate to urban areas, impacted by economic and policy linkages, they stop managing *bofedales*, often resulting in radical consequences for mountain sociohydrological systems.

This consideration invites us to re-examine proximate (both social and natural) and underlying causes related to structural institutional, political, economic, and social processes of *bofedal* change. For example, Lima et al (2016) stated that a change in climatic variability was a crucial factor in the depopulation of the *puna* region in northern Chile. Today, many pastoralists in highland regions must manage radical changes in both climate and social systems. A transdisciplinary approach (which considers the social production of *bofedales*) both characterizes "natural" drivers of highland depopulation and considers the possibility of social processes influenced by nonenvironmental factors (eg proletarization processes, forced migration) that also lead to environmental change in the *puna* highlands.

Natural resources management policies that view *bofedales* as separate from human practices will overlook the imperative role of herders in conservation planning. Even within protected areas, increasing trends of land fragmentation and fencing, loss of community-based water management, and increasing privatization have led to *bofedal* degradation (Yager et al 2019). When institutional arrangements ignore local knowledge and practices and present them as *terra nullius* (land without owners), land-tenure rights among pastoralists are threatened. An example of this latter situation has led to dispossession of herder's land (or land access) and violation of indigenous ancestral rights (Verzijl and Quispe 2013). Promarket managerial policies have further radicalized this effect. When applied in biased economic policy, water rights have been denied to local communities in favor of extractive users (Prieto 2015). Conservation and legal discourses that present *bofedales* as pristine ecosystems tend to overlook local managerial practices, and even forbid some of them (Dransart 2002; García et al 2021). They conceive herder's activities as separate from nature and picture them as an external threat rather than necessary for *bofedal* sustainability.

Extractive activities (eg mining and water supply to companies) are a major threat to *bofedales* (Castro 1997; Verzijl and Quispe 2013; Scheihing and Tröger 2017; Prieto et al 2019; Cabanillas-Trujillo and Madrid-Ibarra 2020). In particular, many extractive companies are required to evaluate the impacts of implementation on *bofedales* through technical studies of environmental impact assessments, which are often used to justify *bofedal* removal for exploration and extraction tests. These studies are conducted by contracted consulting firms that do not have advanced knowledge of mountain ecosystems, neglect linkages between *bofedales* and water security, and ignore the role of herders and pastoral livelihood resources. Furthermore, rather than conducting rigorous research and environmental protocols, they respond to institutional agendas and nonarticulated macroframeworks that prioritize industrial development for export over mountain ecosystem services and local communities. In addition, the physical perturbations of mining activities (both legal and illegal, at large and small scale) affect *bofedales* by pumping groundwater from them, modifying the hydrological flows to systems (eg channeling water in pipes), and building infrastructure (eg roads that cut off water flow to *bofedales*). A paradigmatic illustration is the Chilean case of the Chuquicamata Mine (the largest open-pit copper mine in the world), which has caused irreversible destruction to several *bofedales* located in the San Pedro de Inacaliri river basin that had sustained indigenous communities since pre-Hispanic times (Prieto et al 2019). The brine mining boom (eg lithium, potassium, borax) is also a current threat to *bofedales* located near salt flats. Brine mining employs an industrial process that can be understood as a form of water mining (Garcés and Alvarez 2020; Bustos-Gallardo et al 2021). The encroachment of mining in pastoral regions often divides community alliances and drives migration to urban centers and population abandonment of the highlands. This, consequently, results in the loss of local *bofedal* management and fractured or discontinued community pastoral identity (Babidge et al 2019).

Another significant extractive activity is the expansion of dams to supply water or hydropower for rapidly growing urban populations, for which the infrastructure is frequently constructed on *bofedales* (eg Cordillera Real, Bolivia, and the Cordillera Vilcanota, Peru), many of which are critical habitats for endangered and threatened species (Seimon et al 2017). In Tacna (Peru), the water demand for urban consumption and agriculture has increased water extraction from *bofedales* located in the highlands (eg *Jachajawira* and Mauri river) (Carbonell 2002; Molina-Carpio et al 2012). In the arid regions of northern Chile, the expansion of industrial agriculture and mining has increased water extraction from afar, often sourced from highland *bofedal* systems (eg Glassner 1970; Bernhardson 1985; Romero et al 2017; Prieto et al 2019).

Reframing cross- and interdisciplinary research approaches has resulted in an expansion of our conceptual understanding of nature–culture relationships, including the concept of verticality, and realignment of its conceptual boundaries and practical applications (Murra 1985; Zimmerer 1999), as well as zonal classifications, including the biogeographic typology of biomes (eg *puna*) reframed through a social science lens as production zones (Mayer 2002). Similarly, we invite a conceptual reconsideration of *bofedales*—toward recognition of these unique biogeophysical mountain wetland systems as culturally produced sociohydrological systems—as an opportunity to initiate new research questions for expanding translational knowledge and to identify relevant and empowering local initiatives that recognize pastoralists as significant stakeholders in securing water tower assets.

We support transdisciplinary research that considers the proximate and underlying factors influencing land-use and land-cover change (Geist and Lambin 2002; Coppock et al 2017; Izquierdo et al 2018) and local decision-making (Gilles et al 2013; Valdivia et al 2013) to inform conservation planning. Pastoral management and highland landscapes are rapidly changing across Andean communities, and identification of the multiscale processes and drivers impacting sociohydrological outcomes is necessary to secure sustainable water outcomes (Brelsford et al 2020). We propose reframing *bofedal* research to include the role of pastoralists as key managers of sociohydrological infrastructure in Andean water tower regions. In particular, we seek to further answer the following questions.

- What multiscalar factors (climate, sociopolitical, socioecological, and socioeconomic) and processes (including proximate and systemic) influence local pastoral decision-making regarding *bofedal* management?
- Are there shared dominant challenges of *bofedal* management across Andean water tower regions? What are some effective risk management strategies for *bofedal* management in relation to climate change and socioecological processes at multiple governance scales (including water extraction and market changes)?
- What translational knowledge, socioeconomic networks, technologies, and resources can be coproduced and shared across institutions, policymakers, and local stakeholders to support and extend the resilience of *bofedales* and increase the sustainability of sociohydrological systems across the Andes?

Conclusion

We posit that if the study and identification of *bofedales* remain limited to their biophysical dimensions, confounded as purely natural, and or left broadly defined as a mountain wetland, the outcome could result in erroneous assessments of land-use and land-cover change, which could then result in counterproductive and misinformed policies, or institutional neglect of local water rights and needs. Obfuscation of pastoralists in their roles as creators and maintainers of *bofedales* as key sociohydrological systems will contribute to further displacement of mountain communities, increase threats to water security on a regional scale, and cause the loss of Andean practices that have endured for millennia. Instead, we recognize that continuity of pastoral practices that support sociohydrological systems is especially critical given rapid climate change and socioeconomic processes that threaten the sustainability of mountain water towers.

Accepting the above articulated premise that pastoralists and their practices have created critical sociohydrological systems that are key components of Andean water towers, researchers and policymakers concerned with water conservation planning should reframe questions that recognize the ways in which pastoralists act as stewards of Andean water regions and identify the current and potential threats to this role. Increasing the resilience of water resources in mountain regions entails working together across disciplines and with stakeholders in order to devise actionable knowledge and practices that contribute to, rather than endanger, the sustainability of the *bofedales*.

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OPEN PEER REVIEW

This article was reviewed by Cecilia Turin and Manuel Peralvo. The peer review process for all MountainAgenda articles is open. In shaping target knowledge, values are explicitly at stake. The open review process offers authors and reviewers the opportunity to engage in a discussion about these values.

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