WETLAND RESEARCH

Peatlands of the Central Andes Puna, South America

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ABSTRACT

The Andean puna is the highest elevation mountain and plateau region in the western hemisphere, extending from northern Peru to central Chile and Argentina, with vast areas above 4,250 m elevation. The Atacama Desert on the western side of the Andes is the world's most arid region, and this aridity extends across the mountains. The upland vegetation is mostly continuous in the more humid north but becomes more and more patchy and barren composed only of bunch grasses in the central and southern region. Extensive upland talus, moraines, and colluvial deposits of the mountains produces perennial ground water flow systems that support thousands of peatlands and other wetlands that are regionally termed "bofedales" or "vegas". The peatlands are dominated by several species in the family Juncaceae, most famously *Distichia muscoides*, that forms dense clonal cushions that characterize the alpine peatlands and landscapes. Being close to the equator, the growing season extends across the entire year, and continuous growth of the cushion plants have produced high carbon accumulation rates and peat bodies 7-10 m thick in many areas. The region supports unique plants and animals, and ecosystems, and the wetlands are threatened by overuse for livestock grazing, and climate changes that could reduce water provision may lead to some bofedales completely drying.

INTRODUCTION

The Andes form the world's longest mountain system extending more than 7000 km along the entire western edge of South America, and continuing the American Cordillera from the Arctic to the Antarctic. The mountain region from central Peru through Bolivia, northern Chile and Argentina is the highest alpine region in the western hemisphere with many peaks over 6000 meters and extensive plateaus at 3200 to 5000 meters asl. The only region on Earth with similar extensive high elevation is the Tibetan Plateau. The central Andes is bordered on the east by the Amazon basin, the world's most biodiverse region, and on the west by the Atacama Desert, the world's driest region. The region has complex geodynamic and volcanic processes geologic origin (Strecker et al. 2009) Above 3500 meters asl, these geodynamic factors have combined with glacial processes to shape the landscape.

The central Andes alpine region is termed "Puna", a treeless windswept area of the higher Andes, a word derived from the Quechua language. Its climate is cold and

FIGURE 1. Location of Central Andes Puna ecoregions in western South America (Olson et al. 2001). A and B: Current study areas in central and southern Peru. A: Nor Yauyos – Cochas Landscape Reserve, Cordillera Central. B: Vilacota – Maure Regional Conservation Area, Cordillera del Barroso.

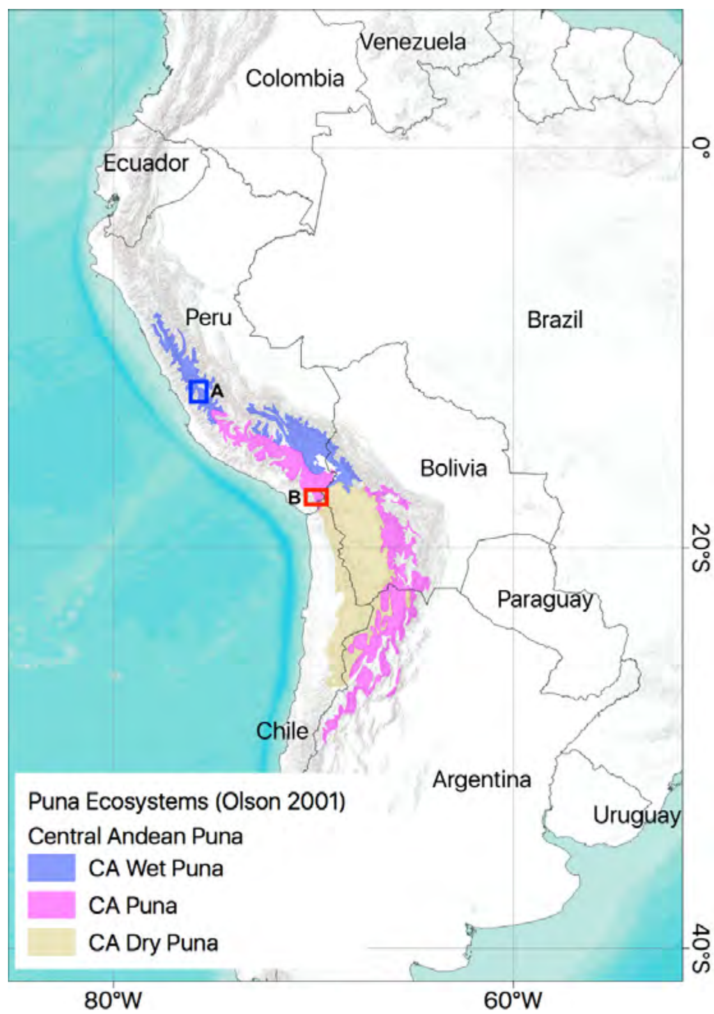

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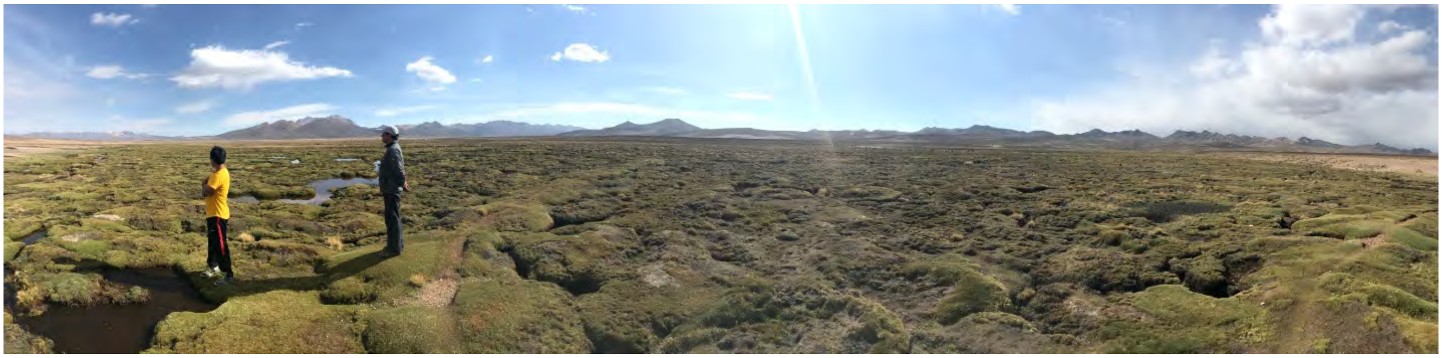
FIGURE 2. Expansive bofedale in the highlands of southern Peru, at 4,500 m elevation. Surrounding peaks all 5200-5500 m high. (Photo by D.J. Cooper.)



semi-arid, with annual precipitation ranging from 200 to 700 mm per year. It is influenced by the movement of wet air masses from the Amazon, the temperature and currents in the Pacific Ocean, and the presence of Lake Titicaca (Falvey and Garreaud 2005)precipitation over the high-altitude plateau of the South American Altiplano exhibits a marked intraseasonal variability which has been associated with alternating moist and dry conditions observed at surface stations near the Altiplano western cordillera. In this study the characteristics of humid (wet. It is well known for having "summer every day and winter every night", with freezing or near freezing temperatures in all seasons (Rundel et al. 1994). The puna is climatically variable, with "wet puna" in central Peru, "puna" in southern Peru and northern Argentina, and "dry puna" on the Peruvian-Bolivian Plateau called "altiplano" and in northern Chile (Figure 1).

The vegetation is composed of open to continuous bunch grasses and shrubs on upland slopes with wetlands in the valley and basin bottoms. Stands of *Polylepis* spp. (Rosaceae) forest can occur to over 4800 m elevation on western slopes of the Andes forming one of the world's highest elevation forest types, for example on Nevado Sajama, the highest mountain in Bolivia. On the eastern edge of the Andes cloud forest forms the upper treeline. Many wetlands in the valleys and basins are supported by groundwater discharge and are peat accumulating fens (Cooper et al. 2010, 2019). Those peatlands are termed 'bofedales' in Peru, Bolivia and northern Chile, and 'vegas' in central Chile and Argentina (Rojo et al. 2019) (Figure 2). They have some of the most rapid known rates of peat accumulation, up to 1.4 - 2.2 mm/yr and a long term carbon accumulation rate of 37 - 47 g C/m^2/yr (Hribljan et al. 2015). Carbon storage is a key ecosystem service provided by bofedales, but they also represent important refugia for many organisms, particularly during the prolonged dry seasons.

Bofedales are critical pastures for indigenous pastoral communities (Yager et al. 2019) whose inhabitants live at extreme high elevations. Aymaran highlanders, who live in the puna of Bolivia, are often cited as examples of human adaptation to extreme high elevations, with blood hemoglobin oxygen levels, and lung capacity, higher than any other people. Bofedales are under intensive pressure due to direct

FIGURE 3. Intact peatland during the dry season with water table near the surface and cushions and pools separated in most areas; Apolobamba, Bolivia, 4350 m elevation. (Photo by D.J. Cooper.)

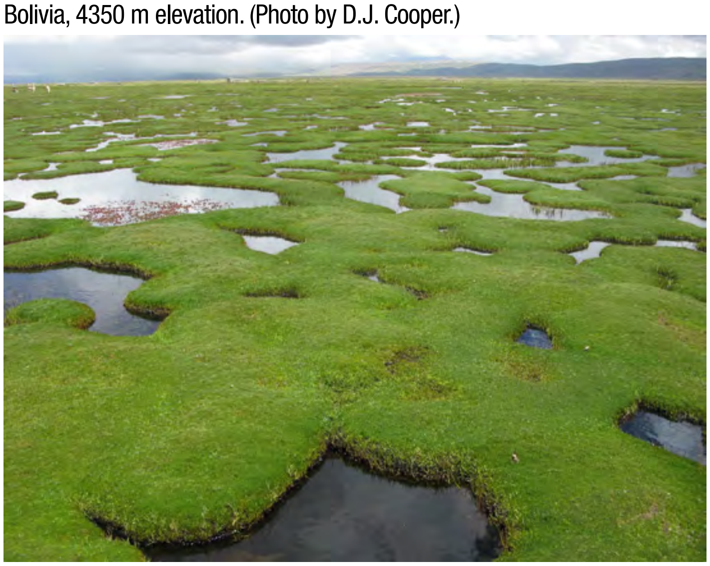


FIGURE 4. Heavy stocking rates of alpaca in bofedale in southern Peru, Vilcanota Mountains (4570 m elevation). (Photo by D.J. Cooper.)

uses including grazing by the domesticated Andean livestock llama and alpaca, and also by European domesticated livestock particularly sheep and cattle. Many bofedales have been ditched and drained or irrigated to "improve" the pastures.

PEATLAND TYPES AND CHARACTERISTICS

'Bofedales' and 'vegas' are terms used to denotate many types of Andean wetlands, including fens, wet meadows with mineral soils, and stream floodplains (Chimner et al. 2019). However, fens are the most conspicuous and characteristic wetland in the puna. From central Peru to northern Chile fens are dominated by cushion-plants, particularly *Distichia muscoides* and *Oxychloe andina* in the family Juncaceae. In central Chile and northern Argentina fens are dominated by cushion plants with a higher presence of bunch grasses, such as *Deyeuxia* spp. In southern Bolivia and northern Chile and parts of Peru highly saline closed basin lakes and flats are common, including the famous Salar de Uyuni in Bolivia the world's largest salt flat and important habitat for several species of flamingos that also inhabit many bofedales.

Natural bofedales have a distinctive cushion and pool structure (Figure 3). The cushion plant shoots grow so densely packed that they form an almost waterproof dam that limits lateral water movement, and when the cushions touch they isolate pools which prevents rapid drainage.

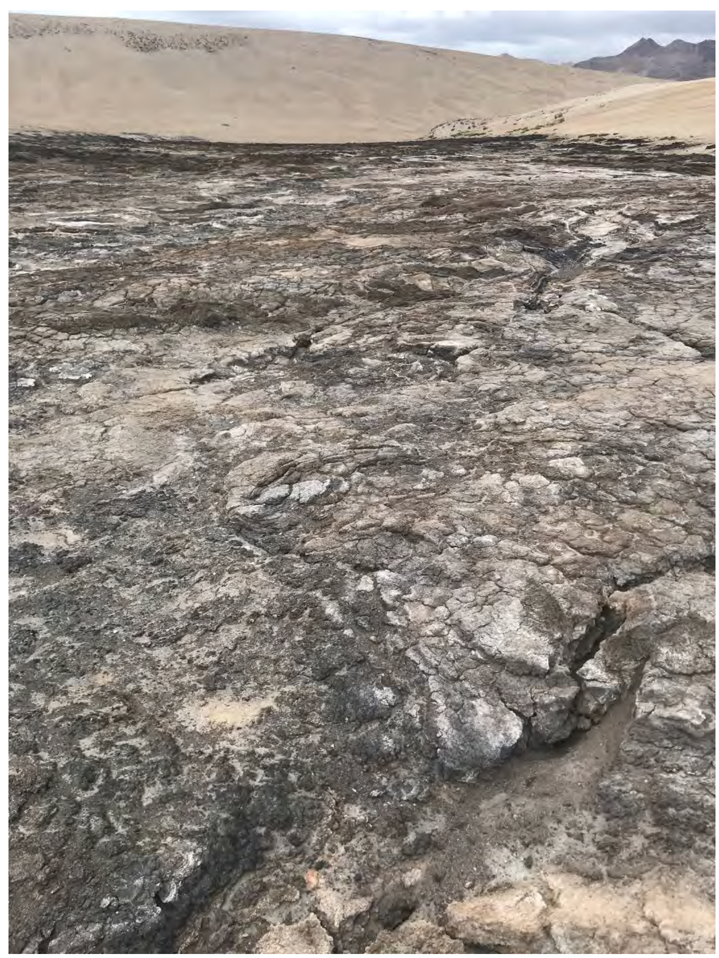
Overgrazing is common as the uplands provide little forage. In addition, because there is no long lasting winter snow grazing occurs every day of the year. Stocking rates can exceed 500 animals per pasture in some districts (Figure 4). Heavy grazing can break the cushion margins allowing the pools to connect creating drainage paths that can dewater bofedales. Cushion plants are sensitive to grazing. Llama and alpaca use their chisel like teeth to scrape the hard *Distichia* shoots from the cushions, and with heavy use the cushions are killed and replaced by short-lived and shallow-rooted plants (Figure 5).

Other factors also stress these wetlands. Some industries, such as metal mining, can have significant environmental effects due to ground water extraction and pollution. The climate is also changing, as is well known from the rapid loss of glaciers throughout the tropical Andes (Rabatel et al. 2013). Some bofedales in small watersheds have completely desiccated for unknown reasons (Figure 6), while others persist but have dry season water level declines of nearly one meter (Figure 7).

The hydrological functioning of Andean peatlands has been discussed and many conflicting viewpoints provided. Some have proposed their importance as reservoirs and water providers to downstream communities. Others have suggested they are dependent on glacier meltwater. However, glaciers cover < 5% of the Peruvian highlands and most fens in the puna occur in regions lacking glaciers. In

FIGURE 5. Highly degraded cushion plant peatland with most cushions destroyed and bare ground exposed. (Photo by D.J. Cooper.)

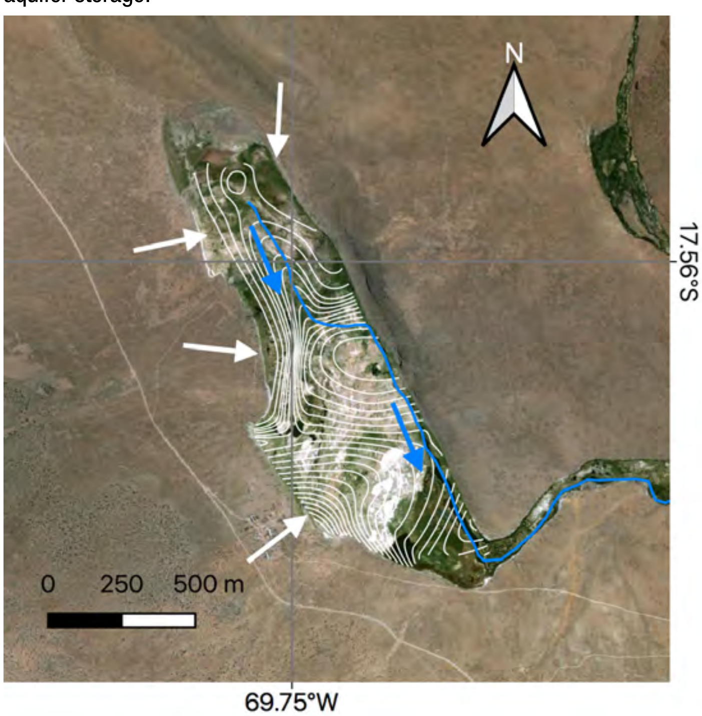
FIGURE 6. Dessicated bofedale with bare exposed peat near Huaytire, Peru (4570 m elevation). (Photo by D.J. Cooper.)



the puna, as elsewhere in the world, fens are groundwater dependent ecosystems, with discharge from hillslope and other aquifers and their evapotranspiration consumes water resources. The remarkable aridity of the puna ecoregion, with only 200 - 500 mm of total annual precipitation and strong seasonality with a 7 to 9 month- long dry season, reinforces bofedale dependence on perennial groundwater discharge, the only water resources available during long dry periods (Falvey and Garreaud 2005)precipitation over the high-altitude plateau of the South American Altiplano exhibits a marked intraseasonal variability which has been associated with alternating moist and dry conditions observed at surface stations near the Altiplano western cordillera. In this study the characteristics of humid (wet.

FIGURE 7. Dry season water table decline in peatlands dominated by *Distichia muscoides* cushions, Nor Yauyos – Cochas, Peru (4630 m elevation). Surrounding peaks are up to 5750 m in elevation. (Photo by D.J. Cooper.)

FIGURE 8. Interpolated groundwater isolines and dominant flow patterns in Paucarani an *Oxychloe andina* dominated peatland. Vilacota – Maure Regional Conservation Area, Tacna Region, southern Peru. Ground water is flowing (white arrows) from ancient glacial moraines that function as aquifer storage.



The stability of water provision is a key element for the ecological functionality of these ecosystems. The hydrological stability combined with the relatively constant year-around thermal regime and daylight intensity due to proximity to the equator, allows peat to accumulate (Cooper et al. 2014; Hribljan et al. 2015). These peatlands form potentially important but usually neglected natural carbon storage systems in tropical and sub-tropical regions where extensive lowland peatlands such as the Amazonian palm swamps in the Pastaza Marañon, the Congo Basin, or Indonesian swamp forests were considered more important. The importance of the alpine peatlands is accentuated when considering the modelled thermal future under climate change because carbon emissions for the tropical lowland areas are predicted to rise due to higher water demands while less significant changes are predicted for the highlands (Gallego-Sala et al. 2018).

PEATLAND USES AND CONSERVATION

Andean peatlands are intensively used by pastoralist communities as grazing fields for native and introduced livestock and these wetlands are the only ever-green fields. That capacity for permanent use combined with the low-income of local communities mean that they must constantly increase their flock size and expose the wetlands to over use, affecting the native vegetation cover and its ecological functioning. In some native communities in central and southern Peru, Bolivia and northern Chile, which preserve traditional knowledge practices, the wetlands are managed by artificially spreading water through irrigation with the aim of increasing the grazing areas. But in the northern range of the central Puna as in Cordillera Blanca, or in the more humid eastern slopes, peatland drainage is more common than irrigation, especially in communities where traditional camelid-based livestock are replaced by introduced sheep or cattle.

The peatlands are key nesting, forage and water provision habitat for native wildlife including vicuna (*Vicugna vicugna*), small mammals, amphibians and numerous birds including the South American species of *Rhea* (*R. pennata* and *R. americana*). In central Peru, cushion-plant peatlands dominated by *Distichia muscoides* are the only known feeding habitats for *Cinclodes palliatus*, a critically endangered bird species whose total population has not surpassed 250 adult individuals in recent decades. The Peruvian government is the only central Andean country that requires priority protection for wetland ecosystems (article 99 of the General Environmental Law - Law No 28611) and considers bofedales to be fragile ecosystems needing special protection and compensation measures if disturbed. But the threats to those peatlands are varied and continue: overgrazing, illegal peat extraction, drainage, and mining and gas activities.

Current and future conditions of changing climate also can affect the functionality of these peatlands changing the amount and timing of rainfall events, modifying the infiltration-runoff patterns, and altering the evapotranspiration loses.

OUR RESEARCH PROGRAM

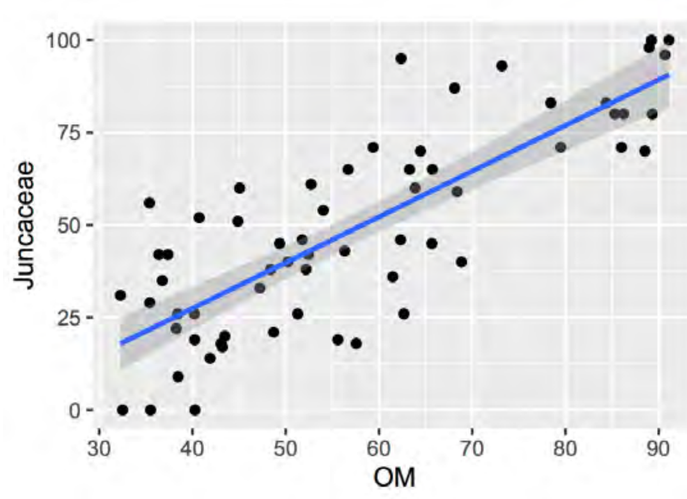
Our research has focused on understanding the hydrological and ecological processes that support wetlands in the Andes. We use ground water monitoring wells, piezometers, and geochemical tracers to understand the hydrologic regimes that support different wetland types and the water sources that support them (Cooper et al. 2019). The northern Andes from Colombia to northern Peru are generally much lower elevation and wetter alpine regions (termed "paramos") where a higher diversity of peat accumulating wetland communities exist. For example, in northern Peru we identified 20 peat accumulating communities (Cooper et al. 2010). However farther south the elevation of the puna rises to much higher levels, and typically only a couple of communities occur, all dominated by cushion plants or bunch grasses. The same is true for the Andes in Colombia, where lower elevation peatlands have higher species and community richness and the highest elevations are occupied primarily by *Distichia muscoides* dominated cushion plant communities (Benavides and Vitt 2014).

We have also focused on the processes of peat accumulation to determine whether in today's climate and under current land uses the fens are accumulating carbon. We have used the "moss wire" method (Cooper et al. 2015), cores with ^{14}C aging (Hribljan et al. 2015), and the use of C gas fluxes measures to demonstrate that intact cushion communities are peat forming. We are expanding into analyses of ditched, drained, and heavily grazed peatlands, as well as restored peatlands, as has been done by Rod Chimner and his students (Planas-Clarke et al. 2020).

Currently, we are developing a series of research projects to understand the hydrological behavior and carbon dynamics of peatlands in Nor Yauyos – Cochas Landscape Reserve and Vilacota – Maure Regional Conservation Area, two remarkably different areas of the Peruvian puna (Figure 1, A and B). Nor Yauyos – Cochas is located in the Central Cordillera, one of the highest mountain ranges in Peru with tropical glaciers, a relatively humid climate with rain that varies between 400 to 700 mm/year and a seven-month dry period from May to November. Vilacota – Maure located in Tacna province, the most southern administrative region in Peru including the Atacama Desert and the dry puna includes the completely deglaciated Cordillera del Barroso as the main mountain range. The climate in Vilacota Maure is semi-arid, with precipitation varying from 200 to 400 mm/year and a long dry season from April to December. In both areas the vast majority of bofedales are cushion plant-dominated peatlands with groundwater flowing from hillslopes to bottom valleys (Figure 8) where peat thickness can be more than 10 meters. In Nor Yauyos – Cochas the dominant species is *Distichia muscoides* while in Vilacota Maure *D. muscoides* is replaced by *Oxychloe andina* that forms less-compact cushions and spreads more extensively reducing the presence of pools.

Both in Nor Yauyos – Cochas and Vilacota – Maure the best-preserved sites with the thickest accumulated peat layers and highest organic matter content are associated with intact cushion plant communities (Figure 9). Higher diversity of plant species occurs usually in places influenced by high grazing pressure, reduced water provision, a combination of these two pressures, or in artificially created wetlands. Usually, areas with higher plant diversity have lower organic matter content and lower values of hydraulic conductivity in upper peat layers. Meanwhile, at deeper and permanently saturated levels, the peat characteristics as OM content and hydraulic conductivity as well as porosity and structure, remains relatively homogeneous, indicating possible common vegetation in the past, that has changed in modern times due to climate changes or human interventions.

FIGURE 9. Correlation between % cover of Juncaceae (*Distichia muscoides* and *Oxychloe andina*) vs. % organic matter in peatlands in the Vilacota – Maure Regional Conservation Area.



A key research goal for the future is to quantify the condition of peatlands, their carbon stock, and the processes that sustain and degrade them. A large proportion of bofedales are highly degraded by land uses, particularly heavy and continuous grazing, and their cushion plants have been partly or completely killed. We need to understand the level of grazing that is sustainable for the persistence of ecosystem services provided by the peatlands and for the persistence of indigenous communities that rely on grazing for their livelihood. For ecosystems that are already highly degraded we need to understand how to restore their hydrologic regimes, successfully introduce cushion plants, and rebuild plant production and carbon storage. There are many challenges ahead as the people of the Andes depend on these bofedales almost completely for their livelihoods, but have used them intensively, to the point of severe degradation and collapse in some areas. The future will require intensive management and restoration to have a sustainable peatland resource in the puna. ■

REFERENCES

Benavides, J.C. and D.H. Vitt. 2014. Response curves and the environmental limits for peat-forming species in the northern Andes. *Plant Ecology* DOI 10.1007/s11258-014-0346-7.

Chimner, R., L. Bourgeau-Chavez, S. Grelik, J. Hribljan, A. Planas-Clarke, M. Polk, E. Lilleskov, and B. Fuentealba. 2019. Mapping mountain peatlands and wet meadows using multi-date, multi-sensor remote sensing in the Cordillera Blanca, Peru. *Wetlands* 39: 1057-1067.

Cooper, D.J., E. Wolf, C. Colson, W. Vering, A. Granda, and M. Meyer. 2010. Alpine peatlands of the Andes, Cajamarca, Peru. *Arctic, Antarctic and Alpine Research* 42: 19-33.

Cooper, D.J., K. Kaczynski, D. Slayback, and K. Yager. 2015. Growth, production, and short-term peat accumulation in *Distichia muscoides* dominated peatlands, Bolivia, South America. *Arctic, Antarctic and Alpine Research* 47: 99-104.

Cooper, D.J., J. Sueltenfuss, E. Oyague, K. Yager, D. Slayback, E.M.C. Caballero, … and B.G. Mark. 2019. Drivers of peatland water table dynamics in the central Andes, Bolivia and Peru. *Hydrological Processes* 33: 1913–1925.

Falvey, M. and R.D. Garreaud. 2005. Moisture variability over the South American Altiplano during the South American low level jet experiment (SALLJEX) observing season. *Journal of Geophysical Research Atmospheres* 110: 1–12.

Gallego-Sala, A.V., D.J. Charman, S. Brewer, S.E. Page, I.C. Prentice, P. Friedlingstein, … and Y. Zhao. 2018. Latitudinal limits to the predicted increase of the peatland carbon sink with warming. *Nature Climate Change* 8: 907–913.

Hribljan, J.A., D.J. Cooper, J. Sueltenfuss, E.C. Wolf, K.A. Heckman, E.A. Lilleskov, and R. Chimner. 2015. Carbon storage and long-term rate of accumulation in high-altitude Andean peatlands of Bolivia. *Mires and Peat* 15: 1–14.

Olson, D.M., E. Dinerstein, E. Wikramanayake, N.D. Burgess, G.V.N. Powell, E.C. Underwood, … and K.R. Kassem. 2001. Terrestrial Ecoregions of the World: A new map of life on Earth. *BioScience* 51: 933–938.

Planas-Clarke, A., R. Chimner, J. Hribljan, E. Lilleskov, and B. Fuentealba. 2020. The effect of water table levels and short term ditch restoration on mountain peatland carbon cycling in the Cordillera Blanca, Peru. *Wetlands Ecology and Management* 28: 51-69.

Rabatel, A., B. Francou, A. Soruco, J. Gomez, B. Cáceres, J.L. Ceballos, and P. Wagnon. 2013. Current state of glaciers in the tropical Andes: a multi-century perspective on glacier evolution and climate change. *The Cryosphere* 7(1): 81–102. https://doi.org/10.5194/tc-7-81-2013.

Rojo, V., Y. Arzamendia, C. Perez, J. Baldo, and B. Vila. 2019. Spatial and temporal variation of the vegetation of the semiarid Puna in a pastoral system in the Pozuelos Biosphere Reserve. *Environmental Monitoring and Assessment* 191: 635.

Rundel, P.W., A.P. Smith, and F.C. Meinzer. 1994. Tropical Alpine Environments. Cambridge University Press, Cambridge, U.K.

Strecker, M.R., R. Alonso, B. Bookhagen, B. Carrapa, I. Coutand, M.P. Hain, … and E.R. Sobel. 2009. Does the topographic distribution of the central Andean Puna Plateau result from climatic or geodynamic processes? *Geology* 37: 643–646.

Yager, K., C. Valdivia, D. Slayback, E. Jimenez, R. Meneses, A. Palabral-Aguilera, … and A. Romero. 2019. Socio-ecological dimensions of Andean pastoral landscape change: bridging traditional ecological knowledge and satellite image analysis in Sajama National Park, Bolivia. *Regional Environmental Change* 19: 1353–1369.