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ORIGINAL PAPER

Challenges and opportunities for restoration of high-elevation Andean peatlands in Ecuador

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Abstract

Páramo peatlands are a regional reservoir of biodiversity and ecosystem services, accumulating large amounts of carbon and buffering water flows. Despite their importance, they have a long history of use and impacts including drainage for agriculture and grazing, and water withdrawal for human uses. Here we present a preliminary assessment of the conservation status of páramo peatlands in Ecuador and, using a case study, discuss peatland restoration as a tool for mitigation and adaptation to the impacts of current climate change. Through a simple index assessing the cumulative presence of signs of human activities on 163 peatland sites, we found that the level of impact was higher for peatlands located in the Western branch of the cordillera, whereas current human population density, precipitation, and elevation were not significant predictors of the levels of impact. Also, starting in 2017, we implemented a pilot restoration initiative on a 21-ha peatland which had been drained and converted into pasture for at least 150 years. The restoration consisted of two ditch blocking techniques implemented to stop fast-moving water and promote the rewetting of the peatland. During the next 3 years, water table increased from 27 ± 3 cm below the soil surface to 7 ± 1 cm by 2021, while wetland plant communities are colonizing and closing the pools in the blocked ditches. Re-wetting of the peatland has led to an increase in the abundance of native species. This case study suggests that restoration initiatives are an efficient and cost-effective approach to a better management of páramo peatlands, with high potential as a tool for mitigation and adaptation to climate change.

Keywords Páramo · Peatlands · Ecuador · Restoration · Andes · Human impact

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1 High-elevation Páramo peatlands in Ecuador

The páramo ecosystems, a complex mosaic of vegetation types occupying the Northern Andes —roughly from 8°N to 5°S, and between ~ 3000 m and the limits of perpetual snow — are a key environment of regional importance (Hofstede et al. 2014). Serving both as a high corridor allowing the movement of some species and as a diversification center for other taxa (Flantua et al. 2019), the páramo is a regional reservoir of endemic biodiversity and a natural laboratory where extremely fast evolutionary rates have been reported (Diazgranados and Barber 2017; Cortes et al. 2018; Diaz-Acevedo et al. 2020). At the same time, páramo ecosystems provide a wealth of ecosystem services including carbon sequestration, potable water supply, irrigation, recreation, agriculture, and soil stabilization, which serve millions of people in the region (Buytaert et al. 2011).

Owing to the complex topography and the heterogeneous influence of geological setting, glacial history, and volcanic activity, páramos are dotted by numerous and extensive peatlands that are receiving increased attention due to their biodiversity, their large carbon stores and high rates of carbon accumulation, and their role in water regulation and supply (Chimner and Karberg 2008; Benavides et al. 2013; Mosquera et al. 2015). In northern Ecuador, for example, peatlands can cover up to 23% of the páramo landscape and provide carbon storage in excess of 2000 MgC ha^{-1} (Hribljan et al. 2016, 2017). The structure and vegetation of these peatlands are heterogeneous, depending on the geomorphological setting, local weather patterns, and elevation, ranging from small peatlands (<0.5 ha) dominated by cushion-forming plants (mainly *Plantago rigida* and *Distichia muscoides*; Fig. 1a and b) in small topographic depressions to large peatlands (10 to >100 ha) dominated by graminoids, mosses, and shrubs at intermediate elevations (Fig. 1b and c), or sedges and rushes in the bottom of large glacial valleys (Fig. 1e-h). In general terms, these communities are similar to those described previously for the Páramo and Puna environments of Bolivia, Perú, and Colombia (Cooper et al. 2010; Benavides and Vitt 2014).

Although páramo ecosystems cover only approximately 5% of the territory in Ecuador, and páramo peatlands represent roughly 20% of the páramo (Hribljan et al. 2017), carbon concentration in the peatland soils is so high (more than 2000 MgC/ha) that they could harbor a substantial proportion of the total carbon storage in the country (Hribljan et al. 2016, 2017). From this perspective, the comparatively small area and the concentration of ecosystem services of páramo peatlands represent an excellent opportunity to protect and restore these critical ecosystems with high returns for relatively low investments. In this paper, we present a preliminary assessment of the conservation status of Ecuadorian páramo peatlands, describe a case study of restoration of a high-elevation peatland in Northern Ecuador, and discuss the challenges and opportunities for restoration and management of páramo peatlands as a tool for climate change mitigation and adaptation in the country.

2 Assessment of human impacts on páramo peatlands in the Ecuadorian Andes

Despite their importance, páramo peatlands in Ecuador have been largely overlooked and explicit plans for their protection or management are lacking. On one hand, large-scale use of peat as fuel or potting substrate has not been reported in Ecuador. On the other hand,

Fig. 1 Examples of the general vegetation types found in páramo peatlands in Ecuador. **a**–**b**) Peatlands dominated by cushion-forming plants (e.g., *Plantago rigida*, *Distichia muscoides*); c–d) peatlands dominated by graminoids and mosses (e.g., *Cortaderia sericantha*, *C. nitida*); **e**–**f**) peatlands dominated by sedges and rushes (e.g., *Carex pichinchensis*, *C. lehmanniana*); g–h) heterogeneous peatlands in the bottom of large glacial valleys usually exhibiting several vegetation types

despite their unique functional and structural characteristics, the physiognomy of páramo peatlands tends to be less distinctive in comparison with the surrounding humid páramo, which may have resulted in peatlands being lumped together as undistinguishable components of the páramo. At the same time, their relatively flat topography with abundant water makes them particularly vulnerable by facilitating their use for agriculture and cattle raising. As in other regions (Chimner et al. 2010), peatland drainage (Fig. 2a and b), agriculture (Fig. 2c-f), overgrazing (Fig. 2f-h), and water removals are some of the most common impacts that Ecuadorian peatlands are experiencing (Laine et al. 2009). In order to provide a preliminary assessment of the conservation state of páramo peatlands in Ecuador, we collected field information regarding signs of human activities on 163 peatlands encompassing all the major environmental gradients (elevation, latitude, and precipitation) that can be found across the high Andes of Ecuador. The types of activities recorded were selected based on previous observations of their frequency during field surveys. Although we tried to randomly select the peatlands, many of them are located in remote regions and, as a result, our sampling is biased by the availability of roads. This bias, however, was constant throughout the country. Based on this information, we constructed an arbitrary index in which the presence of each activity adds a number of points to the index corresponding to the potential impacts of that activity on the structure and function of the peatland (Table 1). For example, the presence of garbage would add only 0.5 points, whereas the presence of agriculture would add 6 points, as this activity drastically changes the structure of the soil and usually requires draining of the peatland. For this index, we did not take into account potential additive or synergistic effects of human activities. For example, the density or type of cattle, or the interaction between drainages and trampling, was not considered in the index. However, by adding the values corresponding to the presence of different human activities at each site, this index allows us to rank and characterize the level of anthropogenic impacts across the country. In order to explore the factors influencing the distribution of human impacts for each peatland site, we also gathered information on elevation (field data), human population density of the county in which each peatland was located (2010 National Census Data), precipitation, and mountain range (Eastern or Western branch of the cordillera; see Supplementary Tab. S1). We tested for multicollinearity in the four independent variables by running a Pearson correlation analysis and a multiple linear regression using the tolerance and variation inflation factor options. In both analyses, multicollinearity was not an issue and the tolerance values were greater than 0.4 and the variance inflation factor was less than 2.5 for all variables (Allison 1999). These two analyses were performed to ensure that the estimates for the negative binomial regression (see below) were valid. Because of the discrete nature of the response variable, negative binomial regression was used to analyze the data. These variables were used as explanatory factors against the level of impact, using the negative binomial distribution with the log link function to account for overdispersion of the data. We used an alpha level of 0.05 for detecting statistical significance, and the analysis was carried out using SAS® 9.4 via the GLIMMIX procedure (SAS Institute Inc. 2011).

Based on this preliminary analysis, distribution of anthropogenic impact on páramo peatlands in Ecuador is heterogeneous (Fig. 3). Peatlands in the Western cordillera had significantly higher levels of impact (mean index ± standard error: 5.2 ± 0.4) than peatlands in the Eastern cordillera (3.3 ± 0.3; Table 2). Interestingly, although the Western cordillera, especially in the central Andes of Ecuador, tends to have higher rural population, and lower precipitation levels, these variables were not statistically significant (Table 2). We think that this pattern could be explained by the nature of the data that we used. While the precipitation and human population density data entered in the model represent the

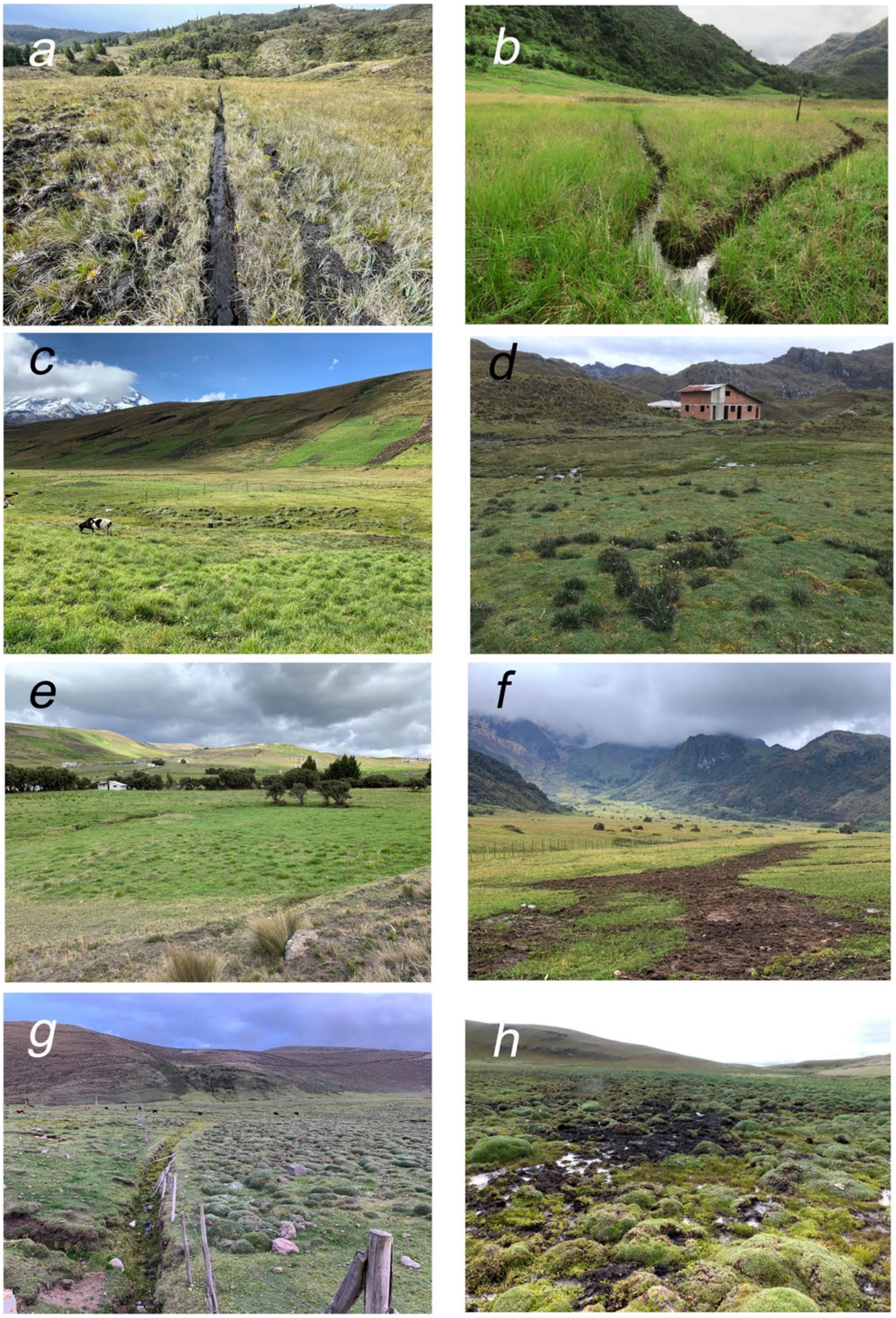


Fig. 2 Common anthropogenic impacts found in páramo peatlands in Ecuador. **a**–**b**) Agriculture and infrastructure; **c**–**d**) overgrazing; **e**–**f**) drainages; **g**–**h**) soil disturbance. Typically, several of these impacts occur in the same sites

Table 1 Structure of the index used to quantify the concentration of impacts of human activities on Ecuadorian páramo peatlands. The presence of signs of each type of activity on any give peatland adds a number of points to the index for that site corresponding to the relative impact of that activity on the structure and functioning of the peatland. This index does not quantify the intensity or frequency of each type of disturbance. For details, see text

Type of activity	Points
Garbage	0.5
Impacts on surrounding slopes (e.g., roads, fire scars, agriculture)	1
Infrastructure (e.g., houses, fences, water management infrastructure)	1.5
Cattle	2
Drainage	3
Agriculture/pastures	6
Total	14

recent (short-term) patterns of these variables, the location of the peatlands in the Eastern or Western cordillera probably reflects their long-term historical effects. This pattern is also evident in the distribution of the individual impacts. While all the types of human activities were slightly more frequent in the Western than in the Eastern cordillera, the number of peatlands transformed to agriculture or pastures, and the number of peatlands that exhibited infrastructure was, respectively, 3.1 and 2.5 times higher in the Western than

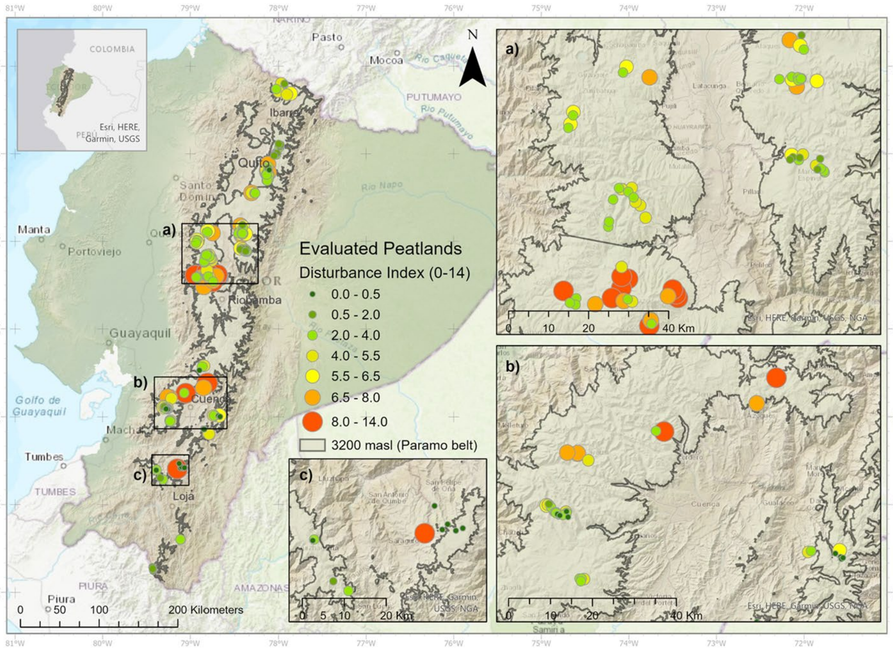


Fig. 3 Distribution and intensity of anthropogenic impacts on 163 Ecuadorian páramo peatlands. Marker size increases with increasing concentration of signs of anthropogenic activities in each peatland, measured through an arbitrary index that ranges between 0 (no signs of human activity) and 14 (maximum concentration of signs of activities). For details, see text

Table 2 Result of the negative binomial regression model used to analyze the effects of elevation (field data), human population density (2010 National Census Data), precipitation, and mountain range (Eastern or Western branch of the cordillera), on the concentration of signs of human activities on Ecuadorian páramo peatlands. The analysis was carried out in SAS® 9.4 using the GLIMMIX procedure, using the negative binomial distribution, and the log link function to account for overdispersion in the response variable

Type III tests of fixed effects				
Effect	Numerator DF	Denominator DF	*F* value	Pr > *F*
Mountain range	1	158	5.86	0.0166
Population density	1	158	1.50	0.2222
Elevation	1	158	0.67	0.4147
Precipitation	1	158	1.34	0.2483

in the Eastern side of the Andes (see supplementary Tab. S2). This pattern was mostly due to the concentration of highly impacted peatlands that we recorded in the central provinces of Tungurahua, Chimborazo, and Bolivar. These provinces have a long history of human occupation with high population densities and strong ties to the páramo landscape. In contrast, influenced by the Amazon basin, the Eastern cordillera of Ecuador has much higher precipitation levels, especially in the Northern and Central Andes, and a much larger area of páramo in ecological reserves and national parks. In combination, these patterns suggest that national policies should emphasize sustained conservation for the Eastern sites, versus restoration and improved management initiatives in the Western peatlands. Moreover, peatland restoration initiatives could serve the double objective of improving water availability and quality for marginalized populations, while contributing to national and local opportunities for adaptation and mitigation of climate change.

3 A case study of peatland restoration from Northern Ecuador

In 2017, we initiated a restoration project in the Chakana peatland, a 21-ha peatland located at 3750 masl within the Chakana Reserve owned by Jocotoco Foundation. On average, this peatland has 3.5 m of depth, an average carbon content of 23.5 ± 4.1%C, and mean bulk density of 0.22 ± 0.03 g cm^3. This peatland had been used for cattle grazing for at least 150 years, and eight ditches (total length of 3.9 km) had been cut parallel to the slope of the peatland in order to drain it (Fig. 4). Additionally, between 2014 and 2015, 20 additional ditches (between 220 and 310 m in length) were cut across the slope of the peatland as part of a misguided initiative to increase the habitat for migratory bird species, adding approximately 4.8 km of ditches (Fig. 4). As a result, native vegetation was almost completely replaced by exotic pasture species (mainly *Anthoxanthum odoratum*), and the peatland was permanently drained through the deeply cut ditches that water carved through time. Previous to this restoration initiative, cattle were permanently removed from the site as part of the conservation strategies carried out by Jocotoco Foundation.

In order to restore the hydrology and vegetation of the Chakana peatland, we followed general approaches described for mountain peatlands (Chimner et al. 2017, 2019; Planas-Clarke et al. 2020). Two different blocking techniques were used depending on the characteristics of the ditches. Deep ditches with fast-moving water and following the direction of

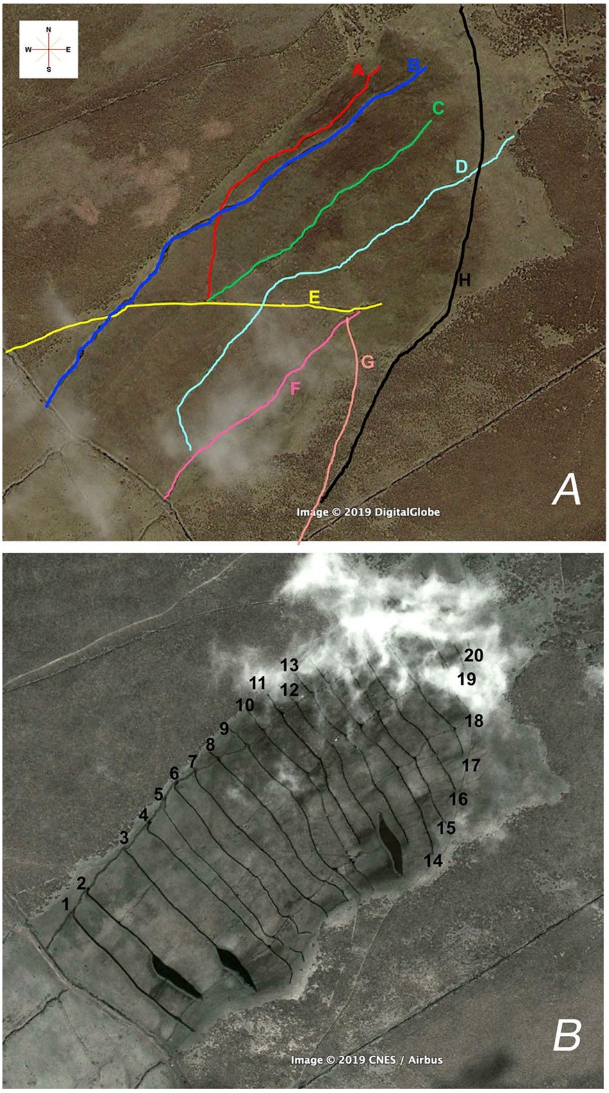


Fig. 4 Satellite images (Google Earth ©) of the Chakana peatland site before the restoration initiative. **A**) Longitudinal ditches cut along the peatland at some point during the past 150 years of grazing in this area. **B**) Additional ditches cut between 2014 and 2015 to create habitat for migratory birds

the slope were blocked with a combination of wooden barriers and straw bales (Fig. 5a and b), with a separation between 3 and 10 m, depending on the steepness of the terrain. The barriers had the purpose of reducing the energy of the moving water, while the straw bales were placed downstream, behind the barriers, in order to provide a substrate for plant colonization and further stabilize the blockades. For the 20 ditches cutting across the peatland, we only used barriers built with straw bales (Fig. 5c and d) because the channels were not very deep (30–40 cm) and the water velocity was low. On average, these barriers were placed every 10 m along the ditches, for an average of 20 barriers per ditch, or approximately 400 barriers in the whole peatland. As with the wooden barriers, the straw bales used in these ditches were covered with pieces of turf cut from the surrounding areas, in order to stabilize the barrier and accelerate the recovery of the vegetation. The construction of the barriers was carried out between November 2017 and February 2018, and the

Fig. 5 Examples of the barriers constructed with wood planks (**a** and **b**) or straw bales (**c** and **d**) to slow down water movement along the ditches, and promote rewetting in the Chakana peatland

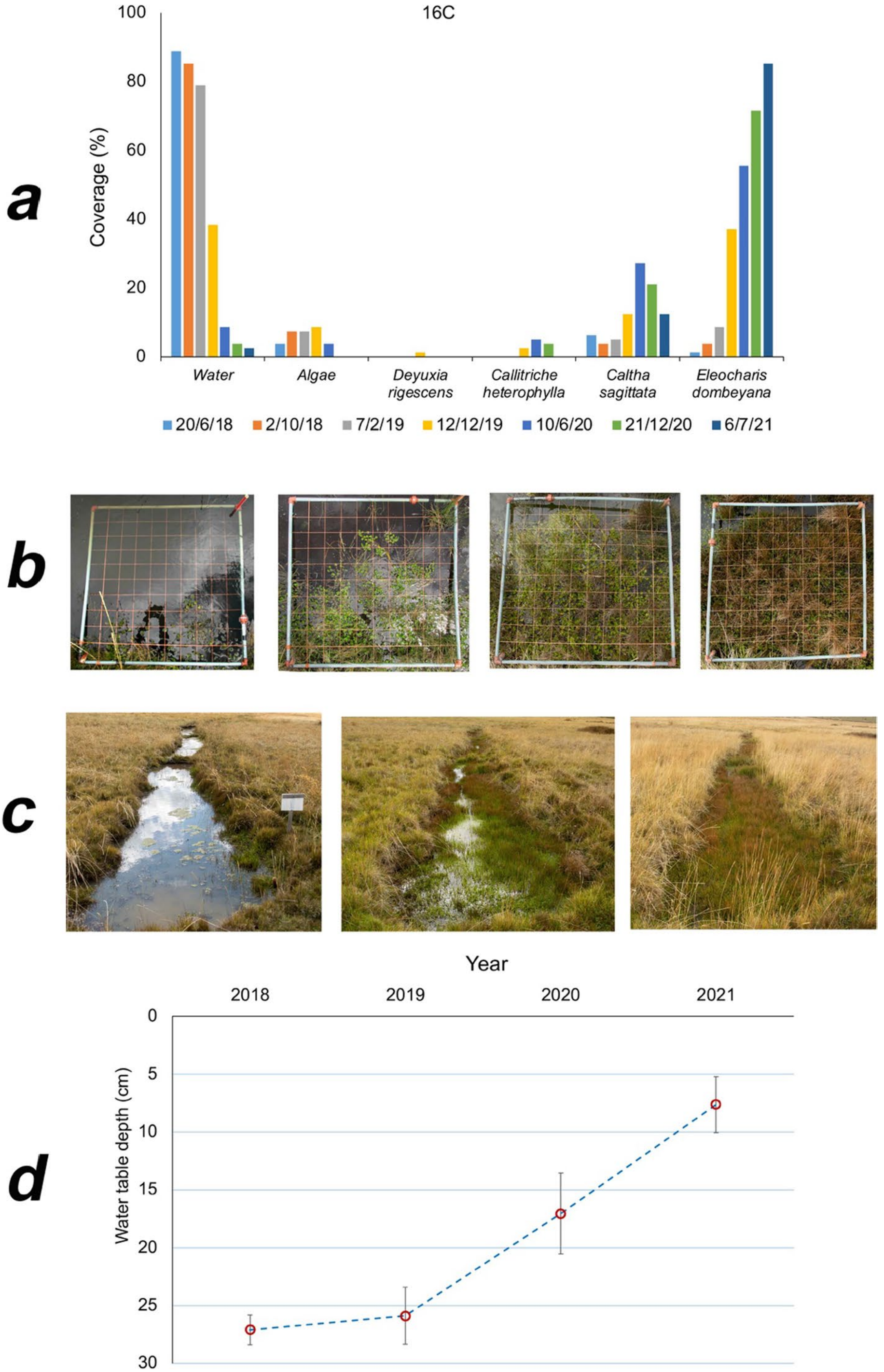
Fig. 6 Results of the monitoring of the restoration of the Chakana peatland. **a**) Changes in percentage of ground cover in the channels that resulted from the construction of ditch plugs in 2017, with examples of corresponding pictures shown in panel **b**. **c**) Overall view of the changes in vegetation along the restored channels. **d**) Temporal trends in water table level in the Chakana peatland. Each point represents the mean and standard error of monthly water table measurements taken between 2018 and 2021 on six wells distributed throughout the peatland ▶

effects of the restoration have been evaluated by periodic monitoring including (i) 16 permanent vegetation plots (1 × 1 m) randomly placed on four of the horizontal ditches and sampled twice a year; and (ii) a system of vegetation plots (1 × 1 m) randomly distributed across the peatland, which were sampled in 2017 (30 plots), 2019 (30 plots), and 2021 (143 plots). These quadrats were divided in a 10 × 10 cm grid, and species composition and percent coverage were estimated by recording the first species coinciding with each of the 100 resulting intersections of the grid. Additionally, we installed six ground water monitoring wells spread along the elevation gradient of the peatland, which were monitored at least eight times per year.

Water table depths averaged 27 ± 3 cm below the soil surface in 2018 but rose to 7 ± 1 cm by 2021 (Fig. 6a; Mann–Whitney test W value: 49; $p = 0.009$) and annual variation at individual wells decreased by 25% during the same period, even during the dry season that this area usually experiences between July and August (see Supplementary Fig. S1). Together, these measurements suggest that the peatland has been rewetted and is becoming more hydrologically stable in response to the ditch blocking. Following the blocking of the ditches, vegetation expanded and is successfully filling in the ditches (Fig. 6b-d). Within a month after the construction of the dikes and as a result of the reduction in water velocity, the channels were colonized by algae (unidentified species). As the algae increased in coverage, it started dying and decomposing, thus adding organic matter which served as substrate for the establishment of other peatlands species, including *Caltha sagittata* and *Eleocharis dombeyana*. Specifically, the coverage of *E. dombeyana* increased from 1% 6 months after the restoration to 85% after 3 years, with a concomitant decrease in the amount of open water in the channels.

The rewetting of the peatland also resulted in a striking change in the plant community composition in the non-ditched areas in the peatland. In order to explore these changes, we performed a nonmetric multidimensional scaling (nMDS) using Bray–Curtis Distance in R® 4.1.1. For this, we used the species percent coverage recorded in 30 plots (1 × 1 m) in 2017 and 2019 and 143 plots in 2021. Species that were present in less than 20 plots were excluded from the analysis. The r-function *meta*MDS was used for constructing multiple runs, finding the best solution for each dimensionality. The vegetation plots sampled in 2021 clearly separated from the 2017 and 2019 plots, suggesting large changes in species composition (Fig. 7). Among these changes, some of the most important are a 10% reduction in the mean percent coverage of *Anthoxanthum odoratum*, an exotic pasture species, and a concomitant increase in the coverage of *Plantago rigida*, *Bromus lanatus*, and *Geranium multipartitum*, all native species that are frequent in high-elevation páramo peatlands, as well as in many upland páramo sites (personal observation). The increase in the representation of *P. rigida* is of special importance as this cushion-forming species is considered an important peat forming species in these Andean systems (Suárez et al. 2021). The rapid colonization by this species could be indicative of a recovery of the functionality of the peatland.

The estimated cost of this restoration initiative, including labor, materials, monitoring, and transportation is USD $10,000, or approximately USD $470 ha^{-1} (USD $119 ha^{-1} year^{-1}). These costs could be further reduced if the restoration activities are implemented through


a
16C
Coverage (%)
100
80
60
40
20
0
Water
Algae
Deyuxia rigescens
Callitriche heterophylla
Caltha sagittata
Eleocharis dombeyana
20/6/18
2/10/18
7/2/19
12/12/19
10/6/20
21/12/20
6/7/21
b
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Year
2018
2019
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Water table depth (cm)
0
5
10
15
20
25
30

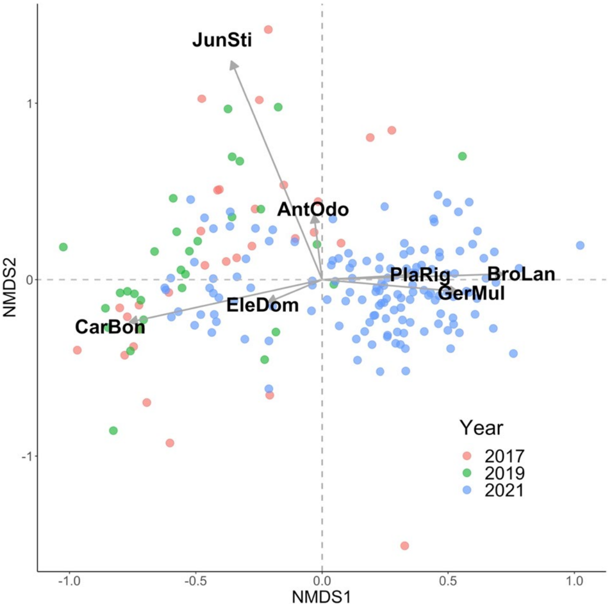

Fig. 7 Nonmetric multidimensional scaling (nMDS) ordination of individual plots for each sampling year: red dots: 2017, green dots: 2019, and blue dots: 2021. Vectors show the direction and magnitude of selected species that presented changes in abundance through the sampling years. JunSti, *Juncus stipulatus*; AntOdo, *Anthoxanthum odoratum*; CarBon, *Carex bonplandii*; EleDom, *Eleocharis dombeyana*; PlaRig, *Plantago rigida*; GerMul, *Geranium multipartitum*; BroLan, *Bromus lanatus*

participatory approaches with local people and other stakeholders with interest and responsibility on the conservation of these ecosystems. At the same time, native vegetation is responding very quickly to the rewetting of the peatland. From this perspective, this pilot initiative strongly suggests that restoration can become a very efficient, and cost-effective approach to contribute to local efforts to improve adaptation to climate change, by protecting ecosystem services, and creating opportunities for local people and institutions.

Previous experiences in the Central and Southern Andes have shown that hydrological restoration in high-elevation peatlands is feasible and can have profound impacts on biodiversity and ecosystem services. In the Andes of Perú, for example, ditch restoration in a drained bofedal increased net ecosystem exchange, thus improving the capacity of the system to store carbon (Planas-Clarke et al. 2020). Similarly, a landscape-level study in the Bolivian Andes showed that areas with high density of check dams and other erosion control structures had a higher normalized difference vegetation index (NDVI), which suggested an increase in the greenness of vegetation in the bofedales (Hartman et al. 2016). Interestingly, traditional communities in Perú have also developed their own restoration and management techniques, using small flat stones (trancas) and other structures to manage flows of water as a way to expand and maintain bofedales that are used for herding llamas and alpacas (Verzijl and Guerrero-Quispe 2013). In the páramo of the Northern Andes, however, less information is available which calls for renewed efforts at developing and synthesizing what is known about better management practices and restoration initiatives in the vast system of peatlands that characterize this bioregion.

4 Challenges and opportunities for peatland restoration

Restoration of páramo peatlands in Ecuador is a promising alternative for enhancing ecosystem services from high-elevation ecosystems, including both mitigation and adaptation to climate change. Well-conserved páramo peatlands exhibit a high concentration of ecosystem services and management targets (e.g., carbon storage, GHG uptake, water supply and regulation, biodiversity conservation) in a relatively small area (Buytaert et al. 2011; Bremer et al. 2019). Direct beneficiaries of the services provided by páramo peatlands are numerous and include local people, water companies, large and small-scale farmers, and electricity generation companies. In this context, management and restoration of these environments could be implemented with relatively low investments, large conservation returns, and active involvement of a diverse array of stakeholders. In order to promote these activities, additional information will be needed regarding what type or level of farming in peatlands is compatible with carbon storage, clean water supply, and other ecosystem services provided by these environments.

The potential for functional restoration appears substantial, given both the extent of human impacts on these systems and the GHG consequences of these land uses (Sánchez et al. 2017; Planas-Clarke et al. 2020). As a result of their position in the landscape, many páramo peatlands could be seen as integrators of the effects of land-use practices either by receiving the effects of fire, agriculture, and grazing in their catchment areas or by conditioning the patterns of extraction and use of water from páramo regions. For example, intensively grazed areas of páramo peatlands have been found to release large amounts of methane, a potent greenhouse gas with 32×the global warming potential of carbon dioxide, to the atmosphere (Sánchez et al. 2017). From this perspective, management and restoration of páramo peatlands could be used as a tool for promoting integrated land-use plans involving different users throughout the watershed. A promising example is the development of water funds, such as the Trust Fund for the Conservation of Quito's Water Sources (FONAG). By collaborating with the water company of the city and other private stakeholders, FONAG can secure long-term funding which is used, among other things, to develop conservation and restoration initiatives of páramo peatlands, thus conserving the water sources that are critical for the city.

Finally, as a result of their high concentration of carbon and their ability to continue to take up CO_2 from the atmosphere for millennia, conservation and restoration of páramo peatlands could be seen as a substantial contribution to the mitigation of the effects of climate change (Planas-Clarke et al. 2020) and as an important tool for supporting national efforts at carbon accounting and reporting for international agreements. In general, tropical countries have concentrated their carbon accounting efforts in forest biomass. However, the recent realization of the large amounts of carbon stored in high-elevation peatlands in the Tropical Andes (Hribljan et al. 2015, 2017) opens a promising new path to explore opportunities for adaptation and mitigation of climate change, by engaging local people and national institutions in the conservation and restoration of these carbon rich ecosystems.

Regarding the challenges for future restoration of páramo peatlands, perhaps one of the most important obstacles emerges from the very nature of these ecosystems. By forming in relatively flat areas within the rugged topography of the Andes, páramo peatlands offer attractive land for agriculture and grazing and, in drier regions, the most reliable source of easily accessible water for human consumption. As a result of these factors, it might be difficult to remove or modify the stressors that are affecting these peatlands, thus reducing the feasibility of their restoration. This problem is compounded by current lack of incentives and alternatives that could encourage local people to engage in the conservation or restoration of páramo peatlands. Research efforts should be focused on finding socially acceptable sustainable alternatives to these land uses, or on the cost-effectiveness of providing payments for ecosystem services to landowners. For example, in Peru, alternative grazing systems use water management structures and native camelids rather than sheep or cattle, which are thought to have less erosive impact because they have a different, softer hoof anatomy (Verzijl and Guerrero-Quispe 2013). Is this system ecologically, socially, and economically feasible in the region and, if so, what are the GHG consequences of this grazing system relative to the current uses? Camelids are also ruminants, and do produce methane during digestion (Dittmann et al. 2014; Clauss et al. 2020) but to our knowledge the whole-ecosystem GHG consequences of camelids vs. ruminants have not been examined.

Another important obstacle is the lack of appropriate reference sites to guide restoration and conservation initiatives. In areas like the central portion of the Western branch of the Ecuadorian Andes, it is very difficult to find relatively undisturbed peatlands. Moreover, historical descriptions or studies of these systems are lacking, making it very hard to define targets for restoration. From this perspective, restoration initiatives can only be implemented with a very vague sense of the type of biotic community that will be restored. If additional funds and human resources are available, this problem could be partly solved through the use of stable isotopes and macrofossils (Skrzypek et al. 2011). However, our experience in the Chakana peatland also suggests that hydrological restoration can lead the plant community to revert to one dominated by native species. In the absence of reference vegetation data, the target for restoration initiatives could be hydrologic, biogeochemical (e.g., GHG fluxes), or land-use based rather than vegetative. In any case, this limitation highlights the need to increase research into the structure and function of páramo peatlands throughout the region, in order to inform future conservation and restoration initiatives.

A final but very important challenge for the restoration of páramo peatlands emerges from the striking unfamiliarity that people in Ecuador show towards páramo peatlands ecosystems. Although these wetlands are a prominent element of páramo ecosystems and have a crucial role in the supply of water across the Andean region of the country, the vast majority of people have virtually no knowledge even about their existence. This lack of knowledge extends into the academic and management realms, and it is only in the last decade that the first studies have been done looking into the structure and function of these peatlands. As a result, páramo peatlands have been ignored and their conservation has been largely contingent upon the conservation of the larger páramo landscapes in which they occur. In order to promote public support, funding, and development of local capacities for the conservation of páramo peatlands, large efforts are needed in terms of informing the general public about the importance, uniqueness, and intrinsic values of these ecosystems. Only then will we be ready to use the full potential of páramo peatlands as tools for climate change mitigation, biodiversity conservation, and protection of ecosystem services.

5 Implications for climate change mitigation

Páramo ecosystems have been recognized for the high carbon content of their soils and their role in water regulation and supply (Tonneijck et al. 2010; Benavides et al. 2018; Lazo et al. 2019). Although ample variation in soils characteristics occurs across the region, in general, it is accepted that these large accumulations of soil carbon are a consequence of the reduced decomposition of organic matter that results from cold weather and, in some areas, stabilization effects brought about by the presence of volcanic ash deposits (Poulenard et al. 2003, 2004; Tonneijck et al. 2010). Under these conditions, páramo soils have been acting as important carbon sinks since at least the end of the last glaciation. However, a recent report suggests that upland páramo ecosystems could be losing carbon, probably as a result of recent changes in temperature and precipitation in these tropical mountains (Carrillo-Rojas et al. 2019). If this pattern is widespread, it would represent a serious threat to the integrity of páramo ecosystems and to the services they provide. In contrast, páramo peatlands could be more resilient than the surrounding well-drained páramo, because organic matter decomposition might not be controlled only by temperature and soil characteristics, but also by water table levels which could rise if precipitation increases, as has been projected by some climatic models for the Northern Andes (Cuesta et al. 2012). In this context, the conservation and restoration of high-elevation peatlands, with their high rates of carbon accumulation and their disproportionate role in water regulation (Mosquera et al. 2015; Hribljan et al. 2016), could become a fundamental tool for adaptation and mitigation to climate change in the Northern Andes. Specifically, if peatlands can maintain negative climate forcing despite increasing temperatures in the páramo, their contribution to carbon dynamics could be essential in terms of maintaining the role of these landscapes as regional carbon sinks.

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