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A Conceptual Model for Rehabilitation of Puna Grassland Social–Ecological Systems

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The impacts of both climate change and socioeconomic processes are driving the degradation of mountains and the ecological services they provide worldwide. In the tropical Andes, compounding glacier retreat, altered hydrological and precipitation regimes (eg off-season alternation of extreme dry and wet periods), and expansion of mining and other land uses are modifying hydrological services. Although initiatives to restore ecosystems and their services are increasing, conceptual models emerging from experiences on the ground are scarce. Based upon the experience of Peru's National Institute for Research on Glaciers and Mountain Ecosystems (INAIGEM) in the Piuray Ccorimarca microbasin (Cusco) in combining participatory action research and experiments at the plot scale, this article elaborates a conceptual model for the rehabilitation of hydrological services on the social–ecological systems of puna grassland. The model proposes multiscale (plot–pilot–microbasin) rehabilitation. At each level, the actions proposed include designing plots, selecting sites, implementing restoration activities, and evaluating and monitoring the sites. Our inductive model from the ground and plot can inform rehabilitation of hydrological services on puna grasslands elsewhere.

Keywords: *ecosystem restoration; microbasin; hydrological services; grasslands; adaptive management; participatory action research; puna grassland; Peru; tropical Andes.*

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Introduction

The dramatic images of land degradation across the planet accurately represent the strained relationship between nature and society. In response to this critical situation, ecological restoration has gained global prominence among academics and practitioners (Berger 1990). The Intergovernmental Panel on Climate Change considers that restoration of ecosystems "reduces the vulnerability of biodiversity to climate change" (Pörtner et al 2022: 24). Among practitioners, it is highly significant that the United Nations has declared 2021–2030 the Decade on Ecosystem Restoration (United Nations General Assembly 2019) and linked restoration to addressing climate change (Suding et al 2015). The Sustainable Development Goals (SDGs) seem even more relevant, because they entail restoration of mountain ecosystems. For instance, SDGs 6 and 15 propose ecosystem restoration to recover hydrological ecosystem services and improve the condition of land, respectively (Soh et al 2019).

Climatic, environmental, and socioeconomic changes drive the growing degradation of mountain social–ecological systems (Poudel and Duex 2017; Hurlbert et al 2022; Olsson et al 2022). These comprise the services that these systems provide to the people living nearby, who depend upon them for their livelihood (Adler et al 2022), and those living downstream, who benefit from ecosystem functions. The growing need to restore these degraded landscapes faces challenges that question mainstream restoration. The goals of ecosystem restoration range from the complete recovery of primary ecosystems to a more realistic reduction of human impacts, passing through remediation and rehabilitation of ecosystems. A reference ecosystem, with the attributes of a native ecosystem, provides insights into the characteristics of a healthy ecosystem that are essential to guide rehabilitation efforts (Gann et al 2019). Rehabilitation of mountain hydrological services is particularly relevant, because most of the world's population relies on freshwater from mountain regions (Grêt-Regamey et al 2012).

The Andes mountain range offers an excellent case study for rehabilitation of mountainous environments globally. As degradation continues to expand over the Andes (Magrin et al 2014), restoring high Andean ecosystems is crucial to secure the critical hydrological services of mountains (Sun et al 2016; Bonnesoeur et al 2019). Water from the Andes, specifically, is critical for millions of people, because it generates power, irrigates crops, supports industry, feeds rivers, and replenishes aquifers (Bradley et al 2006; Vergara et al 2007). It also brings floods and landslides, which particularly affect vulnerable and marginal populations. In this article, we leverage the work of Peru's National Institute for Research on Glaciers and Mountain Ecosystems (INAIGEM) in the Piuray Ccorimarca microbasin, Cusco, Peru, to develop a conceptual model for rehabilitating hydrological services provided by the wet puna grassland ecosystem. The model is relevant because, according to the National Ecosystem Map of Peru, wet puna grassland comprises 9.26% (11,981,914.03 ha) of the country (MINAM 2018).

The model draws on participatory action research and adaptive management, encompassing management actions to tackle the causes of ecological deterioration and implement rehabilitation. This includes planning, scaling up from plot to microbasin, and monitoring.

Literature review

Ecosystem restoration has emerged to address the critical impacts of anthropogenic degradation of the worlds' ecosystems (Nilsson et al 2016), but the challenge has grown as the uncertainties and risks for ecosystems have increased with intensification of climate change (Jackson and Hobbs 2009; Olsson et al 2022). This is even more severe for mountains (Hock et al 2019; Rasul and Molden 2019). High erosion and degraded ecosystems strongly affect hydrological functions (infiltration, groundwater recharge, and runoff) and reduce the provision of hydrological ecosystem services (Buytaert et al 2006; Soh et al 2019). Rehabilitation interventions could contribute to recovering those functions.

We argue that rehabilitating puna grassland social–ecological systems requires adaptive ecosystem-based management (called adaptive management henceforth). It involves governance systems at multiple levels (from farmers to subnational and national authorities) that simultaneously show autonomy and overlap (Folke et al 2005). Adaptive management provides institutional flexibility to respond to anthropogenic disturbances (Folke et al 2005), reducing uncertainties through learning by doing, providing feedback from the test site, monitoring impact, and adjusting rehabilitation practices (Murray and Marmorek 2003). However, the nonhierarchical structure of adaptive management can make it challenging to assign responsibilities among the actors at different levels (from farmer to government official) in dynamic social–ecological systems (Folke et al 2005).

One way of navigating the distribution of responsibilities is a participatory approach from the conception of the rehabilitation project to monitoring and evaluation (Murray and Marmorek 2003; Gann et al 2019). This approach considers local participation and partnerships to make the process sustainable in the long term (Gann et al 2019). It includes the social dimensions of rehabilitation of mountain ecosystems—for instance, the socioeconomic objectives underlying local participation (Christmann and Menor 2021).

Case study: rehabilitation of the Piuray Ccorimarca microbasin

Study area

The Piuray Ccorimarca microbasin (between 13°25′10″S and 72°01′01″W) has an area of 42.53 km^2. It lies in Chinchero district, surrounding Piuray Lake (Cusco, southeastern Peru; Figures 1, 2A). The average annual precipitation between 1970 and 2000 was 686.2 mm/y, but seasonality is important. In the wet season (January–March), the average precipitation was 371.5 mm, whereas in the dry season (June–August), it was 17.7 mm. For these same 3 decades, the average annual minimum and maximum temperatures were 1.5 and 17°C, respectively.

An aquifer connects the headwaters with Piuray Lake, although there are springs in the middle section of the microbasin. Some areas of the microbasin are geologically unstable, facilitating erosion, chiefly in the headwaters. Moderate gullies are dominant in the Piuray Ccorimarca microbasin. Natural vegetation covers less than 50% of the microbasin. Plant cover is less than 80%, and areas with scarce or no vegetation constitute 12%. Wet puna grassland is the dominant ecosystem in the microbasin.

The Piuray Ccorimarca microbasin has 14 peasant communities, with 18 population centers (Figure 1). All communities conform to the Management Committee of the Piuray Ccorimarca Microbasin (Comité de Gestión de la Microcuenca Piuray Ccorimarca), a key stakeholder in the social–ecological system. The committee, Cusco's water utility company (Servicio de Agua Potable y Alcantarillado de Cusco [SEDA-CUSCO]), and the municipality of Chinchero together established the Mechanism of Retribution for Ecosystem Services (MERESE) under Peruvian Law 30215 (Lindsay 2018; Jenkins et al 2020). MERESE provides compensation for securing water provision to Cusco city. Its operation contrasts with the lack of coordination among authorities, organizations, and communities and the weak capacity of local organizations to manage natural resources for rehabilitation measures and ecosystem conservation (Lindsay 2018; Jenkins et al 2020).

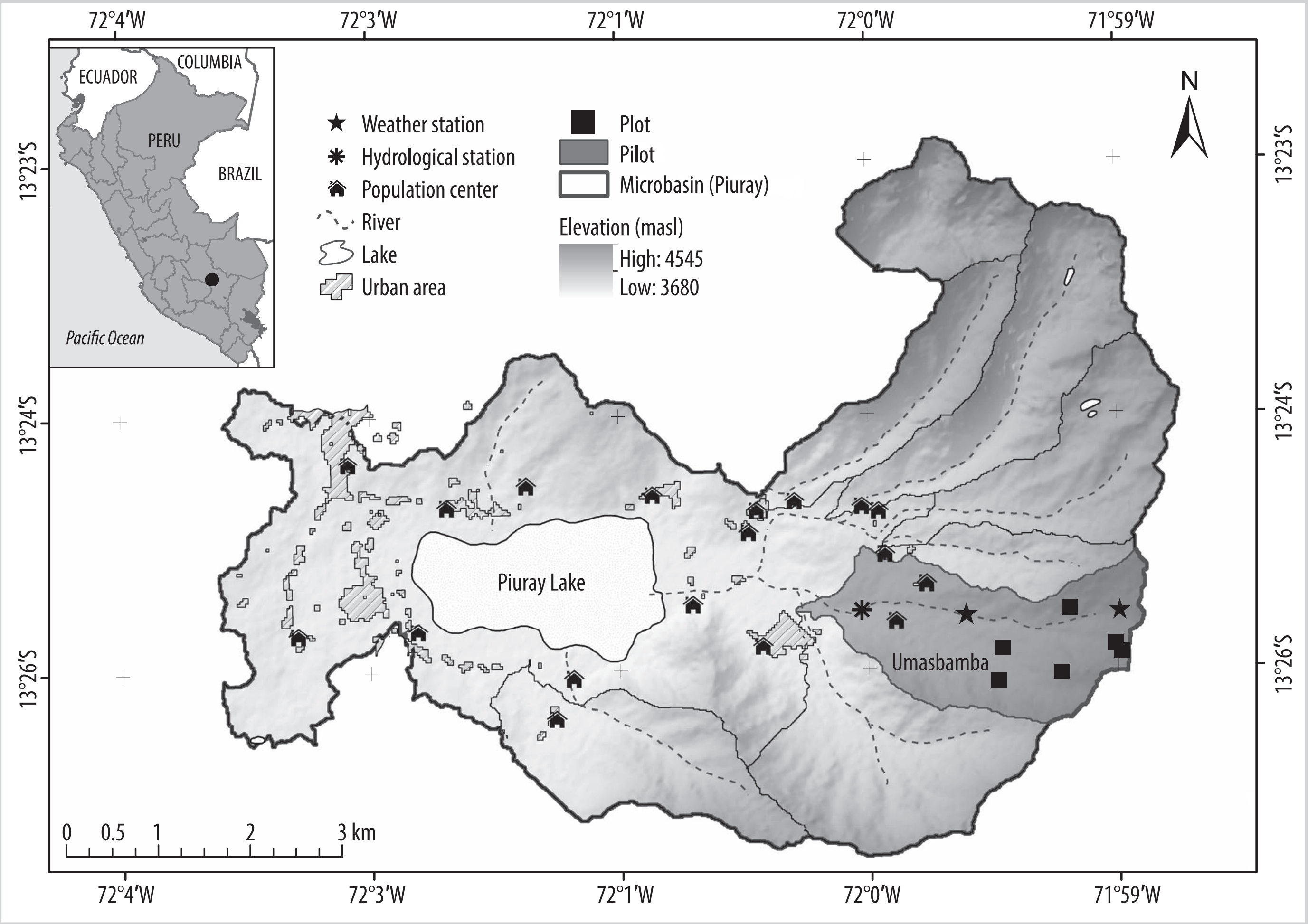
Several springs along the microbasin provide water for people. However, water demand is increasing because of urbanization in the middle and lower parts of the microbasin (Lindsay 2018). Urbanization has been further encouraged by the proposed opening of the Chinchero Cusco International Airport, which has brought thousands of workers to live nearby (Wade 2019). The consequent rising demand for food has fostered the expansion of the agricultural frontier to the hillsides. This is likely to increase existing conflicts over resources such as land and water. If the situation is left unaddressed, it will limit local development and cause environmental degradation (Wade 2019).

The Indigenous peasant community of Umasbamba is one of the main communities in the microbasin. The community lives at 3742 to 4364 masl, occupying 3 sectors and an area of 429.4 hectares. The main land uses are agriculture, pasture, and urban areas. The total population is 523 settlers and 145 dwellings. In the last 20 years, extensive agropastoralism has intensified with improved livestock. Only a few families still practice extensive livestock herding (llamas and sheep) on common native pastures.

INAIGEM's experience of rehabilitation in the Piuray Ccorimarca microbasin

Our current work with INAIGEM at the plot scale aims to identify which rehabilitation practices work best and are scalable to recover hydrological ecosystem services, particularly recharge and regulation. This involves 3 stages: selecting sites for experimental plots, designing and implementing plots, and monitoring.

FIGURE 1 Location of the Piuray Ccorimarca microbasin. (Map by Renny Diaz)



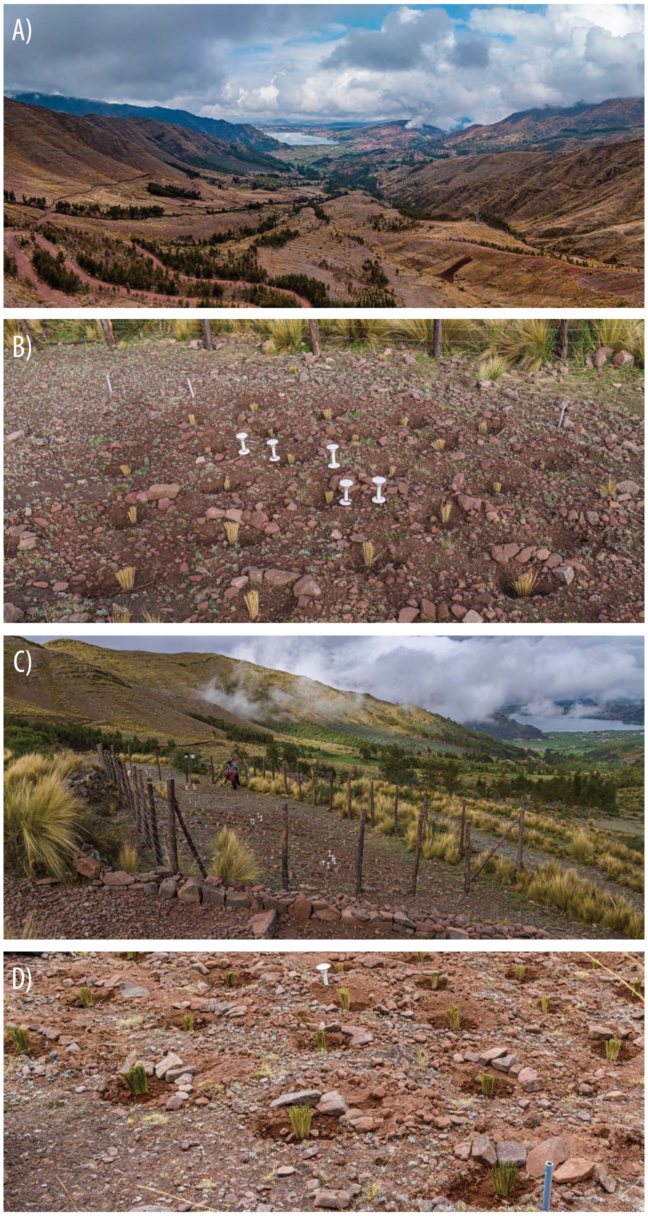
Site selection for experimental plots: There are 3 steps in selecting sites for plots, namely assessing the biophysical context, selecting an area, and identifying specific plot locations (Figure 3). We assessed the context by analyzing primary and secondary data, such as precipitation and temperature, soil characteristics, soil humidity, and vegetation composition; all of these variables are key drivers of mountain ecosystems. Understanding the context allowed us to adjust the research and next steps at the plot scale. To select an area to set up the plots (ie the rehabilitation pilot site), the following parameters were used: slope, vegetation cover of the headwaters, and contribution of the headwaters to hydrological recharge and regulation. In our case, the area selected was the Umasbamba Valley (Quebrada Umasbamba), with slopes of less than 20°, different land covers (including a site with terraces), and an normalized difference vegetation index between 0.185 and 0.275. At this point, we approached the authorities of the Indigenous peasant community of Umasbamba to ask for a social license. After this, the authorities were involved in deciding on potential sites for a rapid ecological assessment and in applying the assessment. The rapid ecological assessment evaluated vegetation, the physical and chemical composition of soils, and soil hydrology. Three vegetation types were identified: short grasses, tussock grasses, and a mix of both (ecological corridor). The range of values of each characteristic was divided into 3 equivalent sections corresponding to poor, regular, and good condition. Table 1 shows the results of the rapid ecological assessment for the selected sites of the plots.

All sites were covered by plants on around half of the area (49 and 51.2% plant cover for plots 2 and 3, respectively) or more. The shares of rock cover and bare ground ranged from 4 to 40%, and the shares of plants indicative of degradation ranged from 0.2 to 30.0%. Using the results of the assessment (Table 1), we identified plots in poor, medium, and good condition.

Design and implementation of plots for ecosystem rehabilitation: The size of the plot depends on the type of automatic moisture sensor used, because the sensors have different ranges. For instance, we used soil moisture sensors (TOMST TMS-4 datalogger) with hourly records (Figure 2B) at 15 cm underground in the 10-m^2 plot. However, when sensors measure humidity at depths of −20, −60, and −100 cm, the size of the plots should be more than 20 m^2.

We set up 6 experimental plots with different characteristics (Table 1; Figure 2C) in the middle and upper sections of the Piuray Ccorimarca microbasin (Figure 1). These were fenced to keep livestock out. Within the plots, we monitored ecological and hydrological variables, including soil moisture.

FIGURE 2 (A) View of the Piuray Ccorimarca microbasin from the upper area of Umasbamba Valley; (B) distribution of humidity sensors; (C) research plot; (D) transplanting grass. (Figure by Renny Diaz)



We divided each plot into 4 treatment subplots (**Figure 4A**): revegetation of tussock grassland with bovine manure, revegetation of tussock grassland with diammonium phosphate ($(NH_4)_2HPO_4$), tussock grassland revegetation without fertilizer, and control. Revegetation was conducted by transplanting grass (**Figure 2D**) from sites with good plant cover. Five soil moisture sensors were set on each treatment subplot (**Figure 4B, C**). Revegetation practices had been used to recover the hydrological functions of grasslands, but they had not been tested at the local and plot scales. Therefore, we decided to test revegetation practices under different fertilizers to determine which technique offered the best cost–benefit ratio. As part of our participatory approach, members of the Indigenous peasant community of Umasbamba were involved in setting up the plots. In so doing, they learned about the experimental design and the exact location of each plot.

Monitoring rehabilitation plots: There was a lack of reference values for water-related ecological functions of the Piuray Ccorimarca microbasin. Therefore, we used the values of the ecological characteristics of native puna grasslands from a case published by the Peru Ministry of the Environment (MINAM 2016) and considered international principles and standards for ecological restoration (Gann et al 2019). **Table 2** compares a plot in poor condition in our microbasin and the reference ecosystem, considering percentage of ground cover, vegetation species richness, percentage of soil organic matter, and percentage of cover of vegetation species indicative of degradation. Moreover, monitoring data are being used to obtain the rate of soil water change.

We continue to monitor the vegetation in each treatment plot twice a year (wet and dry season) and monitor moisture, downloading data monthly. Vegetation is evaluated using a 1 × 1 m quadrant divided into 100 squares of 10 cm^2 each. We also regularly measure soil cover, plant species cover, and phenology. For each transplanted grass, we measure height, canopy cover, basal cover, and vigor. We also evaluate variables in the soil: moisture at a 15-cm depth and temperature at +10, 0, and −15 cm. In addition, we record the air temperature (in degrees Celsius) and precipitation (in millimeters) of each plot or subplot with 2 meteorological stations, one in the lower zone (4008 masl) and one in the upper zone (4206 masl; **Figure 1**). Both precipitation and soil moisture are key variables for water gain and loss in the top 15 cm of soil.

A conceptual model to rehabilitate hydrological services in the puna grassland social–ecological system

Our model proposes multilevel rehabilitation of hydrological services in the puna grassland social–ecological system that begins at the plot and scales up to the microbasin (**Figure 5**). The spatial unit of observation and analysis is the plot. The knowledge gained at this scale provides a foundation for understanding both the condition of the ecosystem and the rehabilitation actions required. This knowledge stems from carefully identified relevant variables and systematic and consistent data collection using appropriate and calibrated instruments. Sound data analysis generates useful knowledge to select our sites and distribute our plots, covering the diverse locations and the heterogeneous mosaic of puna grassland.

At the plot scale, we gain knowledge about the biophysical context, which provides insights into the problems grasslands face and their causes, including social, political, and environmental factors; land use; and suboptimal groundwater recharge. This guides the actions that need to be taken and the target of rehabilitation. The design and location of the plots cover a range of variation in mountain ecosystems, providing a foundation for scaling up the intervention. In the plots, we test rehabilitation strategies in controlled conditions (excluded from grazing). Once the results show a suitable rehabilitation strategy, it is scaled up to a pilot that covers larger multiple sites in the

FIGURE 3 Steps to selecting sites for experimental plots to recover hydrological functions in microbasins. (Figure by Angela Mendoza-Ato)

microbasin. Similarly, the intervention is monitored at this larger scale, and when positive results are obtained, it is scaled to a microbasin. Continued monitoring at the plot scale while scaling up the intervention is crucial. It provides biophysical data for adjusting rehabilitation strategies whenever necessary. At the pilot (valley) and microbasin scales, the main changes are in the experimental design of the monitoring and hydrological variables (Murcia et al 2016; Christmann and Menor 2021).

The different successional stages of mountain ecosystems are another source of variability. Each stage is a different starting point for rehabilitation, leading to diverse trajectories toward the goal. Considering different trajectories of complex ecosystems, such as high mountain areas, gives the intervention a diverse portfolio of options that can be applied depending on the context (Gann et al 2019). Reference values for the ecological characteristics, based on information generated at different stages (plot and pilot scales), allow the options used to be managed across these trajectories (Gann et al 2019).

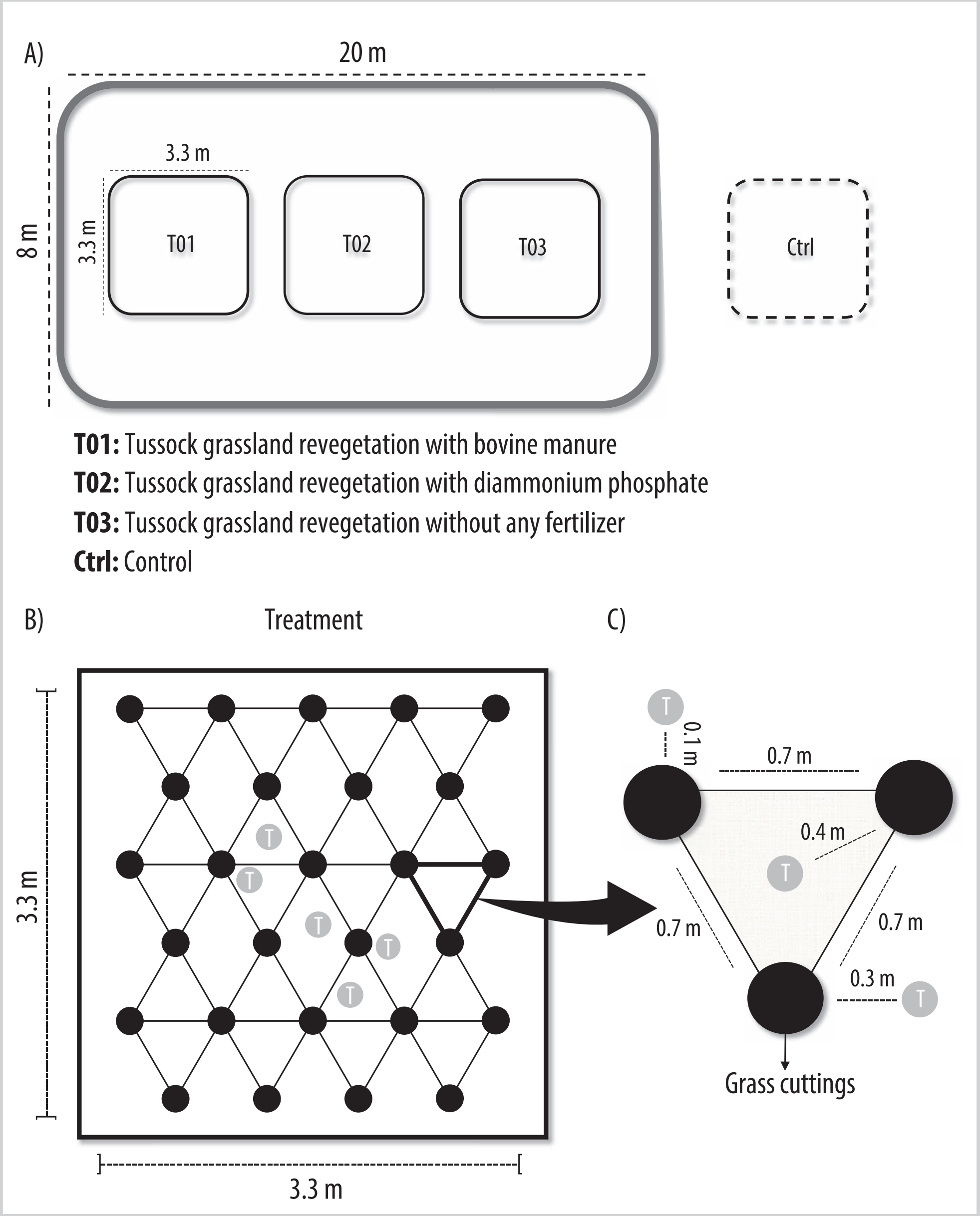
To scale up the intervention, it is crucial to have social legitimacy with the relevant stakeholders. As scales of

TABLE 1 Characteristics of the 6 plots in the Umasbamba Valley of the Piuray Ccorimarca headwaters based on data from the rapid ecological assessment.

Variable	Plot code					
	P1	P2	P3	P4	P5	P6
Vegetation type	Short grasses	Short grasses	Short grasses	Tussock grasses	Mixed	Mixed
Elevation (masl)	4005	4043	4208	4249	4266	4160
Plant cover (%)[a)]	67.4[b)]	49.0[c)]	51.2[c)]	68.2[b)]	81.2[d)]	84.0[d)]
Rock fragment cover (%)	14.2[b)]	31.8[c)]	21.4[b)]	9.0[d)]	0.8[d)]	0.6[d)]
Bare ground cover (%)	16.2[c)]	8.2[d)]	15.0[c)]	13.6[c)]	3.4[d)]	8.8[c)]
Other cover (feces, ferns, lichens, mulch, mosses) (%)[e)]	2.2	11.0	12.4	9.2	14.6	6.6
Plant species indicative of degradation (%)[f)]	22.2[c)]	0.2[d)]	29.8[c)]	16.0[b)]	10.2[d)]	12.4[b)]

[a)] Included only angiosperm and gymnosperm plants.
[b)] Regular condition.
[c)] Poor condition.
[d)] Good condition.
[e)] This type of cover was not included in the assessment of condition following MINAM (2016).
[f)] Plant species indicative of degradation are included in the plant cover percentage.

FIGURE 4 (A) Experimental design of plots. Treatment subplots (T01–T03) within the closed experimental area (dark gray rectangle) and control (dotted square). (B) Design of the distribution of soil moisture sensors (T) in each treatment. (C) Proposed distances (in meters) of the sensors from the transplanted grass (0.1, 0.3, and 0.4 m) to capture the range of moisture. (Figure by Angela Mendoza-Ato)



intervention change, the objective of rehabilitation, experimental design, and indicators must be reassessed and adjusted (DiGennaro et al 2012; Murcia et al 2016; Gann et al 2019). Another strategic element for scaling up is partnering with stakeholders at different scales to secure social and political will and financial support (Catacutan and Cramb 2004). Furthermore, stakeholder partnerships help to guarantee the sustainability and legitimacy of the multiscale intervention.

The participatory approach involves the integral participation of the local stakeholders in all the stages of the rehabilitation process (Figure 5). This type of participation increases the legitimacy and sustainability of rehabilitation. In practical terms, the participatory approach entails that community members, government agencies, and practitioners working in the territory actively contribute to the identification of the problem and its causes and to the design, implementation, and monitoring of the rehabilitation actions from the plot to the microbasin. Working on a shared agenda with agreed facilitation of meetings builds both trust and conflict-solving mechanisms among stakeholders. Building on trust and a shared agenda, stakeholders can identify and discuss parameters for monitoring, sites for the plots, and responsibilities.

Moreover, our model incorporates gaining knowledge from stakeholders at the plot and pilot scales. This is helpful when designing strategies for intervention at the microbasin level to ensure the sustainability of management. It is expected that the amount and participation of stakeholders will increase at the microbasin scale. Consequently, the

TABLE 2 Reference values for puna grassland ecosystems (puna short grasses, mixed, and puna tussock grasses), according to MINAM (2016) and Gann et al (2019), and values of an experimental plot in poor condition in the study area.

Ecological characteristics	Puna short grasses	Mixed	Puna tussock grasses	Poor condition (plot 3)
Plant cover (%)	90	88	85	51.2
Bare ground cover (%)	≤0	≤1	≤2	15.0
Species richness (S)	≥30	≥34	≥38	8.2
Soil organic matter (%)	≥8	≥8	≥8	5.4
Cover of plant species indicative of degradation (%)	0	0	0	29.8

Note: Values for mixed ecosystems were extrapolated from available data for puna short grasses and puna tussock grasses.
S means the number of species within a defined region.

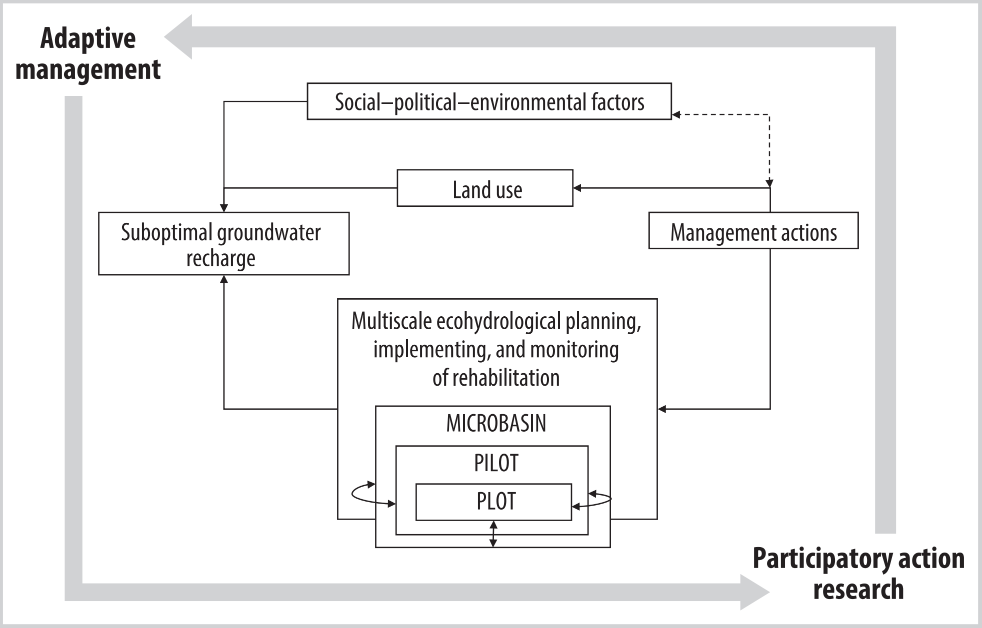
objectives and actions of the intervention should be aligned with other ecosystems and land uses in the area of intervention.

Local knowledge (ie traditional and Indigenous) is crucial in the participatory approach. It also increases the legitimacy and sustainability of the intervention (Romañach et al 2018; Gann et al 2019; Martos-Rosillo et al 2019). The convergence of multiple knowledge systems may redefine some of the problems to be addressed (Goldman et al 2016). For instance, the attribution of land degradation might be overgrazing, mismanagement of prairie fire, or intensive herding or farming. Weak organization, regulation, and enforcement are socioinstitutional factors favoring the degradation of high-elevation landscapes (Gurung et al 2022). In the case of Umasbamba, local people of the Indigenous peasant community identified a weakness in community organization and participation, which adds to the population's distrust of interventions that do not generate benefits immediately.

Although we consider rehabilitation part of a suite of management actions, it is a deliberate intervention that aims to improve ecological conditions to recover hydrological functions. Another management action mentioned in Figure 5 is land use, which does not necessarily aim to improve ecosystem functioning but will affect groundwater recharge. The model recognizes the influence of sociopolitical–environmental factors on management, and vice versa. These factors are among the causes of land degradation, which, in turn, is one of the drivers of the reduced groundwater recharge (Malik et al 2014). Addressing these factors entails management measures ranging from capacity building to participatory monitoring, as well as the involvement of all local stakeholders throughout the rehabilitation process (from planning to implementation) and in all scaling phases (from plot to microbasin scale).

Our model for the ecohydrological rehabilitation of puna grasslands is multiscale, linking plot experiments with efforts at the microbasin level. We propose that this multiscale rehabilitation be managed adaptively to address biophysical, environmental, and socioinstitutional challenges. The main issues the high mountains face are: constraints of topography, elevational gradients, geomorphological heterogeneity that interacts with diverse

FIGURE 5 Conceptual model for rehabilitation in a microbasin with an ecohydrological approach. (Figure by Angela Mendoza-Ato and Julio C. Postigo)



microclimatic zones, the El Niño Southern Oscillation influence, and impacts of climate change. In addition heterogeneous governance institutions and expanding urbanisation make the scenarios acute (Solimano 2003; Hock et al 2019; Rasul and Molden 2019). The heterogeneity of the puna grassland ecosystem because of environmental factors and different land use patterns makes it important to identify reference ecosystems for rehabilitation measures. In our case, we used puna short grasses, mixed ecosystems, and puna tussock grasses.

Finally, monitoring at all scales requires automatic micrometeorological stations for monthly monitoring of hydroclimatic variables and seasonal vegetation evaluation. The scaling up of the intervention will require larger budgets, hence the relevance of funding strategies that secure the financial sustainability of rehabilitation processes (Gann et al 2019).

Discussion and way forward

We present a model for the rehabilitation of hydrological services in puna grassland social–ecological systems based upon INAIGEM's work at the plot level. Rehabilitation is part of a suite of management actions, addressing the drivers of declining groundwater recharge. As a way forward, we argue that our conceptual model draws on the approaches of adaptive management and participatory action research as it scales up to sustainably improve puna grasslands (Gann et al 2019). Adaptive management is flexible and dynamic, allowing an iterative cycle of evaluation, adjustment, and reevaluation in all components of rehabilitation (Murray and Marmorek 2003; Bryce et al 2011; Suding et al 2015; Nilsson et al 2016). This flexibility enables agile responses to changing conditions both in the landscape and in communities. For instance, if there were a disturbance where the sensors are located or if stakeholders wanted to use the land, it would be easy to relocate them to sites with similar conditions. Furthermore, our experience of puna grassland rehabilitation ensured the participation of community members by obtaining a social license, involving leaders in the site selection for the plots and the identification of shared objectives. A step further would entail evaluating the effectiveness of the rehabilitation and designing strategies to ensure local participation throughout the interventions.

Our model argues for a multiscale intervention that is based on the plot, although it scales up to the microbasin. A multiscale approach allows us to account for the high variability and diversity of factors shaping puna grasslands. The use of multiple scales complements previous rehabilitation perspectives focusing on restoration at the scale of large flat areas (eg Bainbridge 1990; De Jonge and De Jong 2002). The scaling relies on biophysical and environmental multicriteria evaluations to identify both key areas for rehabilitation and specific sites for setting up plots within these areas (Nilsson et al 2016). Each criterion has variables that are monitored using sensors, providing data at meaningful spatial and temporal scales, considering fundamental properties of the system (De Jonge and De Jong 2002). Data from multiple scales allow comparison of rehabilitation strategies. For instance, our plots have different comparable treatments (Figure 4A) to account for multiple factors shaping hydrological behavior. Comparable treatments also allow the most efficient ones for specific contexts to be selected. Furthermore, flexibility in monitoring instruments enables the heterogeneity of biophysical and social contexts of rehabilitation to be captured.

The conceptual model is based upon our experience at the plot level, although it aspires to inform rehabilitation at larger scales. However, we have not yet evaluated the impacts of our approach at the microbasin level. This limitation notwithstanding, adjustments would be achievable because of the flexibility embedded in the model. This flexibility enhances the model's applicability to rehabilitation of microbasins in other mountain ranges. Overall, the model contributes to enhancing the resilience of puna grassland social–ecological systems to global change and their capacity to provide ecosystem services.

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