Paramos Soils

Pascal Podwojewski
L'Institut de Recherche pour le Développement (IRD), Hanoi, Vietnam

Jérôme Poulenard
Université de Savoie, Le Bourget du Lac, France

INTRODUCTION

The Spanish word *páramo* refers to the deserted, windy, humid, and cold North Andean areas. This high-altitude grassland ecosystem, which has large plant diversity, covers 35,000 km^2 and is distributed as discontinuous islands between the high altitudinal forest and the permanent snow line. In the *Páramos*, soils evolve in relation with low temperature, high soil moisture, and Al availability of the parent rock. Carbon content and water retention are very high. Páramos soils are considered as a "sponge" which enhance water retention and buffer the water flow downstream. However, new agricultural practices modify soil properties, altering infiltration and run-off regime and disturbing the primary hydrological function of the Páramos.

PÁRAMOS ENVIRONMENT

Páramos Location

The Páramo is located in intertropical Central and South America, between 11° latitude North and 8° latitude South (Fig. 1), mainly situated in Colombia (14,500 km^2), in Ecuador (12,600 km^2), but also in Venezuela with small extensions in Costa Rica, Panama, and Northern Peru[1–3] (Table 1). It occurs at an altitude generally ranging between 3200 and 4800 m.

Páramos Climate

With an average decrease of 0.6°C for 100 m change in elevation, temperatures are cold with an annual average of 9°C at 3500 m. Day–night amplitude is over 15°C with temperatures dropping randomly below 0°C over 4200 m. Annual variation is very low.

The windward external sides of the cordilleras receive more rainfall than the leeward internal sides (interandean valleys side), where rainfall increases with altitude. Annual Precipitation ranges between 1000 and 1500 mm with extremes between 500 and 3000 mm. In the northern tropical areas, the rainfall has a unimodal distribution with one dry season, in the southern area closer to the equator, rainfall occurs all year long with a bimodal distribution of two drier seasons. Intensities are very low, rarely exceeding 40 mm/day. Frequent fogs, drizzles, and hailstorms contribute to maintain a humid climate, and air moisture ranges between 70% and saturation.[4]

Páramos Vegetation

The Páramo is a grassland biotic formation of the high Andes and contains between 3000 and 4000 species of vascular plants with 60% estimated endemism.[5]

The vegetation of the Páramos can be divided into three belts:[3]

- The *super-Páramo*, at high altitudes ranging between 4200 and 4800 m, represents a periglacial environment with sparse vegetation cover and species adapted to nocturnal freezing and high solar radiation by leaf xeromorphic adaptation (reduced surfaces, folded, densely woolly, whitish leaves).
- The *proper-Páramo* (3500–4200 m) has an open-type vegetation dominated by bunchgrasses (tussocks). Poaceaes (*Calamagrostis* sp., *Festuca* sp.) and dwarfed bamboos form the *pajonal* and cover 70% of the soil surface. The giant rosettes are the most remarkable plants [*Espeletia* sp. (Photo 1), *Puya* sp.]. Acaulescent rosettes, cushion-like vegetation (especially in swampy areas), and some shrubs complete vegetation. Patches of forest (*Polylepis* sp.) grow up to an altitude of 4200 m.
- The *sub-Páramo* (3200–3500 m) is a transitional zone between the Páramo and the Andean forest; the coverage of small trees and scrubs is greater than in the proper-Páramo. The sub-Paramo surface extends toward lower altitude with human land clearing to provide pasture and farmland.

Geology–Geomorphology

The Páramos follow the summital portion of the main northern Andes Mountain chain. The most important part of this belt from the center of Colombia to the center of

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Table 1 Extension of the *Páramo* in different countries (% of the total)

Country	Surface (km^2)	% of total
Colombia	14,430	1.3
Costa Rica	80	0.2
Ecuador	12,600	5.1
Peru	4200	0.3
Venezuela	3990	0.4

Source: Robert Hofstede, Proyecto Páramo (www.paramo.org).

these chains; and 2) nonvolcanic rocks or hard lava flows with notched summits and steep slopes.[4]

SOILS

Páramos soils have been described by Jenny since 1948.[6] Soils evolve in function of the convergent effects of low temperature, high soil moisture, and Al availability.[7]

In the supra-Páramo, organic matter production decreases with altitude, and soils are very shallow, with umbric epipedon[8] and periglaciar features. In nonvolcanic Venezuelan areas, Cryepts are dominant. The presence of giant rosette plants gives the soil pattern discontinuous properties with higher carbon content only at soil surface and around the rosette.[9] In volcanic areas, during glacier periods, ice caps protected soils from ash deposits. The most recent deposits are weakly weathered and form Vitrandic Cryents.

At lower altitudes, in humid conditions, the availability of Al is the second important factor in soil formation. When Al availability is very low, Humods and Fragiaquods are observed on gneiss and micaschists rich in quartz (Podocarpus Paramo in the south of Ecuador). With higher Al availability, Inceptisols (Dystrudept) form with an umbric epipedon. With high Al availability, Al forms very stable complexes with organic matter.[10] The main pedological process is an acidic complexolitic andosolization with Al + 1/2 Fe oxalate extract >2% and Al% pyrophosphate/Al% oxalate >0.5 characteristic of nonallophanic Andisols,[11] which are the more extended soil types in the Páramos. On recent volcanic ashes, important Al availability leads to a very fast soil formation, with Vitrands forming in less than 1000 years. The farther the deposits are from their emission source, the finer are the ashes, and the faster is the rate of weathering. The older, most evolved soil profiles (±3000 years) have the lowest base reserve and can been classified as Udands. The nonallophanic andosolization process could also be active on nonvolcanic Al-rich substrates (paleo-oxisols or metamorphic rocks). All of these soils are acidic and have anionic retention capacities (especially for P and S).

Páramo Soils and Carbon Content

All Páramo soils are very rich in organic carbon. In the Paramo of Northern Peru, soils contain over 10 kg m^{-2} C, whatever the nature of the parent rock (limestones, volcanic rocks, or sandstones).[12] Low temperatures and stable organo-metallic complexes[7] reduce the biological activity and therefore decrease the rate of organic matter mineralization. High carbon accumulation results from different pedologic processes on successive ash layers, but also on colluvial buried soils on steep slopes. Carbon sequestration can exceed 85 kg m^{-2} in the polygenic nonallophanic matured Andisols of Northern Ecuador[13] (Table 2, Photo 1). Altitude increases the soil organic carbon content with a maximum density (reaching 10 g cm^{-3}) at around 3900 m. These Andisols have black thick melanic epipedon attributed to the presence of humic acids produced by the degradation of Poaceae family plants,[11] and can been classified as Melanudands[8] (Photo 1).

Páramos and Water Cycle Regulation

The water content in nonallophanic Andisols at 1500 kPa is over 1000 g kg^{-1} (Hydric properties.[8]) and can be 2000 g kg^{-1} at field capacity. The formation of an organometallic complex network leads to important microporosity. The more mature the soils, the richer they are in humic substances, and the higher is their microporosity. For matured Andisols, micropores with a radius <0.1 μm can form over 50% of the soil volume[14] Water content is stable all year long. The measured hydraulic conductivity of this mature Andisol reaches 60 mm h^{-1} and runoff is unlikely.

After drying, a new and extremely rigid structure appears: drying is therefore partially irreversible. As

Table 2 Carbon Pool (kg m^{-2}) of some *Páramos* soils

Place	Pichincha (1)	Carchi (2)	Cajas (3)	Fierro Urcu (4)	Cerro Toledo (5)	Sabanilla (6)
A	35.6	46.3	36.4	34.1	15.8	11.2
B	56.7	86.4				

1: Thaptic Hapludand; 2: Hydric pachic Melanudand; 3: Hydric Melanudand; 4: Humic Andic Hapludox; 5: Humic Dystrudept; 6. Typic Fragiaquod.
A: First meter of the profile; B: whole profile.

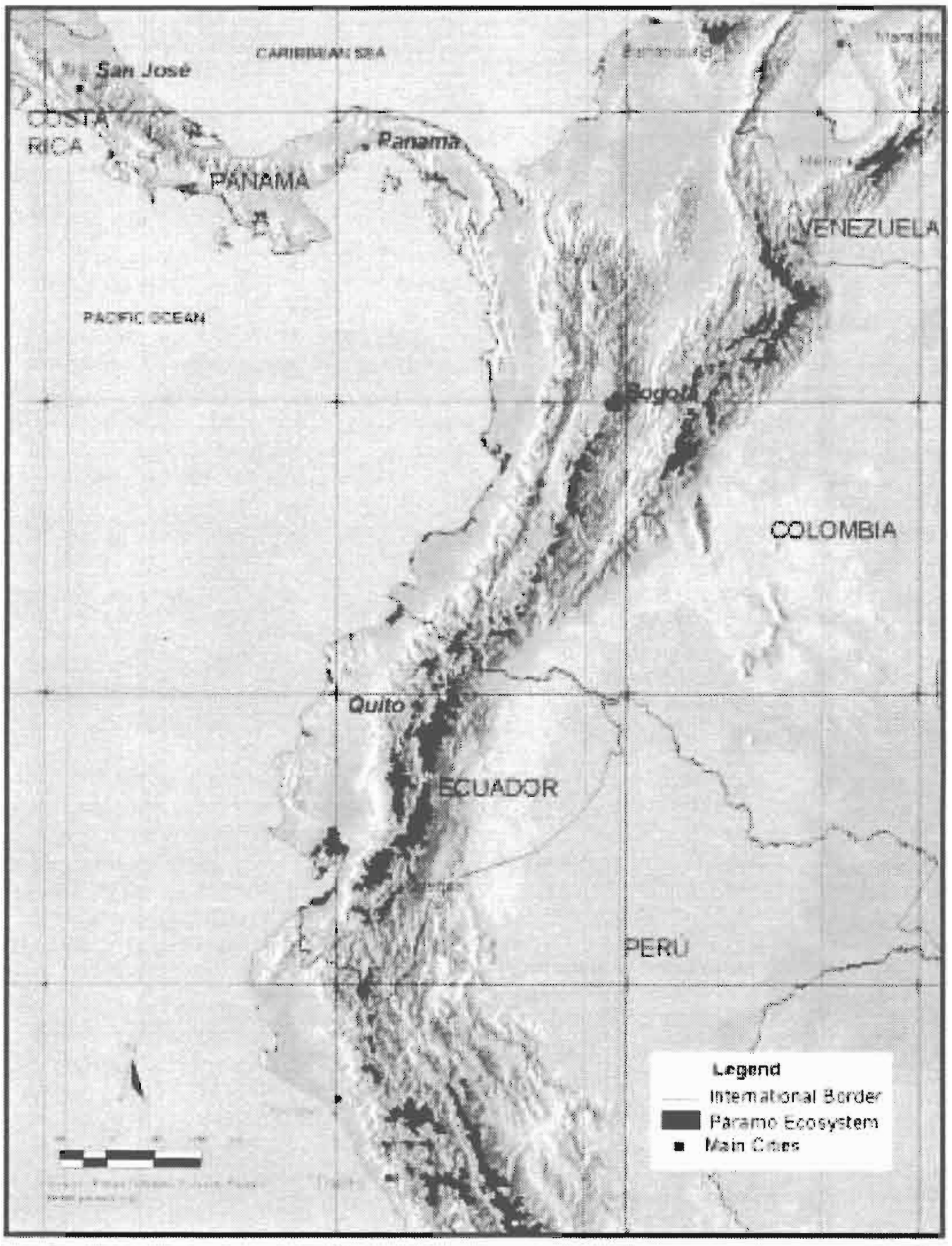

Fig. 1 World distribution of the *Páramo* Ecosystem. *Source:* Robert Hofstede, Proyecto Páramo (www.paramo.org). (*View this art in color at www.dekker.com.*)

Ecuador has a strong recent volcanic activity. Ash falls are mainly rhyodacitic to andesitic in composition and cover the basement of the Andean belt made of sedimentary or metamorphic rocks.

The geomorphology of the Páramo was modeled by glacier extension during the major glacier phases at altitudes of over 4000 m, with large U-formed valleys, many lakes and smoothened relieves.[4] Two main forms can be distinguished: 1) highly erodible forms affected by recent volcanic ash deposits, with uniformed small hills of convex concave forms, gentle slopes, and isolated volcanic cones (>5000 m in altitude) emerging from

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Photo 1 Profile of a Melanudand in the *Páramo* of the ecological reserve of El Angel, Carchi province, north of Ecuador. (*View this art in color at www.dekker.com.*)

porosity increases, so does sensitivity to modification of the pores architecture and the loss of water-storage properties after drying.[14] Water-repellent surfaces develop during drying.

Degradation of the Páramo Soils

In recent decades, more than half of the *Páramos* surface was used as extended land with an increasing rural population for grazing and cultivation. First, burning formed temporary bare surfaces,[2,15] which are receptive to structural decay by the kinetic energy of raindrops or hailstorms. Second, black carbon-rich bare surfaces absorb solar radiation, which favors irreversible drying and water repellency at soil surface. The upper 20 cm of Andisols are deeply affected with a convergent decrease of more than a third of their original value in carbon, water, and Al contents. A highly water-repellent soil microstructure replaces the stable macrostructure.[16]

After tillage, juvenile vitric Andisols crust and runoff coefficient increases by a factor of 3. On mature Andisols, soil packing and the development of water repellence lead to severe decrease in hydraulic conductivity. At the same time, soil loss is very high (over 1500 g m^{-2}) and occurs via the entrainment of hydrophobic aggregates in the surface runoff.

CONCLUSION

Though covering relatively small surfaces, paramos soils present specific properties in water retention and carbon sequestration. Any degradation or inappropriate land use alters these soils durably with a negative effect on the water availability for a large population living downstream.

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