



Changes in soil cryptogamic communities in tropical Ecuadorean páramos

Y. González^{1,3}, G. Aragón², A. Benítez¹ and M. Prieto²

¹ *Departamento de Ciencias Biológicas, Sección de Ecología y Sistemática, Universidad Técnica Particular de Loja, San Cayetano Alto s/n, Loja, Ecuador*

² *Departamento de Biología, Geología, Física y Química Inorgánica, Área de Biodiversidad y Conservación ESCET, Universidad Rey Juan Carlos, Móstoles, E- 28933, Madrid, Spain*

³ *Corresponding author. E-mail: xygonzalez@utpl.edu.ec, phone: +593 992626460*

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Abstract: Altitudinal gradients involve macroclimatic changes that can affect the diversity of several organisms. We tested the effects of elevation and small-scale variables on the diversity and composition of terricolous communities (lichens and bryophytes) in five páramos in southern Ecuador. The altitudinal range considered (from 2700 to 4000 m a.s.l.) is associated with changes in rainfall, temperature and irradiance. At each páramo, forty 40 x 40 cm² sample plots were randomly selected in similar areas of vegetation (grass páramo) and conservation status. The presence/absence and cover of lichens and bryophytes were recorded in 200 sample plots. A total of 90 species (46 lichens and 44 bryophytes) were identified. Our results showed that total species richness, lichen and bryophyte richness, Simpson's inverse and Shannon's index were related to elevation and slope. Nevertheless, the response to elevation was dependent on the organism considered. Thus, meanwhile lichens had their maximum richness at the highest elevation (3930 m a.s.l.), bryophytes had a maximum peak at middle elevation (3300 m a.s.l.). Species composition also differed significantly among the five páramos, especially in bryophytes. We conclude that differences in the elevation of these páramos and small-scale variables such as slope significantly affect the diversity and composition of terricolous communities.

Nomenclature and identification for lichens: Lumbsch 1989, Goward et al. 1995, Sipman 1997, 2002, Ahti 2000, Brodo et al. 2001, Nash et al. 2002, 2004, Smith et al. 2009, Rivas Plata et al. 2010, Moncada 2012, Lücking et al. 2013, Rincón-Espitia and Mateus 2013.

Nomenclature and identification for bryophytes: Churchill and Linares 1995, Gradstein et al. 2001 and Gradstein and Costa 2003.

Abbreviation: PERMANOVA—Permutational Analysis of Variance.

Introduction

Understanding the relationship between elevation and species richness has been a general challenge addressed over the past years. In various organisms and geographical areas, main findings point to a decrease in species richness with increasing elevation (Terborgh 1977, Stevens 1992) or a humped-shaped relationship, with a peak in richness at intermediate elevations (Rahbek 1997, Grytnes and Vetaas 2002, Krömer et al. 2005, Brehm et al. 2007, Baniya et al. 2010). Apart from the environmental changes associated with the altitude, biotic, abiotic and historical factors have also been discussed as having a possible impact on species richness along these gradients (Rahbek 1995, Lomolino 2001).

The published studies about species richness and diversity along elevational gradients are strongly biased towards plants and temperate zones (Brehm et al. 2007). In tropical areas altitudinal gradients have been considered in several diversity studies (Terborgh 1977, Sipman 1989, Gradstein et al. 1989, Krömer et al. 2005, Brehm et al. 2007, Jankowski

et al. 2013). However, very few are focused exclusively on the study of altitudinal gradients in high Andean páramo ecosystems (Sipman 1989, Keating 1999, Sklenář and Ramsay 2001, Paredes 2006, Sklenář et al. 2010). Páramo ecosystems provide several ecological functions and environmental services such as the regulation of hydrology, protection from erosion, carbon storage and its function as a biological corridor for many species of flora and fauna (Hofstede et al. 2003, Buytaert et al. 2006). Furthermore, páramos host the richest high mountain flora of the world (Smith and Cleef 1988), being considered as a hotspot within a hotspot (Myers et al. 2000) with a high endemism and with the fastest diversification rates of all hotspots (Madriñán et al. 2013). In these páramos, climatic factors, orography, age of the substrate, land use or dispersal have an influence on the diversity patterns (Acosta-Solis 1984, Luteyn 1992, Sklenář et al. 2010).

Terricolous cryptogams are an important fraction of the high diversity of these ecosystems and also play a relevant role in terms of biomass, carbon/nutrient cycling, ecosystem functioning, water-storage and soil cohesion (Pérez 1997,

Gradstein and Holz 2005, Rai et al. 2010). However, very few studies have focused on their response to altitude in the Neotropics (Sipman 1989, Van Reenen and Gradstein 1983, Gradstein et al. 1989, Kessler 2000) and even less in páramo ecosystems (Paredes 2006).

Although it has been reported that the diversity of soil lichens and bryophytes is structured along an altitudinal gradient in different geographic regions and ecosystems, there is no clear pattern of changes in the richness and diversity in relation to elevation. Thus, different responses have been found: increases in richness or cover with altitude, decreases, humped relationships with maximum richness at intermediate altitudes or different responses for bryophytes and lichens separately (Thompson et al. 2005, Bruun et al. 2006, Grytnes et al. 2006, Paredes 2006, Grau et al. 2007, Tusiime et al. 2007, Stehn et al. 2010, Vittoz et al. 2010, Sun et al. 2013, Rai et al. 2015). Differences found in these responses could be related to environmental variables operating at different scales. Thus, local factors such as slope, aspect, soil properties (pH, texture, acidity, electrical conductivity), micronutrients, moisture, herb and shrub cover, or land use intensity also have a significant effect on the ground communities (Ponzetti and McCune 2001, Bowker et al. 2005). Additionally it has highlighted the role of biotic interactions structuring these communities, affected by the availability of resources like space, nutrients or water (Maestre et al. 2008, 2009, Bowker et al. 2010). Other factors explaining the different patterns found could be related to different scales of the studies, diverse methodologies used or differences in the studied organisms (Grau et al. 2007).

Altitudinal gradients within the tropics constitute an important tool to improve the knowledge of ecosystem ecology and function, as well as to determine its influence on diversity and species distribution (Malhi et al. 2010). In this context, the main objective of our study was to ascertain whether elevation influences the diversity and composition of terricolous cryptogamic communities of five páramos in southern Ecuador. Specifically, we aimed to address the following questions: (1) Are richness and composition of lichens and bryophytes structured along an altitudinal gradient? (2) Do lichens and bryophytes respond in the same way to these differences in elevation and the ecological factors associated? (3) Which other factors affect these communities?

Materials and methods

Study site

The study area included five páramos located in Loja (Punzara, Loma del Oro, Cajanuma and Jimbura) and Azuay (El Cajas) provinces (southern Ecuador) (Fig. 1). The selected páramos range between 2700 and 4000 m above sea level (Table 1). Punzara is considered an azonal páramo due to the influence of strong winds. The vegetation is characterized by grasses with some shrubs scattered and small herbs (León-Yáñez 2000). The most important genera of grasses are *Calamagrostis*, *Festuca* and *Stipa* (León-Yáñez 2000).

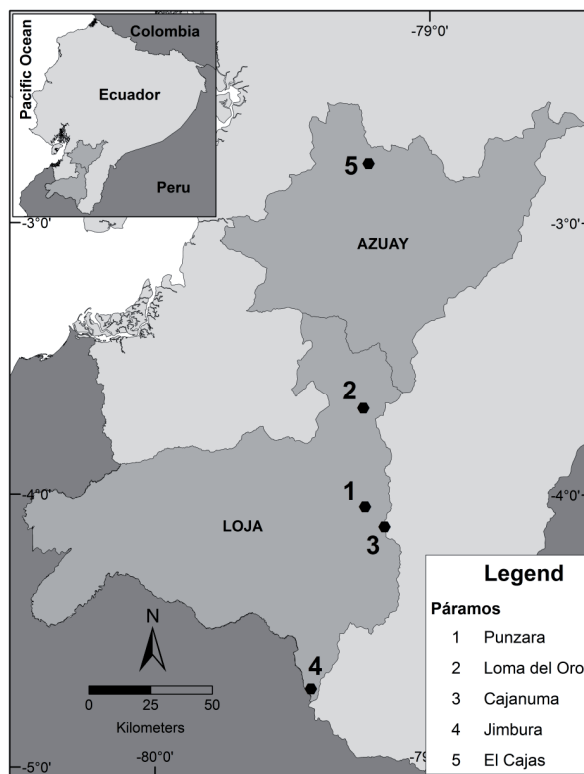


Figure 1. Location of the five studied páramos in Ecuador.

Cajanuma, El Cajas, Jimbura and Loma del Oro correspond to grass páramo (Cueva and Chalán 2010, Hofstede et al. 2002). Main genera dominating in these areas are *Calamagrostis*, *Carex*, *Festuca* and *Paspalum* (León-Yáñez 2000). Cajanuma is the only one covered by montane forest close to the páramo and below 3000 m. In the five sampled localities some other common species were *Loricaria thuyoides* (Lam.) Sch. Bip., *Lycopodium clavatum* L., *L. vestitum* Desv., *Oreobolus* sp. and *Puya* sp.

The climate in the Ecuadorian páramos is generally cold and humid throughout the year, with extremely changing daily temperatures. In the five localities, the mean annual temperatures range from 5 °C to 14 °C (Table 1) and annual rainfall between 936-1440 mm (Table 1). The soils in southern Ecuador páramo ecosystems are highly variable, coming from Paleozoic metamorphic rocks, except in El Cajas, where the soils are enriched with volcanic ash deposits (Podwojewski and Poulénard 2000).

The five studied páramos are similar both in plant composition and conservation status, corresponding to grass páramo of the Ecuadorian southern region with similar floristic composition which differs from the northern Ecuadorian páramos (Valencia et al. 1999, Hofstede et al. 2002).

Sampling design and data collection

Undisturbed zones were selected within each páramo with the same plant composition and well developed cryptogamic communities (3 ha approximately). Within these zones, forty plots of 40 × 40 cm² were randomly placed, with a minimum

Table 1. Environmental variables of the five studied páramos.

No.	Name	Elevation (m a.s.l.) (min – max)	Slope (°) mean ± S.E.	Aspect (°) mean ± S.E.	Annual pre- cipitation (mm)	Average temp. ^a (°C)	Min. temp. ^a (°C)	Max. temp. ^a (°C)
1	Punzara	2770 (2700 – 2900)	33±2.3	0.15±0.11	936	14	9	18
2	Loma del Oro	3245 (3100 – 3300)	25±2.6	–0.11±0.11	1256	10	5	15
3	Cajanuma	3337 (3300 – 3400)	12±1.4	0.06±0.11	1295	10	5	16
4	Jimura	3450 (3400 – 3500)	17±2	–0.08±0.11	1140	7	2	14
5	El Cajas	3930 (3850 – 4000)	22±1.7	–0.03±0.10	1440	5	2	10

^a Source: Ministerio del Ambiente, Ecuador, 2010.

distance of 1 m between them to avoid spatial autocorrelation (Maestre et al. 2008).

We estimated the cover values of all terrestrial species of lichens and bryophytes in each sampling unit through visual detection and we collected samples for posterior identification. For lichen nomenclature and identification we used the following literature: Lumbsch 1989, Goward et al. 1995, Sipman 1997, 2002, Ahti 2000, Brodo et al. 2001, Nash et al. 2002, 2004, Smith et al. 2009, Rivas Plata et al. 2010, Moncada 2012, Lücking et al. 2013, Rincón-Espitia and Mateus 2013, and for bryophytes we used Churchill and Linares 1995, Gradstein et al. 2001 and Gradstein and Costa 2003.

Additionally, we measured the cover of vascular plants (%) at plot level and the slope (°) and aspect (compass direction of the slope, cosine transformed) as both are related to microclimatic conditions as irradiance, stability of the substrate, soil temperature or soil moisture (García-Pichel and Belnap 2001). The macroclimatic variables (annual rainfall, mean annual temperature and monthly mean minimum and maximum temperature) at páramo level were provided by the Ministry of Environment of Ecuador (MAE 2010). We considered the minimum temperature important as a limiting factor because páramo ecosystems reach extreme temperatures at night (León-Yáñez 2000), affecting growth and development of cryptogams (Kappen 2000, Bramley-Alves et al. 2014). Elevation was obtained with a GPS (Garmin GPS).

Data analyses

The community variables analyzed were Simpson's and Shannon's indices, Pielou's evenness, total species richness, the richness of lichens and bryophytes separately and the cover and richness of the lichen family *Cladoniaceae* (i.e., *Cladia* and *Cladonia*, which were considered together). *Cladoniaceae* family was analyzed separately because they are very important components of the terricolous communities within páramos and dominate in these habitats (Ahti 1992). Simpson's and Shannon's indices allow to combine species richness and relative abundance into an estimate of diversity when data from multiple sites exist (Gorelick 2006). Simpson's index is determined by the most dominant species and the Shannon's index assumes that the individuals are selected randomly and that all species are represented in the

sample (Magurran 2004). Pielou's evenness is calculated as the ratio between the observed diversity and the maximum diversity (Magurran 2004).

To determine the effect of the macroclimatic (elevation, annual rainfall, mean annual temperature, monthly mean minimum and maximum temperature) and the small-scale factors (slope, aspect and plant cover) on the community variables, we used generalized linear models (GLMs). In order to test non-linear relationships we introduced a quadratic term for the elevation. Elevation showed high correlations with annual rainfall, mean annual temperature and monthly mean minimum and maximum temperatures (Pearson's correlation $r^2 > 0.800$, $p < 0.05$ in all cases). Thus, in order to prevent multi-collinearity problems, elevation was the only variable at páramo level included in the model. For total richness, richness of lichens, bryophytes and *Cladoniaceae* we used a Poisson distribution with a "log" link function and for Simpson's inverse, Shannon's index, Pielou's evenness and *Cladoniaceae* cover we used a Gaussian distribution with "identity" link function. Poisson distribution is usually employed to fit count data, and inspection of our data confirmed that this distribution fitted better than alternative distributions, such as the normal distribution. All statistical analyses were performed in R version 3.1.1.

The composition of soil species of the five páramos was compared using the PRIMER multivariate statistical analysis software version 6.1.11 (Anderson et al. 2008). In this analysis, the experimental design included one factor: páramo (five levels) with 40 replicate units per páramo. The cover data (percentage cover per species) were $\log_{10}(x + 1)$ transformed to downplay the influence of abundant taxa. We used the Bray-Curtis distance measure to test whether the five páramos had significantly different composition of cryptogams and we performed a one-factor permutational multivariate analysis of variance (PERMANOVA) on the cover data. For all tests, we allowed 9999 random permutations under the reduced model. Non-metric multidimensional scaling (NMDS) was used to determine the main factors (elevation, slope, aspect and plant cover) influencing total species composition and lichens and bryophytes composition separately. NMDS ordination was performed using 50 random restarts. We computed the resemblance matrix using the Bray-Curtis dissimilarity index. Values of relative species abundance and environmental variables were then fitted onto the first two axes of

Table 2. Species richness and exclusive taxa of the five studied páramos.

Páramo	Elevation (m a.s.l.)	Total taxa				Exclusive taxa			
		Total number	Bryophyte		Lichen		Total	Bryophyte	Lichen
			Number of species	Cover* (%)	Number of species	Cover* (%)			
1	2770	19	5	11	14	59	6	1	5
2	3245	42	20	33	22	48	10	3	7
3	3337	39	28	36	11	61	13	11	2
4	3450	31	16	31	15	49	3	2	1
5	3930	39	15	24	24	63	14	3	11

* Average cover for each páramo.

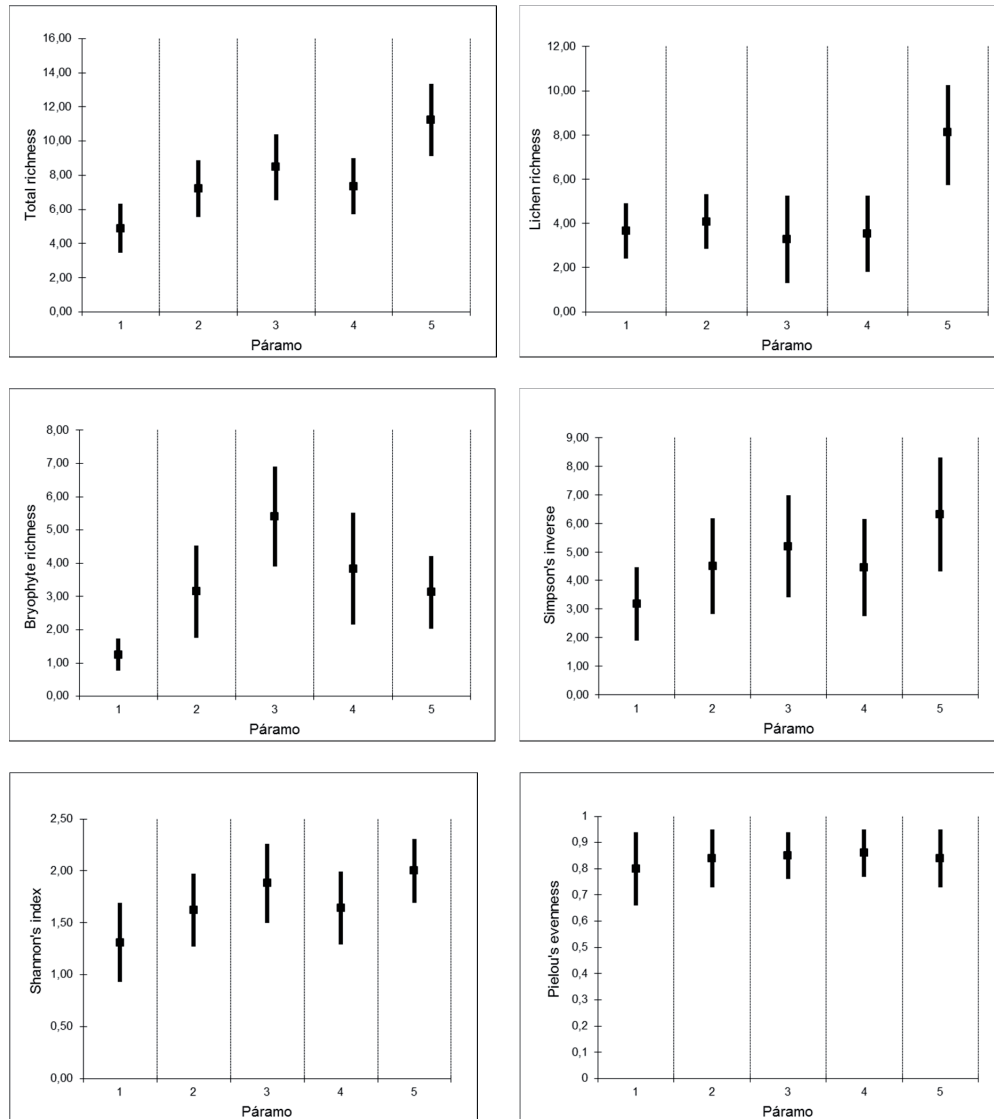


Figure 2. Species richness and diversity patterns in the five studied páramos. Values represent the means (\pm SD) of the 40 plots per páramo. Páramos are arranged according to elevation, so axis X corresponds to an elevation gradient.

the NMDS ordination. For these linear fittings squared correlation coefficients (r^2) and empirical p -values (p) were calculated. Variables with $r^2 \geq 0.3$ were considered as correlated. To identify the taxa that contributed most to the similarity and dissimilarity among páramos in the NMDS ordination plot,

we used the BVSTEP statistical routine. This routine identifies the smallest subset of species capable of reproducing the differences in community patterns among páramos that were obtained in the NMDS ordination ($\rho = 0.95$, with 100 restarts) (Clarke and Warwick 1998).

Table 3. Results of the generalized linear models on the community variables. Coef.: coefficient of the variable in the model, S.E.: standard error.

	Coef. (S.E.)	<i>t</i> -value	<i>p</i> -value
<i>Species richness</i>			
Elevation	0.0044 (0.0012)	3.657	0.0003
Elevation ²	-6.1×10^{-7} (1.8×10^{-7})	-3.454	0.0006
Plant cover	0.0017 (0.0014)	1.199	0.2306
Slope	-0.0056 (0.0020)	-2.777	0.0055
Aspect	0.0293 (0.0376)	0.778	0.4365
<i>Lichen richness</i>			
Elevation	-0.0035 (0.0016)	-2.211	0.0270
Elevation ²	5.4×10^{-7} (2.3×10^{-7})	2.337	0.0194
Plant cover	0.0010 (0.0018)	0.549	0.5828
Slope	-0.0051 (0.0028)	-1.846	0.0649
Aspect	0.0457 (0.0519)	0.882	0.3781
<i>Bryophyte richness</i>			
Elevation	0.0156 (0.0020)	7.707	< 0.001
Elevation ²	-2.3×10^{-6} (2.9×10^{-7})	-7.593	< 0.001
Plant cover	0.0024 (0.0021)	1.126	0.2603
Slope	-0.0060 (0.0030)	-2.008	0.0447
Aspect	0.0108 (0.0547)	0.196	0.8443
<i>Simpson's inverse</i>			
Elevation	0.0122 (0.0060)	2.042	0.0425
Elevation ²	1.6×10^{-6} (8.8×10^{-7})	-1.833	0.0683
Plant cover	0.0127 (0.0071)	1.793	0.0745
Slope	-0.0267 (0.0101)	-2.638	0.0090
Aspect	0.1157 (0.1984)	0.583	0.5603
<i>Shannon's index</i>			
Elevation	0.0038 (0.0012)	3.186	0.0017
Elevation ²	-5.1×10^{-7} (1.8×10^{-7})	-2.931	0.0038
Plant cover	0.0030 (0.0014)	2.165	0.0316
Slope	-0.0066 (0.0020)	-3.265	0.0013
Aspect	0.0377 (0.0394)	0.957	0.3396
<i>Pielou's evenness</i>			
Elevation	0.0003 (0.0003)	0.883	0.3785
Elevation ²	-4.0×10^{-8} (5.0×10^{-8})	-0.802	0.4235
Plant cover	0.0008 (0.0004)	1.950	0.0526
Slope	-0.0010 (0.0006)	-1.745	0.0825
Aspect	0.0039 (0.0112)	0.348	0.7279

p-values < 0.05 are considered significant and marked in bold.

Results

We recorded 46 lichens belonging to 16 families and 44 bryophytes belonging to 24 families in the five studied páramos (Appendix 1). The total number of species ranged from 19 in Punzara páramo to 42 in Loma del Oro (Table 2). The number of exclusive taxa ranged from 3 in Jimbura to 14 at the highest elevation (El Cajas) (Table 2, Appendix 1). Lichens dominated in all sampling units, with an average cover between 48% and 63%, while bryophytes cover never exceeded of a 36% (Table 2). The family *Cladoniaceae* was the most predominant and the best represented lichen family with 20 taxa belonging to the two genera *Cladia* (2 species) and *Cladonia* (18 species) (Appendix 1). Members of the *Cladoniaceae* appeared in 98% of plots, showing an average cover of about 50%. The predominant species were *Cladia aggregata* and *Cladia fuliginosa*, which were presented

in 142 and 114 plots, respectively, out of 200 plots in total (Appendix 1).

We found significant relationships between the elevation (including the quadratic term) and all community variables, except Pielou's evenness (Fig. 2, Table 3). The slope had a negative and significant effect on the species richness, bryophyte richness, Simpson's inverse, Shannon's index and the *Cladoniaceae* cover (Tables 3 and 4).

A significant component of the variation of the species composition was associated with páramo (Table 5). The NMDS ordination for the total species composition showed that the highest variability was explained by the elevation (Axis 1: -0.36; Axis 2: 0.93; $r^2 = 0.38$; $p = 0.000999$). This variable was weakly correlated to lichen (Axis 1: -0.99; Axis 2: -0.03; $r^2 = 0.08$; $p = 0.000999$) and bryophyte composition (Axis 1: -0.24; Axis 2: -0.97; $r^2 = 0.21$; $p = 0.000999$) (Fig.

Table 4. Results of the generalized linear models on the *Cladoniaceae* richness and cover. Coef.: coefficient of the variable in the model. S.E.: standard error.

	Coef. (S.E.)	t-value	p-value
<i>Cladoniaceae</i> richness			
Elevation	0.0003 (0.0003)	1.140	0.2556
Plant cover	0.0042 (0.0052)	0.803	0.4230
Slope	-0.0138 (0.0070)	-1.955	0.0520
Aspect	0.2356 (0.1459)	1.615	0.1080
<i>Cladoniaceae</i> cover			
Elevation	0.0013 (0.0044)	0.289	0.7729
Plant cover	-0.0895 (0.0831)	-1.076	0.2832
Slope	-0.2484 (0.1129)	-2.201	0.0290
Aspect	1.2107 (2.3369)	0.518	0.6050

Table 5. Results of one-factor PERMANOVA analysis by páramo ecosystem. Values for the total composition, lichen composition and bryophyte composition. Degrees of freedom (df); mean sum of squares (MS); F value by permutation (Pseudo-F); significance level (P); coefficient of variation (CV).

Source	df	MS	Pseudo-F	P	CV (%)
Total					
Páramo	4	50453	23.738	0.0001	34.759
Residual	195	2125.4			46.102
Lichens					
Páramo	4	30863	12.868	0.0001	26.676
Residual	195	2398.4			48.974
Bryophytes					
Páramo	4	84177	44.917	0.0001	45.36
Residual	195	1874			43.29

3). The NMDS ordination showed a clear separation between páramos for total and bryophyte composition (Fig. 3A-C). Although significant, the correlations were weak ($r^2 < 0.15$) for the remaining variables (slope, aspect and plant cover). Ninety-five percent of the variation in the NMDS ordination was explained by ten taxa. Of the ten species identified by the BVSTEP routine six were bryophytes (*Breutelia tomentosa*, *Campylopus richardii*, *Leptodontium* sp., *Polytrichum juniperidium*, *Rhacocarpus purpurascens* and *Racomitrium lanuginosum*) and four were lichens (*Cladia aggregata*, *C. fuliginosa*, *Cladonia arbuscula* subsp. *boliviana* and *C. calycantha*). When these species were excluded, the next-best model contained 22 species, which explained 90% of the observed pattern.

Discussion

In this study we found evidence of changes in the richness, diversity and composition of soil cryptogamic communities, comparing for the first time páramo ecosystems (grass páramo) situated at different altitudes.

Main changes are related to elevation and slope. However, when we consider lichens and bryophytes separately, we found different and contrasting patterns with elevation.

Meanwhile lichen richness is maximum at the highest elevation, bryophyte richness showed a hump-shaped relationship. Several authors found similar patterns with a higher richness of lichens at elevations above 3000 m (Sipman 1989, Paredes 2006, Baniya et al. 2010) and the highest diversity at middle elevations for bryophytes (Grau et al. 2007, Sun et al. 2013), although these studies included different ecosystems at different altitudes.

As the studied páramos are similar in plant composition and disturbance level, differences in altitude might rather reflect a gradient in precipitation, temperature and irradiance, with a trend showing an increase of precipitation and irradiance (Kessler 2002), and a decrease in mean annual temperature with altitude. Thus, differences observed in the patterns for different groups along the same gradient may be attributed to different physiological responses to the changing environmental conditions (Bhattarai and Vetaas 2003, Ah-Peng et al. 2012). Although bryophyte richness usually increases with humidity (Sun et al. 2013), the highest species richness was not found in the páramo with the highest rainfall, but instead at middle altitudes, with less rainfall. In general terms, with increasing altitude, the substrate tends to dry faster by the more intense solar radiation meanwhile in the lower elevation, a similar pattern occurs with the raise in temperature (Vittoz et al. 2010), increasing the evapotranspiration and

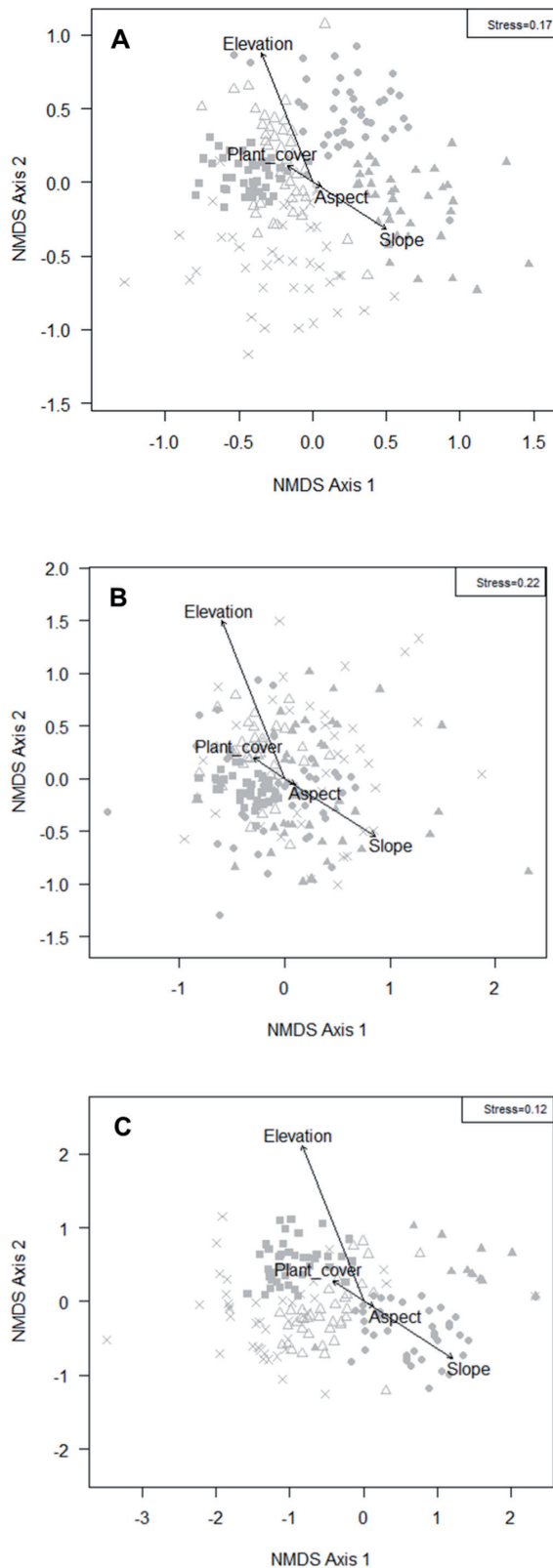


Figure 3. Non-metric multidimensional scaling analysis for species composition of sampled units (plots) in the five studied páramos: Punzara (▲), Loma del Oro (×), Cajanuma (■), Jimbura (△) and El Cajas (●). (A) Total species composition; (B) lichen composition; (C) bryophyte composition.

making the air drier. Thus, desiccation and air temperature may be affecting species of bryophytes that only survive in more favorable sites situated at middle elevations (Walker et al. 2006, Vittoz et al. 2010, Sun et al. 2013). The highest bryophyte richness found in Cajanuma páramo (at middle elevation) was also associated with an increase of the number of exclusive species (11 exclusive species). This highest richness could also be related to the proximity of montane forests that can serve as a source of species to colonize the nearby páramo.

On the other hand, lichen richness was maximum at the highest elevation, with more precipitation, less average temperature and higher inputs of solar radiation (Kessler 2002). Certain lichens show preferences for high light levels, adjusting their physiology to high light intensities by increasing thallus thickness or the concentration of protective pigments (Gauslaa and Solhaug 2001, Kranner et al. 2008). Moreover, lichens possess several mechanisms assuring cell functioning at low temperatures (Barták et al. 2007). The increase in lichen richness at higher altitudes has been previously found in Paredes (2006) in páramos but different patterns have also been found including broader altitudinal ranges and different ecosystems (Baniya et al. 2010, Vittoz et al. 2010, Rai et al. 2015). Although the lichen family *Cladoniaceae* is an important component of the páramo communities, we did not find the same altitudinal pattern as in the total lichen richness. Soto-Medina (2013) found two peaks in the *Cladoniaceae* at 0–1000 m and 2000–3000 m; however, these results are not fully comparable since the altitude considered and the geographic range were much greater.

Another significant variable structuring these communities at all levels (total species, bryophytes, lichens and *Cladoniaceae* richness and diversity) is the slope, showing an inverse relationship. Slope is related to the stability of the substrate, radiation levels, soil temperature and soil moisture (García-Pichel and Belnap 2001). Thus, microclimatic conditions related to the slope are affecting richness and composition of terricolous communities, a fact that has been demonstrated for bryophytes and lichens separately (Hauck et al. 2007, Mandl et al. 2009).

The composition of terricolous communities in Ecuadorian páramos is also correlated to the elevation, with a stronger pattern in the bryophytes. This evidences the remarkable influence of environmental variables related to differences in elevation (temperature, solar irradiation, humidity, rainfall) on the structure of these communities. Small scale variables at the páramo level, such as slope or plant cover, also influence the composition of terricolous communities. Although other studies (e.g., Sipman 1989) found a different floristic zonation with altitude, they compared different ecosystems (e.g., superpáramo, páramo, montane forest) and different substrates (trees, soils, rocks), contrary to this study in which we found floristic differences comparing the same type of habitat (grass páramo) and substrate (soils).

We therefore conclude that elevation and slope are important factors affecting the diversity and composition of terricolous communities of tropical páramos, probably related

to changes in rainfall, humidity, temperature and irradiance. Patterns of response to elevations were different in lichens and bryophytes. The maximum lichen richness was found at the highest elevation. For bryophytes, a humped relationship between the amount of species and elevations below 4000 m a.s.l. was found, probably linked to the less hospitable climate at higher and lower altitudes or the proximity of more suitable areas serving as a source of species. Many factors such as temperature, rainfall, radiation, soil conditions and human disturbance should be assessed along elevational gradients in páramo ecosystems to gain better understanding of diversity and composition of lichens and bryophytes in these ecosystems.

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Electronic supplement

Number of sampling units and mean cover on which each species appear in each of the five páramos. The file may be downloaded from www.akademai.com.