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Regional variability of volcanic ash soils in south Ecuador: The relation with parent material, climate and land use

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Abstract

The high Andes region of south Ecuador is characterised by intense land use changes. These changes affect particularly the páramo, which is a collection of high altitudinal grassland ecosystems. In this region, the interaction between airborne volcanic ashes and the cold and wet climate results in very typical soils, with an elevated organic C contents. The physical soil properties are closely related to the high and reliable base flow in rivers descending from the páramo, which makes them important for the socio-economic development of the region. In this study, we analyse the regional variability of the soils in the south Ecuadorian rio Paute basin. In a first part of the study, data from soil profiles along north–south transects are used to determine the soil properties, and to relate the spatial variability of these properties to the major trends in parent material, volcanic ash deposits and climate. The profiles are Histic Andosols and Dystric Histosols devoid of allophane, with very high amounts of organic matter. Significant differences between the western and central mountain range are observed, as well as a general decrease in Andic properties from north to south, coinciding with the decrease in volcanic influence. Finally, the impact of human activities on the soil properties is assessed in a case study in the Machangara valley. Data from 5 profiles, located in an area with natural grass vegetation and a low degree of human impact are compared with 4 profiles in a heavily disturbed, intensively drained cultivated area. Despite the intensity of the land use, very few significant differences are found.
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Keywords: Andosols; Land use; Ecuador; Páramo; Organic matter; Cultivation

1. Introduction

1.1. Soils of the Ecuadorian páramo

The páramo is a neotropical alpine ecosystem covering the upper mountain region of the Andes of Venezuela, Colombia, Ecuador and northern Peru. It consists of vast grasslands, extending from the continuous forest border (about 3500 m altitude) up to the perennial snow limit (about 5000 m altitude). The total area covered by páramo is estimated between 35,000 (Hofstede et al., 2003) and 77,000 km^2 (Dinerstein et al., 1995). This discrepancy is primarily due to uncertainties in the lower limit of the páramo. The vegetation is dominated by tussock grass species and xeromorphic herbs, with a high number of endemic species (Luteyn et al., 1992). In valley bottoms and near streams, scattered shrubs occur, consisting mainly of *Polylepis* sp. (Vargas and Zuluaga, 1986).

The major factors affecting soil formation in the páramo are the occurrence of Holocenic ash deposits and the cold and wet climate (FAO/ISRIC/ISSS, 1998). In locations with high volcanic ash deposits and a relatively dry climate, Vitric Andosols develop. For example, these soils occur around Quito and Latacunga in northern Ecuador, where they developed on fairly young, rhyolitic volcanic ashes from Pichincha, Cotopaxi and other volcanoes. As a result, these soils contain significant amounts of volcanic ash, have a rather high pH (5.7 to 6.5), a low organic carbon content (between 2.6% and 8%) and a marked concentration of basic cations and volcanic

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minerals such as allophane (FAO, 1964; Wright, 1968; Colmet-Daage et al., 1969; Poulenard, 2000). On the other end of the spectrum, highly weathered Hydric Andosols, almost devoid of allophane, occur in locations with a wet climate and limited ash deposits (Buytaert et al., 2002; Poulenard et al., 2003). These soils are found for instance, in the Austro Ecuatoriano, the Ecuadorian Andes region between 2°15′ and 3°30′ south (Dercon et al., 1998).

The rio Paute basin (Fig. 1) is the largest hydrological basin in the Austro Ecuatoriano. It is located about 100 km south of the southernmost volcanoes of the Northern Volcanic Zone (i.e., the Sangay and Tungurahua volcanoes, Fig. 1), belonging to the Carnegie ridge (Barberi et al., 1988; Monzier et al., 1999). As a result of this distance, volcanic ash deposits are thin and highly weathered (Buytaert et al., 2005a). Although Andosols have been observed as far south as Loja (PRONAREG, 1983), it is more probable that they gradually evolve into Histosols and Umbrisols in the south of the basin. The exact limit, however, is unknown.

1.2. Land use impacts

Despite the remoteness, the difficult access and the cold and wet climate, human activity in the páramo is not uncommon. Human presence in the upper Andes dates from prehistorical times (Chepstow-Lusty et al., 1996), but until recently, these activities were limited to extensive cattle grazing, which did not pose a significant pressure on the ecosystem. However, because of population growth, increased urbanisation and soil degradation in the lower valleys, human activities have increased drastically during the last decade. In the densely populated area around Quito in the northern part of the country, these activities started more than 20 years ago, and have resulted in severe soil degradation. Physical soil properties are irreversibly damaged, resulting in a decrease in soil stability, water retention capacity and soil structure, and an increase in water repellency and erosion susceptibility (White and Maldonado, 1991; Basile and De Mascellis, 1999; Poulenard et al., 2001; Podwojewski et al., 2002). Chemical changes include a decrease in oxalate extractable Al (Al$_o$) and Fe (Fe$_o$) content, as well as organic carbon, all of which have an impact on the hydrophysical soil properties (Buytaert et al., 2005a).

These changes strongly affect the hydrological behaviour, in particular the water storage and regulation capacity of the páramo soils. The base flow in rivers descending from the páramo is very large, with a peak over base flow ratio as low as 5 (Buytaert et al., 2004). Although the exact mechanism is not completely understood, studies suggest that the high porosity, combined with a high saturated conductivity, allows for high infiltration rates. The hydraulic conductivity, however, drops fast in only slightly unsaturated conditions and results in a slow subsurface drainage, which is sustained by the elevated water storage capacity of the soils (over 30 vol.%) (Buytaert et al., 2005a).

Because of this high and reliable base flow, and because groundwater extraction is complicated and expensive, surface

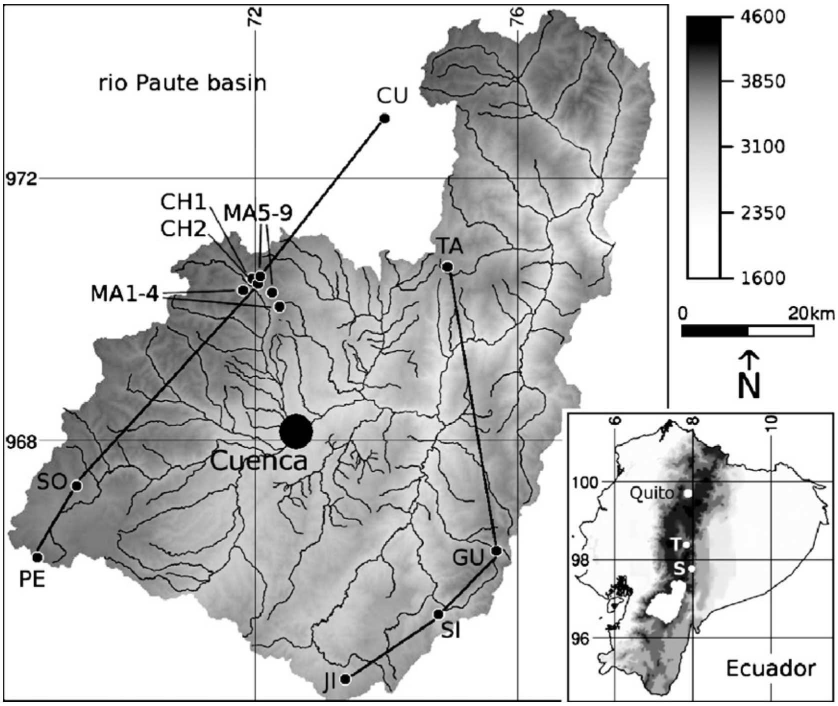

Fig. 1. Geographical location of the rio Paute basin and the location of individual sampled pedons. North–South transects used to study soil properties on natural páramo ecosystems were located on the western mountain range (pedons, CU, CH1, CH2, SO, PD) and on the central mountain range (pedons, TA, GU, SI, JI). An additional 9 pedons were located in the Machangara catchment (pedons MA1–4 and MA5–9) to study the effect of land use on soil properties. S = Sangay volcano, T = Tungurahua volcano.

Fig. 2. Picture of the natural páramo ecosystem. Inset: Picture of profile JI. On the border of the A and C horizon, a continuous placic layer of about 2 cm thick was observed.

water from the páramo is the major water source for the Interandean region. Water is used for urban and agricultural purposes as well as hydropower generation. As such, an adequate soil management program in the Ecuadorian páramo is of high social and economic importance.

In contrast to the rest of the country, land use changes, cultivation and intensive grazing are a very recent phenomenon in the páramo of the Paute basin, and both the regional variability of the soil properties and the impact of land use changes are rather poorly documented. This study describes the properties of the soils in this region and identifies the major spatial patterns, by describing and analysing soil profiles from transects over each mountain range. These patterns are then correlated with the major soil formation factors in the region, i.e., climate and geology. Finally, the impact of land use changes on the major soil properties is studied in the Machangara catchment. Here, natural páramo (Fig. 2) coexist with intensively cultivated, drained and grazed plots (Fig. 3). Soil profiles were described under both land uses in order to compare the chemical soil properties.

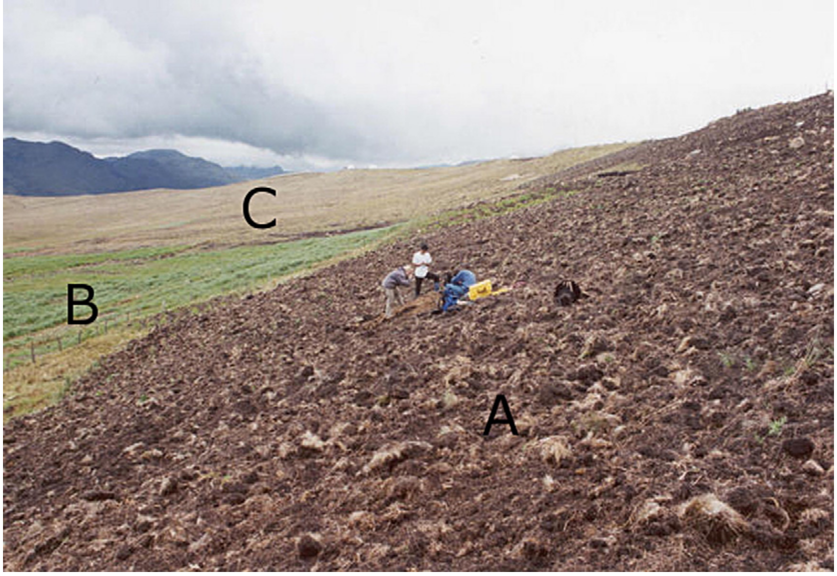

Fig. 3. Picture of an interfered part of the Machangara catchment. A: intensive cultivation of potatoes with complete removal of the original vegetation; B: drainage and intensive grazing with replacement of the grass vegetation for more nutritive species; C: drainage and extensive grazing on the natural grasslands.

2. Materials and methods

2.1. The study region

The study region is the Paute basin, covering about 5000 km^2 of the Austro Ecuatoriano, the Andean region around Cuenca, the 3rd largest city of Ecuador (Fig. 1). In Ecuador, the Andes consists of 3 north–south oriented mountain ranges or cordilleras. Only the western and central mountain range were investigated in this study, as the eastern mountain range is much smaller in Ecuador, only reaches an altitude of around 1600 m, and does not form part of the Paute basin. About 50% of the area of the Paute basin is located above 3300 m, which is locally considered as the lower limit of the páramo ecosystem (Dercon et al., 1998). Rainfall is well distributed over the year and averages between 1000 and 1500 mm year^{-1}, but with strong spatial gradients. The average temperature at 3500 m altitude is 7 °C. Below 4000 m, no snowfall occurs.

The soil parent material is highly variable (Buytaert et al., 2005a). The oldest formations are found in the upper parts of the mountain ranges. In the central mountain range, they consist largely of Paleozoic metamorphic rocks (Coltorti and Ollier, 2000). In the upper parts of the western mountain range, the Macuchi formation crops out (Cretaceous and early Tertiairy), consisting of a thick sequence of pillow lavas and andesitic volcanoclastic deposits. In between, younger formations are found. They include the Late Oligocene to Early Miocene Saraguro formation, extending from Riobamba to Saraguro (Hungerbühler et al., 2002). In the study area, the Saraguro formation consists of intermediate to acid pyroclastics, with andesitic to dacitic tuffs and lava flows prevailing in the lower parts. The Late Miocene to Plio-Pleistocene Tarqui formation is about 300 m thick and abounds in the northern part of the Paute basin. A large variety of lithologies, including rhyolitic to andesitic volcanic breccias, ashflow tuffs, pyroclastic flows, ignimbrites and many airborne tuffs are observed. The influence of the Quaternary volcanoes to the north of the basin (i.e., Sangay, Tungurahua) are limited to thin layers of fine-grained ashes that are largely restricted to the northwestern part of this basin. They are Late Quaternary to Holocene in age and belong to the Alausi formation, which forms part of the mostly andesitic Quaternary Northern Volcanic Zone (Barberi et al., 1988; Monzier et al., 1999).

2.2. Profile location and physical description

Two north–south oriented transects were established on the western and central mountain ranges (Fig. 1). Five pedons (CU, CH1, CH2, SO, PE) were sampled along the western mountain range. Four pedons (TA, GU, SI, JI) were sampled on the central mountain range. The large distance between GU and TA in the transect on the central mountain range is due to the canyon of the rio Paute, creating a local depression while flowing towards the Amazon basin. The location of the pedons on the transects was primarily determined by practical constraints, including access to the páramo, which is limited. The actual site where the profile was dug was selected at random within the environmental constraints. Geographical and ecological factors that could influence soil properties, such as elevation, vegetation, orientation and slope were kept as constant as possible. The sites were chosen on a uniform hill slope, with a slope between 10% and 20%. On lower slopes, water logging may occur and Histic soil properties may have developed, while the higher slopes are prone to erosion. On average, the transect in the central mountain range is situated about 250 m lower than the western transect as the general elevation of this mountain range is lower. The pedons were described according to the FAO guidelines (FAO, 1990) and samples were taken for chemical analysis. Additionally, as a case study for the impact of land use changes, 9 pedons were randomly selected in the Machangara valley, in the north-east of the rio Paute basin (Fig. 1). Of these 9 pedons, 4 are located under intensive grazing or potato cultivation (MA1–4), and the other 5 are located under extensively grazed grasslands (MA5–9).

2.3. Sampling and analyses

Disturbed and undisturbed soil samples were taken from every genetic horizon. The C horizon was not sampled if it consisted of firm bedrock or stones. About 0.5 kg of disturbed soil was collected for each horizon and thoroughly mixed. The undisturbed soil samples were taken in steel rings having a diameter of 5 cm and a volume of 100 cm^3.

The disturbed soil samples were air-dried and sieved at 2 mm. The pH(H_2O) of the <2 mm fraction was measured using a 1:2.5 suspension after 2 h of mechanical shaking. The pH in 1 M KCl was determined in a similar way. Overnight extraction with 0.1 M sodium pyrophosphate solution was used to measure Al_p and Fe_p. Al_o and Fe_o were extracted after 4 h in a 0.2 M ammonium oxalate at pH 3 (Mizota and van Reeuwijk, 1989). The standard soil moisture correction factor of 1.2 (Van Reeuwijk, 2002) was replaced by the actual air-dry soil moisture. Organic carbon was determined by elemental analysis using the Dumas-method on an EAS varioMax N/CN (Elt, Gouda, The Netherlands).

Particle size distribution was determined by the pipette method after removal of organic matter using H_2O_2, and dispersed using hexametaphosphate (Van Reeuwijk, 2002). It has to be noted that this method is not recommended for Andosols, as dispersion is in many cases incomplete, and Na-resin should be used instead (Bartoli et al., 1991). However, for practical reasons, this was impossible. Therefore, these data are only used for comparison within the dataset, and the results should be treated with care. The undisturbed soil core samples were saturated and then sequentially used for the determination of the saturated hydraulic conductivity and the bulk density. Saturated conductivity was measured using the constant head method. Bulk density was determined by weighing the soil cores after drying for 24 h at 105 °C. Water retention at −1500 kPa was determined on the disturbed soil samples using a suction plate.

The spatial variability of the soil properties was analysed with unbalanced ANOVA and linear regression. ANOVA was also used to assess the differences in soil properties between the two mountain ranges. Linear regression with the distance towards the Sangay volcano north of the study area was used to assess the impact of volcanic ashes on the soil properties. For the impact of cultivation ANOVA was performed on a dataset containing only the upper horizon (Ah and Ah1), and also on the full dataset (except the C horizon). While it is expected that the greatest impact of cultivation and intensive grazing will occur in the upper horizon, this dataset may be too small to yield significant differences and therefore, also datasets for the entire profile were analysed.

3. Results and discussion

3.1. Soil properties and classification

3.1.1. Morphology and classification

The major soil properties are given in Tables 1 and 2. The soils appear in the landscape as a homogeneous, darkly coloured layer consisting of volcanic ashes mixed with organic matter (Fig. 2). This layer, containing the Ah and A horizons, is between 44 and 135 cm thick and is sharply separated from the C horizon which consists of tertiary bedrock. The uniform appearance is reflected in the chemical properties. Both the Ah and A horizons are characterised by a very high organic carbon content (up to 44%), a low pH(H_2O) (between 4.1 and 5.6) and a bulk density down to 0.13 g cm^{-3}. Aside from the C horizons, they have a typically black colour, a large porosity, good rooting and a friable consistency. When classified according to the World Reference Base for Soil Resources (WRB) (FAO/ISRIC/ISSS, 1998), 13 pedons key out as Histic Andosols, whereas the other 5 are Dystric Histosols. The difference in classification is the result of slight variations in Al_o and Fe_o content. The major requirement for Andosols in WRB is $Al_o + 0.5\ Fe_o > 2\%$, which is only valid for the profiles in the NW of the study region. The low Al_o and Fe_o content is both the result of the fairly large distance from the northern volcanic zone, resulting in thin ash deposits, and the advanced weathering stage because of the wet climate. Advanced weathering and leaching of Fe is confirmed by the occurrence of a placic horizon in several soil profiles (e.g., TA, SI). In the presence of organic matter, Fe-complexes dissolve and precipitate at the borderline of the oxymorphic and redoxymorphic layers. Because of the narrow and marked transition from the A to the C horizon, precipitation occurs in a small layer, resulting in a thin, strongly cemented surface. The formation of Placic layers is not uncommon in Andosols in wet climates (e.g., Mizota and van Reeuwijk, 1989; Dondeyne et al., 1993) and differs from podzolisation processes because of the absence of a depth gradient above the Placic layer.

3.1.2. Chemical properties

The Al_p/Al_o ratio > 0.5 indicates the soils are dominated by organometallic complexes rather than allophane (Mizota and van Reeuwijk, 1989). In some profiles, the difference between Al_p and Al_o indicates minor amounts of allophane (e.g., CU), which may be more abundant in the C horizon (e.g., MA6, MA9). The presence of organometallic complexes is strongly suggested by the significant correlation ($P < 0.001$) between the organic carbon and the Al_p content (Fig. 4A). In páramo soils, however, the presence of free Al is not a necessary condition for organic carbon accumulation, as samples with a high organic carbon content but almost devoid of Al_p are also present (Fig. 4A). These samples belong to the Histosols in the southern portion of the catchment, where volcanic ash depositions are negligible. Here, organic carbon accumulation is exclusively a result of the cold and wet climate and the high altitude. Locally, organic carbon accumulation also occurs in convex areas and near streams, where frequent water logging occurs (Buytaert et al., 2006).

3.1.3. Physical properties

In aluandic Andosols, an elevated organic matter accumulation is often responsible for the development of extraordinary physical properties, such as an open and porous, but strong soil structure, a high infiltration capacity, a high water retention capacity and a low bulk density (Nanzyo et al., 1993). The relation between the organic carbon content of the soil and the physical properties of the studied soils is given in Fig. 4B, C and D. Indeed, a very good, significant correlation is found between the organic carbon content and both the water retention at −1500 kPa ($r = 0.87$, $P < 0.001$, Fig. 4B) and the bulk density ($r = -0.55$, $P < 0.001$, Fig. 4D). It is interesting to note that a similar elevated water retention capacity is also found in silandic Andosols. However, in these soils it is due to the typical spherical, hollow structure of allophane, retaining water at high suction (Nanzyo et al., 1993). Finally, no significant relation could be found between organic carbon and soil hydraulic conductivity, which may be attributed to the large variability of the hydraulic conductivity, ranging between 1 and 32 mm h^{-1} (Fig. 4C).

The high porosity of the natural soils along the N–S transects is reflected in the bulk density, which is as low as 0.23 g cm^{-3}. Combined with the extremely high water retention capacity, these properties are considered as a key element in the high water regulation capacity of the páramo, despite the fact that the exact hydrological processes in the páramo soils are hitherto unknown (Buytaert et al., 2005a). As noted before, the páramo is known for its high and reliable base flow and surface water from the páramo is frequently used as the primary water source of the Andean highlands.

From a land management perspective, the strong relation between the soil organic carbon content and the hydrological behaviour of the catchment is very important. It stresses the necessity of agricultural practices that maintain the level of organic carbon in the soil. Similarly, practices that are known to accelerate organic carbon decomposition, such

Table 1
Chemical properties and classification of soils studied on two mountain ranges (western and central) and the Machangara catchment in south Ecuador

Name	Horizon	pH	pH	SOC	Al_o	Al_p	Al_p/Al_o	Fe_o	Fe_p	Classification
		H_2O	KCl	%	mg g^{-1}	mg g^{-1}	–	mg g^{-1}	mg g^{-1}	
Western cordillera										
CU	Ah1	5.1	4.5	22.8	37.3	29.6	0.79	14.3	11.9	Histic Andosol
	Ah2	4.8	4.2	24.1	24.0	23.1	0.96	11.7	9.4	
	A	5.1	4.6	13.5	49.5	19.3	0.39	12.2	8.8	
CH1	Ah1	4.7	4.0	16.7	21.6	21.9	1.01	11.4	11.3	Histic Andosol
	Ah2	5.0	4.3	29.1	40.4	32.7	0.81	18.5	16.6	
	A	4.8	4.4	17.5	24.8	33.8	1.36	8.6	16.1	
CH2	Ah1	4.8	4.0	32.1	21.2	22.0	1.04	13.0	12.7	Histic Andosol
	Ah2	4.9	4.2	36.1	38.7	39.3	1.02	21.3	20.2	
	A	4.7	4.3	32.6	39.4	43.8	1.11	24.1	21.7	
SO	Ah	4.7	4.0	14.9	14.4	14.8	1.03	6.3	5.8	Dystric Histosol
	A	4.7	4.1	16.9	16.4	17.3	1.05	6.5	6.2	
	C	4.7	4.3	11.2	15.0	12.4	0.83	5.4	4.3	
PD	Ah	5.0	4.1	22.1	11.4	11.7	1.03	5.5	3.8	Dystric Histosol
	A	5.0	4.2	14.2	13.3	12.9	0.97	6.4	4.5	
	C	5.5	4.4	n.r.	12.3	3.0	0.24	5.4	2.2	
Central cordillera										
TA	Ah1	4.8	3.9	33.0	21.2	21.4	1.01	11.4	9.1	Histic Andosol
	Ah2	4.9	4.2	31.1	35.9	39.3	0.91	18.2	15.8	
	A	4.5	4.2	26.4	38.0	37.7	0.99	19.1	17.4	
GU	Ah	4.6	3.9	10.6	4.9	4.9	1.00	9.8	7.0	Dystric Histosol
	A	4.5	4.2	4.6	4.9	4.5	0.92	5.0	2.8	
	C	4.9	4.5	n.r.	1.4	1.3	0.92	1.3	1.5	
SI	Ah	4.4	3.7	27.1	10.5	9.9	0.94	7.9	6.2	Dystric Histosol
	A	4.5	3.9	18.7	14.9	13.6	0.91	9.6	8.0	
	C	5.0	4.7	n.r.	21.7	2.9	0.13	6.3	0.6	
JI	Ah1	4.1	3.4	17.1	7.2	6.3	0.87	14.0	9.4	Dystric Histosol
	Ah2	4.1	3.6	8.3	5.9	6.4	1.08	11.8	12.5	
	A	4.2	3.7	n.r.	4.4	3.6	0.85	7.4	7.2	
Machangara catchment										
MA1	Ah1	4.7	4.2	31.0	21.8	22.6	1.03	12.8	9.8	Histic Andosol
	Ah2	4.8	4.3	36.9	31.7	32.8	0.98	16.1	13.5	
	A	5.0	4.3	31.3	44.5	43.6	1.02	21.9	19.5	
MA2	Ah1	4.8	4.2	35.3	16.2	16.5	1.02	30.7	25.9	Histic Andosol
	Ah2	5.1	4.4	28.2	36.6	28.7	0.78	24.3	21.3	
	A	4.8	4.3	14.1	21.9	19.6	0.89	3.2	2.9	
MA3	Ah1	4.4	3.9	28.6	15.6	15.5	0.99	10.4	9.8	Histic Andosol
	Ah2	4.7	4.2	26.2	24.1	23.8	0.99	14.4	14.1	
	A	4.6	4.4	17.8	19.9	18.7	0.94	12.4	11.1	
MA4	Ah1	4.8	4.1	34.5	10.5	10.2	0.97	12.3	6.9	Histic Andosol
	Ah2	4.8	4.3	31.2	56.0	41.3	0.74	27.8	7.8	
	A	5.0	4.3	30.6	39.6	37.5	0.95	14.0	9.3	
MA5	Ah	4.6	4.2	29.6	27.0	27.4	1.03	22.0	16.6	Histic Andosol
	A	4.9	4.4	44.0	48.0	51.0	1.06	15.8	13.2	
	C	4.5	4.1	n.r.	3.7	3.3	0.89	0.4	0.3	
MA6	Ah	4.3	3.9	34.7	25.9	22.9	0.88	n.r.	n.r.	Histic Andosol
	A	4.7	4.0	34.5	34.1	38.0	1.11	n.r.	n.r.	
	C	4.9	4.3	1.8	24.7	11.8	0.48	n.r.	n.r.	
MA7	Ah	4.6	4.0	34.7	22.7	24.8	1.09	n.r.	n.r.	Histic Andosol
	A	5.0	4.3	32.5	53.1	40.0	0.75	n.r.	n.r.	
	C	5.2	4.3	0.0	19.5	10.5	0.54	n.r.	n.r.	
MA8	Ah1	5.2	4.4	38.1	10.4	9.8	0.94	n.r.	n.r.	Histic Andosol
	Ah2	5.4	4.5	29.7	33.0	39.9	1.21	n.r.	n.r.	
	A	5.6	4.6	34.1	62.9	48.1	0.76	n.r.	n.r.	
MA9	Ah	4.9	4.4	36.6	10.9	11.4	1.04	n.r.	n.r.	Histic Andosol
	A	5.0	4.3	17.5	47.9	14.5	0.30	n.r.	n.r.	
	C	4.5	3.6	3.3	18.6	7.6	0.41	n.r.	n.r.	

SOC = Soil organic carbon.

Table 2
The physical and hydrological properties of soils studied on two mountain ranges (western and central) and in the Machangara catchment in south Ecuador

Name	Horizon	Sand	Silt	Clay	K_s	BD	−1500 kPa	Depth	Colour	Altitude	Land use
		%	%	%	mm h^{-1}	g cm^{-3}	g g^{-1}	cm	(Munsell)	(m asl)	
Western cordillera											
CU	Ah1	59	25	16	26.4	0.38	1.28	0–17	10YR1.7/1	3700	Natural
	Ah2	40	42	18	32.0	0.37	1.12	17–55	10YR1.7/1		
	A	83	15	2	16.2	0.37	1.03	55–88	10YR2/2		
CH1	Ah1	40	43	17	7.7	0.29	1.58	0–18	7.5YR1.7/1	3550	Natural
	Ah2	32	30	38	4.9	0.30	1.80	18–60	7.5YR1.7/1		
	A	63	17	20	9.8	0.30	1.24	60–78	7.5YR2/1		
CH2	Ah1	37	44	19	n.r.	0.29	1.69	0–20	7.5YR1.7/1	3580	Natural
	Ah2	21	50	29	15.0	0.29	2.26	20–49	7.5YR1.7/1		
	A	24	35	41	13.0	0.23	2.03	49–70	7.5YR2/2		
SO	Ah	31	31	38	12.0	0.47	0.79	0–21	10YR1.7/1	3660	Natural
	A	34	27	39	7.1	0.58	0.95	21–42	10YR1.7/1		
	C	50	16	34	27.5	0.95	0.36	42–62	10YR1.7/1		
PD	Ah	26	42	32	22.3	0.46	1.03	0–12	10YR2/1	3630	Natural
	A	36	37	27	2.5	0.55	0.84	12–30	10YR1.7/1		
	C	68	16	16	n.r.	0.76	n.r.	30–47	10YR1.7/1		
Central cordillera											
TA	Ah1	29	50	21	20.4	0.31	1.68	3–24	10YR1.7/1	3400	Natural
	Ah2	18	39	43	1.0	0.48	1.53	24–58	10YR1.7/1		
	A	19	0	81	5.0	0.55	1.27	58–74	10YR2/1		
GU	Ah	62	18	20	3.3	0.42	0.71	0–15	7.5YR2/1	3350	Natural
	A	63	21	16	2.5	0.60	0.45	15–40	7.5YR3/1		
	C	67	23	10	n.r.	1.59	0.07	>40	2.5YR4/1		
SI	Ah	25	36	39	5.3	0.28	1.27	0–20	7.5YR1.7/1	3250	Natural
	A	23	31	46	5.8	0.36	1.03	20–40	7.5YR1.7/1		
	C	79	18	3	n.r.	0.99	0.20	>40	7.5YR4/6		
JI	Ah1	55	12	33	4.9	0.34	0.90	0–15	10YR1.7/1	3350	Natural
	Ah2	53	14	33	4.6	0.42	0.97	15–34	10YR2/1		
	A	57	20	24	1.5	0.61	0.30	34–70	10YR3/3		
Machangara Catchment											
MA1	Ah1	30	49	21	9.5	0.44	1.11	0–27	7.5YR1.7/1	3500	Cultivated
	Ah2	20	52	28	7.5	0.28	1.90	27–54	7.5YR1.7/1		
	A	32	43	25	3.1	0.25	1.69	54–70	7.5YR1.7/1		
MA2	Ah1	31	51	18	3.6	0.31	1.70	0–22	7.5YR2/1	3520	Cultivated
	Ah2	40	35	25	1.5	0.30	1.75	22–50	7.5YR1.7/1		
	A	63	20	17	1.3	0.33	0.85	50–79	7.5YR2/2		
MA3	Ah1	28	45	27	3.7	0.40	1.46	0–13	10YR1.7/1	3600	Cultivated
	Ah2	49	23	28	10.0	0.36	1.42	13–27	10YR1.7/1		
	A	24	38	38	n.r.	0.54	1.31	27–50	10YR1.7/1		
MA4	Ah1	38	62	0	23.0	0.30	1.44	0–15	7.5YR2/3	3600	Cultivated
	Ah2	28	47	25	4.0	0.31	1.74	15–38	7.5YR1.7/1		
	A	24	55	21	1.0	0.38	1.61	38–53	7.5YR1.7/1		
MA5	Ah	36	12	52	10.8	0.29	1.63	0–30	7.5YR2/1	3600	Natural
	A	27	51	22	4.9	0.30	1.96	30–60	7.5YR1.7/1		
	C	65	16	19	n.r.	0.30	0.17	>60	2.5YR6/3		
MA6	Ah	12	55	33	44.1	0.23	2.09	0–12	10 YR 2/1	3800	Natural
	A	26	33	41	12.1	0.25	2.28	12–44	10 YR 1.7/1		
	C	58	19	23	29.0	0.95	0.31	>44	10 YR 4/4		
MA7	Ah	23	40	37	14.9	0.28	1.32	0–24	7.5 YR 1.7/1	3915	Natural
	A	34	41	25	45.3	0.25	2.40	24–56	7.5 YR 1.7/1		
	C	39	15	46	n.r.	n.r.	n.r.	>56	7.5 YR 5/3		
MA8	Ah1	40	32	28	176.7	0.16	1.80	0–15	10 YR 2/3	3790	Natural
	Ah2	39	31	30	243.9	0.18	2.30	15–41	10YR 1.7/1		
	A	27	31	42	10.6	0.23	1.83	41–62	10YR 1.7/1		
MA9	Ah	34	29	37	29.6	0.13	1.66	0–18	7.5 YR 2/1	3645	Natural
	A	44	31	25	10.4	0.19	1.34	18–110	7.5 YR 4/1		
	C	27	20	53	2.3	0.58	0.63	110–135	7.5 YR 3/1		

K_s = saturated hydraulic conductivity; BD = bulk density; −1500 kPa = water retention at −1500 kPa (wilting point).

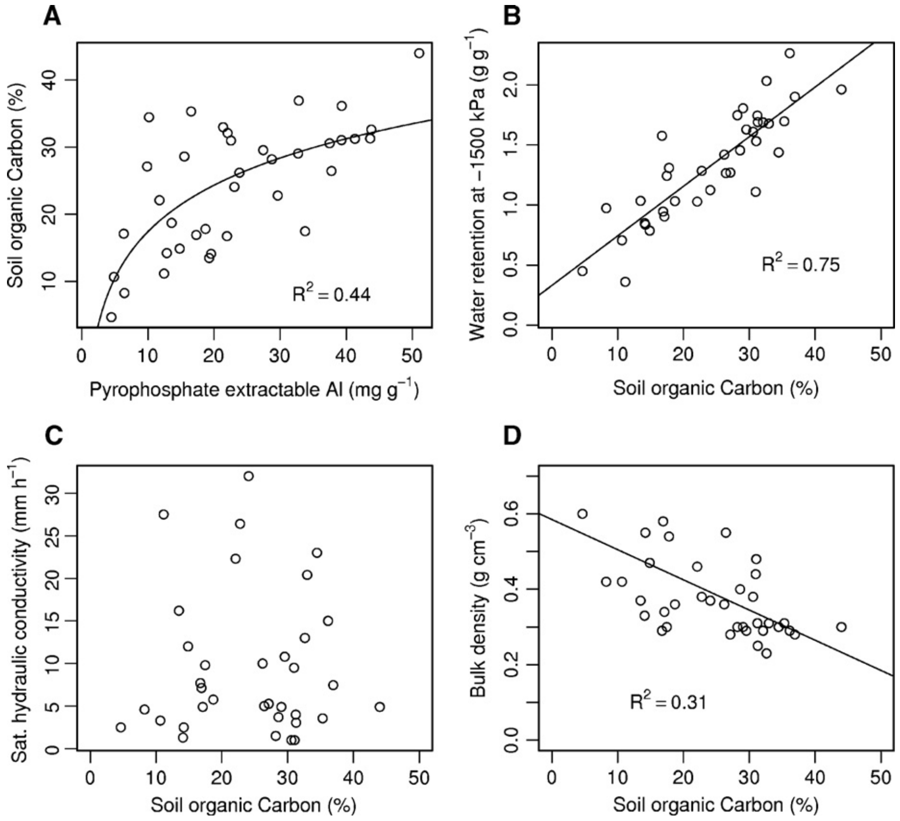

Fig. 4. The relationship between Soil Organic Carbon (%) in volcanic ash soils with: (A) pyrophosphate extractable Al (mg g^{-1}), (B) water retention (−1500 kPa) (g g^{-1}), (C) saturated hydraulic conductivity (mm h^{-1}), and (D) bulk density (g cm^{-3}). Only statistically significant R^2 values are shown on the graphs.

as artificial drainage of water logged areas, should be discouraged.

3.2. Regional trends and soil formation

The variation measured in the major soil properties along the study transect indicates that the ash released and deposited by the Sangay volcano, affected several soil properties (Fig. 5). The variations in Al_o, Al_p and Fe_o, as well as the pH in water and KCl show a significant correlation with the distance towards Sangay. For the Al_o contents of the soil, a negative correlation is observed, with an R^2 of 0.60 and 0.59 for the western and the central mountain range respectively (Fig. 5A). The decreasing impact of these ashes with increasing distance divides the soils in two major groups. The soils in the north-west of the basin are clearly influenced by volcanic ash deposits. The high Al and Fe content can be linked to weathering of volcanic ash, leaching of silica in the wet climate, and formation of complexes between organic soil constituents and Al and Fe. On the other hand, soils in the southern part of the basin are characterised by a lower Al and Fe content. Here, the contribution of volcanic ash weathering to the Al and Fe content is negligible. Less Fe and Al were released from primary and secondary minerals present in the regolith than from the volcanic ash because this rocky parent material was much more resistant to weathering (Buytaert et al., 2005b). In between these two groups, at a distance of 115 km to Sangay, very low Al and Fe values can be observed in Fig. 5A. These points represent the GU profile. A follow-up reexamination of the local topography revealed that the site might be located on an old landslide, where older, tertiary bedrock is exposed. As a consequence, the parent material of this pedon is relatively young, which may well explain the low Al and Fe content of the soil.

The clear north–south pattern of the volcanic ash deposits, combined with the significant correlation between Al and organic carbon content of the soils (Fig. 4A), suggests a north–south pattern in the organic carbon content. However, no significant correlation is found (Fig. 5D). This lack of correlation may be attributed to the superimposed impact of climate. Detailed precipitation and temperature maps do not exist for the páramo region, and therefore, these factors could not be included in the statistical analysis. However, in general, the north east of the catchment is influenced by the drier Cañar region with a monomodal climate, in particular the northernmost CU profile. A drier climate prevents leaching of Si, and thus favours the formation of allophanic minerals over organometallic complexes. As well, in a dryer climate, soils tend to be less water logged, and organic matter decomposition is therefore faster. Both processes prevent the organic matter accumulation that can be observed in the rest of the study basin. The presence of allophane and other amorphous minerals is reflected in the slightly lower Al_p/Al_o ratio of the CU profile (Table 1 and Fig. 5A and B).

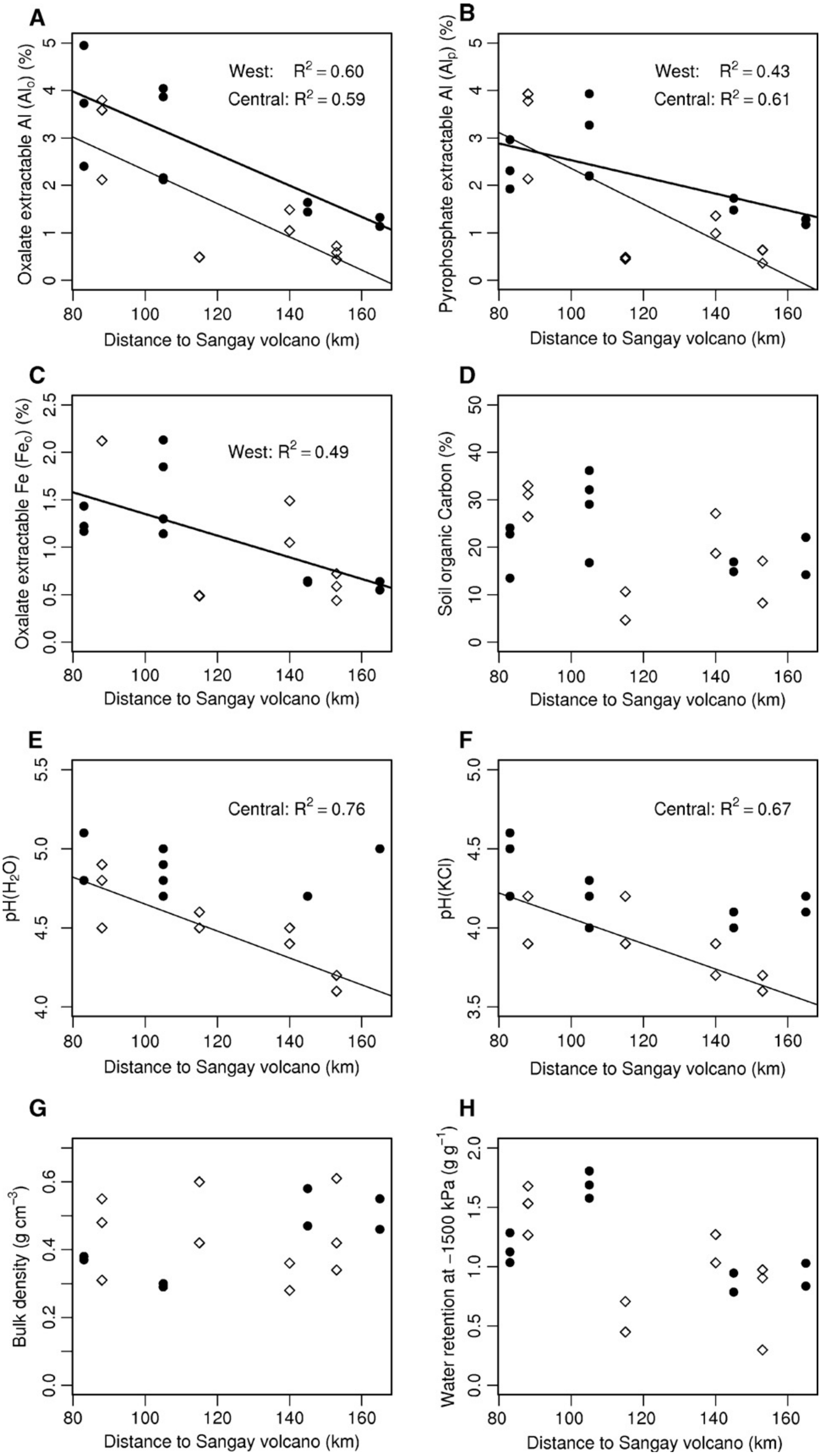

Fig. 5. Changes in selected soil properties on transects on the central and western mountain ranges as related to the distance from the Sangay volcano in the study region (see Fig. 1). The soil properties are: (A) oxalate extractable Al, (B) pyrophosphate extractable Al, (C) oxalate extractable Fe, (D) soil organic carbon, (E) pH (H_2O extraction), (F) pH (KCL extraction), (G) bulk density, and (H) water storage capacity. Only where the linear regression is significant (at a 0.05 confidence level), R^2 is given and trend lines are drawn. ● = western mountain range; ◊ = central mountain range.

Similarly, the wetter climate in the south of the basin generates soils with a high organic carbon content, despite the relative absence of volcanic ashes and thus a low Al content. These samples can be observed in the upper left region of Fig. 4A and indicate that a logarithmic function is better correlated than a linear function.

Apart from the significant spatial trends in Al_o and Al_p contents, the difference in volcanic ash deposits hardly affects the other chemical and physical soil properties. The trends in pH(H_2O) and pH(KCl) are significant but only in the central mountain range (Fig. 5E and F), and the bulk density is hardly affected (Fig. 5G).

The differences in soil properties between the mountain range (i.e., in E–W direction) can be related to volcanic ash deposits, parent material and climate. The base rock of the upper western mountain range consists of pillow lavas and andesitic volcanoclastic deposits. The central mountain range is less volcanic, and Paleozoic metamorphic rocks outcrop (Coltorti and Ollier, 2000). Furthermore, mineralogical analysis revealed that ash deposits have a stronger effect in the western mountain range than in the central mountain range (Buytaert et al., 2005b) due to prevailing winds from the Amazon basin. These differences in parent material result in a significantly higher Al_o and Al_p content ($P > 0.05$ for equality in the means) in the western mountain range, with major differences in the northern part of the basin (Fig. 5A and B). Despite organometallic complexation, differences in organic carbon are insignificant. Again, a major reason for this lack of difference may be the climate. As a result of the orographic effect, the central mountain range experiences a higher rainfall regime, up to more than 2000 mm year^{-1} in some locations, compared to an average of about 1000 mm year^{-1} in the western mountain range. Given the strong relation between soil organic carbon and precipitation in the region (Miller and Birkeland, 1992), this effect may compensate for the higher organometallic complexation in the western mountain range.

3.3. Land use impacts

In the Machangara catchment (Fig. 1), most of the páramo consists of quasi natural grasslands. These grasslands are not completely natural, because extensive grazing is very common. However, the páramo is communal land, and because of the absence of private land ownership and unrestricted access to the ecosystem, completely safeguarded areas do not exist in the Paute basin. Therefore, the extensively grazed grasslands must be taken as a reference for sustainable land use, which is not a real problem, as several studies point out that the infiltration and water storage capacity of an extensively grazed páramo is sufficient to maintain a sustained base flow in rivers descending from the páramo (Hofstede, 1995; Buytaert et al., 2005a). However, parts of the páramo have now been converted for cultivation of potatoes and beans and for intensive grazing (Fig. 3). At the time of this study, the age of these conversions was about 5 years.

The differences in soil properties between the intensively cultivated areas (profile M5–9) and the original grasslands (MA1–4 and CH1–2) are given in Table 3. The analysis on the datasets containing only the upper horizon (Table 3, left) and the whole soil profile (Table 3, right) give similar results: despite the intensive drainage, ploughing and exposition of the soils to direct sunlight, a remarkable homogeneity in soil properties is observed. The general trends are in accordance with the other studies on Ecuadorian Andosols. A slight but insignificant decrease in Al_o and Al_p agrees with studies of Poulenard et al. (2001) and Podwojewski et al. (2002) who attribute it to a destruction of volcanic minerals, if present, and the organometallic complexes. However, in contrast to these studies, the observed differences are very small and not significant. A large but insignificant difference in saturated conductivity is found, but this difference can be attributed to one profile (MA8), with extremely high values. Buytaert et al. (2002 and 2005a) observed a significant decrease in water retention at −1500 kPa in the same region, a trend that is confirmed. Finally, the significant increase in bulk density suggests a possible vulnerability for crust formation and decreasing hydraulic conductivity.

The minimal differences in the chemical soil properties and the lack of significance contrast with the severe changes observed in the páramos of Tungurahua (Podwojewski et al., 2002), Pichincha and El Angel in Ecuador (Poulenard et al., 2001) and in Andosols in other parts of the world (e.g., Higuchi and Kashiwagi, 1993; Poudel et al., 1999; Dorel et al., 2000). It is possible that the land use changes in Machangara are too recent to have a significant impact on the soil properties. However, other studies in the same region (Buytaert et al., 2002; Buytaert et al., 2005b) and elsewhere (Shepherd et al., 2001) have shown that some types of Andosol cultivation may have little or no effect on the hydrophysical soil properties. Similar observations were

Table 3
Differences in properties between natural and cultivated Andosols in the Machangara catchment

	Upper soil horizon			Complete profile		
	Natural	Cultivated	*P*	Natural	Cultivated	*P*
SOC	31.7	32.3	0.88	32.0	28.8	0.25
pH(H_2O)	4.73	4.67	0.72	4.90	4.79	0.30
pH(KCl)	4.12	4.10	0.86	4.23	4.24	0.83
Al_o	20.0	16.0	0.33	33.2	28.2	0.39
Al_p	20.0	16.2	0.35	29.6	25.9	0.43
Sand	31.7	31.7	0.99	13.6	33.9	0.56
Silt	36.5	51.6	0.07	37.9	43.2	0.17
Clay	31.7	16.6	0.07	31.6	22.9	**0.02**
K_s	29.6	9.5	**0.03**	45.1	6.19	0.09
BD	0.23	0.36	**0.02**	0.24	0.35	**0.001**
−1500 kPa	1.68	1.42	0.12	1.86	1.45	**0.003**

The analysis was performed for only the upper soil horizon (left) and the complete profile, except the C horizon (right). SOC = Soil Organic Carbon; K_s = saturated hydraulic conductivity; BD = bulk density; −1500 kPa = water retention at −1500 kPa. *P* indicates the chance of equal means. Bold values are significant at a 0.05 significance level. Data from the C horizon were excluded, as this horizon is not affected by land use.

made at some locations in the páramo of northern Ecuador (Robert Hofstede, Proyecto Páramo, Quito, pers.comm.). In fact, in natural conditions, Andosols generally have excellent and stable physical properties (Nanzyo et al., 1993). The resistance of the páramo soils to degradation may be related to the organic carbon content, which is much higher in the Paute basin than in the soils of Tungurahua and Pichinca. However, the exact mechanism is unknown. As these differences are of high importance for an adequate land management, it is suggested as a major topic for future research.

4. Conclusions

After physical and chemical analysis of 18 soil profiles in the páramo of the south Ecuadorian Paute basin, the following conclusions can be drawn:

- The soils are very dark, humic soils containing only small amounts of volcanic ash and large amounts of organic C (up to 44%). The high organic carbon carbon is the result of the formation of organometallic complexes, as well as organic matter accumulation in a cold and wet climate at high altitude. As a result of the high organic C content, the physical properties are determined by a high porosity and a high water retention capacity. The soils are classified as Histic Andosols in the northern part of the basin and Dystric Histosols in the south.
- Clear spatial patterns can be observed in the soil properties. A major source of variability is the proximity of the Sangay volcano, north of the study area, which is the primary source of volcanic ash. As a result, a gradual N–S decrease of the Andic soil properties can be observed. A second source of spatial variability is the difference in parent material between the western and the central mountain range, which is reflected in the soil properties. Finally, local variations in climate affect the accumulation of organic C and the ratio of the Al_p/Al_o content.
- Very few significant differences could be found between soil properties beneath natural grasslands and intensively drained and cultivated páramos, contrary to other studies on páramo soils. The lack of degradation may be related to the young age of the cultivation practices, or a better resistance of the soils in the study areas. At present, the exact mechanism is unknown and further investigation is suggested.

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