

Soil changes after a fire event in a páramo ecosystem:

Natural National Park Los Nevados , Colombia

Cambios en las propiedades del suelo posteriores a un incendio en el Parque Nacional Natural de Los Nevados, Colombia

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Abstract

A fire event occurred in 2006, affected about 2400 ha of Páramo ecosystem located in the surrounding areas of Otún lagoon (4 ° 46' 58.4" N y 75° 24' 26.8" W) in the Natural National Park Los Nevados, Colombia. Considering the possible affectation of the ecosystem services provided by soil, and the need to find variables that can be used as indicators of soil conditions, an evaluation of physical and chemical properties were assessed in affected and non-affected areas by fire. The soil assessment was conducted in the areas where restoration strategies had been implemented besides two geomorphologic positions (valleys and hills). Sampling for monitoring soils was done after the fire, two years (2008) and three years (2009) later. To identify differences in the soil characteristics between affected and non-affected sites, topographic positions and restoration treatments, a Kruskal-Wallis nonparametric test was applied. Subsequently, using the correlation coefficient of Spearman, the relationships between variables was analyzed. Soils of valley positions were drastically affected and more than 50% of organic matter was lost. Consequently, physical properties of soils such as bulk density and structural stability were also deteriorated. Three years after the implementation of restoration activities, there are not evidences of improvement in the soils conditions; in fact, some properties tend to be more deteriorated. Results obtained from this study permit to elucidate some variables, which could be used as indicators for monitoring programs with emphasis on this resource. Also, the fragility of Páramo moor ecosystems is showed by means of soils deterioration. The restoration of soils properties affected by fire is indeed a very slow process, even beyond of the time used in this study. In fact, to determine the effect of restoration strategies, defining the most adequate might take a long time. Therefore, it is imperative to avoid any activity or event capable of generating deterioration of this strategic ecosystem.

Key words: Colombia, forest fires, Natural Park Los Nevados, moor ecosystem, physicochemical soil properties.

Resumen

En 2006 ocurrió un incendio en el Parque Nacional Natural de Los Nevados, Colombia, que afectó aproximadamente 2400 ha de ecosistema de páramo de sectores aledaños a la laguna del Otún (4 ° 46'

58.4" N y 75° 24' 26.8" O). Teniendo en cuenta la posible afectación de algunos servicios ecosistémicos proveídos por el suelo y la necesidad de encontrar variables que puedan ser utilizadas como indicadores del estado de este recurso, se realizó una evaluación de las propiedades físicas y químicas de los suelos en áreas afectadas (AA) y no afectadas (NA) por el incendio. Las evaluaciones se realizaron inmediatamente después del evento (2006), 2 años (2008) y 3 años (2009) después. Se incluyeron áreas donde se implementaron estrategias de restauración y dos posiciones en el relieve: valle (turberas) y laderas. Para identificar diferencias en las características del suelo evaluadas entre sitios afectados y no-afectados, posiciones topográficas y los tratamientos de restauración, se realizó una prueba no-paramétrica de Kruskal-Wallis. Posteriormente, para verificar relaciones entre variables, se realizó un análisis de correlación usando el coeficiente de Spearman. En general, la posición de valle mostró los cambios más drásticos en el suelo a través del tiempo de evaluación. Allí, más del 50% de la materia orgánica se perdió, generando cambios también en algunas propiedades físicas como la densidad aparente y la estabilidad estructural, que después de 3 años, y a pesar de las actividades de restauración, muestran evidentes problemas de degradación. Con los resultados obtenidos ha sido posible definir variables indicadoras de las condiciones del suelo, que podrían ser usadas en programas de monitoreo de este recurso. Así mismo, se evidencia que los procesos de restauración en este ecosistema son lentos y se requiere un tiempo prolongado para generar cambios positivos en las propiedades de los suelos afectadas, que incluso superan el empleado en esta investigación. De esta manera, determinar el efecto de las estrategias de restauración y definir cuáles pueden ser las más apropiadas es de hecho un proceso que toma tiempo. Por tal razón, es imperativo evitar cualquier actividad o evento que genere deterioro sobre este ecosistema.

Palabras clave: Colombia, ecosistema de páramo, incendios forestales, parque natural Los Nevados, propiedades físico-químicas del suelo.

Introduction

The páramo are humid ecosystems from high mountains found in the Andes between Venezuela, Colombia, Ecuador and Peru. Those ecosystems are extended from an altitudinal range of 3500 MASL, mainly formed by glaciated valleys where lakes, wetlands and peatlands can be found. The vegetation is dominated by grasses with some shrubs fragments and low altitude forests (Luteyn, 1992, Brown, 2002; Hofstede *et al.*, 2003) that includes species such frailejones (Hofstede *et al.*, 1995, Hedberg, 1992, Vargas and Zuluaga, 1986). This vegetation has been adapted to specific conditions such as low temperature, low atmospheric pressure, high ultraviolet radiation and strong winds that generate dry conditions (Luteyn, 1992). Under these conditions, and due to the fragility of the ecosystem, the inclusion of new species (even forest) could generate unwanted changes (Buytaert *et al.*, 2007; Hofstede *et al.*, 2002).

In South America the páramos occupy about 75,000 km². They have important functions and provide ecosystem services for about 10 million people (Buytaert *et al.*, 2006a). among these services are, the accumulation of large amounts of soil organic car-

bon (Poulenard *et al.*, 2002) and climate change mitigation as carbon sinks. Other functions, such as water regulation, which is of great importance in the study area, may be favored by the high content of organic matter and soil parent materials (Poulenard *et al.*, 2001). These are predominantly pyroclastic that form organic-mineral complexes for increasing water retention capacity.

In July 2006, at the National Natural Park Los Nevados, a forest fire occurred that affected the surrounding areas of Otún Lake (4° 46' 58.4" N and 75° 24' 26.8" W): Lomabonita, La Leona, Bagaseca and El Bosque, covering approximately 2400 hectares of páramo vegetation (Loterio *et al.*, 2007). This event led to negative effects on natural resources like grass-frailejon land ecosystems, scrub and peat, which are in a strategic area of production of goods and ecosystem services in the jurisdiction of the department of Risaralda in Colombia. After this event, different strategies have been applied for ecological restoration including active and passive methods in order to improve the conditions of affected ecosystems (Loterio *et al.*, 2010). However, due to the magnitude of the mentioned event, the restoration process continues and requires longer periods to determine which strate-

gies are most effective and contribute to the restoration of ecosystems.

The genesis of the soil is a very slow process (Malagon, 2005), nonetheless degradation can occur quickly while restoration can take long time. After a fire event, changes in soil properties appear and their correction is difficult (Mils, 2006, Vargas *et al.*, 2002; Vargas and Rivera-Ospina, 1990). Therefore, to know which and how some soil characteristics are affected by this event is very important.

To contribute in the most appropriate way to promote ecological restoration strategies after a fire in páramo ecosystems, changes in some physical and chemical soil properties of the affected area in 2006 were studied, using the influenced area of the Otún Lake. Although soil organisms are an important source of information to reveal changes in this resource, these were not assessed in this research due to inherent logistical limitations.

Materials and methods

The study area is part of Los Nevados National Park, Colombia, specifically in the area of influence of the Otún lake where a fire event occurred between June 5th to 12th, 2006. This event affected a total of 2,374 hectares confined in the department of Risaralda. This area is located at 4° 46' 58.4" N and 75° 24' 26.8" W. According to Lotero *et al.* (2007), most of the páramo cover vegetation was grass, frailejon, thickets and peat bogs.

In geomorphological terms, the area is a complex of hills and ridges, slopes, semiflat zones and narrow valleys. Soils in the steepest parts originated from volcanic ash while flat and concave areas were from organic materials (IGAC, 1995). However, the last areas have also been influenced by volcanic ash. The estimated annual average rainfall is 1096 mm and the average temperature is 7°C (Lotero *et al.*, 2007).

Sampling design

Physical and chemical soil properties were assessed by a two-stage systematic sampling. First, it was the selection of the primary units representing areas affected and unaffected by fire. Second, within each primary unit, secondary units were defined according to the

predominant landforms: narrow valley and hills. Then within each of the last units were defined three plots of 10m x 10m. A total of 18 plots were selected for soil evaluation conducted in 2006 (two weeks after the fire), 2008 and 2009. Despite the high variability in physical and chemical properties of the soil regarding parent material, it is important to take into consideration the topographical position of the páramos, which has a significant effect on the change of some of these properties (Buytaert *et al.*, 2006a).

In the analysis of chemical properties, a composed sample was collected from each plot from 0 - 25 cm depth. For analyzes of physical properties, three points were randomly selected in each plot from 0 - 15 cm depth. Then, disturbed samples were taken in bags, and non-disturbed samples were taken with cylinders of known volume. The choice of depth is performed taking into account the soil that was exposed the most to fire.

The soil samples for chemical analyzes were sent to the Soil Chemistry Laboratory of the Universidad Tecnológica de Pereira. The soil samples for physical properties were sent to the Soil Laboratory of the International Center for Tropical Agriculture (CIAT). The chemical properties evaluated were: pH, organic matter (OM), total nitrogen (total N), phosphorus (P), cation exchange capacity (CEC), potassium (K), calcium (Ca), magnesium (Mg), sodium (Na) and exchangeable aluminum (Al) (Table 1). The measured physical properties were: bulk density (BD), real density (RD), total porosity, hydraulic conductivity, air permeability, moisture retention curves, gravimetric and volumetric humidity, size distribution of aggregates, water stable aggregates and texture (% sand, silt and clay) (Table 2).

Total bases were calculated from the cations, aluminum saturation from its relative weight regarding the effective cation exchange capacity. Also, the organic carbon (OC) was calculated from the organic matter (OM) ($CO = MO/1.724$) and, the carbon dioxide (CO_2) from the CO, the BD, the depth (Schlegel *et al.*, 2001) and the 44/12 factor or molecular weight ratio CO_2/CO . Similarly, the soil water storage capacity (SWS) was calculated from the moisture retention curves.

Table 1. Evaluated chemical properties and determination methods.

Property	Method
pH	Distilled water
Organic matter (%)	Walkley-Black Colorimetry
Total Nitrogen (%)	Kjeldahl
Exchangeable potassium (cmol/kg)	Ammonium acetate
Exchangeable calcium (cmol/kg)	Ammonium acetate
Exchangeable magnesium (cmol/kg)	Ammonium acetate
Exchangeable sodium (cmol/kg)	Ammonium acetate
Exchangeable aluminum (cmol/kg)	KCl - IM EAA
Phosphorus (mg kg ⁻¹)	Bray II Colorimetry Bray Kurtz
Cation Exchange Capacity (cmol/kg)	Ammonium acetate 1N, pH 7.0

Source: Soil Chemistry laboratory from Universidad Tecnológica de Pereira.

Table 2. Evaluated physical properties and determination methods.

Property	Method
Bulk density (g/cm ³)	Cylinders method
Real density (g/cm ³)	Pycnometer method
Total Porosity (%)	Calculated from densities
Hydraulic conductivity (cm/h)	Permeameter
Water stable aggregates (%)	Yoder method
Size distribution aggregates (%)	Screening and shaker movement
Penetration resistance (kg/m ²)	Penetrometer
Moisture retention curves	Pressure cooker
Texture (% clay, % sand, % silt)	Bouyoucos

Source: Soil laboratory of the International Centre of Tropical Agriculture (CIAT).

Data analysis

Given that sampling was systematic and no randomization was made at the time of selecting the sampling area, a Kruskal-Wallis non-parametric test was applied to identify statistical differences in the evaluated soil characteristics between affected and non-affected sites, topographic positions and restorative treatments. Subsequently, to check relationships between variables, a correlation analysis was made by using Spearman's coefficient. Analyses were performed using SPSS statistical software 10 for Windows (Ferran, 2001).

Results and discussion

When comparisons were made between sites, taking into account only the effect of fire, all

chemical variables showed significant changes ($P < 0.05$), except for phosphorus (P). Although pH, on average, increased slightly in these soils, the bases showed lower values for these sites ($P < 0.05$). Therefore, base saturation was only 35% of the value found at sites unaffected by fire (28.9% versus 10.2%). The most dramatic effect observed in the soil was OM that increased from 31% to 12% after the fire. A similar trend is also observed for total N and organic carbon (OC).

The OC, between 0 and 25 cm depth in non-affected soils was 69 t/ha in the valley areas and 103 t/ha on the hillside areas; these values are equivalent to 302 t/ha and 378 t/ha of CO₂, respectively. In Ecuador, the volcanic and páramo ecosystems soils have high levels of stored carbon according to Podwojewski (2006) and Poulénard *et al.*, (2001). To avoid an over-estimation of the

carbon content in the soils, it was used the density of the non-affected sites to calculate the mass of soil, since it is likely that the soil BD on the surface is increased due to erosion (Moreno and Lara 2003).

After the fire, without adjustment of the bulk density, the trend showed an increase in organic carbon (OC -t/ha). After an adjustment, OC values tended to be lower, particularly in the valley position (Table 3). However, these values were considered high compared with other soil ecosystems. In páramo Andean ecosystems, soils have an important carbon storage capacity due to the conditions of low temperature, low rates of mineralization and recycling of nutrients, which favor the accumulation of soil OM (Rondon *et al.* 2002).

Considering the vegetation characteristics of this ecosystem, in which low shape grasses predominate, soil is a major carbon sink, contributing to the stabilization of atmospheric CO₂ and global climate. To this process, the low temperature and the formation of organo-mineral complexes between MO and amorphous materials also contribute, which

have significantly influenced the formation of soils in this area. These complexes are difficult to break and therefore very stable (Ballesteros *et al.*, 2002).

When topographic position (valley and hillside) were included in the analysis, the pH shows a tendency to be higher ($P < 0.05$) in areas affected by the fire, finding the highest value in 2008 in both positions. However, those values were very similar in affected and non-affected areas (Table 3).

In general, after the fire, a reduction of the organic matter was about 50% ($P < 0.05$). Total N, which depends largely on the OM, showed the same trend with a decrease in the valleys ($P < 0.05$) after the fire and showed a 65% lower value two years later (2008). The change in the OM seems to have an effect on the increase in pH and a significant reduction of the CEC and total bases ($P < 0.05$), which changed from 73 to 19 cmol / kg and from 18 to 2 cmol/kg, respectively.

In hillside areas, the behavior was less dynamic and values remained very similar, even among the affected and non-affected sites by the fire. The above results show a

Table 3. Changes in pH, total nitrogen, organic matter and organic carbon in soils of valley and hill between 0 and 25 cm depth, after a fire in páramo ecosystem. Years 2006, 2008 and 2009.

Property		Valley				Hillside			
		NA*	AF	AF	AF	NA*	AF	AF	AF
			(2006)	(2008)	(2009)		(2006)	(2008)	(2009)
pH	Mean.	4.97c	4.93c	5.37 ^a	5.21abc	5.00c	5.05abc	5.34a	5.22abc
	SD.	0.15	0.29	0.11	0.23	0.001	0.21	0.13	0.15
N (%)	Mean.	1.39a	0.68b	0.49c	0.35d	0.46cd	0.54cd	0.45cd	0.45cd
	SD.	0.17	0.11	0.07	0.08	0.11	0.15	0.06	0.06
M.O. (%)	Mean	43.27a	20.97b	12.93c	8.55cd	11.75bcd	14.65bcd	11.50cd	11.40cd
	SD	10.10	5.24	2.54	2.50	3.32	5.30	1.80	1.94
CO (%)	Mean	25.10a	12.16b	7.50c	4.96cd	6.82cd	8.50cd	6.67cd	6.61cd
	SD.	5.86	3.04	1.47	1.45	1.93	3.08	1.04	1.12
C/ N	Mean	17.94a	17.69a	15.18ab	14.02b	14.89b	15.69ab	14.74b	14.79b
	SD	1.90	1.85	0.72	0.68	0.77	1.40	0.45	0.52
CO (t/ha)	Mean	69.5b	93.1ab	107.6ab	82.4b	107.5ab	94.2ab	115.2a	120.3a
	SD	16.6	45.9	14.1	13.2	30.6	31.6	18.8	18.2
COa (t/ha)	Mean	69.0b	33.4bc	20.6c	13.6c	107.3ab	133.8a	105.1a	104.2a
	SD	16.1	8.4	4.0	4.0	30.4	48.4	16.4	17.7

NA* = non- affected, average of 2006 to 2009; AF= affected; N= total nitrogen ; OM = Organic matter ; CO = Organic carbon ; C / N = carbon/nitrogen ratio; COa =organic carbon adjusted by the soil bulk density ; SD = standard deviation . Different letters between means are significantly different ($P < 0.05$).

severe effect on the soil of the valley position, possibly due to the state of OM and its lower degree of decomposition (Table 3).

According to Buytaert *et al.* (2006b), the proximity to drainage and convex and flat topography of the valley positions, may facilitate the accumulation of OM. Moreover, vegetation can lead to differences in the characteristics of Andisols in páramo ecosystems, especially associated with the OM and its components, generating different conditions as melanic and fulvic soils (Nierop *et al.*, 2007). Therefore, it is likely that differences in the conditions and the susceptibility of soils to the fire, between hill and valley positions are also associated with local vegetation of each area. Thus, the differences are evident between the two areas, with a predominance of grasses in the valleys. Furthermore, OM can affect the severity of the fire (Certini, 2005) associated with a greater availability of material for combustion dynamics, or mineralogical influence to prevent conversion of some minerals (Ketterings *et al.*, 2000).

Aluminum, which is a major source of acidity in tropical soils (Fassbender and Bornemisza, 1994, Sanchez, 1981), did not show a clear relationship with pH, being higher in the affected areas and lower in non-affected. Regarding the position in the relief, this element tended to be lower in the valley position, which showed a stronger increase immediately after the fire in 2006. The Al saturation values are high and mostly >30%, which shows conditions of high acidity and concentration of this element in the exchange complex. The values were higher for the hillside position, despite the most severe changes occurred in the position of valleys. This is probably associated with the decrease in the bases concentration, making more important the weight of Al in the soil exchange complex. The results are consistent with studies in Ecuador under conditions of páramo where, depending on the availability of Al, stable organic carbon concentrations reached above 20% in complexes with Al and Fe (Podwojewski, 2006).

Heating due to fire events can generate dehydroxylation of some clay minerals. So, an increase of Al, Si and Fe concentrations is expected, although ash can simultaneously generates an increase in pH and cation ex-

change. Subsequently, re-hydroxylation of minerals can be evident, which significantly alters the dynamic of the soil chemistry (Gilkes Yusiarni and 2010).

In the páramo, soils are dominated by organic-mineral complexes, rather than allophane. However, the presence of free Al is not a necessary condition for the accumulation of organic carbon, as it is related to the cold, wet weather and height, as well as local topography with convex positions nearby stream rivers (Buytaert *et al.* 2006b).

In general, the cations that form the basis on the soil (K, Ca, Mg and Na) tended to be higher ($P < 0.05$) in the non-affected areas by the fire. Although the trend is to decrease in the affected areas, the level appears to be stable. This phenomenon was dialed in the valley position, where there was a reduction to less than 30% compared to the initial value (18.5 cmol/kg to 2.1 cmol/kg) (Table 4). The CEC is defined, in this case, especially by the OM, and the output of cations such as K, Ca, Mg and Na in the exchange complex. Then, the Al content is more relevant, which increases the possibility to have more acidic soils due to the presence of this element. This is evidenced by the significant correlation ($P < 0.05$) found between the OM and each of the bases, as well as for Al but in an inverse way.

It is known that fires in forest ecosystems can alter dramatically the structure of clays and thus, their mineralogy. This alteration is more evident around the soil surface (Callanan Reynard *et al.*, 2010). In this study, mineralogical analyzes were not performed, however it is important to note that due to the low temperature, the consequent accumulation of OM and the constant contributions of volcanic ashes throughout history in the páramos (Buytaert *et al.*, 2006a), the presence of clay minerals can be very nascent and therefore less important in the dominant features in the soil.

The abundance of organic acids and acid pH favors the formation of complexes with Al and prevent their joining to amorphous materials such as allophane or imogolite (Buytaert *et al.* 2006a). The genesis of these amorphous materials, which could subsequently lead to other clay minerals, is limited by the OM, which in this case represents a very relevant factor in the genesis of páramo soils.

Table 4. Changes in aluminum (Al) and soil bases between 0 and 25 cm depth in valley and hillside sites after a fire in moor ecosystem.

Variable		Valley				Hillside			
		NA*	AF (2006)	AF (2008)	AF (2009)	NA*	AF (2006)	AF (2008)	AF (2009)
Al (cmol/kg)	Mean.	0.17c	1.10bc	1.30ab	1.29ab	1.20bc	1.15bc	1.67ab	1.66ab
	SD.	0.06	1.31	0.48	0.28	0.00	0.49	0.27	0.02
P (mg/kg)	Mean.	5.33bc	10.67abc	9.60b	2.22c	22.00a	16.00ab	12.10ab	1.89c
	SD	3.21	5.51	7.46	2.17	8.49	4.24	2.64	0.60
Ca (cmol/kg)	Mean	11.37a	3.60b	1.62bc	1.61bc	1.30bc	1.05bc	0.72c	1.24bc
	SD	2.48	2.93	1.44	1.08	0.71	0.07	0.27	0.36
Mg (cmol/kg)	Mean	4.90a	1.10b	0.52bc	0.33bc	0.45bc	0.35bc	0.23c	0.24c
	SD.	0.26	0.87	0.62	0.26	0.35	0.07	0.08	0.10
K (cmol/kg)	Mean	1.54a	0.60b	0.16c	0.18c	0.27bc	0.44bc	0.24c	0.23c
	SD	0.51	0.26	0.04	0.04	0.21	0.09	0.06	0.10
CICE (cmol/kg)	Mean	18.71a	6.50b	3.66c	3.41c	3.27bc	3.04bc	2.90c	3.39c
	SDD	1.49	3.06	1.69	1.41	1.29	0.59	0.60	0.46
CIC (cmol/kg)	Mean	73,0	27,0	19,5	19,3	16,5	17,5	19,1	18,4
	SD	11,5	7,5	2,7	3,7	4,9	3,5	2,8	4,0
BT (cmol/kg)	Mean.	18.54a	5.40b	2.36bc	2.12c	2.07bc	1.89bc	1.23c	1.72c
	SD.	1.53	3.83	2.05	1.35	1.29	0.10	0.40	0.46
Sat. Al (%)	Mean.	0.90c	20.99bc	44.42b	41.82b	39.74bc	36.94bc	58.36a	49.85ab
	SD	0.35	24.86	22.91	13.38	15.65	9.07	5.67	6.28

NA* = non affected, average from 2006 to 2009; CICE = effective cation Exchange capacity ; CIC = Cation Exchange capacity total; BT = total bases; S. Al = AL saturation ; SD = standard deviation . Different letters between means are significantly different ($P < 0.05$).

Phosphorus, one of the most dynamic elements in soil after events such as fires, showed a different behavior according to the position in the relief. Valley positions had a slight tendency to increase P after the fire, which may be associated with the mineralization of OM at the time of burning. However, P was reduced in the subsequent years until it reached the lowest value in the last year of monitoring (2009). Slope positions after the fire (2006) showed higher values of P than in the valley positions; however the P sharply decreased from an average 20 mg/kg to less than 5 mg/kg (Table 4).

The observed changes in soil chemical properties are consistent with those found by Mils (2006), who said that after a fire event, the properties that are most affected and sen-

sible are the OM and CEC which can be used as potential indicators of soil degradation.

Changes in the physical soil properties

Considering the position in the relief and the years after the fire, variables were analyzed and BD was lower ($P < 0.05$) in valley positions, where the changes were more contrasting. The trend was to increase after the fire with stronger changes in 2006 and 2008.

BD performance responded to the changes found in the OM, being higher ($P < 0.05$) as the OM decreased, which is corroborated by the analysis of correlation ($R = -0.66$). The actual density (RD) presented a less dynamic behavior and differences ($P < 0.05$) were only evident in the valley position of affected soils, which was lower than in the other sites. Total

porosity showed higher values ($P < 0.05$) in the valley positions, with a decreasing trend after the fire, equivalent to 17% between 2006 and 2009. On the hillside position, the contrast was lower, but also with decreasing trend (Table 5).

The pore size distribution (macropores, mesopores and micropores) showed significant changes ($P < 0.05$) after the fire, particularly macro-pores, which influence the movement of water by gravity (Montenegro *et al.*, 1990). These were more abundant ($P < 0.05$) in slope positions. Also, in both positions there was a decreasing trend after the fire, which was associated with the loss of pore space in the soil and increased BD. This relationship was confirmed by the significant correlation ($P < 0.05$) between the macroporosity and BD ($R = 0.4$). A similar behavior was observed for the micropores, which are associated with hygroscopic water (non-usable) and tended to decrease after the fire. This is an evidence of total pore space loss of the soil, thus an impairment of its ability for water regulation (Table 5).

The excellent physical properties of páramo soils are responsible for water regulation capacity and consequently high water

content, which is reflected in the moisture storage capacity. This situation is evident despite the percentage of water beyond the permanent wilting point, not-available to plants (Buytaert *et al.*, 2006a) associated with microporosity.

It is important to consider that the older the ash deposits (and more distant to the volcanic activity), the greater the degree of soil evolution. This soil evolution leads to the development of melanin epipedons with hydrological properties, where the storage capacity, especially of micropores, can reach up to 3000 g/kg. Their degree of evolution also means that any damage can generate irreversible changes (Podwojewski, 2006).

No differences ($P > 0.05$) were evident for particle size distribution (texture) in the contents of sand, silt and clay, neither between sites affected and non-affected by the-fire. There was a predominance of sand particles (Figure 1) and therefore coarser textures where OM was the most important element of soil aggregation. Thus, the loss of OM implies an increase in structure soil susceptibility to damage besides soil erosion.

The most severe effects after fire were especially in the soil surface where textures

Table 5. Changes in soil density and soil air space between 0 and 15 cm depth in valley and hillside sites, after a fire in a Páramo ecosystem.

Variable		Valley				Hillside			
		NA*	AF	AF	AF	NA*	AF	AF	AF
			(2006)	(2008)	(2009)		(2006)	(2008)	(2009)
D.A. (g/cm ³)	Mean.	0.11d	0.30c	0.58b	0.69ab	0.63abc	0.45c	0.70ab	0.73a
	SD.	0.01	0.11	0.08	0.11	0.00	0.01	0.08	0.05
D.R. (g/cm ³)	Mean.	1.81	2.36	2.34	2.41	2.39	2.33	2.39	2.36
	SD.	0.15b	0.08a	0.0a4	0.05 ^a	0.03a	0.03a	0.04a	0.03a
Pt (%)	Mean	93.9ab	87.5bc	75.2cd	71.8de	73.6de	80.9c	71.0de	69.1e
	SD	0.7	4.1	3.5	4.4	0.4	0.3	3.4	1.9
Macroporos (%)	Mean	12.71b	13.83b	13.13b	5.14c	18.75a	19.07a	14.20ab	8.68bc
	SD.	3.54	1.33	3.54	2.25	0.82	1.23	5.87	2.55
Mesoporos (%)	Mean	14.24abc	16.43ab	17.00ab	13.92abc	10.34bc	15.77ab	12.37bc	14.62ab
	SD	5.42	0.36	1.81	2.47	2.14	1.98	2.35	2.42
Microporos (%)	Mean.	52.38abc	56.45b	45.09c	52.71b	64.96a	42.73c	44.41c	45.79c
	SD.	10.62	4.84	3.85	2.32	2.17	2.52	3.93	2.36

NA* = not-affected, average years 2006 to 2009, AF = affected, DA = bulk density, DR = actual density, Pt = total porosity. SD = standard deviation. Different letters between means are significantly different ($P < 0.05$).

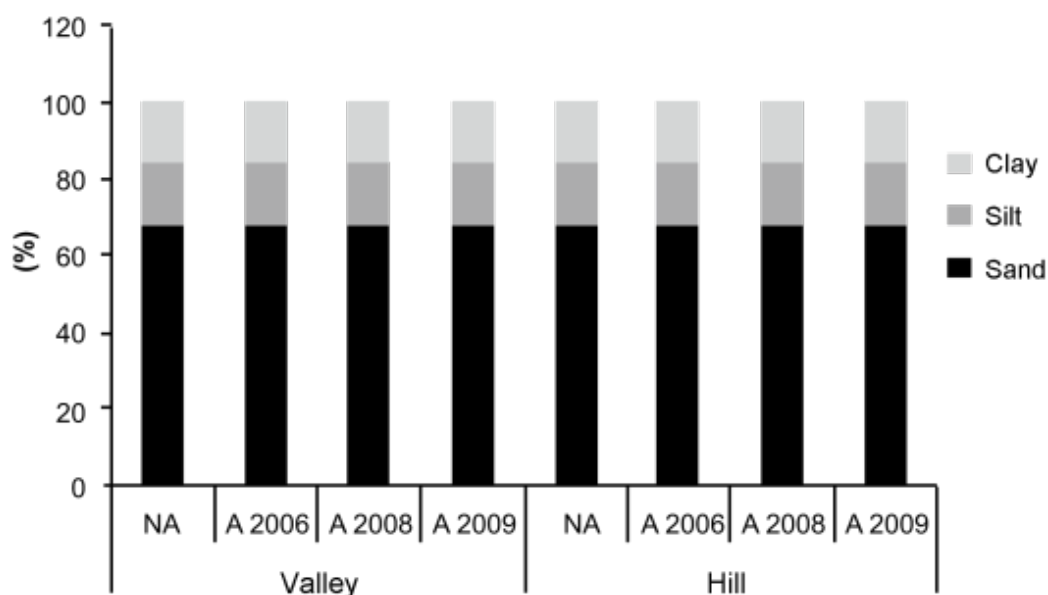


Figure 1. Particle size distribution (%) between 0 and 15 cm depth, for affected and non-affected areas by the fire, according to the position in the relief (valley or hillside). NA * = not affected, average years 2006 - 2009, A = affected years 2006, 2008 and 2009.

tend to be thicker (Ketterings *et al.*, 2000). Moreover, the increase in temperature may increase the hydrophobicity, reducing the capacity of the soil to absorb water and, increasing the susceptibility to erosion (Certini, 2005).

The amount of stable aggregates was similar between affected and non-affected sites. Aggregates > 6.3 mm were more abundant (P

< 0.05) between size classes and were more dominant in the non-affected sites. Valley position has those aggregates in > 80% before the fire (non-affected site), and exhibited a significantly higher value, then this percentage dropped to about half (38%) in 2009 (Figure 2). Slope position showed fewer aggregates in this kind of size (6.3 mm) and an increase (P < 0.05) after the fire (10% to

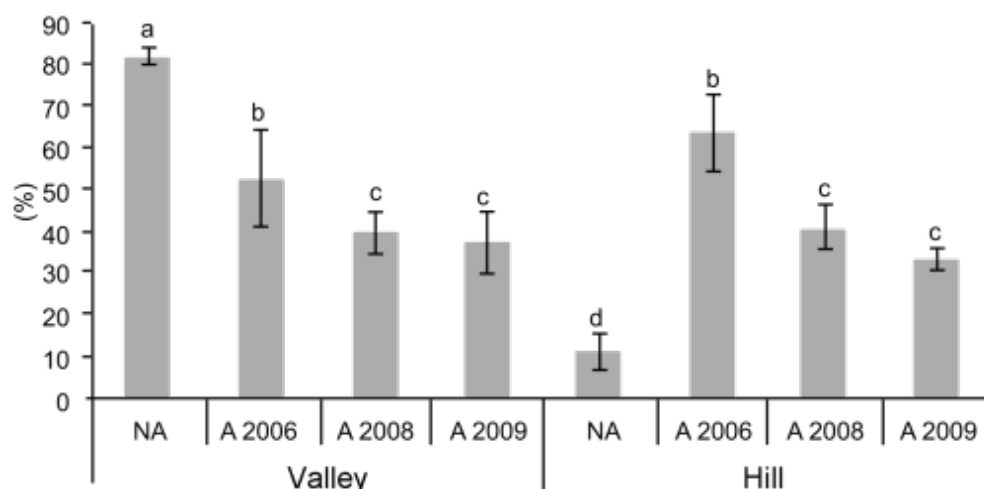


Figure 2. Percentage of aggregates with > 6.3 mm diameters, between 0 and 15 cm depth, for affected and non-affected areas by the fire, according to the position in the relief (valley or hillside), 2006, 2008 and 2009. NA * = not affected, average years 2006 - 2009, A = affected years 2006, 2008 and 2009. Vertical lines on the bars are standard deviation. Different letters between means are significantly different (P < 0.05).

63%). Then, the value dropped to 33% and showed the same downward trend in the last three assessments than the valley positions. Decreasing trend is an evidence of deterioration of the soil structure after the fire, which is related to the increased susceptibility to soil erosion.

The aggregate stability test to water confirms the importance of these in the soil structure, since the greater size and number, the greater its retention in the soil. The percentage of stable aggregates was considerably lower in the finer size classes. For this variable, differences were evident ($P < 0.05$) between the analyzed sites, however no definite trend was observed (Figure 3).

According to Vargas and Rivera-Ospina (1990), burning and grazing generate changes in the micro-topography of the soil, affecting the seed bank and germination rate. Therefore, the natural restoration processes may be slower and possibly not successful. Likewise, the loss of coverage can generate erosion (Cardenas *et al.*, 2002) that under páramo may have a negative effect on the soil.

Soil degradation was also evidenced by the reduction of hydraulic conductivity, which on average was about three times less in the affected soils by the fire. Values were higher ($P < 0.05$) in non-affected hillside, which was significantly correlated ($P < 0.05$) with the

amount of macropores ($R = 0.6$) in this site. After the fire, both positions has a significant ($P < 0.05$) decrease of hydraulic conductivity, equivalent to 71% in valley positions and 91% in slope (Figure 4). This tendency was confirmed by the reduction in permeability ($P < 0.05$), especially in the lower voltages (pF), being 98% at the position of valley, and 92% in slope. When the air space is reduced, as in the affected sites by the fire, the high pressures can greatly affect the forces of surface tension of water (Table 6), having a high impact on the flow.

Values of gravimetric and volumetric soil moisture were indicative of high water retention capacity. Gravimetric moisture was above 100% at lower tensions. However, this capacity was reduced ($P < 0.05$) after the fire especially in valley positions (Table 6).

The storage capacity of the soil was estimated, on average, from 13% to 15 cm deep, which is equivalent to 320 m³/ha. The values varied between 10 and 20% of the total volume (208 m³/ha and 553 m³/ha). Although initially this was higher ($P < 0.05$) in the positions of slope, after 2006 in both positions the values decreased. Here, the usable volume was quantified, considering the tension at which water is retained by the soil. For this reason, the water held at high (pF > 4.17) or very low (pF < 1.8) tensions should not be

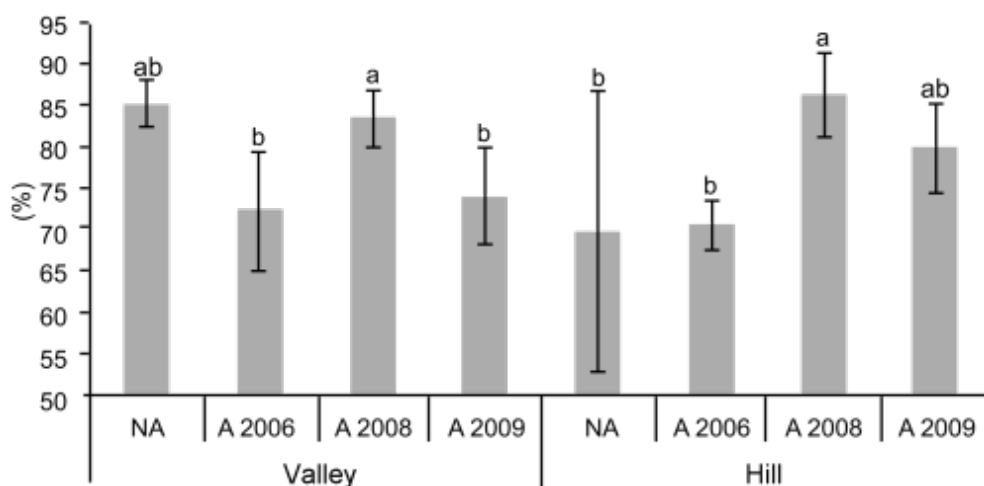


Figure 3. Stable water aggregates with diameter greater than 2.4 mm, between 0 and 15 cm depth, for affected and non-affected areas by the fire according to the position in the relief (valley or hillside) in 2006, 2008 and 2009. NA * = not-affected average years 2006 - 2009, A = affected years 2006, 2008 and 2009. Vertical lines on the bars are standard deviation. Different letters between means are significantly different ($P < 0.05$).

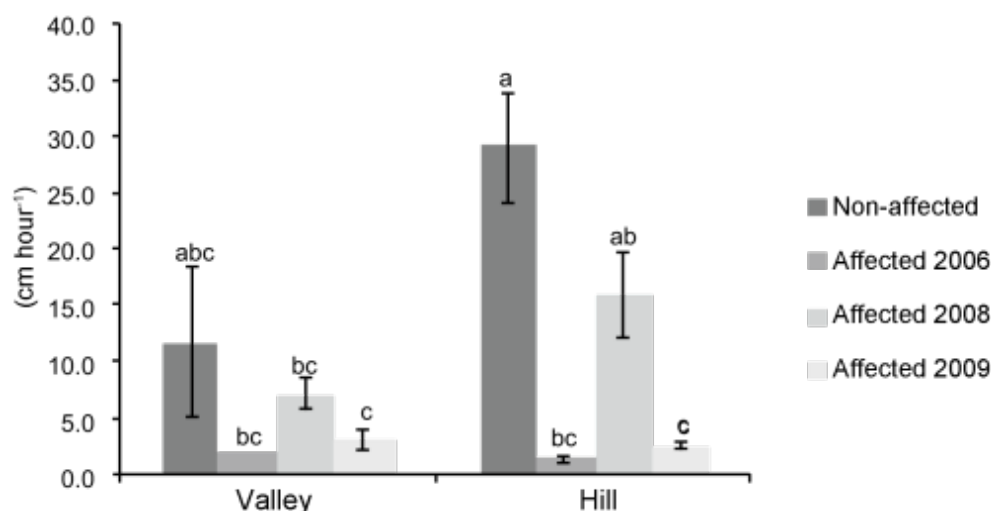


Figure 4. Hydraulic conductivity between 0 and 15 cm deep in the affected and non-affected areas by fire according to the position in the relief (valley or hill) in 2006, 2008 and 2009. Vertical lines on the bars are the standard deviation. Different letters between means are significantly different ($P < 0.05$).

taken into account. Thus, other properties should be considered to conclude about the hydrology capacity of these soils.

The effect of the fire at the National Park Los Nevados was considerably negative as it was evident in the changes of the evaluated properties and the soil vulnerability to degradation. Upon loss of vegetation cover, bare surfaces were highly water repellent, runoff is increased, water repellent aggregates float and erosion increases. Changes are accompanied by structural degradation and loss of OM (Podwojewski, 2006). Low density in this study makes the soil more susceptible to erosion because its particles become repellants and float in the water runoff (Poulenard et al., 2001).

Conclusions

- One of the most serious effects on soil after the fire in the National Park Los Nevados was the loss of OM, especially in the valley position. This loss significantly affects other properties such as bulk density, porosity and soil structure, hydraulic conductivity and permeability. This fact is associated with a significant reduction in ecosystem service like soil water retention capacity and an increase to erosion susceptibility, which seriously threatens the provision of such services to the residents

of the coffee region, mainly the inhabitants of the municipalities of Pereira and Dosquebradas.

- The results of completed restoration strategies did not show evidence, even in the recovery of soil after three years of the occurred event. This is related to the severity of the occurred damage and the slow dynamics of vegetation under the páramo ecological conditions. However, it is considered that these strategies should continue to be promoted, and their effects should be monitored to establish management priorities. The obtained results suggest that an increase of OM is important for the success of the ecological restoration, especially in the valley positions. This will generate better hydrological conditions and less susceptibility to erosion. In this sense, prioritizing restoration strategies to increase the percentage of this material may be the most beneficial for the soil.
- Information about páramo land is, in general, not abundant and, this topic has only few records. Therefore, it is necessary to delve into this type of research in order to generate better criteria for making decisions. More time and resources would be necessary to obtain further information on mineralogy of soils and the various components of the OM. Then, a better

Table 6. Changes over time in the air permeability, gravimetric moisture and soil volumetric moisture from 0 to 15 cm depth in valley and hillside after a fire in páramo ecosystem

Variable			Valley				Hillside			
			NA*	AF	AF	AF	NA*	AF	AF	AF
				(2006)	(2008)	(2009)		(2006)	(2008)	(2009)
Permeability to air (cm/day)	pF = 1.87	Mean.	894.7	341.8	20.8	20.3	122.3	191.2	18.9	8.8
		SD.	48.8	132.9	23.6	27.3	2.6	6.1	9.7	2.8
	pF = 3	Mean.	679.1	277.6	86.3	128.6	75.8	150.2	83.2	56.5
		SD	34.5	102.6	67.0	110.6	4.1	1.0	17.2	29.0
	pF = 4.17	Mean	580.2	222.5	158.7	219.7	57.2	108.7	121.1	174.8
		SD	45.8	73.8	68.1	178.6	0.9	6.1	26.7	75.1
Gravimetric moisture (%)	pF = 0	Mean	894.7	341.8	167.2	135.8	122.3	191.2	123.2	109.6
		SD.	48.8	132.9	44.6	41.6	2.6	6.1	25.3	9.9
	pF = 1.87	Mean	679.1	277.6	126.8	112.7	75.8	150.2	87.0	85.5
		SD	34.5	102.6	35.9	33.7	4.1	1.0	13.0	6.7
	pF = 3	Mean.	627.3	240.2	108.6	97.6	68.7	124.9	73.0	74.3
		SD.	34.5	76.6	28.6	27.2	1.6	10.5	12.3	6.2
	pF = 4.17	Mean.	580.2	222.5	92.5	89.3	57.2	108.7	68.3	64.3
		SD	45.8	73.8	27.4	24.7	0.9	6.1	11.2	5.5
Volumetric moisture (%)	pF = 0	Mean	99.0	91.8	63.4	79.9	77.1	85.2	65.2	76.7
		SD	1.6	4.6	16.7	4.5	1.8	0.3	16.4	1.7
	pF = 1.87	Mean	75.1	75.1	49.3	66.6	47.8	66.9	52.6	60.4
		SD.	0.3	2.4	13.0	3.9	2.5	1.4	12.8	1.6
	pF = 3	Mean	69.4	65.9	42.2	57.6	43.3	55.7	43.7	52.6
		SD	0.7	4.0	11.3	2.9	0.9	6.2	10.5	2.1
	pF = 4.17	Mean.	64.1	60.9	37.3	52.7	36.1	48.5	38.9	45.8
		SD.	2.1	3.8	10.4	2.3	0.6	4.1	9.3	2.4

NA* = not-affected, average years 2006 to 2009, AF = affected, pF = hydric potential of the soil

explanation for the effects generated by fires on the páramos can be possible. However, the findings in this study are enough evidence to avoid any activity that generates changes in soil and cover vegetation of these unique, fragile and highly strategic ecosystems.

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