

# Impact of land use changes on the hydrological properties of volcanic ash soils in South Ecuador

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**Abstract.** The effect of land use on the water retention capacity of Umbric Andosols in south Ecuador was studied. The objective was to acquire a better insight into the hydrological processes of the ecosystem and the role of the soil, in order to assess the impact of changing soil properties due to land use change on the hydrology of the high Andes region. Field data on the water retention capacity at wilting point of Umbric Andosols were collected for both cultivated field conditions and original bush vegetation. The pH in water and in NaF, texture, organic matter content and dry bulk density were measured to show which physico-chemical soil characteristics are responsible for the water retention of the Umbric Andosols and for the irreversible loss in water retention due to air drying. Organic matter content appears to be very important and certainly more important than allophane clay content. Water retention of the organic litter layer was calculated to be 16 mm, this would be lost when vegetation was cleared and the land cultivated.

**Keywords:** Andosols, land use, soil water retention, hydrology, volcanic ash soils, Ecuador

## INTRODUCTION

The southern Andes region of Ecuador (Austro Ecuatoriano) has a complex water supply system, due to the extremely variable rainfall in both space and time. Annual rainfall ranges between 600 and 3000 mm and the climate, ranges from cold tropics in the high altitudes, to temperate tropics in the mid altitudes and warm tropics in the low zones. Competition for water is severe, its main uses being drinking, irrigation and power generation. The major water source of the Austro Ecuatoriano is the Rio Paute river, having its origin in the cordillera at 4300 m above sea level. Most of the water originates from the highlands of the watershed (higher than 3000 m a.s.l.). Between 3000 and 3300 m, 'chaparro' is the main vegetation, which is a low bush vegetation with a height of about 1 to 3 m growing on Umbric Andosols (Figure 1), also called 'subpáramo' (Hofstede 1995). At the upper limit, chaparro changes into a low grass vegetation, the 'páramo'. These zones have a marked buffer capacity for regulating water and hence represent an important factor in the hydrological cycle (Hofstede 1995). However, it is not clear to what extent different factors are responsible for the water retention and

its release: e.g. retention in the soils, in vegetation, in organic litter layers, in swamps, lakes or in forests. Furthermore, the dynamics of these factors in time and space are poorly understood (Buytaert 2000).

Due to population growth and increasing food demand, cultivated land in the upper Andes region is expanding. The vegetation is burnt and the soil ploughed to plant potatoes or beans. Due to the absence of fertilizers and changes in soil structure, the soil is often depleted after two years, possibly longer, and agricultural land is converted to grassland. This pasture is extensively used to graze cattle, sheep and other livestock such as alpacas. The objective of the study was to determine whether these land use changes have an impact on the hydrological properties of the Umbric Andosols, and therefore on the water supply of the region (Buytaert *et al.* 2000).

Andosols are soils developed mainly on volcanic ash. They show a typical toposequence, with Umbrisols in the lower reaches and Histosols higher in the mountains (Figure 1). The rapid weathering of the porous material results in an accumulation of amorphous complexes and short-range-order minerals such as allophane and imogolite (Wada 1985). Short-range-order minerals are hydrous aluminosilicates with Al:Si ratios typically between 1 and 2 (Driessen & Dudal 1991) that show a typical X-ray diffraction pattern of particulate materials of small size with little long-range-order (Wada 1986). Umbric Andosols are characterized by a thick, dark coloured horizon with a loose, fine crumb structure, rich in humus (FAO *et al.* 1998). The high organic content, the low density of the minerals and the

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large amount of non crystalline material results in a soil of low bulk density, high water permeability and high water retention capacity (Swindale 1969; Van Wambeke 1992; FAO *et al.* 1998). These characteristics are favourable for agricultural practices performed in the high Andes regions, such as the Austro Ecuatoriano (Dercon *et al.* 1998).

However, due to its geographical location near the equator and its high altitude, the Austro Ecuatoriano is exposed to intense solar radiation, particularly in the UV-B range (Hofstede 1995). As a result, the large amount of humus that results in the typical fluffy, fine crumb structure and high water retention, undergoes marked structural changes (Ampe 1999; Basile & De Mascellis 1999) and will partially decompose when the vegetation and the thick organic litter layer is removed and the soil is ploughed and exposed to direct sunlight. Nanzyo *et al.* (1999) recently hypothesized that a loss of water retention at wilting point when dried in the laboratory would be a consequence of the breakdown of typical allophane clay. Allophane consists of a collection of naturally formed crystalline hydroxides of aluminosilicates (Wada 1986). The typical hollow spheres of allophane with a diameter of 35 to 50 Å are probably the reason for their high water absorbing capacity and also the high water content of allophane clays at high moisture tension. The spheres contain microscopic pores so that water can be stored inside (Wada 1985). Destruction of the typical form of allophane particles by airdrying causes a reduction in water retention

capacity. Because both organic matter and allophane occur in relatively large amounts in these Umbric Andosols, both processes may occur leading to a reduction in water retention capacity.

Literature is rather scarce on the physical behaviour of Ecuadorian Andosols. These soils are derived from volcanic ashes, but, because the geology of the Andes region is very complex, doubts remain about their age and weathering stage. Population pressure is growing and more of these soils are being taken into cultivation. Due to deforestation and tillage, their key role in regulating water supply may be impaired by a reduction in water retention (Dorel *et al.* 2000). As water coming from the southern Ecuadorian Andes region is used for large scale irrigation of the coastal deserts of northern Peru, the investigation has a geopolitical dimension.

The study focuses on the differences in wilting point of the litter layer and A horizon of Umbric Andosols under different types of land use. Soil samples taken under original undisturbed bush vegetation were compared with soil samples taken from arable fields and pasture.

## MATERIALS AND METHODS

### *Site selection and soil sampling*

The study area is in the Paute catchment in the Ecuadorian Andes region south of Cuenca, at the small village of Jima. Altitude ranges from 3000 to 3300 m a.s.l. The soil is classified as Umbric Andosol (World Reference Base, FAO *et al.* 1998). The typical physical and chemical properties are listed in Table 1.

Eight sites were chosen from an area of about 500 ha, in land with a known history for the last 50 years. Soil samples were taken from both a cultivated field and adjacent bush vegetation, in order to eliminate as far as possible differences in slope, aspect, microrelief and soil. Samples at 15 and 40 cm depth allowed comparison of the impact of soil drying at plough depth and below. At each site, undisturbed samples were taken in two Kopecky rings of 100 cm<sup>2</sup>, and 1 kg of disturbed soil was collected.

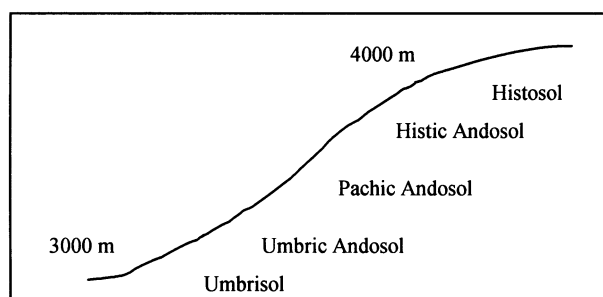


Figure 1. Typical toposequence of the soil types of the high Andes region (after Dercon *et al.* 1998).

Table 1. Chemical and physical characteristics of the investigated soil.

Horizon	O	A1	A2	C1	C2
Depth (cm)	0 – 6	6 – 19	19 – 58	58 – 137	> 137
Bulk Density (kg/m <sup>3</sup> )		670	580	-	-
Munsell colour		7.5 R 1.7/1	7.5 R 1.7/1	7.5 YR 3/4	7.5 YR 7/1
Texture (S/L/C) (%)		56/10/34	50/16/34	32/30/38	40/28/32
pH in NaF		10.1	11.1	11.3	11.4
pH in H <sub>2</sub> O		4.6	4.2	4.9	5.3
Organic carbon (%)		14.2	2.3	1.7	0.8
Phosphate retention (%)		68.0	90.0	85.0	26.0
Base saturation (%)		1.0	0.5	30.1	2.1
Oxalate extraction				-	-
Al <sub>2</sub> O <sub>3</sub> (%)		2.57	2.62		
Fe <sub>2</sub> O <sub>3</sub> (%)		2.62	3.39		
SiO <sub>2</sub> (%)		0.16	0.14		
Pyrophosphate extraction				-	-
Al <sub>2</sub> O <sub>3</sub> (%)		2.82	4.37		

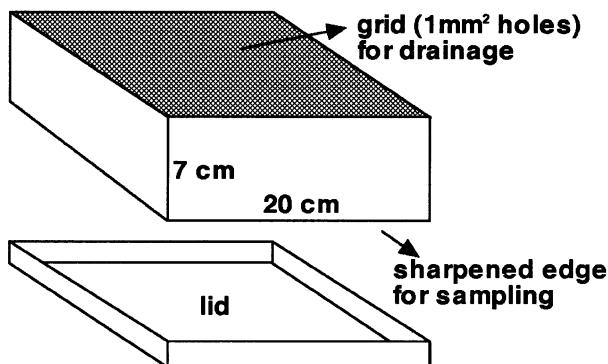


Figure 2. Specially designed iron box to sample organic litter layers.

#### Sample treatment and data analysis

From each disturbed sample a fraction ( $\pm 0.5$  kg) was air-dried in the laboratory at room temperature for at least 30 days while the other part was immediately analysed at field moisture. Wilting point of both dried and moist disturbed soil samples was determined. First, a saturated soil paste was made by saturating the samples with water for about a week. Then the soil paste was placed in small rings on a porous membrane and subjected to a pressure of 15 bars for 7 days. Based on Andosol literature (de Wit 1998), the time to reach equilibrium was set at 7 days. Determinations on all samples were made in duplicate. The complete dataset comprised 128 measurements. The data were compared with the student T-test (The SAS Institute, 1989–1996, version 6.12). The irreversible decrease in water retention caused by air-drying in the laboratory was evaluated by comparing the wilting point of fresh and dried samples. When there was a significant difference ( $P < 0.05$ ), a second comparison was made between the wilting point of moist agricultural field samples and moist bush samples, at 15 and 40 cm.

Particle size analysis (Bouyoucos), pH in water (2:1), pH in NaF (1M), organic matter content (Walkley & Black) and bulk density (Kopecky) for correlation to water retention reduction were also measured.

To evaluate the water retention characteristics of the organic litter layer, four undisturbed samples were taken using a specially designed iron box of 20 by 20 by 10 cm for undisturbed litter sampling (Figure 2). After saturation in the laboratory the samples were weighed. Weighing was repeated after three days of free drainage in the laboratory to determine field capacity. Wilting point was measured as described above. The shrinkage of the Umbric Andosol while drying was measured from volume changes in the Kopecky rings during oven drying. Attempts to establish the field capacity moisture contents were unsuccessful due to large variability between methods which give similar results in other soils.

## RESULTS AND DISCUSSION

#### Water retention reduction at wilting point due to cultivation

Figure 3 shows the wilting point data. They indicate the extraordinarily high water retention capacity of these soils. The wilting points are much higher than the average mineral

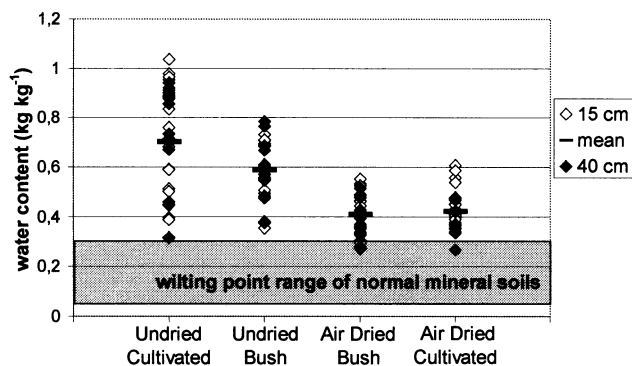


Figure 3. Water content at wilting point of Umbric Andosols under different types of land use (128 samples), compared to the wilting point range of normal mineral soils according to Brady (1990).

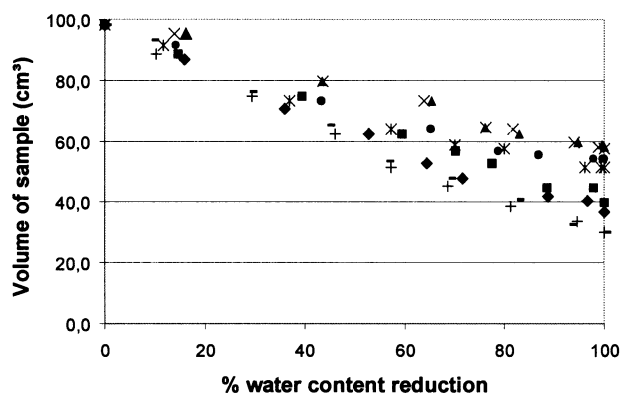


Figure 4. Volume reduction when Umbric Andosol samples taken under natural vegetation are dried in the oven at 105 °C. Twenty four hours of drying is equal to a water content reduction of 100%. Each symbol represents one soil sample.

soil wilting point (Brady 1990, Figure 3). A mean water retention of  $0.7 \text{ kg kg}^{-1}$  was recorded, a value which underwent a reduction of 35% after laboratory drying (Table 2, Figure 3). An overall 16% reduction in water retention at wilting point is caused by cultivation. The major reason for the large difference is the relatively short dry season which provides no opportunity for the extreme drying experienced in the laboratory. Furthermore, a cultivation period of two years is very short. After that period the soil is permanently covered by pasture, eliminating direct exposure of the soil surface to sunshine and thus reducing the irreversible drying process. A 40% reduction in water retention due to air drying in the laboratory at 15 cm depth compares with a reduction at 40 cm of only 30%. The reduction due to cultivation is 21% at 15 cm, but only 10% at 40 cm depth.

Some additional experiments were performed to measure the impact of drying on the structure of the Umbric Andosols. During drying at 105 °C for 24 hours, soil volume reduced irreversibly by more than 60% (Figure 4). No further experiments were performed on the oven dry samples, but the experiment shows the remarkable beha-

Table 2. Data set of the wilting point of Umbric Andosol samples. The field samples were taken when the age of cultivation is less than 2 years and under pasture when older. The bush samples were taken under the original shrub vegetation.

Site <sup>a</sup>	Sample data		Wilting point of undried, moist soil samples				Wilting point of air dried and remoistened soil samples			
	Cultivation time (years)	Depth (cm)	Bush (kg kg <sup>-1</sup> )	s.d.	Cultivated (kg kg <sup>-1</sup> )	s.d.	Bush (kg kg <sup>-1</sup> )	s.d.	Cultivated (kg kg <sup>-1</sup> )	s.d.
1	1.5	15	0.507	0.008	0.501	0.011	0.354	0.023	0.441	0.015
	1.5	40	0.448	0.001	0.481	0.006	0.354	0.004	0.444	0.034
2	25.0	15	0.591	0.002	0.554	0.003	0.388	0.026	0.460	0.016
	25.0	40	0.455	0.008	0.582	0.017	0.331	0.002	0.470	0.003
3	50.0	15	0.392	0.007	0.366	0.017	0.300	0.006	0.385	0.045
	50.0	40	0.316	0.002	0.378	0.004	0.277	0.005	0.301	0.050
4	10.0	15	1.007	0.042	0.700	0.012	0.463	0.001	0.583	0.035
	10.0	40	0.927	0.019	0.686	0.001	0.411	0.023	0.477	0.002
5	10.0	15	0.721	0.055	0.572	0.022	0.453	0.013	0.405	0.007
	10.0	40	0.693	0.031	0.567	0.025	0.410	0.004	0.367	0.001
6	25.0	15	0.863	0.039	0.597	0.019	0.482	0.006	0.402	0.032
	25.0	40	0.720	0.022	0.775	0.013	0.359	0.003	0.346	0.008
7	1.5	15	0.959	0.008	0.714	0.028	0.531	0.005	0.399	0.010
	1.5	40	0.910	0.013	0.600	0.006	0.416	0.008	0.370	0.001
8	1.5	15	0.884	0.001	0.697	0.018	0.539	0.020	0.563	0.033
	1.5	40	0.867	0.014	0.678	0.012	0.503	0.019	0.369	0.001
AVERAGE	-	15	0.740	0.220	0.590	0.120	0.440	0.080	0.450	0.080
AVERAGE	-	40	0.670	0.230	0.590	0.120	0.380	0.070	0.390	0.060
AVERAGE	-	TOTAL	0.700	0.230	0.590	0.120	0.410	0.080	0.420	0.080

<sup>a</sup>Each site consists of two plots under different land use, i. e. cultivated and natural bush. s.d.=standard deviation

viour of the Umbric Andosols when they are exposed to extreme drying.

Comparing wilting points of laboratory air dried and moist field samples show that the phenomenon of drying in the field never reaches the level of drying in the laboratory (Table 2, Figure 3). Nor can any time dependence be observed between the sites with respectively 1 to 2 years of cultivation, 10 years of cultivation, and 25 years of cultivation. This is a once in a lifetime event. No recovery can be discovered, even after 50 years of pasture. This means that the loss of water retention is irreversible, at least over the time interval investigated.

Although the average wilting point at 15 cm is greater for bush samples than cultivated samples, sites 1, 2 and 3 show only small decreases which are barely significant (Table 2). At this stage of the investigation, no parameters are found that can explain this lack of difference. Because of the broad range of the wilting point of these soils, the explanation could be merely statistical. However, further investigation is being carried out.

#### *Physicochemical mechanisms of the water retention reduction*

The results of the regression analysis between on the one hand pH in water, pH in NaF, organic matter content, dry bulk density, clay and sand content, and on the other hand the water retention and the water retention reduction are presented in Figure 5. A significant correlation with the wilting point was detected for all physicochemical parameters investigated, except pH in water:  $P=0.82$  (Figure 5). The correlation between wilting point and organic matter is much more significant than between wilting point and pH in NaF:  $P=0.0001$  versus  $P=0.037$  (Figure 5). The latter is an indication of the active aluminium in the soil, which is significant for the amount of allophane. It shows that mainly

organic matter content and not allophane content is responsible for water retention. As there is also a significant correlation between organic matter content and water retention reduction ( $P=0.0001$ ), the breakdown of organic matter plays a major role in the water retention reduction process. At first sight, this appears to be in contrast with the investigations of Nanzyo *et al.* (1999) who found that in allophanic Andosols in Japan, mainly allophane was responsible for water retention reduction and not the organic matter. However, Driessen & Dudal (1991) describe the role of active aluminium in the genesis of Andosols. Active aluminium is released by the breakdown and weathering of young volcanic soils. After release there are two possibilities. Either it is built into silicates to form the typical allophane clay, or it can be built into stable aggregates of organic matter. The ratio of the two constituents depends on the amount of silica and organic matter but the main factor is pH. Driessen & Dudal propose a pH limit of 5. Below this limit mainly organic aggregates are formed. At pH higher than 5 mainly allophane is formed. The soils investigated in this study have a pH that is almost constant and slightly lower than 5 (Figure 5). This explains the evolution towards a high content of stable organic aggregates that are responsible for water retention capacity at wilting point, and which are partially broken down by drying (Ampe 1999). The high correlation between the pH in NaF and the organic matter content ( $R^2=0.35$ ,  $P=0.002$ ) also indicates that organic matter is mainly present as alumino-organic compounds. The high resistance of these compounds to bacterial breakdown leads to the high organic matter content observed. However, detailed investigation concerning the free aluminium behaviour is required to be sure.

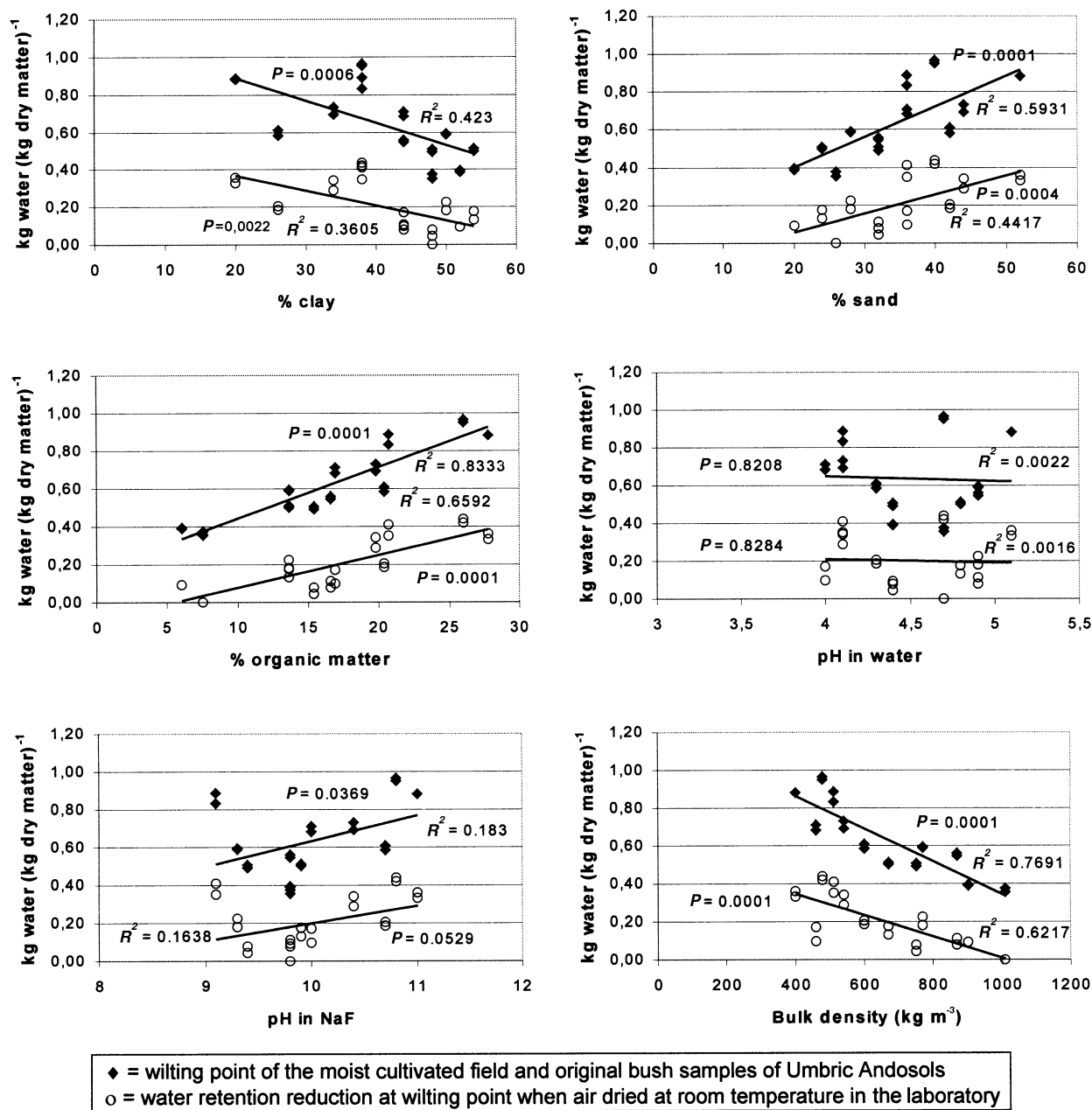


Figure 5. Correlation between the hydrophysical parameters and water retention of Umbric Andosols.

Figure 5 shows a positive correlation between the sand fraction and the wilting point ( $P=0.0001$ ), which is very unusual. Normally a significant negative correlation is measured (Hillel 1971; Brady 1990). Most probably this is a result of the presence of a pseudo structure in the form of aggregates of small soil particles and organic constituents, which are responsible for the high water retention and which are located in the sand fraction during the particle size analysis. When the water retention of these pseudo-sand particles surpasses the clay fraction, this would also explain why there is such a significant negative correlation between the water retention at wilting point and the clay fraction ( $P=0.0006$ , Figure 5).

#### Implications for land use

Although the water retention remains very high, the 20% decrease in water retention due to cultivation can have a large impact on the water management of the region. If the described changes in wilting point do not occur at lower pF, the implications for plant available water and free water in the soil will be rather small. But it is more likely that the wilting point changes are an indication of a change in soil structure that affects the whole pF range, thus leading to a diminishing water buffering capacity. Rainfall is irregular in the region, so water buffering is very important. As the investigated areas function as an important water source for the region, water shortages can occur during dry periods,

Table 3. Water contents of the organic litter layer at different pF-ranges.

Sample	Sample data	Water content at indicated pressure				
	Dry bulk Density (kg m <sup>-3</sup> )	pF = 0 (kg kg <sup>-1</sup> )	pF = 2.3 (kg kg <sup>-1</sup> )	pF = 4.2 (kg kg <sup>-1</sup> )	Free Water (kg kg <sup>-1</sup> )	pF Available water (kg kg <sup>-1</sup> )
1	52	4.3	2.6	1.0	1.7	1.6
2	73	4.1	2.6	1.1	1.4	1.6
3	85	3.3	2.5	1.2	0.9	1.3
4	90	3.5	2.7	1.2	0.8	1.6

Table 4. Total amount of water in the organic litter layer of the investigated Umbric Andosols under different original vegetation together with the average depth of the layer.

Original vegetation	Available water (mm)	Free water (mm)	Average depth (mm)
Páramo	2.2	1.7	20
Chaparro	5.8	4.3	51
Bosque	19.9	15.1	179

while wet periods can be characterized by higher flooding risk and more erosion, as some reported events such as landslides may already suggest. Furthermore, other factors that are affected by changes in land use also have to be taken into account. One of them is the disappearance of the natural vegetation, which also plays an important role because of its water buffering capacity (Table 3). Another aspect is the organic litter layer, which absorbs large amounts of water and can be very deep, as observed during fieldwork (Table 4). A depth of 20 cm was common. Water retention by this organic litter layer can be up to 400% by weight, equal to 15 mm (Table 4). As a result it plays an important role in the hydrological behaviour of the region. The organic litter layer totally disappears when soils are taken into cultivation. This disappearance has to be taken into account when the impact of land use on hydrology is studied at catchment scale.

## CONCLUSIONS

The Umbric Andosols in the Austro Ecuatoriano clearly have an extraordinarily large water retention capacity, making them important in the hydrology of the region. The loss following cultivation of these soils has an obvious impact on its hydrophysical properties. The water retention at wilting point diminishes by an average 16%, after two years of cultivation. This is less than the reduction caused by drying in the laboratory, which reaches an average of 35%. Structural changes affecting water retention stop or stabilize when fields are changed into pasture, however no recovery of the water retention was observed. It seems to be an irreversible event. Also, the water retention loss is much larger at 15 cm depth (21%) than the reduction at 40 cm, beneath the plough layer which is only 10%.

Physicochemical analysis shows that the organic matter is mainly responsible for the high water retention, forming stable aggregates with clay-sized particles. This pseudo-sand was found in the sand fraction during particle analysis, resulting in a positive correlation between the sand fraction

and water retention at wilting point. In view of the low pH of the Umbric Andosols, allophane does not play an important role in the water retention characteristics. As a consequence of the low pH (<5), aluminium released from weathering of volcanic ash is built into stable aluminorganic aggregates, rather than forming allophane.

If the changes in wilting points are an indication for a change in total water buffering capacity, the hydrological behaviour of the area will change and water security during dry periods can be at risk. However, many more aspects affect available water for plants, such as the organic litter layer and water retention of the vegetation. This investigation reveals that disappearance of the organic litter layer can lead to a 16 mm free water reduction. Disappearance of this layer will also result in an important loss of water buffering capacity in the soil. Therefore, implementation of the results in a catchment scale model is required to predict the complex hydrological behaviour of this zone.

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