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Headwaters Deforestation for Cattle Pastures in the Andes of Colombia and Its Implications for Soils Properties and Hydrological Dynamic

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Abstract

Deforestation of headwater in the Andes of Colombia is a historical process that has its origins in pre-Hispanic communities and in nineteenth and twentieth centuries, intensified by settlers and farmers. These lands have been intended mainly to pasture cattle. Soil compaction, caused by the trampling of cattle, was evaluated in soils derived from volcanic ash (Andisols), with reference to values found for variables in undisturbed natural forests in the same region. The compared parameters were bulk density (Db), total porosity (a), soil resistance to penetration (Rp) and pore size distribution, analyzed by water retention curves (WRC). The grazed soils had significant differences with respect to the natural forest reference values: Db was 53.7% higher, a was reduced by 11.0% and Rp in the first 7.5 cm of the top soil was more than double, with an average increase of 275.2 to 527.2 kPa. The analysis indicated that compacted soils had relatively uniform reduction in distribution of macro, meso and micropores. It was concluded that deforestation followed by pasture land destination in steep headwaters generates significant compaction processes that can affect the infiltration, percolation and soil water storage, which would have important hydrological implications: augmentation of surface runoff and soil erosion, decreased the base flow and increased direct runoff. For this reasons, it is considered that forest restoration of headwaters is important for the maintenance of hydrological functions of large river systems.

Keywords

Forest Influences, Deforestation, Soil Compaction, Headwaters

1. Introduction

Soils intensively used in agriculture, livestock and forestry practices tend to be altered

due to the action of loads exerted on the surface, which compress the soil and result in loss of the pore space; this phenomenon is known as "compaction" and, depending on the magnitude, frequency and source of the load, may severely or slightly affect the bulk density, total porosity and pore size distribution. It is an environmental problem of the first order not only due to the extent of compacted soils in the world, some 68 million hectares, but also because identification is often complex because the symptoms are not very visible (Hamza & Anderson, 2005; Herbin et al., 2011). Compaction causes undesirable damage given the impact on several hydrodynamic functions, such as soil water flow and solute transport, water retention, changes in the saturated and unsaturated hydraulic conductivity, reduction in the infiltration capacity and limitations for the development of root systems (Alaoui et al., 2011).

The headwaters in the upper part of the large and medium water systems in the Andes of Colombia, with nearly two million hectares, have been deforested to a large extent, giving way to various forms of agriculture and grazing; another lands have been established with commercial forest plantations after some decades of grazing use (Figure 1). Since the area is sensitive in terms of the hydrological functioning of the large watersheds, which provide the water supply for many populations, industries and hydroelectric projects, changes in land use affect the soils in several ways, particularly through compaction, and therefore affect the hydrological response.

This research was aimed at determining the levels of compaction of volcanic soils (Andisols) caused by the trampling of cattle, which has been used for decades in the headwaters of the Andes in Colombia, with reference values found in equivalent areas with undisturbed natural forest conditions.

Figure 1. Deforested areas in headwaters for cattle pastures in Central Andes of Colombia. Commercial forests of *Pinus* and *Eucalyptus* species are frequently planted in old areas intensively grazing for some decades.

2. Materials and Methods

Two representative areas were selected in the Central Andes of Colombia, in a rural area of the municipality of Santa Rosa de Cabal, Department of Risaralda, intertropical region at 4˚50'N latitude and 75˚34'W longitude; average altitude 1980 m; annual precipitation 2680 mm; and little variation in temperature, with an average of 17.1˚C. The first area is an unaltered mountain native forest (BN), and second area is an extensive cattle pastures (PA) established about eight decades ago on deforested land. These study units were close together (3.5 km), on the same slope, between 50% and 75%, at the same altitude (aprox. 2000 m) and recent volcanic soils (Andisols), deep (+) 120 cm, slightly acidic (pH < 6.5), with 20% - 30% organic matter contents.

In the two headwaters the following indicator variables for the degree of compaction were used: bulk density (Db), total porosity (a), pore size distribution, by interpreting water retention curves (WRC), and soil resistance to penetration (Rp). For the determination of Db, a and Rp, 32 randomly selected sampling sites were selected in the top 10 cm of mineral soil, excluding the layer of litter. Soil samples were taken with a 99.1 cm³ metal cylinder (Vs).The labeled samples were weighed on an analytical balance to obtain the wet weight (Ps). In the laboratory, the samples were dried in an oven at 104˚C and were weighed daily until obtaining a constant weight (dry weight, Vs).

The Db was determined with the following equation:

$$Da = \frac{Ps}{Vs} \tag{1}$$

In order to calculate the total porosity (a), the density value of the particles $Dp = 2.42$ g/cm³ was used, found by Hincapié (2011) for Andisols in the same region:

$$\alpha = \left(1 - \frac{Da}{Dp}\right) * 100 = \left(1 - \frac{Da}{2.42}\right) * 100 \tag{2}$$

The WRC were prepared using the determinations in the laboratory for the content of gravimetric moisture (u in g/g) at pressures of 0.0/0.1/0.3/3.0/5.0/15.0 bar, using the pressure-plate apparatus. The results of the determinations were transformed to the volumetric moisture content (θ) using the bulk density (Db) found for the undisturbed samples taken at the same sites. The general model of the water retention in the soil is expressed as (Seki, 2007):

$$\theta(h) = \left[\theta_r + (\theta_s - \theta_r)\right] * S_e \tag{3}$$

where:

$\theta(h)$: Volumetric moisture content as a function of pressure (h).

θ_r: Residual moisture content.

θ_s: Saturation moisture content.

S_e: Effective saturation (normalized, $S_e = \theta/\theta_s$).

The pedotransfer model proposed by van Genuchten (1980) was used to determine the Se parameters:

$$S_e = \left[\frac{1}{1 + (\alpha h)^n}\right]^m \tag{4}$$

where the α and n are van Genuchten parameters and $m = 1 - (1/n)$.

Because estimating the model parameters, as well as θ_r and θ_s, is inherently nonlinear, the computer program RETC ver. 6.02/2009 was used, based on numerical methods of nonlinear parameter estimation (Van Genuchten et al., 1991). The pore size distribution from the WRC was obtained from the theory of capillary (Leij et al., 2002), which states that radius r of the pores depends on the surface tension of the water, T, and the repose angle of the water contact in the meniscus formed in the pore, φ:

$$r = 2T \cos \varphi / h \tag{5}$$

For the Rp determinations, a digital penetrograph Fiel Scout SC-900®, with a 45 cm stem extension and 1/2 inch diameter cone and 45° angle was used. This device registers to logger data readings every 2.5 cm in kPa; the penetration depth is controlled by an ultrasonic transmitter-receiver. Since Rp is a function of the soil water content, being higher with low moisture contents (high matrix potential) and low with moisture contents that are close to saturation (Wolkowski & Lowery, 2008; Vaz et al., 2013), readings were made in the range of soil moisture more widespread in the study area, which, given the high capacity of water retention in Andisols and the high rainfall and uniform intra-annual distribution, were between 40% and 60% (0.4 to 0.6 cm³/cm³). θ was controlled in the field by direct readings with the TDR device (Time Domain Reflectometer), Hobo Onset 10 HS®; the values were subsequently verified in the laboratory.

The data obtained for each basin were examined for normal distribution using the Shapiro-Wilk test, and the Grubbs test or "studentized extremes test" was used to determine the existence of outliers. Later, the data were subjected to analysis of variance (ANOVA, Statgraphics Centurion XV.I).

3. Results and Discussion

3.1. Bulk Density (*Db*) and Total Porosity (*α*)

Table 1 shows the principal statistics found for the sample series of *Db* and *α* in each headwater. The analysis of variance for the mean *Db* presented significant differences

Table 1. Statistics for the bulk density (*Db*) and total porosity (*α*) (n = 32).

Statistics	Natural Forest(BN)	Pasture(PA)	Sig.
Bulk Density (*Da*)			
Mean (g/cm³)	0.41	0.63	**
Range (g/cm³)	0.13 - 0.72	0.44 - 0.84	
Standard Dev. (g/cm³)	0.14	0.10	
CV (%)	34.11	16.54	
Total Porosity (*α*)			
Mean (%)	83.1	74.0	**
Range (%)	70.4 - 94.6	65. 2 - 81.8	
Standard Dev. (%)	5.8	4.3	
CV (%)	6.9	5.8	

Note: **$P < 0.01$.

between the groups ($P < 0.001$). The BN had a lower mean Db value than the PA soil; this indicates that there was an increase in the soil mass per volume unit and thus a decrease in the pore space where there were compacting loads due to trampling by cattle. The increase in the Db of the grazed soils was 53.7%, as compared to the reference value found for the BN. As such, in the pastures, the total porosity decreased 11.0%.

While a significant increase in the Db was seen in the grazed soils, the mean and range remained in the field of universally reported values for Andisols, less than 0.9 g/cm³, which also occurred for the total porosity (α), which was high to very high for both conditions (Shoji et al., 1993; Nanzyo, 2002; Tobón et al., 2010; Hincapié, 2011).

The CV for the Db in BN was high due to widely changing conditions in the forest ecosystem that were related to the microtopography, accumulation of litter and differential erosion of the ground. Since it was relatively low in PA, it is interpreted as a generalized condition of compaction in all of the pastures because the compacting loads generated by cattle were distributed throughout the area.

Reports from other studies have led to the broad conclusion that almost any agricultural activity involving permanent or temporary land use, change in land use, or incorporation of technological treatments for the establishment, management and harvest of crops, tend to generate compacting loads that increase the bulk density and decrease the pore space. In the Colombian Amazon piedmont and using clay soils and different physiographic positions, Pinzón & Amézquita (1991) found a significant increase in Db because of grazing cattle. In the Amazonian foothills of Caquetá, Colombia, with high rainfall and soils with varying degrees of degradation due to grazing cattle, Jiménez et al. (2012) found significant differences in the Db when increasing the degree of degradation of the pastures. Gómez (2011) in Andisols on the Sabana de Bogotá plains, showed that tasks performed with tractors were a significant cause for an increase in the Db. Similar conclusions were reached by Vzzotto et al. (2000) in clay soils in southern Brazil, where the trampling of cattle caused a significant increase in the bulk density in the first 5 cm of the soils, which remained for at least six months. On the flooded pampas of Argentina, Taboada & Lavado (1988) found slight increases in the Db caused by grazing. In the tropical lowlands of Perú, Alegre & Lara (1991) found a significant increase of between 0.21 and 0.35 g/cm³ in overgrazed areas, as compared to soils in a natural forest. In the Lar River valley, Iran, with a semiarid temperate climate, a concentrated rainy season, and sandy soils and limestone, Chaichi et al. (2005) found significant increases in Db during the rainy season when sheep grazing was intensified.

Since the compaction of soils and consequent loss of pore space is closely related to water dynamics in soil (infiltration, storage and percolation processes), it is possible to say that under the studied pasture conditions (PA), there were greater limitations for the recovery and flow of water with respect to the original conditions of the soils before they were altered (BN). As a whole, the headwaters linked to the medium and large watersheds will have lower water soil recharge, rapid generation of surface and subsurface runoff, and lower or slower generation of base flows. The impulse-response function derived from the rainfall-runoff process, is therefore an acceleration factor that may

become important in hydrographic systems given the significant extension of the areas with those conditions in the Central Andes of Colombia: high rate of deforestation for the development of extensive cattle pastures.

3.2. Pore Size Distribution

Table 2 contains the values of the saturation moisture content (θs) and residual moisture content (θr) estimated with the van Genuchten function to obtain the WRC; Figure 2 has the respective curves. Although no statistical differences were found for the
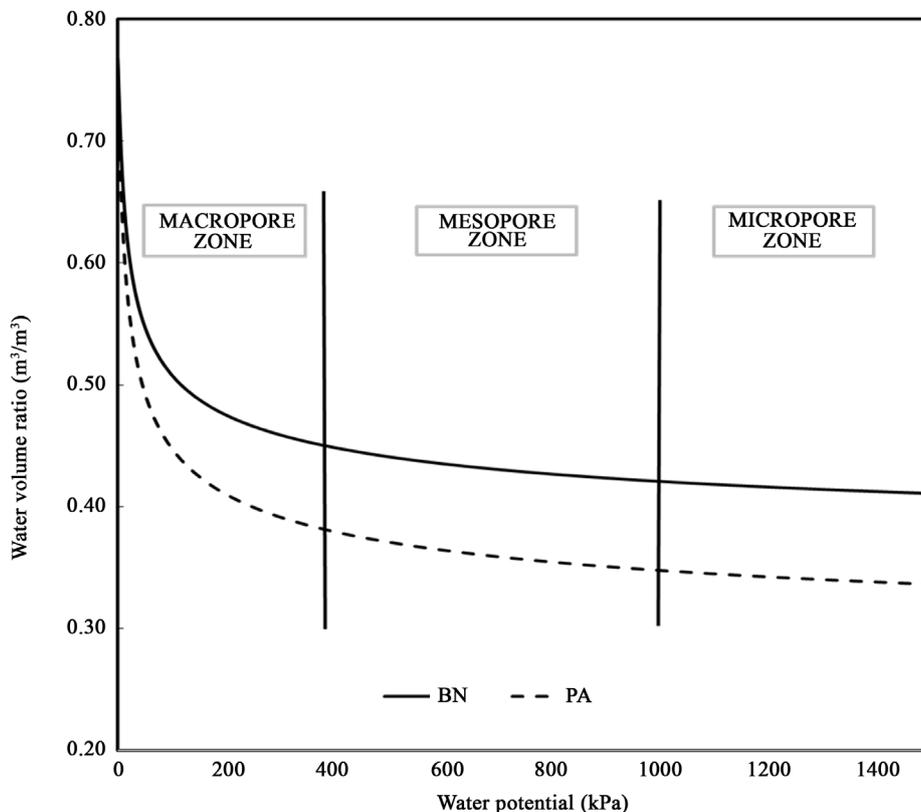

Figure 2. Water retention curves (WRC) for soils in Natural Forest (BN) and Pastures (PA) indicating the zones of porosity defined in Table 2.

Table 2. Estimated parameters for the van Genuchtenpedo transfer function and distribution percentage by pore size in the Natural Forest (BN) and Pastures (PA).

Parameter	BN	PA
Saturation moisture (θ_s) (m³/m³)	0.768	0.747
Residual moisture (θ_r) (m³/m³)	0.336	0.251
Coefficient of determination (R^2)	0.98	0.99
Porosity and Distribution Percentage	**BN**	**PA**
Macropores (diameter > 75 μm and pressure < 390 kPa)	45.9	48.6
Mesopores (diameter 30 - 75 μm and pressure 390 - 1000 kPa)	3.6	4.1
Micropores (diameter < 30 μm and pressure > 1000 kPa)	50.5	47.3

WRC, the BN had higher water contents for all of the examined pressures than the PA. This result is concurrent with the findings for the bulk density and total porosity: soils of BN, in its natural state, are undisturbed, with little erosion and high contents of organic matter, which is why, it is composed of high proportions of macro, meso and micropores; instead, in PA the soil that had less total porosity, as was determined in the previous section, and, as discussed in this research, was attributed to the effect of compaction caused by cattle.

When considering the water available to plants (WAP), defined as the water content between the field capacity (FC) at a pressure of 33 kPa and the wilting point (WP) at 1500 kPa (Reichardt & Timm, 2004), it is verified that, in both WRC, this value was approximately 0.20 m³/m³, but the minimum and maximum thresholds were higher in the BN than in the PA. However, Tobón et al. (2010) argued that the limit value of FC = 33 kPa may not be appropriate for Andisols given the high water storage capacity due to the amorphous all ophanic clays, making a limit of FC at 10 kPa more suitable; when calculating with this value, an WAP of about 0.30 m³/m³ for the three conditions was obtained.

Hincapié (2011) indicated that the mineralogical composition of Andisols, essentially allophane, imogolite and aloisita, defines both a high capacity for water retention, micro and mesoporosity, and a high residual moisture content θr at pressures (negatively) over 1500 kPa. The estimations of θr in the van Genuchten model (Table 2) yielded values exceeding 0.35 m³/m³ for BN and higher than 0.25 for PA. In similar soils of the Central Andes, this author found residual moisture for the first horizon in agriculture soils higher than 0.25 m³/m³, and saturations higher than 0.60 m³/m³, which corresponds with the findings of this investigation.

According to Soil Survey Staff pore size classification (SSS, 2008) and the theory of capillarity and its relationship with the pressure of water in soils (Leij et al., 2002), the zones of porosity were defined as shown in Figure 2 and listed in Table 2. For all of the pressures and for the three regions of defined porosity, there was a uniform difference in the moisture retention, about 0.8 m³/m³ between BN and PA. This indicates that the effect of porosity loss caused by compaction was verified, which was approximately proportionally in all of the pore sizes. However, a slight increase in the percentage of macropores was seen in PA, along with a slight decrease of micropores in BN; this could be an indication that compaction by trampling occurs at high moisture contents, as seen in the study region, characterized by a high and evenly distributed rainfall, which affects the micropores more intensely. Other researchers (Hamza & Anderson, 2005; Tobón et al., 2010; Alaoui et al., 2011; Dorner et al., 2012) have reported on the fundamental effect of macropores.

3.3. Soil Resistance to Penetration (*Rp*)

Table 3 shows the statistics for the determination of *Rp*, carried out at six depths and for the average of the soils in BN and PA. The mean values are shown in Figure 3. The lower resistance to penetration found in BN (reference value) was consistent with the
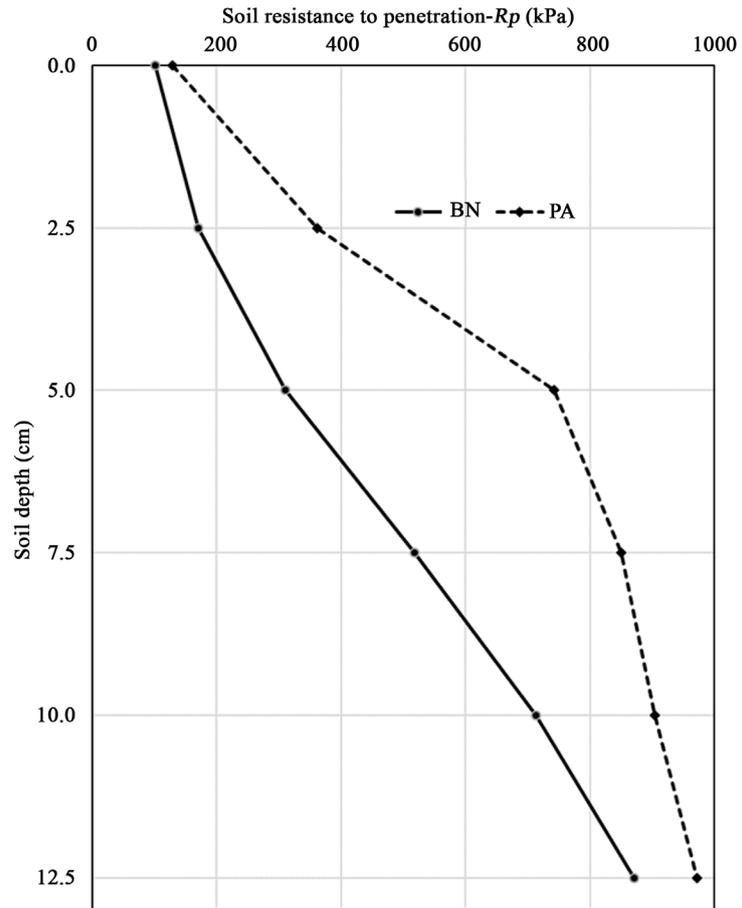
Figure 3. The Rp at six depths in the soils of BN and PA.

Table 3. Statistics for the determination of Rp at six depths in soils of BN and PA.

Depth (cm)	Natural Forest (BN)			Pasture (PA)			Sig.
	X_{Rp} (kPa)	S_{Rp} (kPa)	CV_{Rp} (%)	X_{Rp} (kPa)	S_{Rp} (kPa)	CV_{Rp} (%)	
0.0	101.9	88.9	87.2	128.3	110.2	85.9	n.s.
2.5	170.4	173.3	101.7	361.1	175.8	48.7	*
5.0	310.3	219.3	70.7	742.1	228.4	30.8	*
7.5	518.1	279.9	54.0	851.2	234.6	27.6	*
10.0	713.2	243.3	34.1	904.0	249.7	27.6	*
12.5	870.9	259.6	29.8	971.9	262.0	27.0	n.s.
Mean	447.5			659.8			*

Note: $^*P < 0.05$; n.s.: not significant.

values of Db and a found in soils for this land use, while the areas affected by trampling by cattle for several decades had significantly higher levels of resistance. For depths of 2.5 to 10.0 cm, there were significant differences ($P < 0.05$). Starting at the 10.0 cm depth, the Rp of PA tended to resemble that of BN, which is an indication that the

compaction effect lies in the first centimeters of the soil, where the compacting loads are seen. The *Rp* values obtained in areas subjected to trampling by cattle in this research were much lower than those reported in the first 10 cm in Andisols of Chile (Dorner et al., 2012), with the same conditions. Furthermore, these results are comparable to those reported by Taboada & Lavado (1988) for Andisols in Argentina for both trampled conditions and the control.

4. Conclusion

In soils of the headwaters in the Central Andes of Colombia, where natural forests are converted into cattle pastures, there were significant levels of compaction. The variation in the soil physical parameters used as indicators of the degree of compaction in pastures with respect to the reference values in natural forest were: 53.7% reduction in bulk density, 11.0% decrease in total porosity, approximate 0.8 m^3/m^3 decrease in moisture retention, and increased resistance to penetration the first 7.5 cm of the top soil from 275.2 to 527.2 kPa.

The decrease in porosity was widespread in all of the pore sizes, so that the proportion of macro, meso and micropores remained virtually unchanged in the compacted soils, as compared to those of the soils in the undisturbed natural forests.

Because of the high rainfall and uniform distribution throughout the year and the well-known high capacity for water retention in Andisols, the moisture content of these soils was usually high, close to the field capacity, favoring susceptibility to compaction, as caused by the frequent trampling of cattle in this case.

While there were significant levels of compaction in the soils subjected to trampling by cattle when compared to the reference values of the soils in the natural forest, the bulk density, porosity and penetration resistance remained within the normal ranges that are widely reported for Andisols.

From the above, it follows that the headwaters where land uses that implies compaction predominate, will suffer an accelerated causation for the generation of surface and subsurface runoff, limitations for water infiltration, less water recharge in the soils and low base flows, all of which will be reflected in a hydrological response of the greater watersheds.

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