SOIL PROPERTIES AND LAND USE AFFECTING SOIL WATER DYNAMICS IN ANDISOLS AND INCEPTISOLS AT TWO MID-ELEVATION SITES IN THE COLOMBIAN ANDES

by

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ABSTRACT

Soil has a crucial role in the terrestrial component of the hydrologic cycle, regulating the availability of water for ecosystem services. Yet relationships between soil properties and land use for the major soil types in the Colombian Andes have not been extensively studied. This study evaluated soil water (SW) dynamics of two soils types, belonging to the most common soil orders in the Colombian Andes, Andisols and Inceptisols. The research was conducted in two watersheds at mid-elevation, and focused on the relationships between mineralogical, physical and chemical soil properties with soil water dynamics, including soil water retention (SWR) and field saturated hydraulic conductivity (Kfs).

The Andisols and Inceptisols of this study have a large total porosity compared to typical clay soils, but Andisols, showed higher SWR at every soil tension relative to Inceptisols. Notwithstanding the high hygroscopic water (θ_{PWP}), both soils have a wide pore size distribution, with similar gravitational water and plant available water storage capacities. Despite differences in climate and soil parent material between watersheds, the presence of colloids with high specific surface area in both soils (allophane, imogolite, ferrihydrite and organo-metallic complexes in Andisols and ferrihydrite and Al/Fe oxides in Inceptisols) contribute to high SWR. Within each site, differences in SWR between land uses appear minimal, although soil organic carbon was lower under pasture in both soils. The limited differences in SWR between natural forest and pasture appear to reflect the effects of short-range order (SRO) minerals and organo-metallic compounds on SWR, which offset differences in SOC between natural forest and pasture.

Quasi steady-state infiltration rates measured in the field did not correspond to expected values based on texture alone, highlighting the importance of field based measurements, particularly in soils with SRO minerals. Additionally, there was a pronounced seasonal difference in Kfs under pasture in both soil types, and a negative correlation of soil water content with Kfs in Inceptisols.

Determination of physical, chemical and mineralogical properties was found to be crucial in understanding soil water dynamics in this study, and future work should include an assessment of SRO minerals in addition to SWR characteristics.

LAY SUMMARY

Andisols and Inceptisols are the most predominant soils in the Colombian Andes, and these soils provide important ecosystem services related to food production and water supply. Despite their importance, little is known about the relationships between soil properties and water dynamics in this region. This study contributes to our understanding of the relationships between soil properties and water in two watersheds at mid-elevations in the Colombian Andes. It was found that in spite of differences in climate and geology, both soils have nano-size materials. These materials retain water inside their structure, and contribute to a wide range in soil pore sizes which store and release water. Differences in water retention between natural forest and pasture appear minimal, although forests had the highest soil carbon content. Infiltration under pasture was low, especially in Andisols, highlighting the importance of appropriate land management to minimize runoff.

PREFACE

I was responsible for the development of the research questions and experimental design in consultation with my supervisory committee. Field sampling was conducted in collaboration with Dr. Sandra Brown. I performed the majority of the sample analyses, with the exceptions of particle size analyses and soil water retention which were run by Edinson Suarez and Miguel Angel Caicedo at the International Center for Tropical Agriculture (CIAT) in Palmira, Colombia. Additionally, Maureen Soon ran the inductively coupled plasma atomic emission spectrometer (ICP-AES) at Earth and Ocean Sciences, UBC, which was used in the determination of short range order minerals. I performed all data analysis.

This dissertation is original, unpublished, independent work by the author, C.E. Roa-García.

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Al_o, Fe_o, Si_o: oxalate-extractable aluminum (Al), iron (Fe) and silicon (Si)

Al_p, Fe_p, Si_p: pyrophosphate-extractable aluminum (Al), iron (Fe) and silicon (Si)

Al_{sro}, Fe_{sro}, Si_{sro}: aluminum (Al), iron (Fe) and silicon (Si) associated with short-range order inorganic material

CVC: Corporación Autónoma del Valle del Cauca, local environmental authority from the Valle del Cauca department (province)

ET_c: crop evapotranspiration

ET_o: potential evapotranspiration

f: total porosity

FC: field capacity

GW: gravitational water or hydrological buffering capacity

Kfs: field saturated hydraulic conductivity or field based quasi steady-state infiltration rate

K_{sat}: saturated hydraulic conductivity or steady-state infiltration rate

OF: overland flow

PAWS: plant available water storage

PWP: permanent wilting point

RI: rainfall intensity

Sat: saturation

SOC: soil organic carbon

SRO: short-range order

SWR: soil water retention

TP: total precipitation

θ_{FC}: soil water content at field capacity

θ_{grav}: gravimetric soil water content

θ_{vol}: volumetric soil water content

θ_{PWP}: soil water content at permanent wilting point

θ_{Sat}: maximum retention capacity or soil water content at saturation

ρ_b and ρ_s: soil bulk density and soil particle density

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DEDICATION

To Alex

1. GENERAL INTRODUCTION

1.1 Background

Soil has a crucial role in the terrestrial component of the hydrologic cycle, vital to dry season water supplies, food production, and the resilience of ecosystems.Communities living in the Andean region, are largely dependent on the capacity of soils to regulate water availability (Roa et al., 2011). The Andean region lacks storage infrastructure and relies mainly on soils, glaciers and vegetation to regulate the flows of water, storing it during the wet seasons and releasing it during the dry seasons. Land use and climate change are altering the functions of these storage components of the water cycle, increasing the vulnerability of communities to water and food insecurity. Thus, understanding the ability of soils to hold and release water is critical to rural livelihoods and reducing the vulnerability of these communities to variable climate.

From 1939 to 2006, mean annual air temperatures in the Andes have increased 0.7°C (Vuille et al., 2008); with higher elevations (>2,000 m) anticipated to experience a further increase of 3°C by 2090 (Bradley et al., 2006; Urrutia and Vuille, 2009; Vuille et al., 2015). Precipitation is expected to increase in the wet season and decrease in the dry season (Vuille et al., 2008), with fluctuations from 10 to 40% (IDEAM, 2015). In addition, climatic variability related with the El Niño/Southern Oscillation (ENSO) phenomenon further increases the vulnerability of Andean communities to water scarcity and extreme events (IPCC, 2007; IDEAM, 2010).

The Andes, with its moderate and diverse climate, is the most density populated region of Colombia. The Andean area (287,720 km^2; 500 m and above) represents 25% of the total country (Armenteras and Rodríguez, 2007) but is home to 77% of the urban population and 71% of the rural population (DANE, 2005). Despite being home to the majority of the population of Colombia, the Andean region contributes only 13% of the national water supply (IDEAM, 2010) and "*over 80% of the municipalities are supplied by small sources (streams, creeks, brooks) with low regulation capacity and high vulnerability*" (IDEAM, 2000, p. 38). Some rivers from the Andes have shown stream flow decreases of 40% in the El Niño phase compared to the long-term average (IDEAM, 2010).

Poverty is concentrated in the rural area, where 65% of people are considered to be poor (DNP, 2010) and the majority of the population are reliant on small scale food production for home consumption. It is recognized that the poorest and most vulnerable groups will disproportionately experience the negative effects of climate change.

Land use in the Andes has changed drastically since the introduction of cattle by the Spaniards in the 16th century. Natural land cover such as wetlands, páramo[1] and forest have been converted to pasture for cattle grazing and to agricultural crops, and by the year 2000 less than 40% of the natural vegetation in the Andes still remained (Rodríguez et al., 2006). In 1984, three national institutes determined that the appropriate land cover for 68% of the Colombian Andes is forest; however, just 26% of this area was still covered by forest vegetation (INDERENA et al., 1984) and deforestation continued in the Andes from 1985 to 2005 as montane forest decreased a further 13% (Armenteras et al., 2011).

Due to the dependence of Andean population on ecosystems to provide water for crops and drinking water, it is important to gain a better understanding of the factors (including soil) influencing the regulation and storage of water within ecosystems. This thesis documents the soil properties in two watersheds located on Andisols and Inceptisols, the most common soil orders in the Colombian Andes, and the effects of natural forest and pastures on soil water dynamics.

Andisol is a soil order in the US Department of Agriculture soil taxonomy (Soil Survey Staff, 2014) that refers to soils of dominantly volcanic origin. Their main features are a high proportion of short-range order (SRO) minerals and the presence of a dark surface horizon rich in organic matter. They are very common in the Andean páramos and are characterized by large water holding capacity (Buytaert et al., 2006). On the other hand, Inceptisols lack a well-developed soil profile and are characterized by indistinct horizons.

[1] Ecosystems in the regions above the continuous forest line, yet below the permanent snowline, characterized by vegetation composed largely of tussock grasses, cushion plants and frailejónes (*Espeletia*).

They include soils developed on recent alluvium and lacustrine materials that are quite high in clay. A detailed description of these two soil orders are provided in Appendix A.

In regions of the Colombian Andes with humid climate, the most abundant great groups are Hapludands (within the Udands suborder) and Dystrudepts (within the Udepts suborder), respectively. Hapludands are characterized by the dark color of the surface horizon and their high porosity, while Dystrudepts are characterized by removal of soluble compounds, the addition of organic carbon favored by humid climate, and by its vulnerability to soil erosion (Malagón, 2003). Since these two soil great groups occupy 66% of the Colombian Andes (Malagón, 2003) they were selected as the focus of this study. Within this document, the terms “Andisol” and “Inceptisol” will be used as short forms to distinguish between the soils at the two study sites, and “soil orders” used as a descripter when referring to both soils.

Most studies carried out in the Andes have focused on the effects of different land management practices on crop yields, soil erosion or soil nutrient dynamics; however, only a limited number of studies have evaluated the effects of land uses on the soil water characteristics of the two soil orders in relation to water security. The major land uses in Colombia are natural forest and pasture, covering 53.2% and 30.6% of the country, respectively; while crops cover an area of 4.7% (IGAC, 2012). Most studies on soil water characteristics carried out in the Andes were located in páramo ecosystems at elevations >3,500 m, and have shown that the conversion from natural vegetation (natural forest or páramos) to crops and pasture reduce the proportion of macro and mesopore volume (Diaz and Paz, 2002; Daza et al., 2014; Buytaert et al., 2002; Buytaert et al., 2005b; Podwojewski et al., 2002). However, results from high elevation (> 3,000 m) studies may not be directly applicable to mid-elevation conditions, due to colder and wetter conditions and generally higher soil organic carbon (SOC). In addition, most of these studies do not include an evaluation of soil mineralogical, chemical and physical properties, and their relationships to soil water retention (SWR) and field saturated hydraulic conductivity (Kfs). Overall, Kfs has been poorly studied in tropical ecosystems, despite being related to events such as erosion, floods, landslides and water scarcity (Bonell, 1993; Ilstedt et al., 2007).

The goal of the study was to assess soil properties as they affect soil water dynamics in a watershed context at mid-elevation (1,700-2,300 m) under the two most common soil orders in the Colombian Andes: Andisols located in the Central mountain range and Inceptisols located in the Western mountain range. The assessed soil subgroups of these soil orders were Acrudoxic Hapludands (Andisols) and Typic Dystrudepts (Inceptisols). The specific objectives of the research were to:

- Determine the mineralogy of the soils and relate these properties to water retention characteristics
- Determine soil water retention (SWR) characteristics of A and B horizons
- Compare the effects of natural forest and pasture land uses on SWR characteristics, and
- Determine field saturated hydraulic conductivity (Kfs) during dry and wet seasons.

The contribution of a reconnaissance study of this type, in which two soils from the same region (i.e., mid-elevation region of Colombian Andes) are compared, highlights the influence of climate and geology, on soil properties and soil water dynamics. Understanding the soil processes, and the differences in water availability in two soils (Andisols and Inceptisols), is important for adaptation strategies needed to reduce vulnerability to water scarcity in the Andean region.

1.2 Thesis organization

The thesis is organized in the following seven chapters:

1) General introduction
2) Description of the study area and experimental design
3) Mineralogy of Andisols and Inceptisols at two mid-elevation sites in the Colombian Andes
4) Soil water retention characteristics of Andisols and Inceptisols at two mid-elevation sites in the Colombian Andes
5) Land use impacts on soil water retention characteristics of Andisols and Inceptisols at two mid-elevation sites in the Colombian Andes

6) Field saturated hydraulic conductivity during dry and wet seasons under pasture of Andisols and Inceptisols at two mid-elevation sites in the Colombian Andes
7) General conclusions

Description of the two study watersheds, representative of the two most common soils in the Andean region of Colombia (Andisols and Inceptisols) including climate, ecology, land use, geology and soil characteristics are presented in **Chapter 2**. This chapter also contains a description of the experimental design and the soil sampling design.

Soil water retention depends on soil chemical and physical properties such as SOC, texture and bulk density (ρ_b) (Rawls et al., 2003) as well as soil mineralogy. **Chapter 3** focuses on the mineralogy of Andisols and Inceptisols. Crystalline minerals and concentrations of SRO minerals are compared between Andisols and Inceptisols, and correlations are assessed between mineralogical characteristics and physical and chemical soil properties. Crystalline minerals are estimated by X-ray diffraction, and the concentrations of SRO minerals are quantified using dissolution methods.

Andisols and Inceptisols are common in the Andean mountain region where the majority of the population is located; consequently, they are of particular importance for the regulation of water for local food production and domestic water supply. Some research has been conducted on the SWR characteristics of Andisols; however, they are limited to the páramo and coffee regions. On soils developed on volcanic ash, SRO minerals enhance SWR (Nanzyo et al., 1993), but clay-dominated soils such as the Inceptisols of this study, may have variable SWR characteristics depending on their mineralogy (Hodnett and Tomasella, 2002). In **Chapter 4,** SWR characteristics are compared between Andisols and Inceptisols from mid-elevation sites of the Colombian Andes, SWR characteristics are correlated with soil properties, and similarities and differences are discussed.

With the introduction of cattle, land use in the Andes changed dramatically. Natural forests on sloping terrain were transformed into extensive grazing lands with negative effects such as landscape homogenization and erosion (Etter and Van Wyngaarden, 2000). Although some studies (Diaz and Paz, 2002; Daza et al., 2014; Buytaert et al., 2002; Buytaert et al., 2005b; Podwojewski et al., 2002) have assessed the change in SWR with the conversion of natural land cover to other land uses on páramo ecosystems (located at elevations >3,500 m) the findings of those studies are not directly applicable to lower elevation sites in the Andes. To better understand the impacts of land use type (natural forest and pasture) on SWR of Andisols and Inceptisols at mid-elevation sites in the Colombian Andes, SWR characteristics were compared between pasture and natural forest in both soils. Results were correlated with soil properties, and are presented in **Chapter 5**.

Although water infiltration may be directly related to events such as erosion, floods, landslides and water scarcity, Kfs in tropical ecosystems is poorly understood (Bonell, 1993; Ilstedt et al., 2007). The Colombian National Institute of Meteorology and Environmental Studies (IDEAM, 2000) estimated that by 2025, 55% of total population in Colombia could be affected by water scarcity, 70% of which live in the Andean region. In addition, within Colombia, landslides and floods rank first and third, respectively among catastrophic events leading to deaths (World Bank, 2012). These events may be related with low infiltration rates, potentially associated with the conversion of natural forest to pasture or crops (Bruijnzeel, 1989, 2004; Chaves et al., 2008). However, limited studies have been carried out in the Andes to evaluate quasi steady-state infiltration rates in the field (Kfs) on different soil types. In this study, double ring infiltrometers were used to measure Kfs in the wet or rainy season and the dry season. Differences between soils and seasons were assessed. Results are presented in **Chapter 6**.

Overview, summary, significance, implications for land use management, and suggestions for future research are given in **Chapter 7**.

2. DESCRIPTION OF THE STUDY AREA AND EXPERIMENTAL DESIGN

2.1 Study area

This study was conducted in two watersheds in the Colombian Andes, the Sonora watershed dominated by Andisols (great group Hapludands) located in the Central branch, and the El Chocho watershed dominated by Inceptisols (great group Dystrudepts) located in the Western branch (Fig. 2.1). These two watersheds, located 230 kilometers apart, were selected as they are representative of the most common soil types (Andisols and Inceptisols) and land uses (natural forest and pasture) in the Colombian Andes, and are headwater ecosystems on which rural populations depend for their water supply. Both watersheds are located at similar elevation (>1,700 m), and are of similar size.

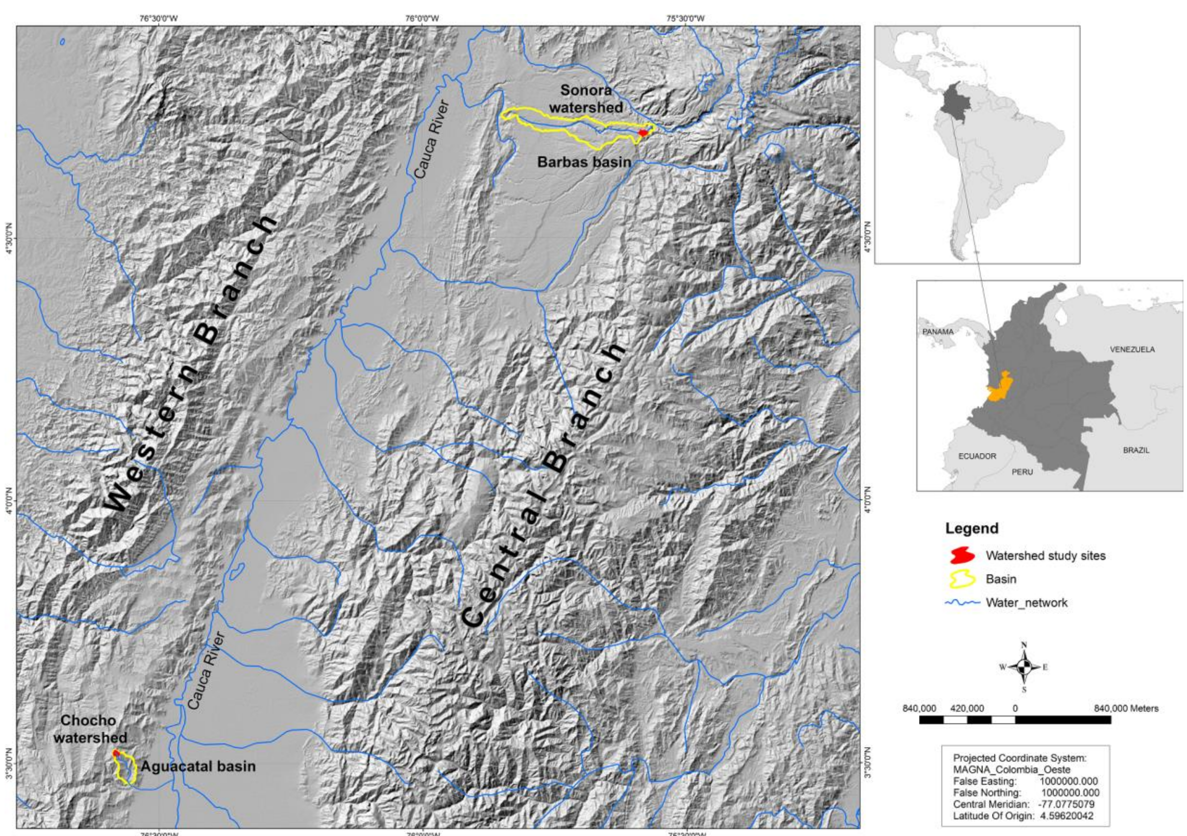


Figure 2.1 Location of Sonora (Andisol site) and El Chocho (Inceptisol site) watersheds

The main characteristics of the two watersheds in terms of their location, geology, climate, and soil type are summarized in Table 2.1.

Table 2.1 Main characteristics of the two study watersheds

	Sonora watershed	**El Chocho watershed**
Mountain range or branch of the Colombian Andes	Central branch	Western branch
Department (provinces)	Risaralda	Valle del Cauca
Drainage basin	Barbas	Aguacatal
Latitude, Longitude	4.41°N, 35.74°W	3.30°N, 76.34°W
Elevation range (m)	2,088-2,331	1,768-2,111
Area (ha)	204	149
Mean annual air temperature (°C)	16.6	16.7
Average annual rainfall (mm)	2,955	1,393
Geology	Fluvio-volcanic sediments above a volcanic and methamorphic basement[1]	Volcanic formation, diabase, basalts and lateritic rocks of volcanic formation[2]
Soil order	Andisol	Inceptisol
Soil suborder	Udands	Udepts
Soil great group	Hapludands	Dystrudepts
Soil subgroup	Acrudoxic Hapludands	Typic Dystrudepts

[1] Guarín, et al. (2004); [2] SGC (1984b)

2.1.1 Geology

The Central Branch is the oldest of the three mountain ranges that form the Colombian Andes. It is dominated by poly-metamorphic and igneous rocks represented by plutons, batholiths and large volumes of volcanic rocks of different ages (Malagón, 2003). The Sonora watershed is located on the Quindío-Risaralda fan, a mass flow of fluvio-volcanic sediments deposited during the last million years above a Cretaceous volcanic and metamorphic basement (Guarín et al., 2004). The geology is classified as volcanic lahar

(Qfs)[2] (SGC, 1984a). The thickness of the lahar deposits varies from more than 200 m in the proximal regions of the volcanoes to less than 20 m in distal regions, and is overlain by a volcanic ash layer that varies from 5 to 20 m thick (Guarín et al., 2004) (Fig. 2.2a). The ice-capped active volcanoes, which are under permanent monitoring in the region, are Huila, Del Ruiz, Tolima, and Santa Isabel (Duque-Escobar, 2007).

The Western branch of the Colombian Andes was formed by igneous, plutonic, and volcanic rocks, partially covered by clastic sedimentary rocks of limestone, which in turn are covered by thick and extensive Quaternary deposits of volcanic, fluvial-volcanic, fluvial and colluvial origin (Malagón, 2003). The El Chocho watershed is part of the Farallones system formed by a cluster of mountains in which stream flows are controlled by multi-directional rock fractures (PNNC, 2005). The geology in the region of the El Chocho watershed consists of: (1) quartz conglomerate, siltstones, dirty sandstones, shales and coal (Tog), (2) volcanic formations, diabase, basalts (Kv), and (3) lateritic rocks of volcanic formation (Ql/Kv) (SGC, 1984b). The dominant rock type in the watershed is basalt, with a composition of approximately equal parts of pyroxenes and plagioclase with traces of olivine and magnetite (Nivia, 2014) (Fig. 2.2b).

[2] Landslide of wet volcanic debris on the side of a volcano

a)

b)

Figure 2.2 Road cuts showing exposed parent materials of a) the Sonora watershed (Andisol site) and b) the El Chocho watershed (Inceptisol site)

2.1.2 Climate

Average monthly precipitation and temperature data for the study sites are given in Figure 2.3. Both sites experience a bimodal annual precipitation cycle, with two wet seasons (April-May and October-November) and two dry seasons (December-February and June-August). The annual precipitation in the region of the Sonora watershed (Andisols) averages 2,955 mm (CRQ, 2015), which is more than double the 1,393 mm average annual precipitation in the region of the El Chocho watershed (CVC, 2014). Given their similar elevation, the two regions have similar average annual air temperatures (around 16.6°C) (CRQ, 2015; CVC, 2014).

a) Andisol site (Sonora watershed) b) Inceptisol site (El Chocho watershed)

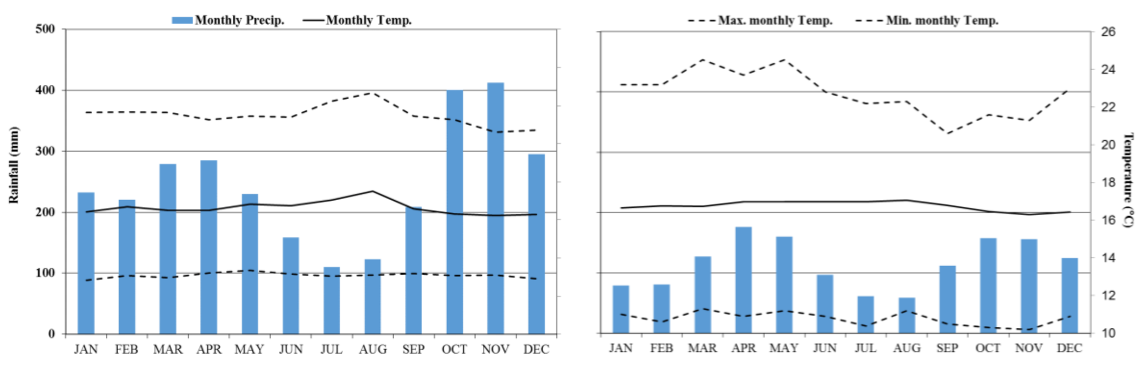


Figure 2.3 Mean annual precipitation and temperature from the nearest climate station for a) the Andisol site (Sonora watershed) and b) the Inceptisol site (El Chocho watershed)

2.1.3 Topography and watershed characteristics

The Sonora watershed has a hummocky topography (Fig. 2.4a) with dominantly east-west trending slopes (Guarín, et al., 2004). Slopes in riparian areas around tributary streams and in the upper watershed are up to 88% gradient, while flatter areas in the central and lower watershed are < 20%. In some parts of the upper Sonora watershed the volcanic ash layer is visible near the soil surface (Fig. 2.4c), while in the lower depositional areas of the watershed, the ash layer is located at depths of two to five meters.

In the El Chocho watershed (Inceptisols), the stream flow direction is north-south, and the watershed form is concave with steep side slopes (Fig. 2.4b). Slopes around streams and in the upper watershed exceed 70%, while flatter regions located in the mid and lower watershed are <20% slope. A dirt road traverses the western slope, with sidecast material deposited downslope. In the center of the watershed land subsidence is visible (Fig. 2.4d), and may be related to subsurface fractures (PNNC, 2005).

a) b)

c) d)

Figure 2.4 a) Hummocky topography in Sonora watershed (Andisol site); b) concave form of El Chocho watershed (Inceptisol site); c) layer of exposed C horizon (volcanic ash) near the soil surface in upper Sonora watershed (Andisol site); and d) land subsidence in the center of the El Chocho watershed (Inceptisol site)

2.1.4 Soils of the watersheds

2.1.4.1 Andisols of the Sonora watershed

Soils in the Sonora watershed are classified as Andisol (soil order), Udand (suborder for Andisols of humid climates) and are Acrudoxic Hapludands (soil subgroup) (IGAC, 1996).

A typical Andisol profile in the Sonora watershed and its associated air-dried soil samples is shown in Figure 2.5. Based on field observations, these Andisols have a sandy texture and lack coarse fragments. After drying, Andisol samples had a light brown color. Munsell colors of the dry samples from this profile were 10YR 5/3 for the A horizon and 10YR 6/4 for the B horizon. The color of the ash was 10YR 8/1. Typically, the A horizon is about 0.20 m thick. The B horizon ranges from 0.20 to 1.0 m depth in the upper watershed, and is thicker in lower sections (0.20 to 5.0 m depth), likely due to erosion in the upper watershed and deposition in lower sections. In one of the analyzed profiles, a placic layer was found at 2.8 m and a perched water table was found at 2 m. Detailed characteristics of Andisol profiles are provided in Appendix B.

a)

b)

Figure 2.5 a) Example of an Andisol profile from the Sonora watershed, and b) associated air-dried soil samples from the A horizon (left) and B horizon (right)

Compared to the El Chocho watershed (Inceptisol site), there were fewer earthworms observed in the Sonora watershed, but termites were found in three pasture sites when the infiltration measurements were taken (Fig. 2.6); no termites were present in any of the sampled soil profiles.

a) b)

Figure 2.6 a) Biopores and b) termite burrows in Andisols of the Sonora watershed

2.1.4.2 Inceptisol of the El Chocho watershed

Soils in the El Chocho watershed are classified as Inceptisol (soil order), Udepts (suborder for humid climates) and Typic Dystrudepts (soil subgroup) (IGAC and CVC, 2004). The Typic Dystrudepts from the El Chocho watershed are moderately deep soils, with fine texture, moderate drainage, strong to highly acidic pH, high aluminum saturation (>60%), and low fertility (IGAC and CVC, 2004). A representative Inceptisol profile and its associated air-dried soil samples are shown in Figure 2.7. Based on field observations, the texture of Inceptisols in the study watershed is described as clay, with cobbles and stones present throughout the soil profile (as opposed to the Sonora watershed where no cobbles or stones were encountered). Small yellow and reddish concretions can be seen as inclusions in the A horizon of this soil profile. Munsell colors of the air-dry samples from the profile were: 10YR 4/3 for the A horizon and 10YR 6/6 for the B horizon. The red colors in subsurface horizons indicate the presence of iron oxides and hydroxides. The thickness of the A horizon in El Chocho watershed averaged 0.30 m, B horizons had a relatively constant thickness (from 0.30 to 2.0 m depth) throughout the watershed. The C horizon which found below 2 m, transitions to saprolite, overlying bedrock which based on field observations is > 30 m thick. Detailed descriptions of the Inceptisol profiles are provided in Appendix B.

a) b)

Figure 2.7 a) Example of an Inceptisol profile from the El Chocho watershed and b) associated air-dried soil samples from the A horizon (left) and B horizon (right)

2.1.5 Land Use

The two most common land use types in the country, natural forest and pasture, occupy more than 80% of the area of each watershed (Table 2.2 and Fig. 2.8).

Table 2.2 Land use in Sonora (Andisol site) and El Chocho (Inceptisol site) watersheds

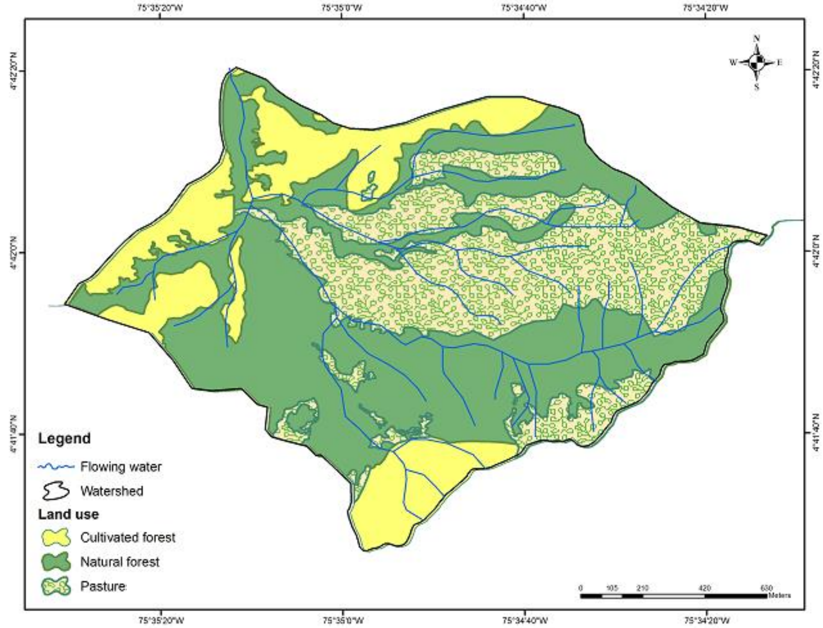
Soil order	Watershed	Area (ha)	% Natural forest	% Pasture	Other land uses	% Other land uses
Andisol	Sonora	204	48	33	Plantation forest	19
Inceptisol	El Chocho	149	50	42	Culinary herbs	8

Logging of the primary forest in both watersheds likely occurred with the expansion of cattle grazing in the early 1800s, and was coupled with exponential population growth and the settling of mid-elevation regions in the country over the last 50 – 60 years (Etter and Van Wyangaarden, 2000). Natural forests in the watersheds today are secondary forests established through natural regeneration, and are recognized by the small diameter at breast height (<10 cm) of the majority of the vegetation (Cardona, 2015a and 2015b). Although there is no tracked history of land use change in either watershed, the naturally regenerated secondary forest was likely established from vegetation not removed during logging of the primary forest. Today, natural forests are located only on slopes > 20% gradient within both watersheds, commonly in stream canyons and at higher elevations. These natural forests are mainly affected by human activity along trails to farms and water intakes in lower parts of the watershed.

Pasture species in both watersheds appeared after logging of the primary forest and the introduction of cattle (Sanchez, 2017) in the early 1800s. Pasture areas in both watersheds are used for cattle grazing. During the study period, around 25 cattle were found in the Sonora watershed (0.4 animals/ha), while around 20 cattle were located in El Chocho watershed (0.3 animals/ha). Animals are grazed throughout the year, utilizing a pasture rotation system with areas separated by fencing. Pasture in the watersheds are located on both flat (<20%) and sloping lands. In general, pasture in both watersheds provides a complete soil cover. Exceptions were small areas (about 40 m^2) near drinking troughs or streams where vegetation was heavily grazed, trampled and soil was exposed, by cattle concentration in these areas. Machinery and fertilizers are not used in either natural forest or pasture.

In addition to the two main land uses, there are secondary land uses which occupy less than 20% of the area of each watershed: plantation forest in the Sonora watershed (Andisol site) and crops in the El Chocho watershed (Inceptisol site). The plantation forest in the Sonora watershed, corresponds to planted eucalyptus and pine trees managed by the Smurfit Kappa Company for the manufacturing of paper and packing products. The secondary land use in the El Chocho watershed corresponds to culinary herbs. As these land uses are small in extent and not common between the watersheds, soils under these land uses were not evaluated in this study.

a) Sonora watershed- Andisol



b) El Chocho watershed- Inceptisol

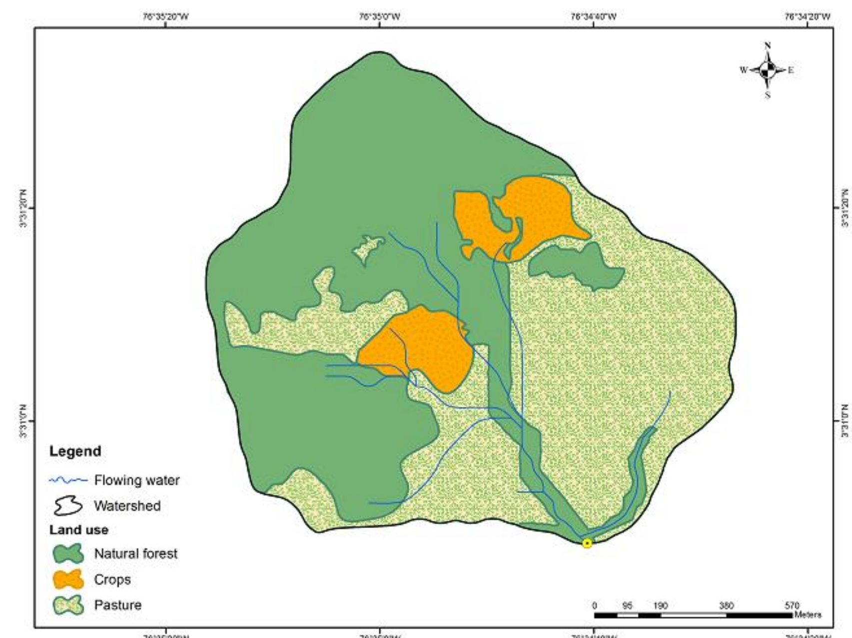


Figure 2.8 Land uses in a) Sonora (Andisol site) and b) El Chocho (Inceptisol site) watersheds

2.1.6 Vegetation characteristics

Natural forest from the studied watersheds, despite being secondary forests, are rich in diversity. Cardona (2015a, 2015b) identified 63 species in the Sonora watershed (Andisol site) and 81 species in El Chocho watershed (Inceptisol site). The Shannon-Wiener index (Shannon, 1948), was greater than 3 in both watersheds, indicating a high species diversity (Cardona, 2015a and 2015b).

Tree species that stand out by their flowers and leaf color in Sonora watershed were *Heliocarpus popayanensis* (Malvaceae family) and *Cecropia telealba* (Urticaceae family) (Cardona, 2015a). Based on the IVI Index (Gentry, 1982), the natural forests of the Sonora watershed are dominated by species of the Cyatheaceae (tree ferns) and Arecaceae family (palm trees) interspersed with flowering shrub and trees from the Melastomataceae, Rubiaceae and Solanaceae families (Cardona, 2015a). *Wettinia kalbreyeri*, a palm tree from the Arecaceae family, an endemic species locally known as palma bolillos, is also found in the watershed.

Tree species that stand out by their height and leaf color in the El Chocho watershed were *Cedrela Montana* (Meliaceae family) and *Cecropia telealba* (Urticaceae family) (Cardona, 2015b). The most dominant plant families, based on the IVI Index (Gentry, 1982) in the natural forest of the El Chocho watershed, were Heliconiaceae (flowering plants) and Arecaecea (palm trees) (Cardona, 2015b). Detailed lists of plant species found in the natural forests of these two watersheds are provided in Appendix C.

Pasture species that were present in both of the study watersheds and that are widespread in the South and Central America (Cardona Mejía, 2012, INATEC, 2016), are *Cynodon plectostachius* (Estrella) and *Pennisetum Clandestinum* (Kikuyo) species. These species occupy approximately 80% of the pasture area of both watersheds.

Additional pasture species throughout the Sonora watershed (Andisol site) include *Paspalum fasciculatum* (Gramalote) and *Axonopus micay* (Micay) (Sanchez, 2017). In the upper watershed there were patches of *Rhynchospora nervosa*. Furthermore, a shrub layer of up to 1.5 m, covered about 5% of pastures on both sloping and flat positions.

Additional pasture species throughout the El Chocho watershed (Inceptisol site) include *Hyparrhenia rufa* (Yaragua). Some patches of S*accharum sinense* (King grass) were found in the upper watershed and *Stipa charruana* (Espartillo) in the mid watershed (Sanchez, 2017). The second tier of vegetation in the El Choco pasture land is *Pteridium aquilinim,* a native fern species which is known as a pioneer species. About 40% of the pasture on slopes and 20% in flat areas was covered by this fern layer.

2.2 Experimental design

A stratified random experimental design was used in this study. Two watersheds with the most common soil orders and land uses in the Colombian Andes were selected: 1) Sonora watershed – Andisols, and 2) El Chocho watershed – Inceptisols. Within each watershed, the two dominant land uses (natural forest and pasture) were delineated. Each land use category was further subdivided by slope into: flat positions (<20% slope) and sloping lands (>20% slope). Flat position was defined as areas feasible for cultivation with low gradients (i.e., <20%) that do not require technologies to protect against erosion (Pasolac, 1999). Note that forests are only located on slopes in both watersheds. Pasture areas with exposed soil and forest areas on slopes >70% and with remote access were excluded.

In each watershed three types of land units were identified: natural forests on slopes, pasture on slopes, and pasture on flat positions. Each land unit was subdivided into three geographical areas (e.g., north east, north west, and south). The geographical areas were also subdivided in 10 blocks, from which two blocks were randomly selected and soil pits were excavated. In this manner two sites were located in each geographical area for a total of 6 sites per land unit (Fig. 2.9).

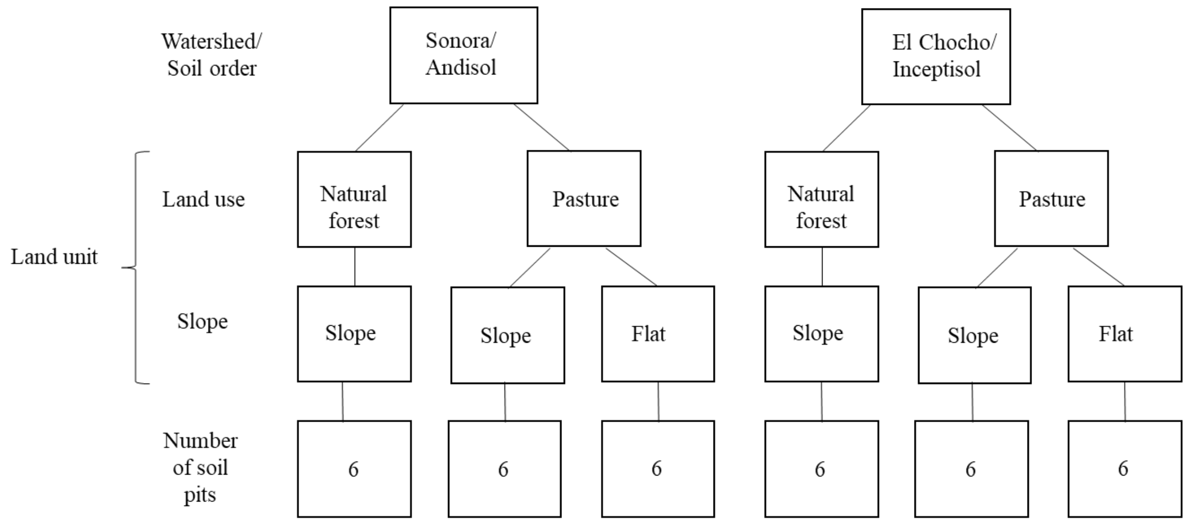
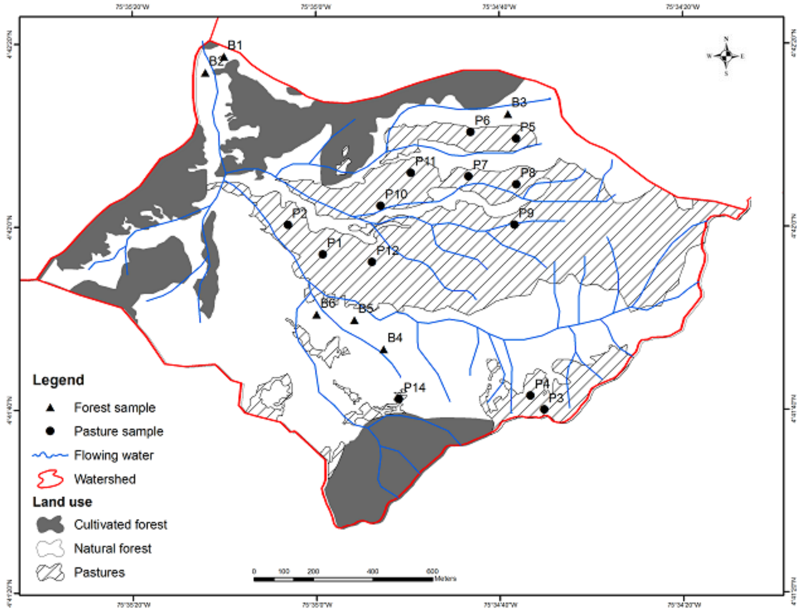


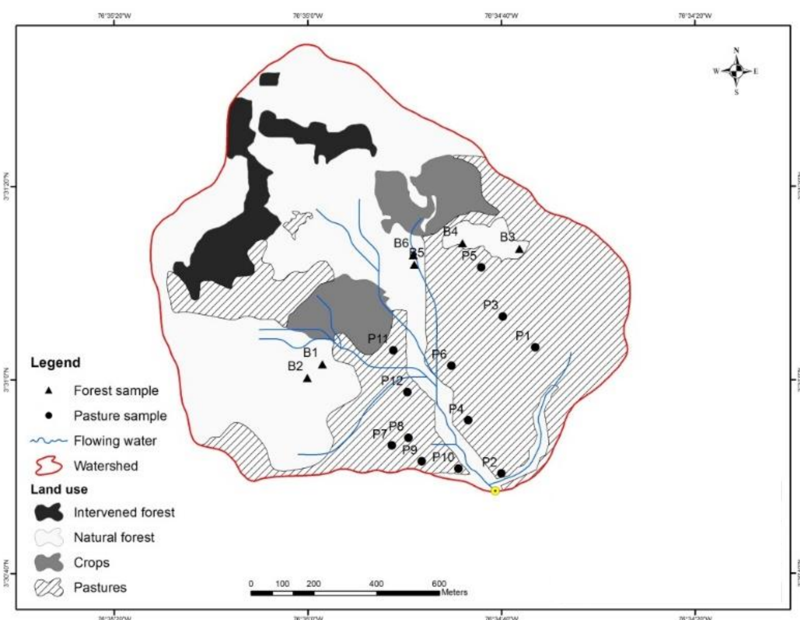
Figure 2.9 Experimental design

All soil pits were georeferenced (Fig. 2.10) and soil samples were taken by horizon. Details on soil sampling are provided in Section 2.3. Field measurements of Kfs were also taken at locations near the excavated pits.

a) Sonora watershed- Andisol



b) El Chocho watershed- Inceptisol



Note: P sites referred to pasture sites, while B sites referred to natural forest sites

Figure 2.10 Locations of soil pits in a) Sonora (Andisol site) and b) El Chocho (Inceptisol site) watersheds that were sampled during this study

2.3 Soil sampling

Soil pits were excavated to a depth of 1.20 m; with the exception of one pit in Andisols which was excavated to a depth of 3.1 m. Samples were taken from A and B, and the C horizon when encountered. Horizons were delineated, horizon thickness measured, and the coarse fragment content was estimated. To obtain additional information about the variability of the soil parent material, three additional C horizons in Andisols were sampled from exposed C horizons at locations near sampling sites.

All soil samples, in both watersheds were collected in May 2012. Composite soil samples, comprised of 3 individual samples vertically distributed within each horizon (i.e. upper, mid and lower depths), were taken for chemical, physical, and mineralogical analyses. The chemical analyses conducted were $pH_{H2O,}$ pH_{CaCl2} and soil organic carbon (SOC); the physical analysis was particle size (% sand, % silt and % clay) and the mineralogical analyses were short-range order (SRO) mineral and crystalline mineral composition. In addition to the composite sampling, undisturbed soil core samples were taken from the mid-depth of each horizon (average depth of 12 cm). For SWR analysis, these undisturbed soil samples were collected in 45 cm^3 steel cores (diameter 4.8 cm and height 2.5 cm) and were also used for soil bulk and particle density analyses.

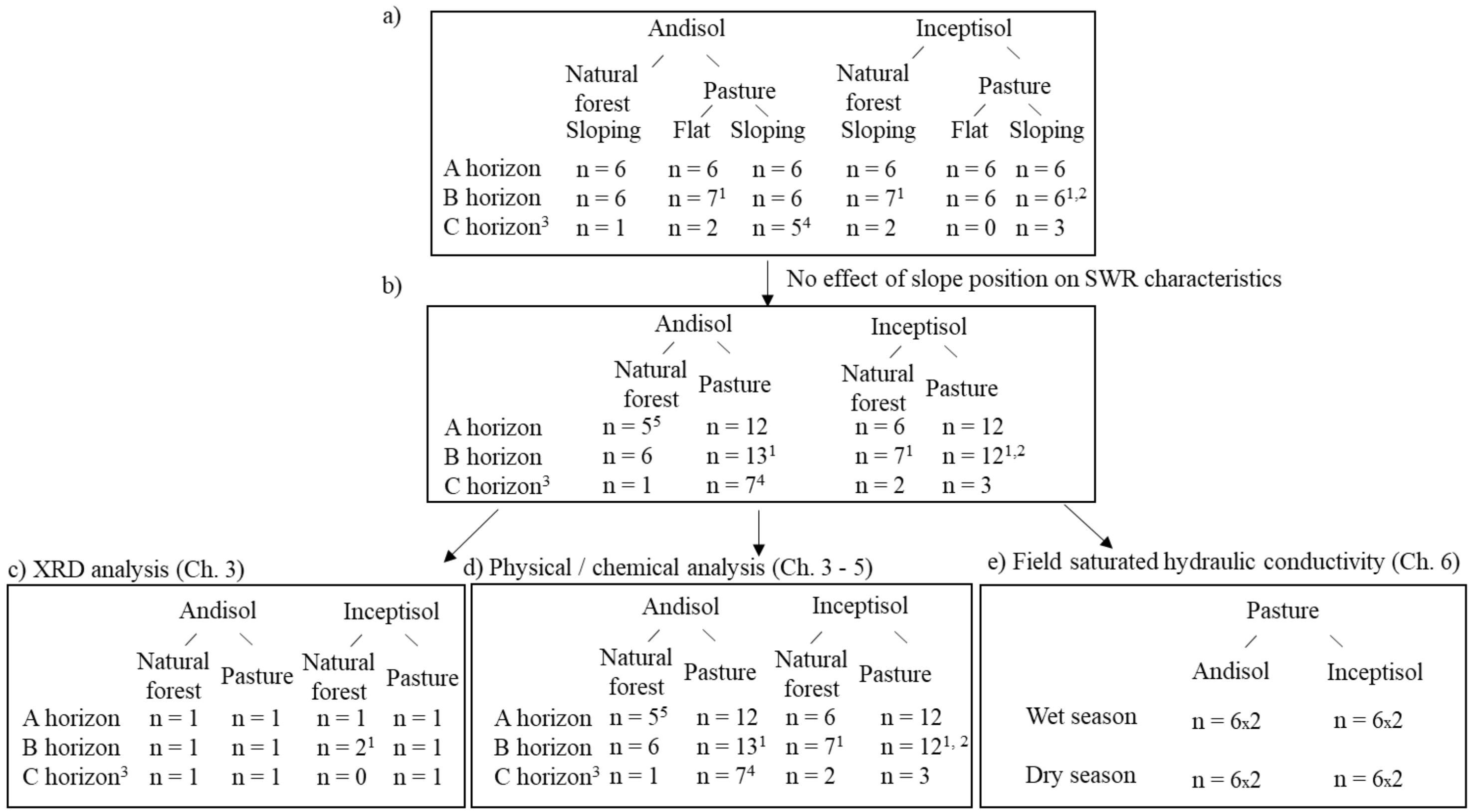
The number of samples for each soil analysis or measurement are summarized in Figure 2.11. Typically, in each land unit, six samples per soil horizon were collected. Exceptions were: 1) a soil pit of Andisols and two soil pits of Inceptisols, where two B horizons (B1 and B2) were delineated, leading to a total of seven samples, and 2) one Inceptisol pit, which did not have a B horizon. The number of C horizons sampled in Andisols were eight, including three additional C horizon samples from locations near sampling sites on pastures with steep slopes. Five C horizons were sampled in Inceptisols (Fig. 2.11a)

Pasture samples from flat and sloping positions were pooled, leading to six samples per horizon for forest and 12 samples per horizon for pasture (with the exceptions explained above). The reason to unify this pool, was that slope showed no effect on SWR characteristics under pastures based on statistical analysis (Mann Whitney U test) (Fig. 2.11b).

Additionally, one sample from the A horizon of forest in Andisols had a very high SOC (26.5%) and was considered anomalous since all other samples in this study and other studies from this region (Roa-García, 2009) had SOC at around 13%. High values of SOC (32-38%) (Diaz and Paz, 2002; Buytaert et al., 2006), are common in páramo ecosystems at high elevations (>3,500 m) but not at mid-elevations. Consequently, this sample was removed from the statistical analyses of physical and chemical soil properties (Fig. 2.11b). Data normality was assessed using skewness and kurtosis values. As soil parameters were not normally distributed, non-parametric tests were used, specifically Mann Whitney U test to compare soil characteristics and Spearman correlations to measure the strengths of association.

For X-ray diffraction (XRD) analysis, one natural forest profile and one pasture profile for each soil order were analyzed (Figs. 2.11c and 2.11d). All samples were analyzed for physical and chemical properties. Results for crystalline minerals and SRO minerals are shown in Chapter 3, while results of physical and chemical analyses are used in Chapters 3, 4 and 5.

Field saturated hydraulic conductivity (Kfs) was determined using a double ring infiltrometer, which provides an index of quasi steady-state infiltration rate as measured in the field (Bagarello et al., 2014; Nimmo et al., 2009). As slope limits the use of the double ring infiltrometer, the six blocks of natural forest, all on slopes >20%, and the six blocks of pasture on slopes >20%, were not evaluated. The measurements of quasi steady-state infiltration rate on pasture were assessed in the six randomly selected blocks with flat slope positions (Fig. 2.11e). In each of the blocks, measurements were taken in duplicate using two sets of double ring infiltrometers. Infiltration measurements are reported in Chapter 6.



[1] Two B horizons in one pit; [2] No B horizon found in one pit; [3] C horizon was sampled when found at ≤1.2m depth; [4] C horizon samples including three exposed C horizons from nearby locations; [5] One A horizon sample excluded due to unusually high SOC content

Figure 2.11 Overview of samples collected and field measurements: a) initial number of samples collected, b) number of samples after slope position was amalgameted, and c) number of samples for specific analyses and field measurements

3. MINERALOGY OF ANDISOLS AND INCEPTISOLS AT TWO MID-ELEVATION SITES IN THE COLOMBIAN ANDES

3.1 Introduction

Soil water characteristics are governed to a large extent by the type and amount of soil colloids (Hodnnett and Tomasella, 2002). Yet in the Andes limited research has been conducted on soil mineralogy, how mineralogy relates to other soil properties, and the implications for soil water retention (SWR). Short range order (SRO) minerals are of particular interest due to their high water holding capacity and their stabilizing effect on soil organic matter (Buytaert et al., 2002; Krammer et al., 2012). In Andisols and Inceptisols, the soil orders predominant in the Colombian Andes, allophane, imogolite and Fe/Al oxides and hydroxides are SRO minerals of interest as they may play a key role in SWR.

SRO minerals are formed from the weathering of framework silicates and ferromagnesian minerals, and are characterized by high specific surface area (SSA) (Table 3.1) and a large number of hydroxyl groups (Krammer et al., 2012; Eusterhues et al., 2005). Allophane and imogolite are SRO alumino-silicates commonly associated with volcanic ash soils (Parfitt, 2008; Nanzyo, 2002). Their nanoparticle size (1-100 nm) and hollow structure result in microscopic pores that can store water within the mineral framework (Wada, 1985). The presence of (pH dependent) positive and negative charges allow SRO minerals to bind to organic compounds and participate in aggregate formation (García et al., 2018). These characteristics also promote low soil bulk density (ρ_b) and a wide pore size distribution (Nanzyo, 2002). Iron and aluminum oxides also play a significant role in SWR and aggregate formation as they also have pH-dependent charges. This especially applies to the non-crystalline ferrihydrite, with its nanoparticle size and high SSA (Table 3.1), which despite its small contribution to soil mass (commonly <1%) (Duiker et al., 2003; Regelink et al., 2015), binds silt and sand particles to soil organic matter leading to creation of stable aggregates (Arias et al., 1996; Sei et al., 2002).

Table 3.1 Characteristics of selected soil colloids

Soil colloid /Formula	Specific surface area (m^2/g)	References for specific surface area	Total charge at pH 7 ($cmol_c+/kg$)[1]	pH dependent charge (%)
Alumino-silicate SRO minerals				
Allophane $Al_2O_3 (SiO_2)_{1.3-2} (2.5-3) H_2O$ and imogolite $Al_2SiO_3(OH_4)$,	700-1500	Parfitt, 2008	30[2]	90
Fe oxides				
Magnetite Fe_3O_4	90	Dixit and Hering, 2003	0	-
Hematite α- Fe_2O_3	14.4	Singh et al., 1996	0	-
Goethite α- $Fe^{3+}O(OH)$	134-139	Matis et al., 1997	4[2]	100
Ferrihydrite $Fe_5HO_8.4H_2O$	220-560	Shoji et al., 1984	-0.5[3]	100
Al oxides				
Boehmite γ-AlOOH	108	Singh and Yadava, 2003	5 to 10[4]	100
Gibbsite α- $Al(OH)_3$	100-220	Kämpf et al., 2012	4[2]	100
Humus	800-900	Handreck and Black, 2005	200[2]	100

[1]Centimoles of charge per kilogram of colloid ($cmol_c+/kg$); [2]Dixon and Weed (1989); [3]Bompoti et al. (2017); [4]Goldberg et al. (1996)

Within Colombia, most soil mineralogical studies have been conducted in Andisols. These soils are largely allophanic[3] with a high content of SRO minerals; although some non-allophanic soils (high in organo-metallic complexes) are found in southern Colombia (Malagón, 1995). Hapludands, the great group of the study area, are allophanic and occupy 11% of the region (Malagón, 1995). In contrast, few studies consider Inceptisols, even though Dystrudepts (the dominant great group) occupy 55% of the region (Malagón, 1995). Given the great diversity of Inceptisols, generalization of their soil mineralogy is difficult.

This chapter provides a comparison of the mineralogical properties of Andisols and Inceptisols located at two mid-elevation sites in the Colombian Andes. This study will help bridge the knowledge gap on the soil mineralogy of the two main soil types in this region and will highlight soil properties that may impact SWR characteristics.

3.2 Experimental conditions and laboratory analyses

Soils were sampled as described in Section 2.3. From the 18 sampled soil pits, one pit from a natural forest and one pit from a pasture from each soil order were randomly selected for mineralogical analysis by X-ray diffraction (XRD). All composite samples of the 18 pits of each soil order, were analyzed for SRO minerals by dissolution extractions and for the following soil chemical and physical properties: pH $_{H2O}$, pH_{CaCl2}, soil organic carbon (SOC), particle size, bulk density (ρ_b) and particle density (ρ_s). Soil samples taken in 45 cm^3 steel cores were used to determine ρ_b and ρ_s. Laboratory analyses of composite soil samples were performed on air dried samples that were passed through a 2-mm sieve, except for the XRD analysis, that was performed on the clay size fraction (<2 μm).

3.2.1 Mineralogy

3.2.1.1 Crystalline minerals

X-ray diffraction (XRD) was performed using Bruker D8 Focus and D8 Advance diffractometers producing Co-Kα radiation (Thorez, 1976). The search-match software by

[3] Allophanic soils are young, dark-colored soils derived mainly from volcanic ash (Juo and Franzluebbers, 2003). These soils typically have a low bulk density (< 900 kg/m^3), a high water retention capacity (100% by weight at field capacity), and contain predominantly allophanes, imogolite, halloysite, and amorphous Al silicates in the clay size fraction.

Bruker (DIFFRACplus EVA 16) was used to identify mineral peaks with d-spacing and their relative intensities. As every mineral has a set of unique d-spacings, the minerals present were identified. Based upon their basal peak areas (Thorez, 1976), the relative abundance of the minerals was classified as dominant, significant, present, or trace as shown in Table 3.2.

Table 3.2 Peak intensities determined by the X-ray diffraction (XRD) analysis and the correspondent relative abundance of minerals

Peak relative intensities	Relative abundance of minerals
>40% to ≤100%	Dominant
>20% to ≤40%	Significant
>10% to ≤20%	Present
≤10%	Trace

3.2.1.2 Short-range order (SRO) minerals

The standard XRD technique for identification of the mineral components in soils is very useful in the determination of crystalline minerals but given the amorphous nature of SRO minerals, XRD is very limited in their determination. Therefore, chemical dissolution extractions were used to assess the SRO minerals in the sampled soils. Pyrophosphate and oxalate extractions were done following the methods of Mizota and Van Reeuwijk (1989).

Pyrophosphate extracts aluminum and iron (Al_p and Fe_p) that are associated with organic matter (Dahlgren, 1994). Al_p and Fe_p were determined by extraction after shaking 1 g of soil with 50 mL of 0.1 *M* pyrophosphate solution adjusted to pH 10, for 10-14 hours and filtering through a 2.5 μm cellulose filter paper (Whatman #42) (Mizota and Van Reeuwijk, 1989).

Oxalate solutions extract aluminum, iron, and silicon (Al_o, Fe_o, and Si_o) from organic complexes, and SRO minerals such as Fe-hydroxides (ferrihydrite) and aluminosilicates (imogolite and allophane) (Dahlgren, 1994). Oxalate extractable Al_o, Fe_o, and Si_o were determined by extraction after shaking 0.5 g of soil with 25 mL of 0.03 *M* ammonium oxalate for 4 hours at pH 3 in the dark, filtering through cellulose filter paper (Whatman # 42) and diluting to 50 mL with 10% HNO_3.

Extractable Al, Fe, and Si were analyzed using an inductively coupled plasma atomic emission spectrometer (ICP-AES).

The results of the pyrophosphate and oxalate extractions are used to determine the allophanic or non-allophanic character of Andisols and to quantify the amounts of SRO mineraloids. The following indices were determined:

- Al_p/Al_o ratio is used to distinguish between soils rich in SRO minerals (Al_p/Al_o <0.5) from soils rich in organo-metallic complexes (Al_p/Al_o >0.5) (Shoji et al., 1993). Andisols rich in SRO are referred to as allophanic, while Andisols rich in humus complexes are non-allophanic.
- $Al_o + ½ Fe_o$ (%), referred to as oxalfe, is used to identify andic properties, a key attribute of Andisols. If oxalfe is greater than 2% then this requirement is met (Van Wambeke, 1992).

The quantity of imogolite and allophane was estimated according to the equation developed by Mizota and Van Reeuwijk (1989):

$$\%\ \text{Allophane and imogolite} = 100\ \frac{\%\ Si_o}{23.4 - 5.1\ x} \qquad \text{Eqtn 2.1}$$

Where:

$x = (Al_o - Al_p)/Si_o$ represents the molar ratio of Al_{sro}/Si_o and

$Al_{sro} = Al_o – Al_p$, gives a measure of Al associated with SRO inorganic material (Parfitt and Childs, 1988; Dahlgren, 1994).

Ferrihydrite occurs in soils undergoing rapid weathering, and in soils containing soluble silicate or organic anions which inhibit the formation of more crystalline iron oxides (Childs, 2007). Ferrihydrite concentration was estimated from Fe_{sro}, according to Childs et al. (1991):

$$\%\ \text{Ferrihydrite} = 1.7 \times \%\ Fe_{sro} \qquad \text{Eqtn. 2.2}$$

Where:

$Fe_{sro} = Fe_o – Fe_p$, gives a measure of Fe associated with SRO inorganic material (Parfitt and Childs, 1988; Dahlgren, 1994).

3.2.2 Soil chemical and physical properties

3.2.2.1 Soil pH

Soil pH was determined in both distilled water and 0.01 *M* $CaCl_2$ on a 1:2 (v/v) ratio (Hendershot and Lalande, 1993). For samples high in organic matter (>12% by weight), the liquid volume was doubled. The pH results for the samples analyzed with double liquid of volume are indicated in Appendix B. This appendix also provides data on soil depth, slope, air dried color, SOC, ρ_b, and texture.

3.2.2.2 Soil organic carbon (SOC)

Soil organic carbon (SOC) was determined by loss-on-ignition (LOI); 5 g of air-dried soil was dried at 105°C for 24 hours and then heated to 300°C for 8 hours in a muffle furnace. Weights were recorded before and after combustion. Soil organic carbon was calculated using the equation formulated by Rahman et al. (2011):

$$SOC = (0.5663 \times LOI) - 0.7589 \qquad \text{Eqtn. 2.3}$$

$$LOI = (W_{105°C} - W_{300°C}) / W_{105°C} \qquad \text{Eqtn. 2.4}$$

Where:

LOI is the % of weight associated to organic matter,

$W_{105°C}$: Initial soil weight after drying at 105°C for 24 hours, and

$W_{300°C}$: Final soil weight after drying at 300°C for 8 hours.

3.2.2.3 Particle size analysis

Determination of texture in Andisols by mechanical (or particle) analysis is challenging due to incomplete dispersion of the mineral particles even with vigorous shaking and the addition of sodium hexametaphosphate as a dispersion agent (Shoji et al., 1993). The incomplete dispersion of mineral particles in Andisols is due to the presence of amorphous minerals and the associated high stability of soil aggregates. Ultrasonic dispersion with a pH adjustment to 4 or 10 using HCl or NaOH may be utilized; however, there is no standardized procedure (Shoji et al., 1993). For this study, the hydrometer method was used for both Andisols and Inceptisols for comparison purposes. Interpretation of particle size analysis for the Andisol samples should consider the potential impact of incomplete dispersion.

Particle size analysis was done with a hydrometer according to the Bouyoucos method (Bouyucous, 1962). All samples were oxidized using H_2O_2 to remove organic matter and dispersed with sodium hexametaphosphate. For 10 samples, insufficient sample volume was available for the Bouyoucos method and particle size was determined following the sieving / sedimentation method of Kettler et al. (2001). Pre-treatment procedures with H_2O_2 and sodium hexametaphosphate were identical for all samples. The samples analyzed by the Kettler method are identified in Appendix B.

3.2.2.4 Soil bulk and particle density

Bulk density (ρ_b) was determined gravimetrically. Soil samples from the 45 cm^3 steel cores were dried at 105°C for 24 h and then weighed. Bulk density was assessed by dividing the dry soil weight over the core volume (Blake, 1965). Soil particle density (ρ_s) was determined using the pycnometer method (Blake, 2008).

3.2.3 Comparative and statistical analyses

Crystalline minerals were compared by soil horizon between Andisols and Inceptisols (Fig. 3.1a). Chemical dissolution results (i.e., Al_p, Fe_p, allophane and imogolite, ferrihydrite, and the indicators: Al_p/Al_o and $Al_o + ½\ Fe_o$,), were compared by horizons between Andisols and Inceptisols to evaluate significant differences using the Mann Whitney U test and probability values (p) of 0.01, 0.05, and 0.1 (Fig. 3.1b).

In addition, relationships were assessed between SRO, and soil physical and chemical properties utilizing the non-parametric Spearman's rank-order correlation. Spearman's Rho correlation coefficients (r) with values > 0.4 and probability values (p) of 0.01 and 0.05 were used to indicate notable relationships.

Correlations were conducted for:

- Andisol and Inceptisol all horizons
    - Andisol and Inceptisol by horizon (A, B, and C horizons)
  - Andisol only, all horizons
    - Andisol by horizon (A and B horizons)
  - Inceptisol only, all horizons
    - Inceptisol by horizon (A and B horizons)

Correlations for the C horizon in individual soil types were not assessed since there were only eight samples for Andisols and five for Inceptisols. Sample numbers for each analysis are provided in Figure 3.1.

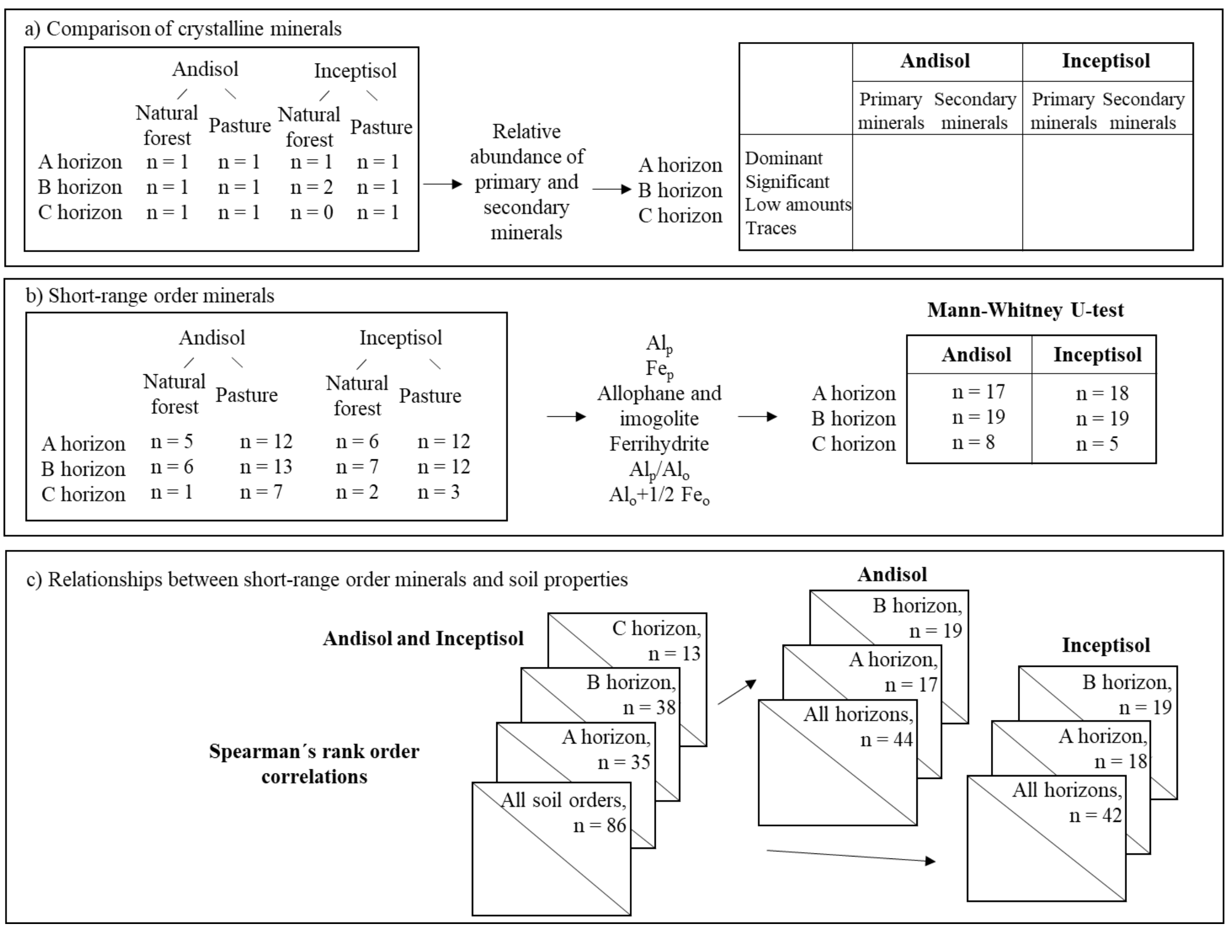


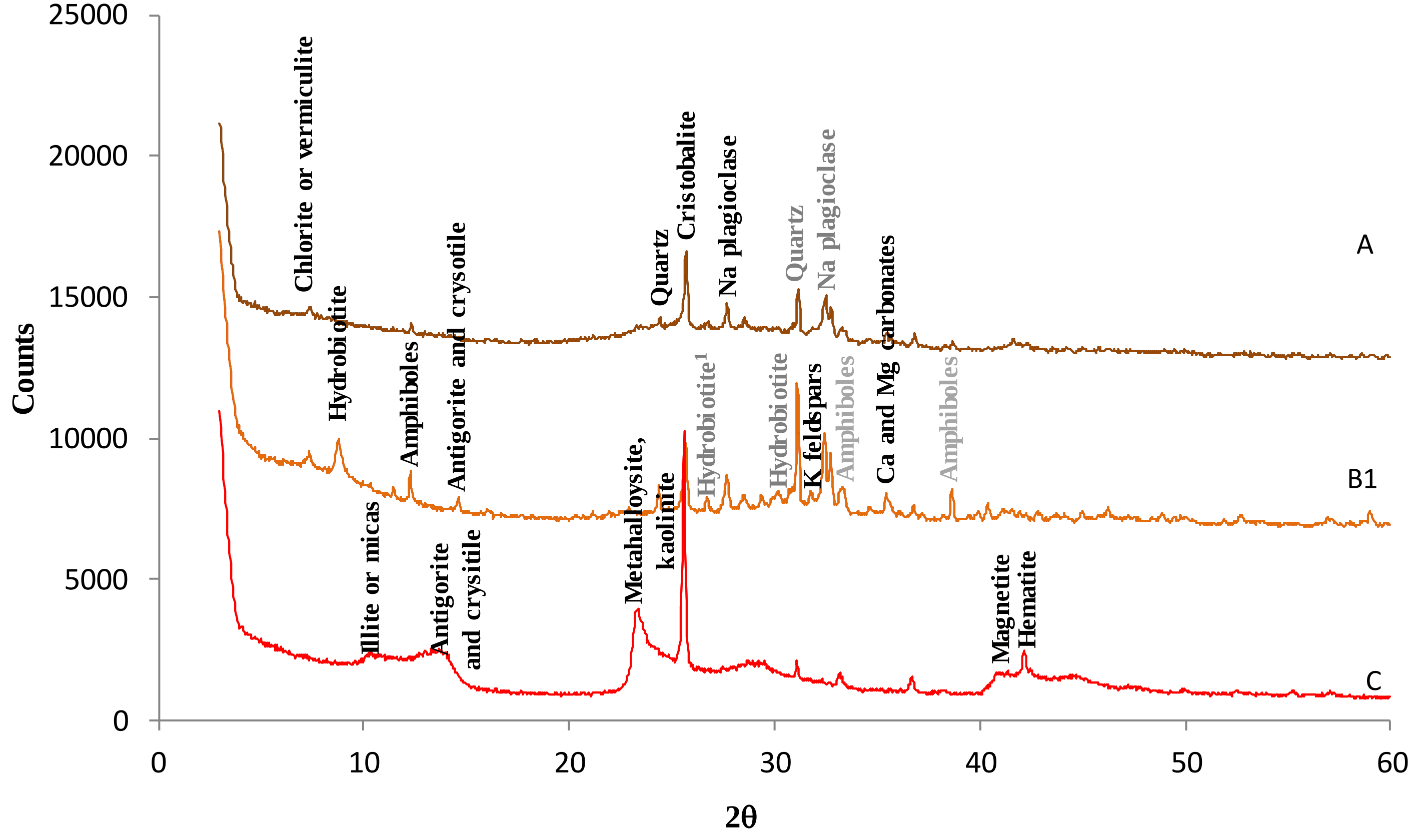
Figure 3.1 Overview of samples collected to compare: a) crystalline minerals of Andisol and Inceptisols; b) short-range order (SRO) minerals of Andisol and Inceptisol; and c) relationships between SRO minerals and soil properties

3.3 Results and discussion

3.3.1 Comparison of crystalline minerals

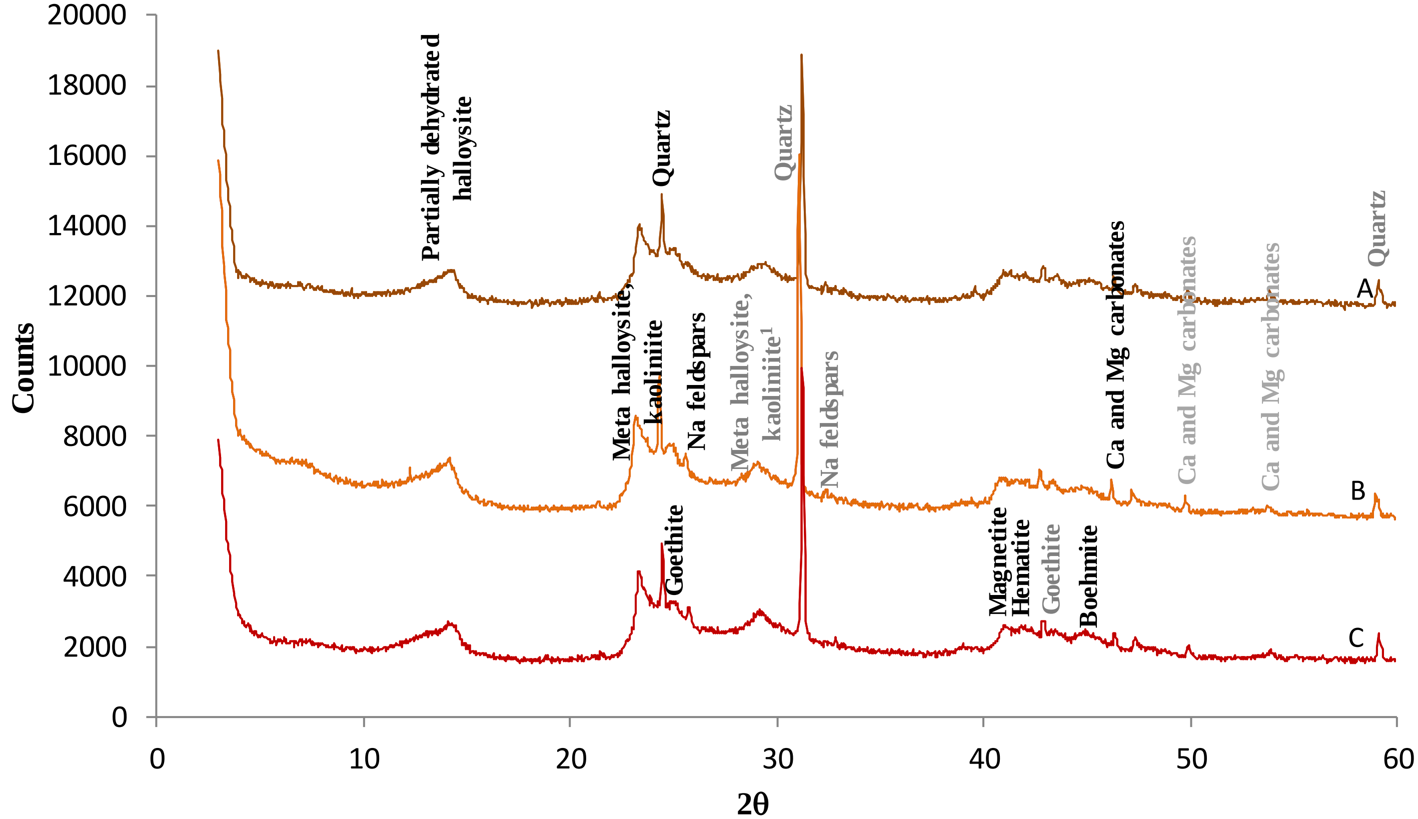
X-ray diffraction (XRD) results presented in this section will be used to assess differences in primary and secondary minerals between Andisols and Inceptisols, the degree of weathering, and the mineralogical characteristics of the soil parent material. X-ray diffractograms and primary and secondary minerals for the pasture and forest samples within each soil order were similar (Appendix D). Thus, results for XRD from the randomly selected pasture soils are presented here (Figs. 3.2 and 3.3); A, B and C horizons were analyzed for both soil orders.

XRD results suggest the presence of SRO minerals in both Andisols and Inceptisols. In Andisols (Fig. 3.2) the initial gently decreasing slope, notably in the B horizons of the diffractograms, suggests short-range order (SRO) minerals. In Inceptisols, although the slope was less steep than that recorded for Andisols, it still suggests the presence of SRO minerals (Fig. 3.3).



[1]Mineral names in gray are of secondary peaks

Figure 3.2 X-ray diffractograms of A, B1 and C horizons of the P4 pasture profile located in the Sonora watershed (Andisol site)



[1]Mineral names in gray are of secondary peaks

Figure 3.3 X-ray diffractograms of A, B and C horizons of the P2 pasture profile located in El Chocho watershed (Inceptisol site)

Primary and secondary minerals found in the Andisol and Inceptisol samples and their relative abundances (Table 3.3) indicate the state of weathering of both soils and the predominantly mafic nature of the parent material.

Results show the young pedogenic age of Andisols. In Andisols, halloysite may be formed by the weathering of imogolite (Cortes and Franzmeier, 1972). Halloysite was found only in the C horizon and there were no crystalline silicates in the A or B horizons. This limited presence of halloysite and other crystalline silicates indicates the limited soil weathering processes in Andisols.

The predominance of primary minerals with a mafic nature, such as cristobalite, micas, feldspars, and amphiboles, suggest the basic nature of the volcanic ash. Cristobalite was the most abundant mineral in the A, B and C horizon samples of Andisols. Cristobalite normally occurs in metamorphosed sandstones and sandstone xenoliths in basic rocks (Kämpf et al., 2012). This, combined with the presence of illite or micas, Na feldspars and amphiboles in the C horizon, suggests the predominantly mafic nature of the volcanic ash in the Sonora watershed. When sufficient bases, notably calcium (Ca) and magnesium (Mg) are present, they neutralize the carboxyl groups of organic acids and relatively high pH values prevail suppressing the formation of Al- and Fe-humus complexes (Van Breemen and Wielemaker, 1974). In C horizon samples, quartz was also found but was less abundant than in the A horizon, which may indicate that quartz (a primary mineral), may have been transported by alluvial processes (Guarín et al., 2004) and is therefore predominant in surface horizons.

In contrast to the limited weathering in Andisols, Inceptisols show more advanced weathering. There were abundant secondary minerals such as kaolinite and Ca and Mg carbonates. Metahalloysite and partially dehydrated halloysite were found in all horizons in the Inceptisols. The presence of kaolinite and halloysite suggests an intense weathering of the sedimentary, diabase and basalt parent rocks, the typical parent material in this region (Section 2.1.1). These parent rocks, diabase and basalt, are also mafic rocks. Magnetite and goethite (Fe oxides), and boehmite (Al oxide) present in the C horizon; and hematite (Fe oxide) present in the A and B horizons, may have also been formed as weathering products of the parent material.

Table 3.3 Mineral abundance in Andisols and Inceptisols

	Minerals abundance	Andisols		Inceptisols	
		Primary minerals	**Secondary minerals**	**Primary minerals**	**Secondary minerals**
A and B horizons	Dominant	Cristobalite and quartz	-	Quartz	Kaolinite/ Metahalloysite
	Significant	Hydrobiotite and plagioclase feldspars	-	Plagioclase feldspar	Hematite
	Low amounts	Amphiboles, chrysotile and antigorite	Chlorite or vermiculite	-	Partially dehydrated halloysite, Ca and Mg carbonates, and magnetite
	Traces	K feldspars	Ca and Mg carbonates, magnetite and hematite	-	Boehmite
C horizon	Dominant	Cristobalite	Kaolinite/ metahalloysite	Quartz	Kaolinite/ metahalloysite
	Significant	-	-	-	Boehmite
	Low amounts	Quartz, crysotile and antigorite, and Na feldspars	-	-	Partially dehydrated halloysite
	Traces	Hydrobiotite, amphiboles, illite or micas and K feldspars	Chlorite or vermiculite, Ca and Mg carbonates, magnetite and hematite	Plagioclase feldspars	Hematite, magnetite, goethite, Ca and Mg carbonates

The mineralogical characteristics of soils in the Sonora watershed are in agreement with studies conducted by Malagón et al. (1995) in the central part of Colombia, where they concluded that: first, Andisols are young soils (decades to centuries) suggested by the limited presence of halloysite and other crystalline silicates; and second, Andisols are developed on mafic ash, with cation rich primary minerals such as amphiboles and plagioclase feldspars. In contrast to the young age of these soils, the Andisols studied by Buytaert et al. (2005a) in páramo ecosystems of Ecuador, were pedologically older as suggested by the abundance of kaolinite and gibbsite. In addition, the Andisol at the Ecuador site, contained more felsic minerals such as K-micas.

In a study of 14 soil profiles from the Western and Central branches of the Andes, Mejia el al. (1968) found a profile of the Western branch showing kaolinite > quartz, cristobalite, and gibbsite. There are two similarities between the Inceptisols of this study and the profile studied by Mejía et al. (1968): first, kaolinite is the predominant secondary mineral in soils in both studies, showing the intense weathering; and second, diabase was the parent material at both sites.

3.3.2 Short-range order (SRO) minerals and organo-metallic complexes

Chemical dissolution was used for comparative purposes between Andisols and Inceptisols, although extractions with pyrophosphate and ammonium oxalate are largely used for Andisols and Spodosols, which are commonly associated with SRO minerals or organo-metallic complexes (Ugolini and Dahlgren, 1991; Algoe et al., 2012). The results of pyrophosphate and oxalate extractions are used to determine parameters for soils containing SRO minerals or organo-metallic complexes. In this study these parameters include: andic properties, the type of Andisols (allophanic or non-allophanic) and the quantity of SRO minerals and organo-metallic complexes.

Table 3.4 gives median dissolution extraction values for SRO minerals and indices, and identifies statistically significant differences between Andisols and Inceptisols. All parameters were significantly different in at least one horizon, and most were different in both A and B horizons.

Table 3.4 Median dissolution extraction values and indices in A, B and C horizons of Andisols and Inceptisols

Horizon	Andisols	Inceptisols
	Al_p[1] (g/kg)	
A	1.4 (1.1-1.7)[2]	0.06 (0.05-0.13)**
B	0.4 (0.3-0.6)	0.08 (0.03-0.14)**
C	0.1 (0.1-0.2)	0.05 (0.02-0.14)
	Fe_p[1] (g/kg)	
A	0.3 (0.2-0.5)	0.02 (0.01-0.05)**
B	0.009 (0.006-0.030)	0.012 (0.004-0.041)
C	$9x10^{-4}$ ($2x10^{-4}$-0.01)	0.007 (0.001-0.02)
	Allophane and imogolite (%)	
A	6.2 (4.5-8.0)	1.4 (1.2-2.1)**
B	14.8 (9.9-16.4)	1.2 (1.1-1.6)**
C	4.0 (1.5-6.7)	-
	Ferrihydrite (%)	
A	0.5 (0.4-0.5)	1.2 (0.9-1.4)**
B	0.7 (0.3-0.8)	0.6 (0.4-1.1)
C	0.2 (0.1-0.3)	0.6 (0.5-0.8)*
	Al_o + 1/2 Fe_o[3] (%)	
A	1.7 (1.4-1.8)	0.7 (0.6-0.8)**
B	3.7 (2.3-4.2)	0.5 (0.4-0.7)**
C	1.0 (0.4-1.5)	0.6 (0.4-0.7)
	Al_p/Al_o[4]	
A	0.10 (0.06-0.13)	0.02 (0.01-0.03)**
B	0.011 (0.07-0.016)	0.02 (0.01-0.04)*
C	0.014 (0.005-0.045)	0.01 (0.01-0.03)

[1]Pyrophosphate-extractable aluminum (Al) and iron (Fe) (Al_p and Fe_p); [2]Values in parenthesis are first and third quartile; [3]Indicator for determining andic properties in soils, called "oxalfe" (Al_o +1/2 Fe_o); [4]Indicator for determining allophanic or non-allophanic soils (Al_p/Al_o); Number of samples (n) for Andisols were 17, 19 and 8 and for Inceptisols 18, 19 and 5 for A, B and C horizons, respectively; *, ** significant differences between Andisols and Inceptisols with Mann Whitney U test at $p<0.05$ and $p<0.01$, respectively

3.3.2.1 Organo-metallic complexes

Organo-metallic complexes were not high in either Andisols or Inceptisols. However, in Andisols formation of organo-metallic complexes was observed; Al_p and Fe_p were higher in the surface horizon relative to deeper horizons (Figs. 3.4 and 3.5), and this increasing trend suggests the formation of Al and Fe-humus complexes in the epidedon of Andisols. Furthermore, Fe_p is lower than Al_p in both soils and was not different between soil orders in the B horizon, indicative of less formation of Fe-humus complexes relative to Al-humus complexes. The predominance of organo-metallic complexes is common in weathered Andisols. Therefore, the low amounts of organo-metallic complexes in the Andisols of this study is in accordance with its young pedogenic stage.

a) Andisols *b)* Inceptisols

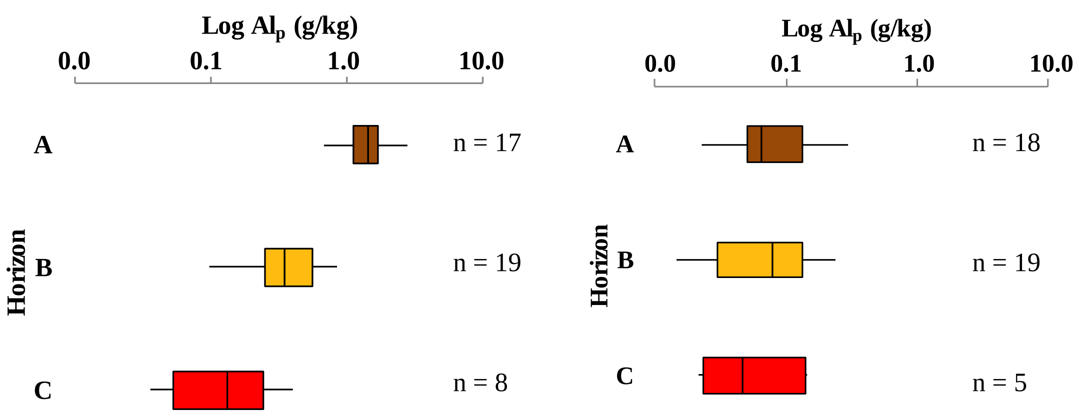


Figure 3.4 Median and quartiles of pyrophosphate extractable aluminum (Al_p) in the A, B, and C horizons of: a) Andisols and b) Inceptisols

a) Andisols *b)* Inceptisols

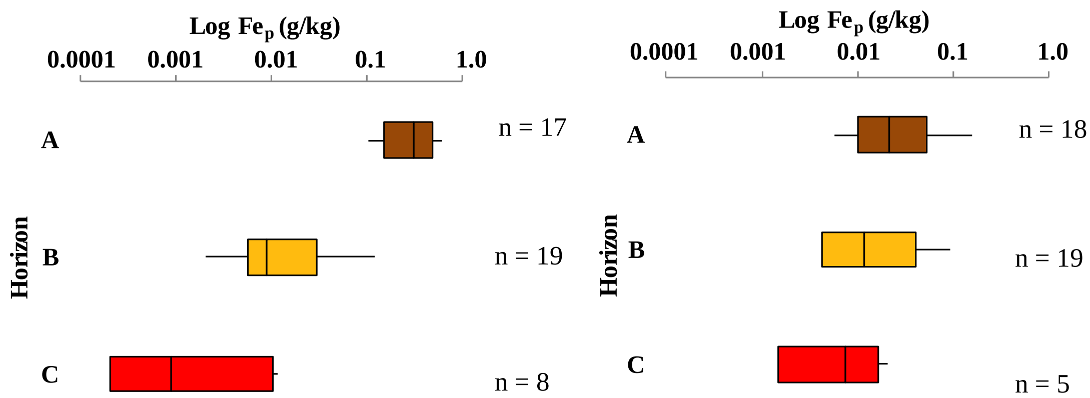


Figure 3.5 Median and quartiles of pyrophosphate extractable iron (Fe_p) in the A, B, and C horizons of: a) Andisols and b) Inceptisols

3.3.2.2 Short-range order (SRO) minerals

Oxalate extraction results show substantial amounts of allophane and imogolite (> 8%) in the B horizon of Andisols, while ferrihydrite was highest (<2%) in the A horizon of Inceptisols. Allophane and imogolite in Andisols were significantly higher in A and B horizons in comparison to Inceptisols (Table 3.4 and Fig. 3.6). Unlike allophane and imogolite, which were higher in Andisols, ferrihydrite was more abundant in Inceptisols and in greater concentration in comparison to Andisols (Table 3.4 and Fig. 3.7). The higher active Fe_o in Inceptisols may be related to the basaltic origin of these soils, which in turn could release compositional Fe to form Fe-hydroxides. Even in humus rich horizons, Fe-humus complexes are very low due to the greater stability of Fe-hydroxides compared to Fe-humus complexes (Shoji et al., 1993).

a) Andisols *b)* Inceptisols

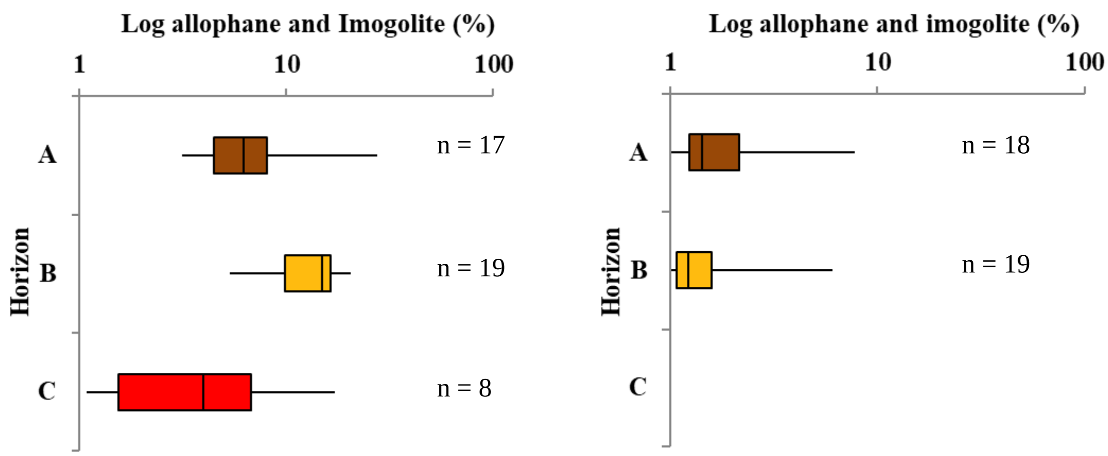


Figure 3.6 Median and quartiles of allophane and imogolite in the A, B, and C horizons of: a) Andisols and b) Inceptisols

a) Andisols *b)* Inceptisols

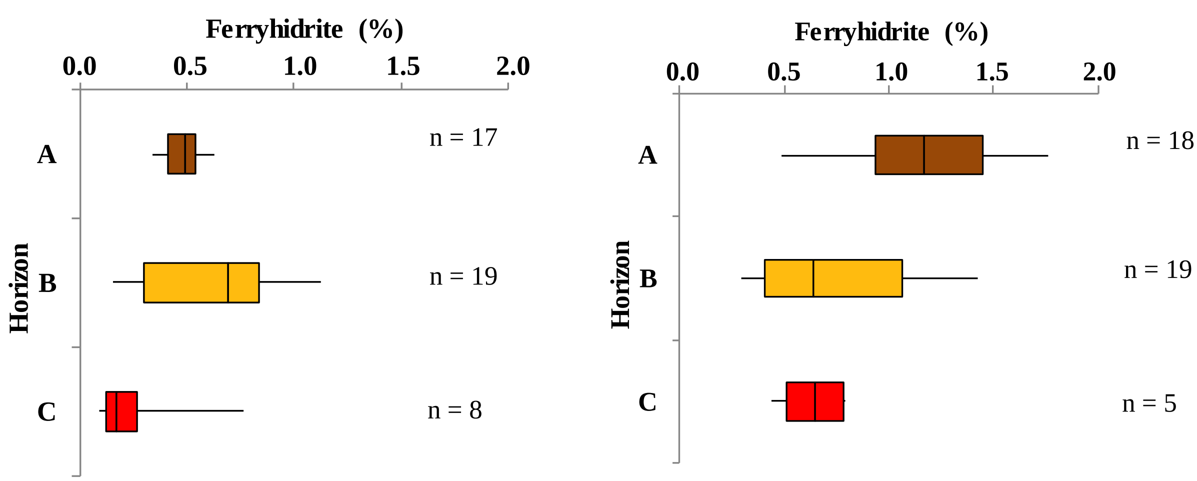


Figure 3.7 Median and quartiles of ferrihydrite in the A, B, and C horizons of: a) Andisols and b) Inceptisols

The grouping criteria formulated by Mizota and Van Reeuwijk (1989) was used to determine if the amounts of SRO minerals found in the allophanic Andisols of the Sonora watershed were substantial (i.e., >8% of SRO minerals in at least one horizon). Based on this criteria, the Andisols of the Sonora watershed have substantial amounts of allophane and imogolite, as 17 of 19 samples of B horizons registered values >8% allophane (Fig. 3.6a).

3.3.2.3 Andic properties

Oxalfe or $Al_o + ½ Fe_o$ (%), is one of the requirements for identifying andic properties, a key attribute of Andisols. Andic properties reflect the presence of volcanic ejecta such as ash, pumice, lava or they indicate the presence of SRO minerals. If oxalfe is greater than 2% then the andic requirement is met (Van Wambeke, 1992).

Oxalfe was significantly higher in A and B horizons of Andisols in comparison to Inceptisols. Oxalfe in the Sonora watershed was greater than 2% in 18 of 19 samples from the B horizon, with a median value of 3.7% (Table 3.4), while in the A horizon only 3 samples met the index.

In Inceptisols, due to the low quantities of Al_o, oxalfe was below 2% and therefore Inceptisols from El Chocho watershed did not meet this criterion for andic properties, which is in accordance with the parent material of this region: igneous and sedimentary rocks (SGC, 1984b).

3.3.2.4 Allophanic and non-allophanic soils

Al_p/Al_o ratio is an indicator used to distinguish between soils rich in SRO minerals (Al_p/Al_o <0.5) from soils rich in metal humus complexes or organo-metallic complexes (Al_p/Al_o >0.5) (Shoji et al., 1993). Andisols rich in SRO are classified as allophanic while Andisols rich in humus complexes are classified as non-allophanic. Median Al_p/Al_o ratios in the Sonora watershed were all <0.5, indicating the predominance of SRO and that Andisols of the Sonora watershed are allophanic in A and B horizons. Al_p/Al_o was significantly higher in the A and B horizons of Andisols in comparison to Inceptisols, showing the low amounts of organo-metallic Al in Inceptisols (Table 3.4).

The ratio of Al_p/Al_o versus soil organic carbon (SOC) for Andisols from the Sonora watershed are presented in Figure 3.8, and the low Al_p/Al_o ratios are evident. Mizota and

Van Reeuwijk (1989) defined an evolutionary criteria using Al_p/Al_o: a weathered Andisol will have two opposite Al_p/Al_o values; one close to 1 in the epidedon (highly humic and acid soil with lower pH) and the other close to 0 in the deeper horizons (lower organic matter and higher pH). Andisols of the Sonora watershed showed a very low value in the B horizon, suggesting a weathered or old Andisol but also a low value in the A horizon, which suggests a young Andisol. Even though these results appear contradictory, there are two conditions that may explain these results. First, the presence of minerals such as amphiboles and plagioclase feldspars, that due to their basic nature, promote the formation of allophane and imogolite rather than Fe- and Al-humus complexes (Shoji and Fujiwara, 1984; Parfitt and Saigusa, 1985) and second, there may be an ongoing input of volcanic ash from active volcanos in the vicinity of the Sonora watershed, that inhibits the formation of metal-humus complexes in the A horizon.

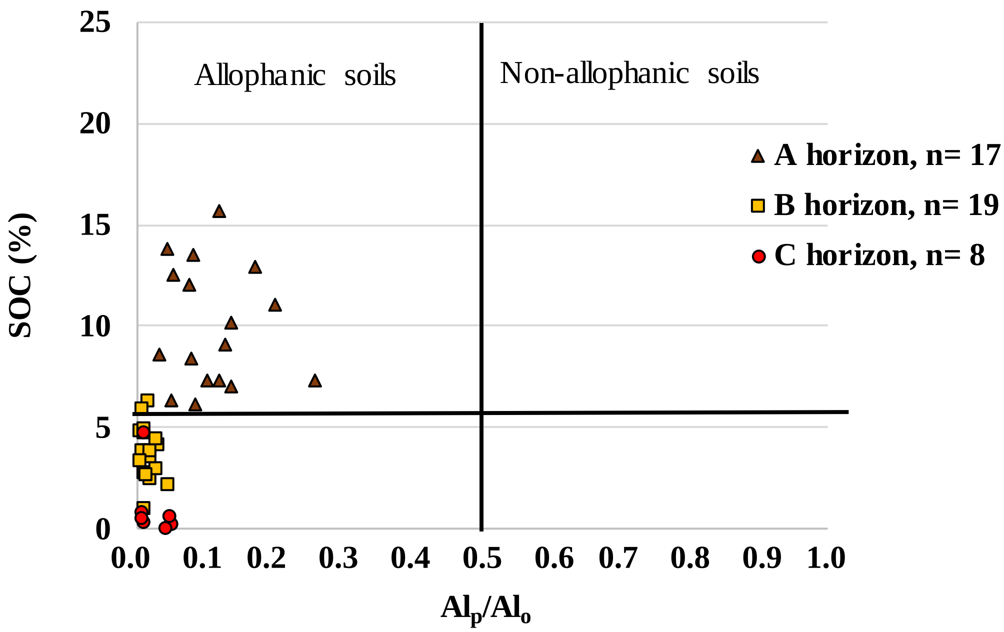


Figure 3.8 Relationship between pyrophosphate and oxalate extractable aluminum (Al_p/Al_o) and soil organic carbon (SOC) in A, B and C horizons of Andisols of the Sonora watershed

The mineralogical results for the Andisol site of this study are in accordance with the definition of the evolutionary tendency of Andisols in Colombia by Malagón et al. (1995). They state that the evolution of Andisols in Colombia is commonly the formation of humus, and allophane and imogolite (with pH between 5.2 and 5.7) rather than the formation of organo-metallic complexes. However, Malagón et al. (1995) noted two exceptions: Andisols with a tendency to form organo-metallic complexes (pH between 4.3 and 5.3) found in Nariño and Cauca departments meaning non-allophanic soils; and an allophanic soil in Tolima department but with less moisture and higher pH (pH between 5.8 and 6.0). In Ecuador, Buytaert et al. (2005a) obtained results indicating a non-allophanic soil where Al_p/Al_o >0.58 in the epipedon with a pH between 4.3 and 5.1.

Although the mineralogy of the sites in Colombia studied by Malagón et al. (1995), were similar to that found in this study, where the mafic minerals plagioclase and amphiboles are the prevailing ones, the ecosystem conditions in Nariño and Cauca departments are different and may explain the differences in the soil; a higher elevation (>3,100 m), with a wetter and colder climate, may favor the accumulation of humus, which in turn decreases the pH, favoring the formation of metal-humus complexes. In the case of the non-allophanic Andisols of Ecuador, they have developed over older volcanic ash deposits with more felsic minerals and lower pH, which also favor the formation of metal-humus complexes.

Another interesting observation of the Andisols in the Sonora watershed was the SOC content found in the A and B horizons (Fig. 3.8). It has been suggested by Shoji et al. (1993) that a SOC value of 6% separates the A and B horizons, since the majority of non-allophanic soils (Al_p/Al_o >0.5) have SOC >6%. The Andisol of Sonora watershed has SOC >6% in the A horizon even though it is an allophanic soil. A high Al_p/Al_o ratio (dominance of Al-humus complexes or non-allophanic soil) is associated with a high organic matter content, but the opposite is not necessarily true (i.e., an Andisol with high organic matter content is not necessary associated with a non-allophanic soil) (Mizota and Van Reeuwijk, 1989).

These results show that the Andisols of this study are allophanic, due to the predominantly mafic nature of the volcanic ash (on which these soils formed) and the ongoing input of ash. This is in agreement with the pedogenic young age of these Andisols. Interestingly, the allophanic Andisols of this study have considerable amounts of SOC (>6%), even though these levels of SOC are more common in non-allophanic soils, in which organo-metallic complexes are dominant.

3.3.3 Relationships between short-range order (SRO) minerals and soil properties

Correlations among all parameters for the two soil orders are given in Appendix E, Table E1. There were few significant correlations using this combined data set, therefore correlations between SRO minerals, and physical and chemical soil properties were assessed for each soil independently. Spearman´s Rho correlation coefficients (r) for Andisols and Inceptisols are presented in Table 3.5 for all horizons and by A and B horizons, individually. Statistically significant relationships are found in Andisols between SRO minerals and organo-metallic complexes and pH, texture, SOC and bulk density. In contrast, within Inceptisols only a limited number of correlations were found.

Table 3.5 Spearman´s Rho correlation coefficients (r) between short-range order (SRO) minerals and organo-metallic complexes (Al_p and Fe_p) with soil physical and chemical soil properties in: a) Andisols all horizons and by horizon; b) Inceptisols all horizons and by horizon

	Al_p[1] (g/kg)	Fe_p[1] (g/kg)	Allophane (%)	Ferrihydrite (%)	Al_p[1] (g/kg)	Fe_p[1] (g/kg)	Allophane (%)	Ferrihydrite (%)	Al_p[1] (g/kg)	Fe_p[1] (g/kg)	Allophane (%)	Ferrihydrite (%)
a) Andisols	All horizons (n= 44)				A horizon (n= 17)				B horizon (n= 19)			
pH H_2O	-0.46	-0.47	0.56					0.50				
pH $CaCl_2$			0.69								0.51	
Sand (%)			0.52						-0.65	-0.55	0.68	
Silt (%)	0.41	0.46							0.59	0.57	-0.66	
Clay (%)			-0.59						0.62			
SOC[2] (%)	0.82	0.82						-0.55				0.71
ρ_s[3] (kg/m^3)												
ρ_b[3] (kg/m^3)		-0.45		-0.43							-0.51	-0.76
b) Inceptisols	All horizons (n= 42)				A horizon (n= 18)				B horizon (n= 19)			
pH H_2O	-0.53								-0.60			
pH $CaCl_2$	-0.57								-0.67			
Sand (%)							0.55					0.59
Silt (%)												-0.52
Clay (%)												
SOC[2] (%)				0.51								0.59
ρ_s[3] (kg/m^3)												
ρ_b[3] (kg/m^3)												

[1]Pyrophosphate-extractable aluminum (Al) and iron (Fe) (Al_p and Fe_p); [2]SOC: soil organic carbon; [3]ρ_s: particle density; ρ_b: bulk density; correlations shown are the ones $r > 0.4$; Gray cells show correlations with $p < 0.01$ and white cells show correlations with $p < 0.05$

3.3.3.1 Relationships between organo-metallic complexes, pH and soil organic carbon (SOC)

Within Andisols, strong relationships were found among organo-metallic complexes, pH and SOC. Organo-metallic complexes are predominately formed in the A horizon with higher SOC (Figs. 3.9c and 3.9d). Higher quantities of SOC and organometallic complexes in turn are related to lower pH in the A horizon (Figs. 3.9a and 3.9b). Although SRO minerals were predominant in the Andisols of this study, organo-metallic complexes were formed in the A horizon where there was higher SOC and lower pH in comparison to the B horizon.

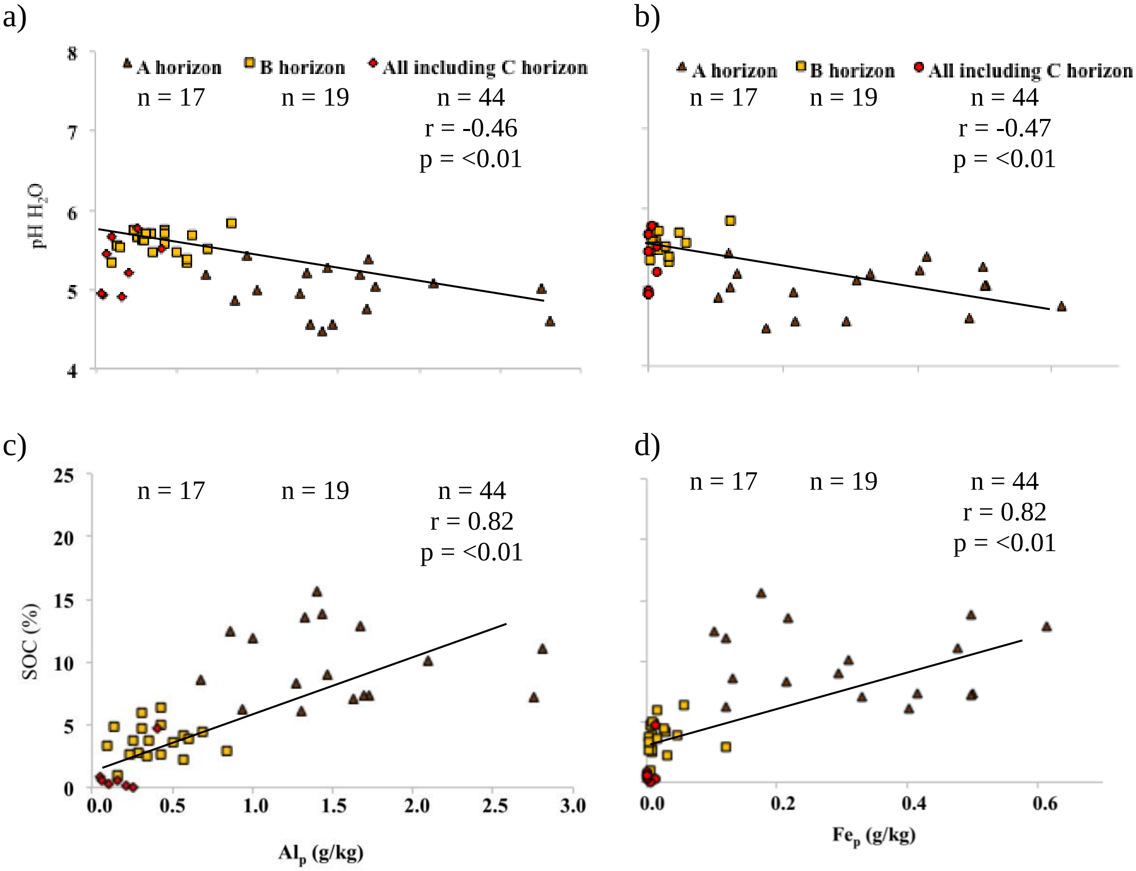


Figure 3.9 Relationships between: a) pyrophosphate extractable aluminum (Al_p) and pH_{H2O}; b) pyrophosphate extractable iron (Fe_p) and pH_{H2O}; c) Al_p and SOC; and d) Fe_p and SOC in A, B and C horizons of Andisols

In contrast to the relationships found in Andisols, there was no significant correlation between pyrophosphate extractable iron (Fe_p) and SOC in Inceptisols (Table 3.5b and Fig. 3.10); however, there was a relation with pH. The lack of relationships between Fe_p and Al_p with SOC, suggests that these metals were not bound strongly to organic matter in Inceptisols. As shown by Kaiser and Zech (1996), pyrophosphate may extract Al attached to hydroxides such as boehmite and gibbsite. It may also extract Fe attached to Fe-oxides such as ferrihydrite and goethite (Parfitt and Childs, 1988). The presence of these minerals in Inceptisols was confirmed by XRD. Boehmite was found in significant amounts in the C horizon and trace amounts in both A and B horizons (Table 3.3). Also, goethite, hematite and magnetite were present in most horizons (Table 3.3). Ferrihydrite was also assessed via oxalate extraction and it was found in higher concentrations in the A horizon of Inceptisols compared to any horizon in Andisols (Table 3.3). There was a correlation between Al_p and pH_{H2O} in the B horizon of Inceptisols (Fig. 3.10a), indicating a lower pH with higher concentrations of aluminum oxides (i.e., boehmite). The lack of a relationship between organo-metallic complexes and SOC in Inceptisols, indicates that pyrophosphate extractable Al and Fe are related to iron and aluminum oxides. These results are in accordance with XRD results (Section 3.3.1).

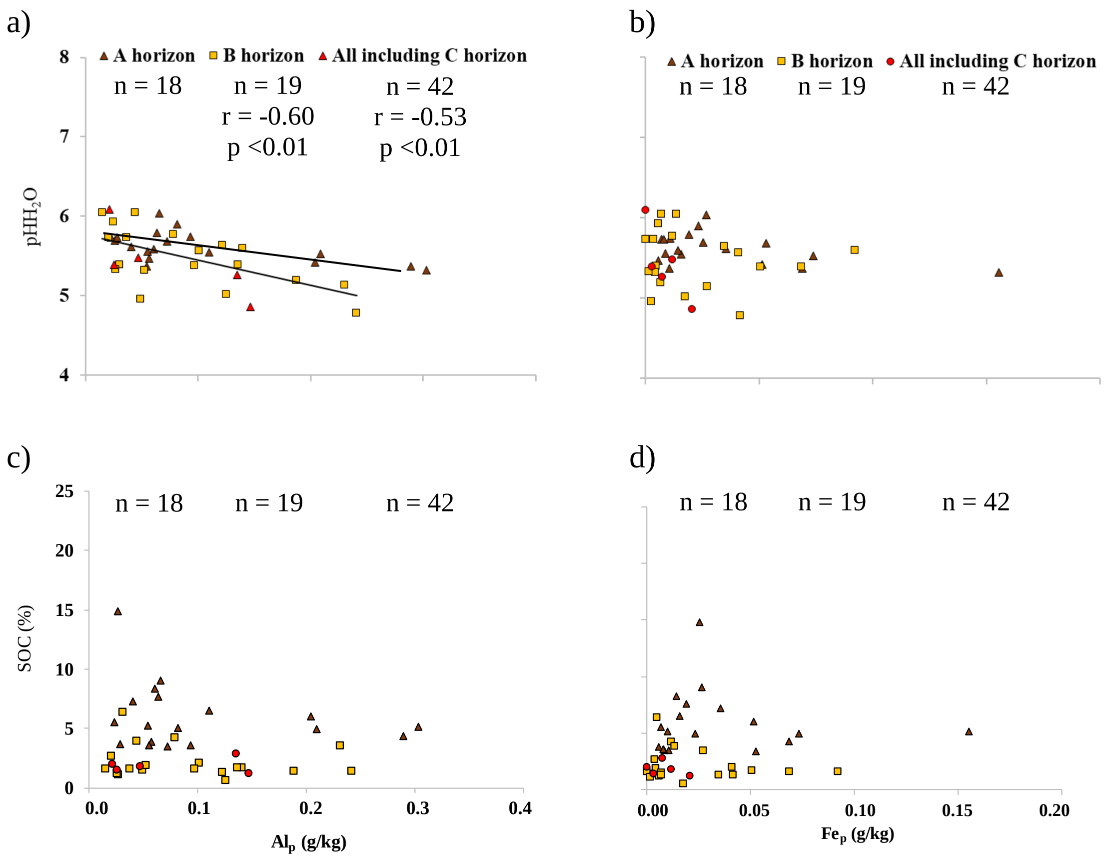


Figure 3.10 Relationships between: a) pyrophosphate extractable aluminum (Al_p) and pH_{H2O}; b) pyrophosphate extractable iron (Fe_p) and pH_{H2O}; c) Al_p and SOC; and d) Fe_p and SOC in A, B and C horizons of Inceptisols

3.3.3.2 Relationships between short-range order (SRO) minerals, pH and soil organic carbon (SOC)

As was the case with the organo-metallic complexes in Andisols, SRO minerals were also correlated with pH and SOC. Andisols of the Sonora watershed, although being allophanic, show a clear differentiation in pH between the two horizons: a pH_{CaCl2} value of 4.5 separates the A and B horizons in Andisols (Fig. 3.11a). This difference in pH, favors allophane and imogolite formation in the B horizon, while inhibiting SRO mineral formation in the A horizon. It is known that pH is an important factor in the formation of SRO minerals; at lower pH, higher amounts of organic matter and felsic minerals favor the formation of metal-humus complexes, while at higher pH, mafic minerals favor the formation of SRO minerals. This can be seen by the correlation between pH_{CaCl2} and allophane and imogolite in Andisols (Fig. 3.11a).

In the B horizon of Andisols, there was a positive correlation between ferrihydrite and SOC (Fig. 3.11d), which suggests a stabilizing effect of SRO on SOC (Broadbent et al., 1964; Dahlgren et al., 2004; Egli et al., 2008; Parfitt, 2008). This is in accordance with Kaiser et al. (2011) and Regelink et al. (2013) who conclude that ferrihydrite dominates the surface area available for sorption of SOC, stabilizing it and forming organo-mineral assemblages, despite their small contribution to soil mass (<1%) (Regelink et al., 2013).

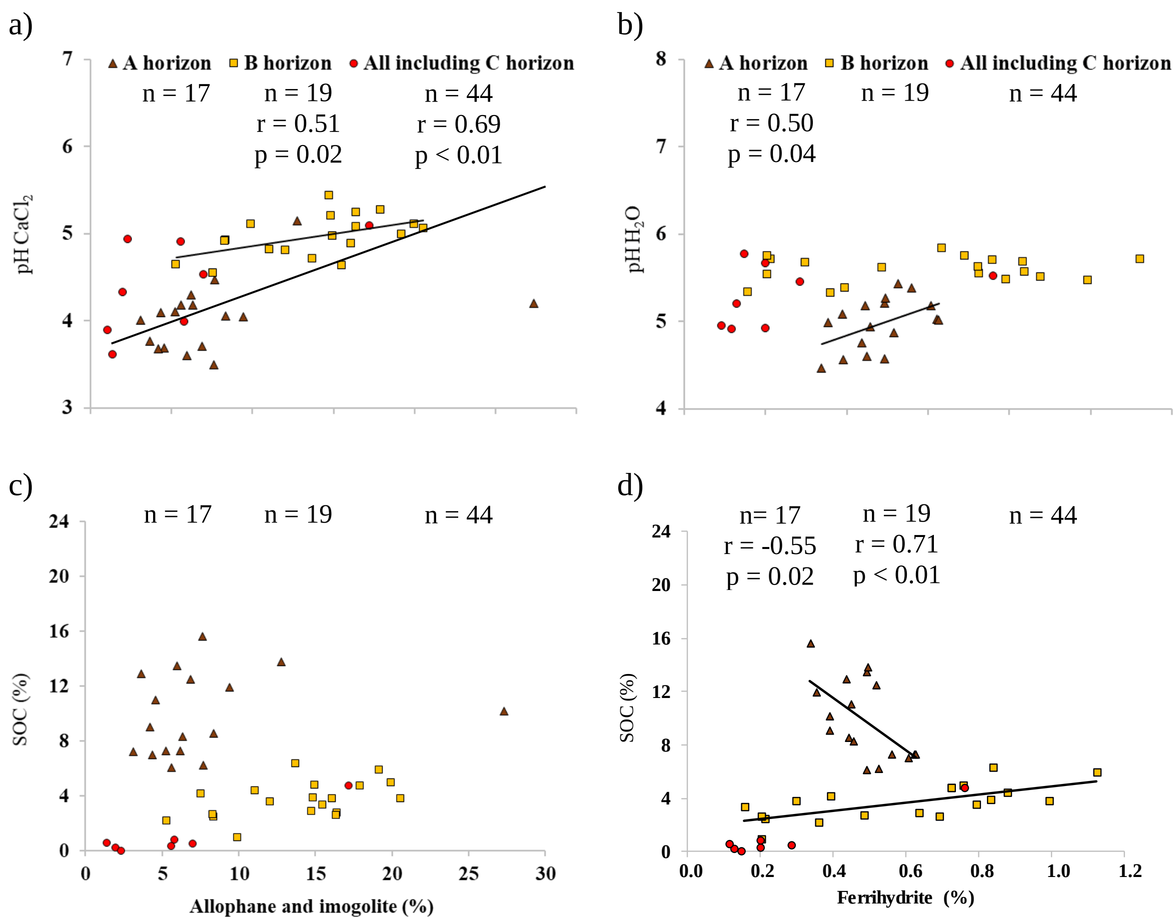


Figure 3.11 Relationships between: a) allophane and imogolite and pH_{CaCl2}; b) ferrihydrite and pH_{H2O}; c) allophane and imogolite and soil organic carbon (SOC); and d) ferrihydrite and SOC in A, B and C horizons of Andisols

There was also a positive correlation between ferrihydrite and SOC in the B horizon of Inceptisols (Fig. 3.12) as occurred with Andisols. This may be interpreted as ferrihydrite having a stabilizing effect on SOC in Inceptisols as well.

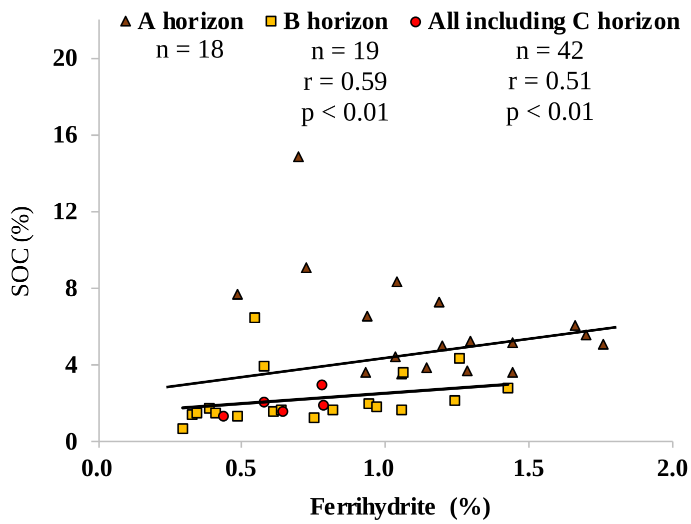


Figure 3.12 Relationship between ferrihydrite and soil organic carbon (SOC) in A, B and and C horizons of Inceptisols

The stabilizing effect of ferrihydrite on SOC is important since assemblages may be less susceptible to decomposition (Broadbent et al., 1964; Dahlgren et al., 2004; Egli et al., 2008; Parfitt, 2008). Both the rate and stability of aggregation generally increases with SOC and surface area (Bronick and Lal, 2005), both of which are relatively high in Andisols and Inceptisols. Thus, both Andisols and Inceptisols at mid-elevations in the Colombian Andes have mineralogical properties that benefit carbon stabilization, in comparison to soils without SRO minerals.

3.3.3.3 Relationships between short-range order (SRO) minerals and organo-metallic complexes with bulk density (ρ_b)

Bulk density (ρ_b) was correlated with SRO minerals and organo-metallic complexes in Andisols, but not in Inceptisols. Low bulk density (ρ_b) is characteristic of Andisols with values typically ranging from 400 to 800 kg/m^3 (Shoji et al., 1993). Median ρ_b in the Sonora watershed was 566 kg/m^3 in the A horizon and increased with depth to 667 kg/m^3

and 766 kg/m^{3}in the B and C horizons, respectively. ρ_b decreased with the increase of SRO minerals in the B horizon (Figs. 3.13a and 3.13b), and with the increase of organo-metallic Fe, which was higher in the A horizon (Fig. 3.13d).

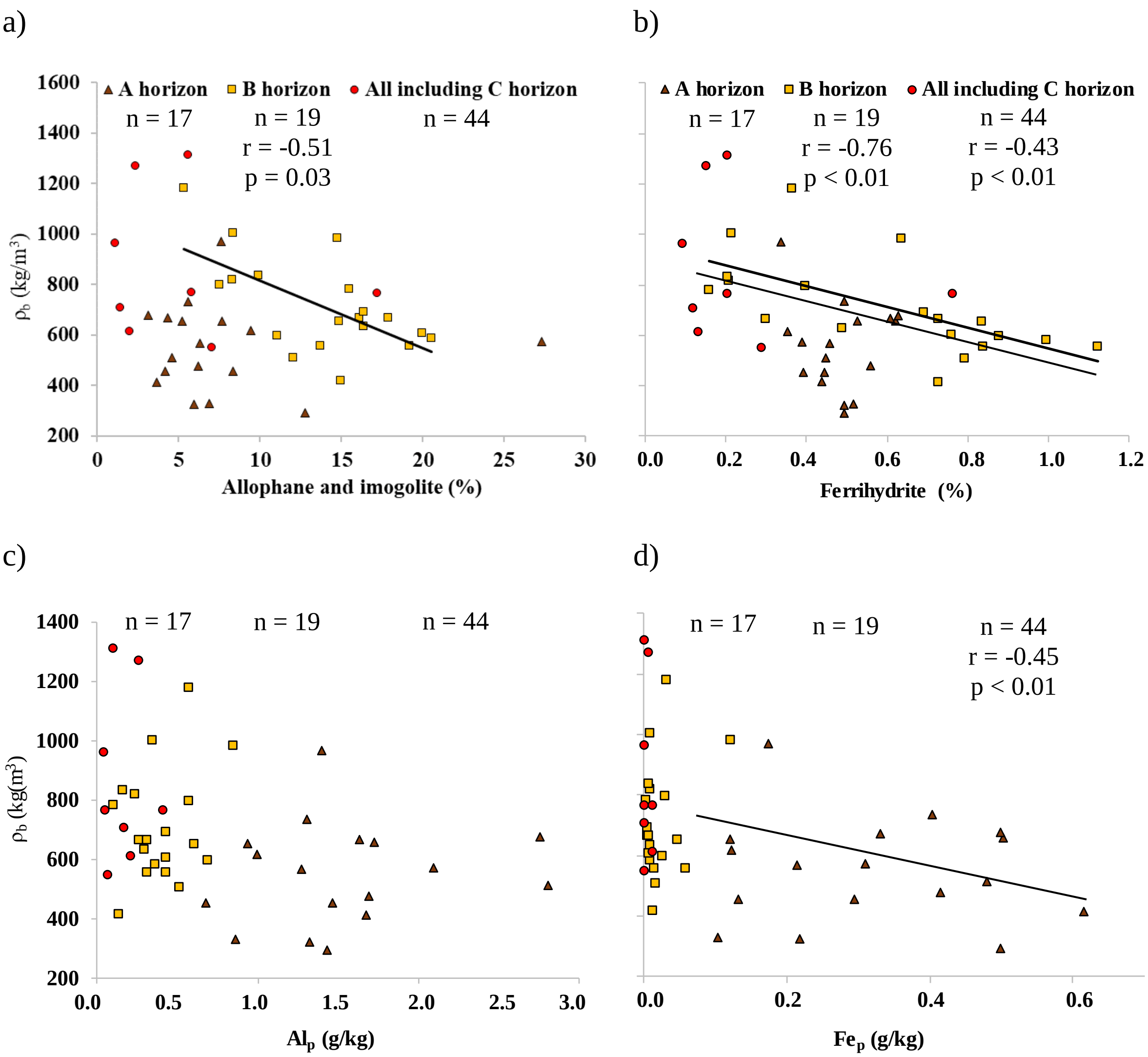


Figure 3.13 Relationships between: a) allophane and imogolite with bulk density (ρ_b); b) ferrihydrite with ρ_b; c) pyrophosphate extractable aluminum (Al_p) with ρ_b; d) pyrophosphate extractable iron (Fe_p) with ρ_b in A, B and C horizons of Andisols

Median ρ_b in Inceptisols of the El Chocho watershed was 852 kg/m^3 in the A horizon and increased with depth to 990 kg/m^3 and 972 kg/m^3 in the B and C horizons, respectively.

3.3.3.4 Relationships between short-range order (SRO) minerals and organo-metallic complexes with soil particle size

The high specific surface area and the pH dependent charge (Eusterhues et al., 2005), allow SRO and organo-metallic complexes to combine silt and clay particles with organic matter into secondary structures or aggregates (Arias et al., 1996; Sei et al., 2002; Kaiser et al., 2011; Regelink et al., 2013). In both Andisols and Inceptisols, the measured sand size fraction increased with an increase in SRO minerals. In the B horizon of Andisols, the sand fraction increased with higher content of allophane and imogolite (Fig. 3.14a) and with less Al and Fe organo-metallic complexes (Figs. 3.14c and 3.14d). In Inceptisols, the sand size fraction increased in the A horizon with the increase of allophane and imogolite (Fig. 3.15a) and in the B horizon with the increase of ferrihydrite (Fig. 3.15b). Allophane, imogolite, and ferrihydrite can cement and coat aggregates (Goldberg et al., 2012; Shoji et al., 1993) and contribute to an over estimation of the sand size fraction. In addition, the polyphenolic groups of organic matter through their hydrophobic properties, may further stabilize aggregates (Bronick and Lal, 2005; Lal, 2007).

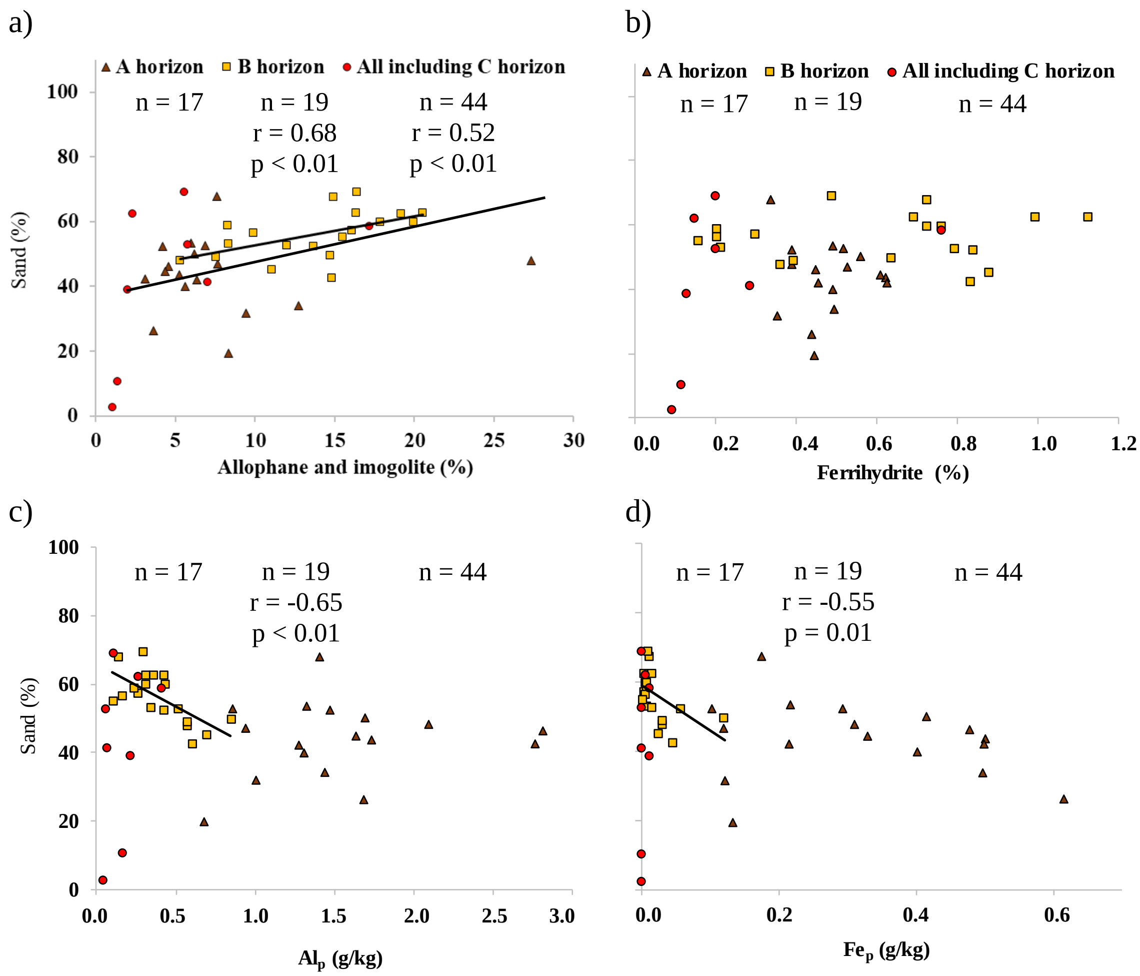


Figure 3.14 Relationships between: a) allophane and imogolite and sand particle size (sand); b) ferrihydrite and sand; c) pyrophosphate extractable Al (Al_p) and sand; and d) pyrophosphate extractable Fe (Fe_p) with sand in A, B and C horizons of Andisols

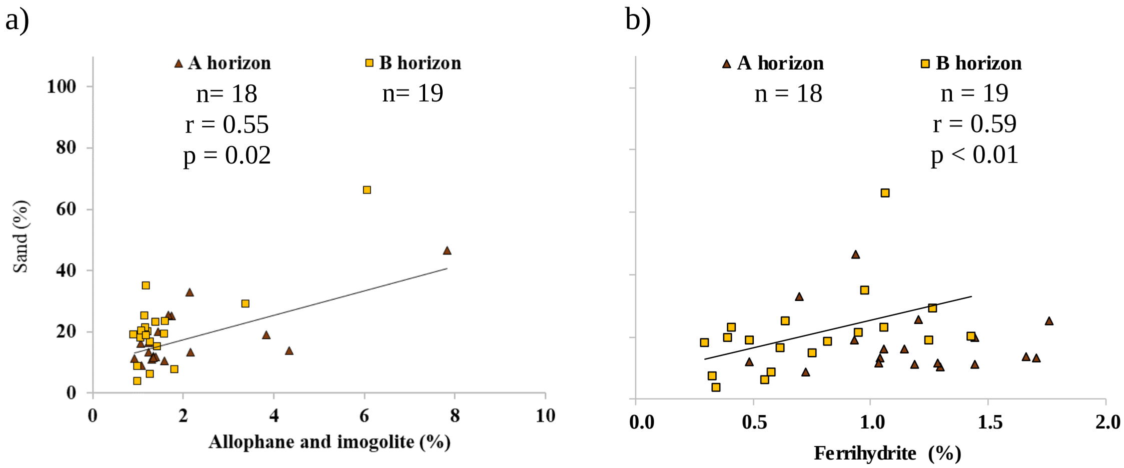


Figure 3.15 Relationships between: a) allophane and imogolite and sand particle size (sand); and b) ferrihydrite and sand in A and B horizons of Inceptisols

The majority of the Andisol samples had < 40% clay size fraction, with lower variability in the B horizon, thus classifying the soils as sandy loam, loam or sandy clay loam. C horizon samples ranged from sandy loam to clay (Fig. 3.16a). In contrast, most samples of Inceptisols had > 40% clay size fraction (Fig. 3.16b). The majority of A and B horizon samples had clay texture followed by silty clay loam. There are only a few samples, largely in the C horizon, in the sandy clay loam texture class.

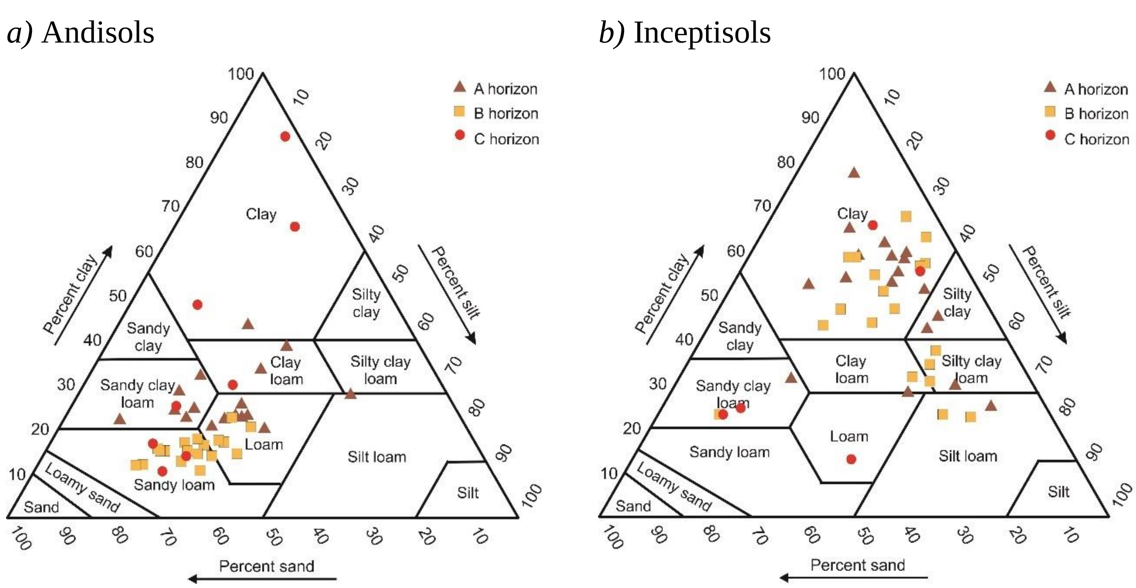


Figure 3.16 Soil texture triangles showing textural classes for the A, B, and C horizons of: a) Andisols and b) Inceptisols

Although texture in Andisols is not a differentiating property for separating Andisols from other orders, findings of this study were similar to studies in Colombia by Diaz and Paz (2002) and Hincapié (2011) that classified Andisols as sandy soils, with >40% sand size particles. Diaz and Paz (2002) used the Bouyucous method and Hincapié (2011) used the pipette method after oxidizing the organic matter with H_2O_2.

Previous studies of the Typic Dystrudepts (Inceptisols) in the El Chocho watershed reported that the soils have a clay texture (IGAC and CVC, 2004). Those results are in agreement with the texture classes found in this study.

3.4 Conclusions

The Andisols and Inceptisols of this study are both formed on mafic parent materials. In Andisols, primary minerals of mafic nature such as amphiboles and micas were predominant, while in Inceptisols, secondary minerals which are products of the weathering of mafic rocks (diabase and basalt) were predominant.

The Andisols, despite being located in the oldest branch of the Andean mountains, are young soils. This may be due to the sporadic deposition of ash and its mafic nature. These mafic minerals increase pH and favor the formation of SRO minerals. Yet these soils are dominated by SOC with limited development of organo-metal complexes in the A horizon, indicating they are young soils. In contrast, the Inceptisols, despite being located in a geologically younger branch of the Andes, contain more weathered secondary minerals such as kaolinite, halloysite, boehmite and hematite, indicating a more advanced stage of weathering.

Andisols and Inceptisols of my study, despite of being developed on different parent materials and climatic conditions, both contain SRO minerals: allophanes, imogolite and ferrihydrite in Andisols, and Al/Fe oxides, especially ferrihydrite in Inceptisols. Although the kind and amounts of these high specific surface SRO minerals vary between both soil types, they all may contribute to the water retention characteristics.

SRO minerals appear important in stabilizing SOC in both Andisols and Inceptisols. Ferrihydrite was in low concentrations in both soils, with the highest concentrations (<2%), found in the A horizon of Inceptisols. However, even at low concentrations, ferrihydrite may stabilize SOC. Correlations between SOC and ferrihydrite were stronger than between SOC and allophane and imogolite, particularly in the B horizons of both soils. Allophane and imogolite may also stabilize SOC in the B horizon of Andisols, where concentrations were the highest.

In addition to stabilizing SOC, SRO minerals appear to increase the apparent proportion of the sand size fraction in both soil orders, by aggregation processes. Significant correlations were found between SRO minerals and the sand size fraction, predominantly in A and B horizons.

SRO minerals in the Andisols and Inceptisols of this study are important for carbon stabilization and aggregate formation, which also may contribute to SWR. As these are the predominant soils in the Colombian Andes, occupying 66% of the region, knowing their mineralogical characteristics is particularly important for understanding their SWR characteristics.

4. SOIL WATER RETENTION CHARACTERISTICS OF ANDISOLS AND INCEPTISOLS AT TWO MID-ELEVATION SITES IN THE COLOMBIAN ANDES

4.1 Introduction

Soil water processes have not received much research attention in Colombia, nor the Andes (Buytaert et al., 2005b; Quintero et al., 2009), or the tropics in general (Hodnett and Tomasella, 2002), despite their relevance for water supplies, food production and the resilience of ecosystems.

Very little is known about SWR characteristics of Inceptisols in Colombia despite the fact they occupy 55% of the Colombian Andean area, in contrast to Andisols which occupy about 11%. The few studies carried out in Andisols and the even fewer carried out in Inceptisols in Colombia have focused on natural forest and páramo ecosystems at high elevation zones (i.e., >2,700 m) and in coffee plantations at lower elevations (i.e., 1,200-1,800 m) (Daza et al., 2014; Diaz and Paz, 2002; Hincapié, 2011). The interest in soils of the páramo ecosystems is based on the importance of these ecosystems for water supply, especially since large cities such as Quito and Bogotá rely almost entirely on surface water from the páramo (Buytaert et al., 2007). The interest in Andisols cultivated for coffee is based on the geographical location of Andisols in the coffee region (i.e., 350,000 ha or about 40% of the total area of this region). The importance of this region, is exemplified by research on SWR characteristics financed by CENICAFE, the Colombian Research Center for Coffee (Hincapié and Tobón, 2010).

Soil water retention (SWR) characteristics are categorized by three main components: (i) hygroscopic water or the soil water content at permanent wilting point (θ_{PWP}), (ii) plant available water storage (PAWS), and (iii) gravitational water (GW). θ_{PWP} is water that is held tightly by the colloidal fraction in soils, and occupies the smallest soil pores and thus it is not available to plants. PAWS is the water that is held by capillary forces, stored in medium size pores and is available to plants. GW corresponds to water in the macro-pores, and moves by gravitational force. Most GW drains from the saturated soil profile during the first few days after a rain event, but GW moves relatively slowly compared to overland flow (i.e., water that does not infiltrate into the soil and moves as surface flow). Soils with high $\theta_{PWP,}$ such as soils with high clay content, generally have lower PAWS, which is often amended by irrigation for plant growth and productivity. In addition, soils with high θ_{PWP}, generally have lower GW, which implies less macro-pore volume to buffer the hydrological response to a rain event (O´Geen, 2013). Thus, GW contributes to hydrological buffer capacity as the soil water storage attenuates stream flow response to rainfall events (Herron, 2001). SWR studies of Andisols in Colombia have shown that in addition to having high θ_{PWP}, they also have high PAWS and GW, indicating high SWR and a wide pore size distribution (Diaz and Paz, 2002; Hincapié, 2011) which may be related to the presence of SRO minerals. Studies of Inceptisols are less easy to generalize because Inceptisols are in the early stages of development, and SWR will depend on soil mineralogy and the local ecosystem conditions.

Despite the recognition of the importance of these soils in Colombia, relationships among mineralogical, chemical and physical soil properties, and SWR have been poorly studied. Given that Andisols in Colombia are mostly allophanic (Malagón et al., 1995; Jaramillo, 2002), studies on water retention would benefit from the determination of short-range order (SRO) minerals, dominant in allophanic soils. However, studies which have been conducted on the water retention characteristics of Colombian soils (Diaz and Paz, 2002; Hincapié, 2011; Henao, 2001) have not included the determination of SRO minerals. On the other hand, studies that evaluated the mineralogical, chemical and physical properties of Andisols in Colombia (Malagón et al., 1995; Jaramillo, 2002; Chinchilla et al., 2011) often lack a description of water retention characteristics. The study by Buytaert et al. (2006) on non-allophanic soils in Ecuadorian páramos found significant relations between soil organic carbon (SOC) content, bulk density (ρ_b), and soil water retention at 1,500 kPa.

The study objectives addressed in this chapter were to compare the SWR characteristics of Andisols and Inceptisols, located at two mid-elevation sites in the Colombian Andes, and to assess the relationships between SWR characteristics and soil properties. Findings of this study will enhance the overall understanding of the differences between these two soil types and contribute to data on the characteristics of soils at mid-elevations in the Colombian Andes.

4.2 Experimental conditions and laboratory analyses

Soils were sampled as described in Section 2.3. From each of the two soils (Andisols and Inceptisols), 18 soil pits (6 under natural forest and 12 in pasture) were excavated and composite soil samples were taken by horizon. These composite soil samples were analyzed for: short-range order (SRO) minerals, soil pH in H_2O and in $CaCl_2$, SOC, soil particle size distribution, soil bulk density (ρ_b), and soil particle density (ρ_s). Analysis of SRO minerals is described in Section 3.2.1.2, while analyses of soil chemical and physical properties are described in Section 3.2.2.

Soil water retention cores (45 cm^3) were also taken from each soil horizon to 1.20 m depth. All cores sampled from the 18 pits were analyzed for the following soil water retention characteristics: soil water content (θ) at saturation (Sat), field capacity (FC), 100 kPa, 500 kPa, and 1,500 kPa or permanent wilting point (PWP). Numbers of soil samples collected from each soil order by land use type and horizon are provided in Figure 4.1.

4.2.1 Soil water retention curves

Soil water retention (SWR) curves were determined on undisturbed soil cores using pressure plate apparatus at tensions ranging from 10 to 1,500 kPa (Klute, 1986). The generally used value for FC (33 kPa) has been reported to be inappropriate for volcanic soils or Andisols from humid regions due to their aggregating properties, and 10 kPa has been suggested as a more appropriate value for estimating FC (Saigusa et al., 1987). In general, 1,500 kPa is considered to correspond to PWP for most soils. Therefore, in this study the following tensions were used: saturation at 0 kPa (Sat); 10 kPa or FC, 100 kPa, 500 kPa and 1,500 kPa or PWP.

The pore radius associated with each pore size class was determined using the capillary rise equation (Eqtn. 3.1) and the associated soil water tension.

$$\mathrm{r} = \frac{2\tau \cos \phi}{h g \rho_w} \qquad \text{Eqtn. 3.1}$$

Where:

r = radius of capillary (or pore)

τ = surface tension of water against air, ~ 0.074N/m at 10°C

ϕ = wetting angle (~0° for clean glass capillary or wettable soil, hence cos ϕ = 1)

ρ_w = water density, 1000 kg/m^3

g = gravitational acceleration, 9.81 m/s^2

h = height of rise at equilibrium

The components of soil water, their abbreviations, definitions, the corresponding pore size classes, the associated pore radius and the soil tensions used in this study are presented in Table 4.1.

Given that 1,500 kPa was defined as the PWP, hydroscopic water was considered as soil water trapped by crypto-pores in pore radii < 0.1 µm.

Table 4.1 Soil water component and associated abbreviations, symbols and pore size class

Soil water component	Abbrevia-tion	Symbol	Pore size class[1]	Pore radius		Soil water tension
				mm	**µm**	**kPa**
Total porosity	f	θ_{Sat}	Macro, meso, micro, ultramicro, and crypto-pores	>0.015 – <0.0001	>15 - < 0.1	< 10 - > 1,500
Gravitational water	GW	$\theta_{Sat} – \theta_{FC}$	Macro-pores	>0.015	>15 µm	< 10
Plant available water storage	PAWS	$\theta_{FC} – \theta_{PWP}$	Meso-pores	0.0015 – 0.015	0.015 mm or 1.5	10 – 100
			micro-pores and	0.0003 – 0.0015	0.3 – 1.5	100 – 500
			ultramicro-pores	0.0001 - 0.0003	0.1 – 0.3	500 – 1,500
Hygroscopic water	-	θ_{PWP}	Crypto-pores	< 0.0001	< 0.1	> 1,500

[1]Based on characteristics and functions of pore size classes as provided by SSSA, 2001.

4.2.2 Statistical analyses

Soil water retention characteristics, including the measured values of θ_{Sat}, θ_{FC}, θ_{100kPa}, θ_{500kPa}, $\theta_{PWP,}$ and calculated values for plant available water storage (PAWS) and gravitational water (GW), were compared by horizons between Andisols and Inceptisols to evaluate significant differences using Mann Whitney U test and probability values (p-value) of 0.01, 0.05, and 0.1 (Fig. 4.1a). In addition, data were separated into natural forest and pasture to evaluate the differences between Andisols and Inceptisols within the same land use (Fig. 4.1a).

Relationships between SWR characteristics and soil physical and chemical properties were assessed utilizing the non-parametric Spearman's rank-order correlation. Spearman's Rho correlation coefficients (r) with values > 0.4 and probability values (p) of 0.01 and 0.05 were used to indicate notable relationships (Fig. 4.1b). Correlations were conducted for:

- Andisol and Inceptisol, all horizons
        - Andisol and Inceptisol by horizon (A, B and C horizons)
    - Andisol only, all horizons
        - Andisol by horizon (A and B horizons)
    - Inceptisol only, all horizons
        - Inceptisol by horizon (A and B horizons)

Correlations for C horizon data in individual soil orders were not assessed since there were only eight samples for Andisols and five samples for Inceptisols. Sample numbers for each analysis are provided in Figure 4.1.

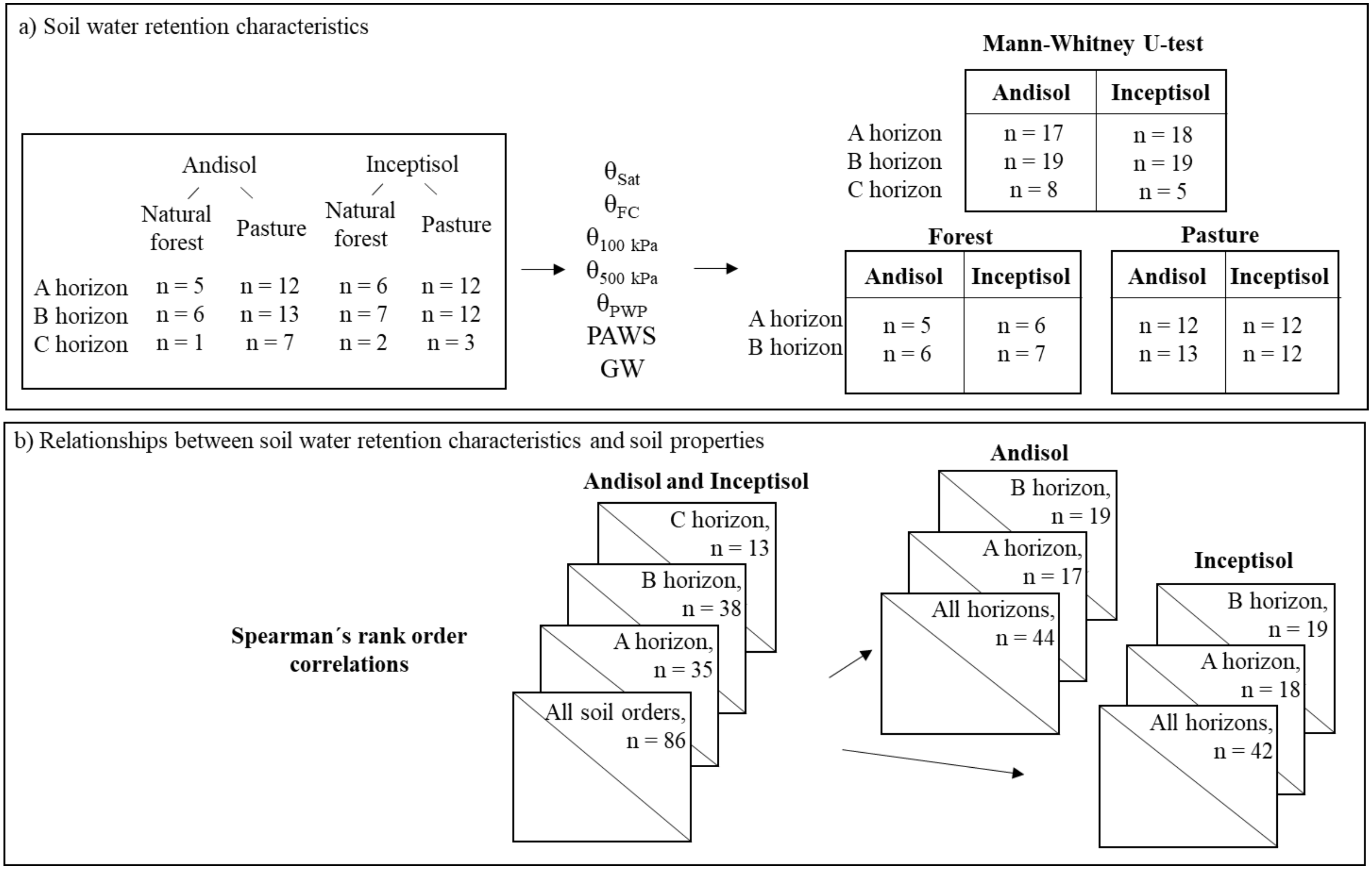


Figure 4.1 Overview of samples collected to a) compare soil water retention (SWR) characteristics between Andisols and Inceptisols and b) determine relationships between SWR characteristics and soil properties

4.3 Results and discussion

4.3.1 Soil water retention characteristics

Soil water retention (SWR) curves for Andisols and Inceptisols for A, B, and C horizons are presented in Figure 4.2. The SWR curves for Andisols are consistently above the curves of Inceptisols, indicating that Andisols hold more water than Inceptisols at every soil tension in all horizons. Soil texture of the Andisols and Inceptisols of this study were classified as loam and clay, respectively (Section 3.3.3.4), yet their SWR characteristics do not correspond with typical values for these textural classes as commonly cited in the literature (Rawls et al., 1982 and 2004.). The soils in this study have greater total porosity and higher θ_{PWP} than values often reported for clay textured soils (i.e., 55-60% total soil porosity and θ_{PWP} 20-24%) (Rawls et al., 1982 and 2004).

The shape of the SWR curves of A horizons in Andisols and Inceptisols were similar (Fig. 4.2a) with both curves displaying a decrease in soil water content from FC to 100 kPa and from 500 to 1500 kPa. The steeper sections of the SWR curve indicate that in the A horizons of both soil orders, there were a higher proportion of meso-pores between 1.5 and 15 μm, and ultramicro-pores with radii between 0.1 and 0.3 μm. When it comes to the B horizon, in Inceptisols, the slope of the SWR curve was relatively uniform from saturation to PWP, indicating a uniform pore size distribution, while in Andisols, the slope was slightly steeper from 10 to 100 kPa, suggesting a larger volume of meso-pores between 1.5 and 15 μm (Fig. 4.2b). Water retention curves for the C horizon, were similar in shape for both soil types with a slight change in soil water content between 100 and 500 kPa for Inceptisols (Fig. 4.2c). SWR characteristic curves under forest and pasture (Figs. 4.3 and 4.4) showed the same trends, but differences between the two soil orders were more pronounced under pasture than forest.

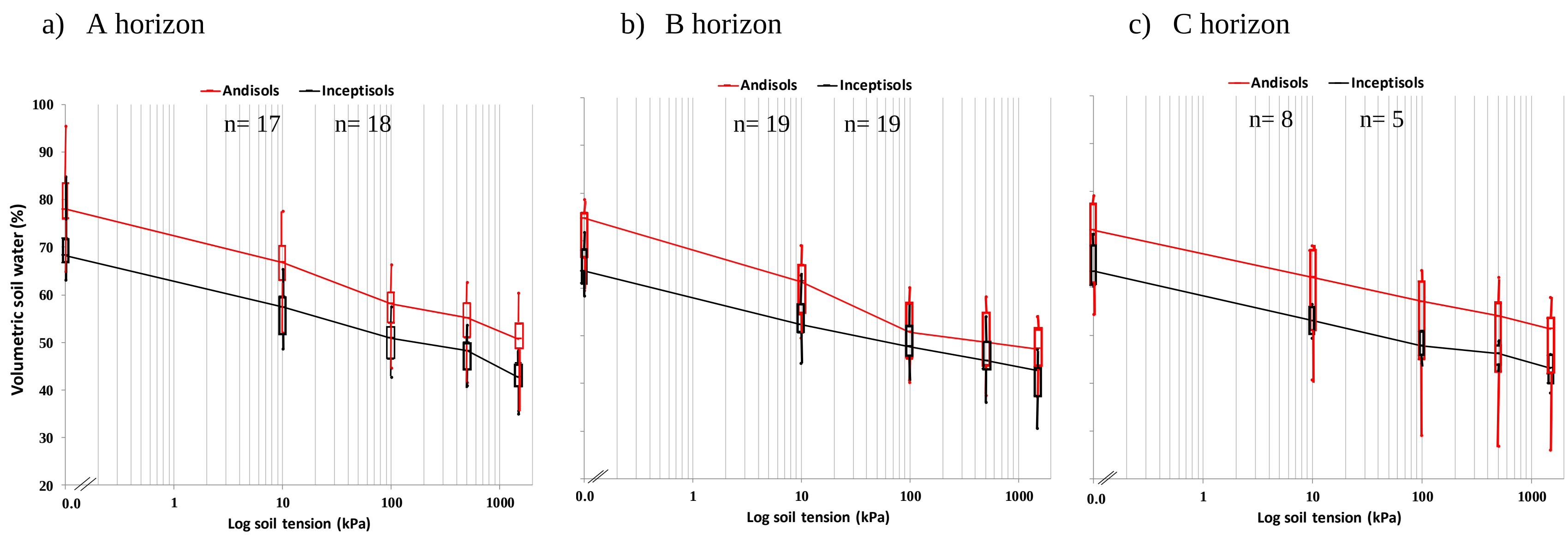


Figure 4.2 Median results by soil horizon for soil water retention (SWR) curves of Andisols and Inceptisols in: a) A horizon, b) B horizon and c) C horizon

a) Forest A horizon

b) Forest B horizon

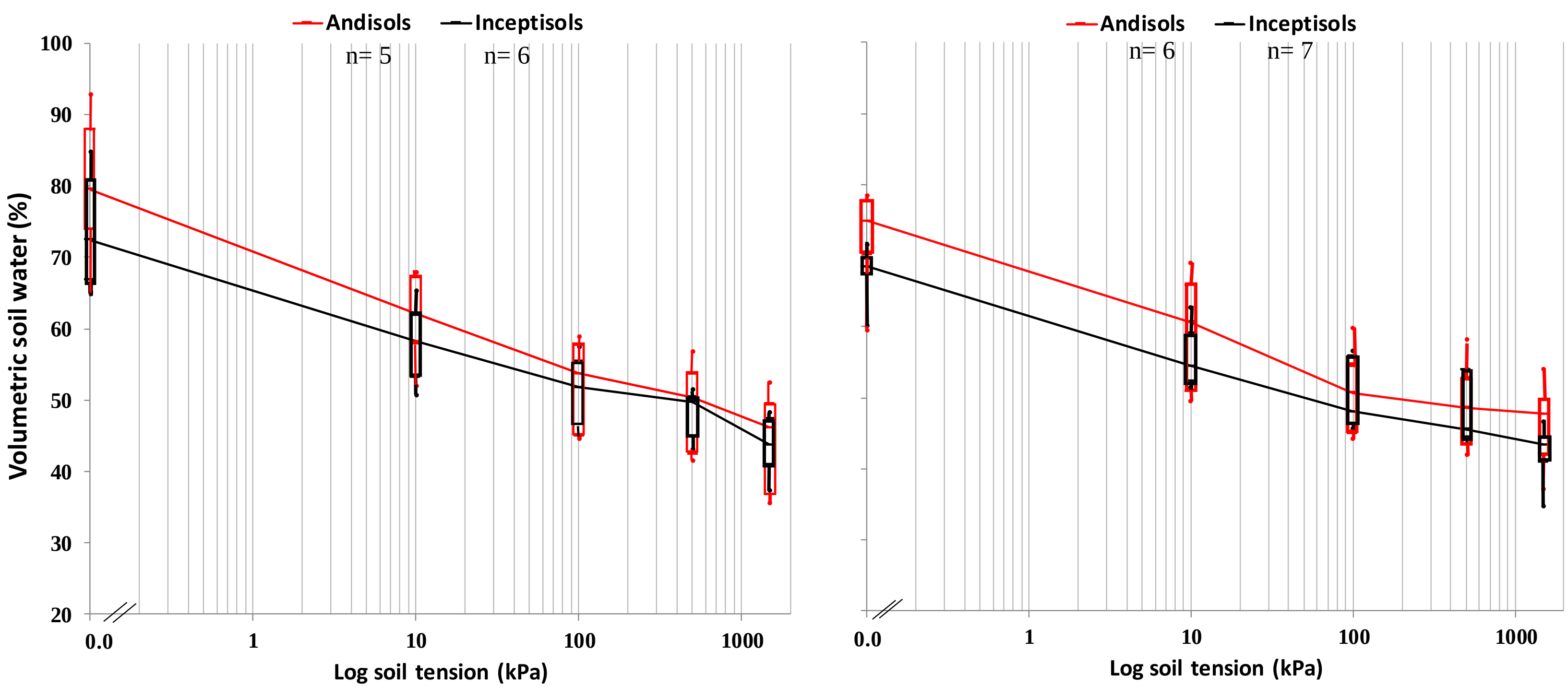


Figure 4.3 Median results and quartiles for soil water retention (SWR) curves in Andisols and Inceptisols for forest in: a) A horizon and b) B horizon

a) Pasture A horizon

b) Pasture B horizon

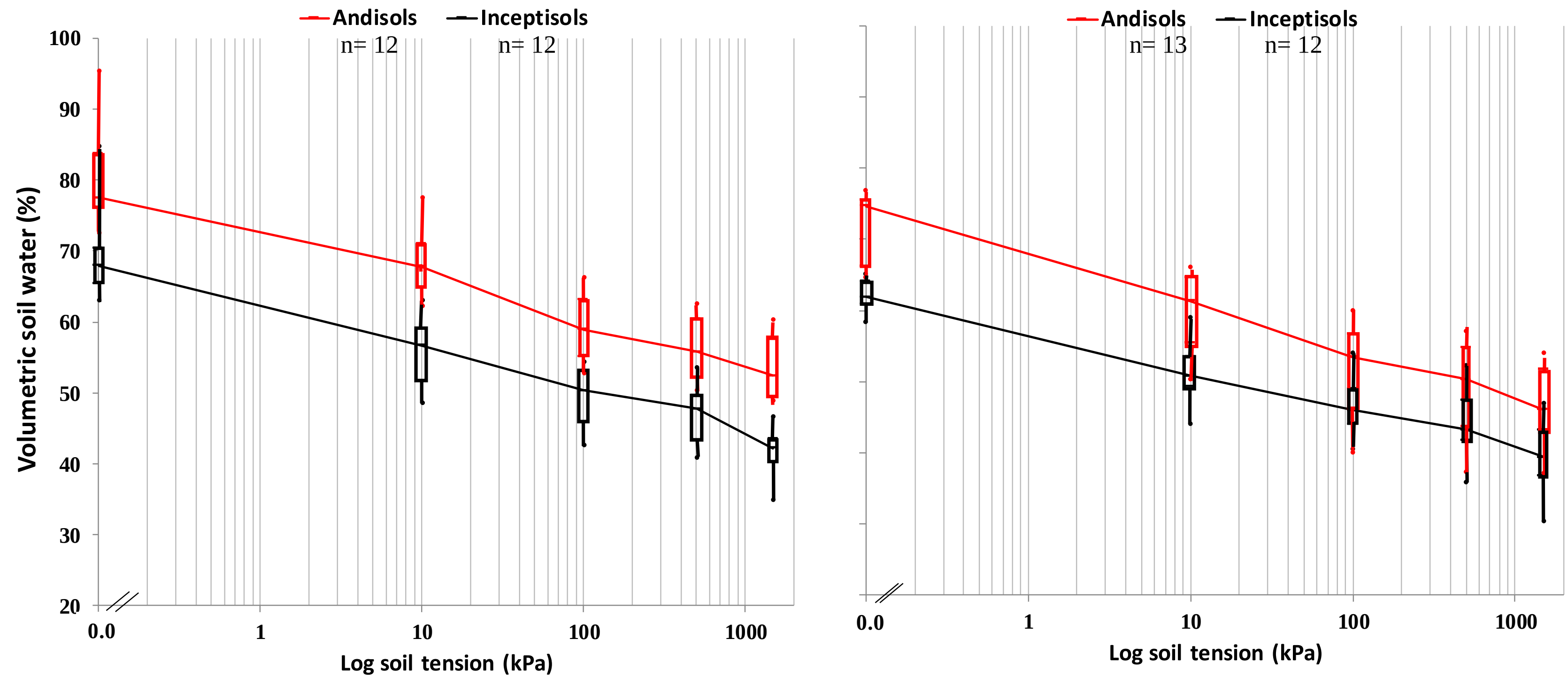


Figure 4.4 Median results and quartiles for soil water retention (SWR) curves in Andisols and Inceptisols for pasture in: a) A horizon and b) B horizon

Median values for SWR characteristics (θ_{Sat}, θ_{FC}, and θ_{PWP}) for each horizon were significantly different between Andisols and Inceptisols (Appendix F). However, when separating natural forests from pastures, statistically significant differences were observed only between Andisols and Inceptisols under pasture (Table 4.2). Differences under pasture were observed at every soil tension in the A horizon and at saturation (Sat), FC, and PWP in the B horizon. Despite these differences, PAWS and GW under pasture were similar between the two soil orders. In constrast, under forest, the two soils have similar SWR characteristics, but PAWS in the A horizon was statistically higher in Andisols than in Inceptisols (Table 4.2).

The SWR characteristics of Andisols and Inceptisols in this study were compared to values reported by Rawls et al. (1982, 2004) who carried out studies to estimate water retention based on soil properties (Table 4.3). Both Andisols and Inceptisols have higher θ_{PWP} than those reported for clay textured soils, and moderate to high values for PAWS and GW. Both soils, but especially Andisols, due to their higher θ_{PWP} and location in a high precipitation region, may be more susceptible to compaction when physical degradation occurs (Toohey et al., 2018). Compaction in the Sonora watershed was observed during field work, particularly at sites such as water troughs where livestock gather, and horse trails used in forest harvesting. Soils at these sites lacked vegetation cover, and due to physical compaction, may be prone to water erosion (Kimble et al., 2000) and to the destruction of soil aggregates (Herrera et al., 2007).

Table 4.2 Median values for soil water retention (SWR) characteristics in A, B and C horizons for natural forest and pasture in Andisols and Inceptisols

	Natural forest		Pasture	
Horizon	Andisols	Inceptisols	Andisols	Inceptisols
		θ_{Sat}[1] (%v/v)		
A	79.2 (70.9-83.1)[2]	72.4 (66.8-80.8)	77.5 (76.1-83.7)	67.9 (65.4-70.4)**
B	74.9 (70.3-77.7)	68.4 (67.4-69.5)$^{+}$	74.7 (66.3-75.6)	61.9 (60.8-64.1)**
		θ_{FC}[1] (%v/v)		
A	63.2 (55.9-67.5)	58.2 (53.2-61.9)	67.8 (64.9-71.0)	56.6 (51.7-58.9)**
B	60.6 (50.9-65.9)	54.5 (52.3-59.1)	61.4 (55.5-64.7)	50.8 (49.3-53.5)**
		$\theta_{100\ kPa}$[1] (%v/v)		
A	55.0 (45.0-58.2)	51.8 (46.5-55.4)	58.9 (55.1-63.2)	50.3 (46.0-53.1)**
B	50.7 (44.9-54.5)	48.1 (46.2-55.9)	53.4 (46.2-56.8)	46.0 (44.1-49.0)
		$\theta_{500\ kPa}$[1] (%v/v)		
A	50.8 (42.2-54.7)	49.8 (45.0-50.4)	55.8 (52.2-60.5)	47.7 (43.3-49.7)**
B	48.6 (43.3-53.0)	45.6 (44.4-53.9)	50.4 (43.8-51.7)	43.3 (41.7-47.3)
		θ_{PWP}[1] (%v/v)		
A	44.1 (36.4-50.5)	43.8 (40.9-47.5)	52.5 (49.5-57.5)	42.2 (40.2-43.5)**
B	47.7 (42.1-49.7)	43.4 (40.9-44.2)	46.1 (43.4-51.7)	39.4 (36.8-43.2)**
		PAWS[3] (%v/v)		
A	18.4 (15.9-20.9)	13.5 (12.1-16.9)$^{+}$	15.4 (11.8-17.3)	13.3 (11.9-15.7)
B	14.3 (10.1-15.4)	12.5 (10.2-19.5)	12.6 (10.3-15.1)	11.0 (9.3-13.5)
		GW[4] (%v/v)		
A	12.8 (10.9-21.2)	16.8 (12.9-18.9)	10.9 (9.5-12.4)	11.4 (8.9-18.1)
B	11.4 (8.9-18.5)	10.4 (8.8-15.1)	11.5 (8.4-14.4)	11.7 (7.3-12.8)

[1]θ_{Sat}, θ_{FC}, $\theta_{100\ kPa}$, $\theta_{500\ kPa}$, θ_{PWP}: soil water content (θ) at saturation (Sat), field capacity (FC), 100 kPa, 500 kPa and at permanent wilting point (PWP), respectively; [2]Values in parenthesis are first and third quartile, [3]PAWS: plant available water storage; [4]GW: gravitational water; Number of samples (n) for natural forest, were 5 and 6 in Andisols, 6 and 7 in Inceptisols; for pasture were 12 and 13 in Andisols, 12 and 12 in Inceptisols, for A and B horizons, respectively; **, $^{+}$ Significant differences between Andisols and Inceptisols with Mann Whitney U test at $p < 0.01$, and $p < 0.1$, respectively

Table 4.3 First and third quartile of volumetric water content for Andisols and Inceptisols in A horizon and literature values for three pure textural classes

Soil water component or pore size class	Volumetric water content (%)						
	Soil textural class[4]			Natural forest		Pasture	
	Sand	Loam	Clay	Andisols (n=5)	Inceptisols (n=6)	Andisols (n=12)	Inceptisols (n=12)
θ_{PWP}[1] or crypto-pores	2-4	8-12	20-24	36-50	41-47	49-57	40-43**
PAWS[2] or meso-, micro- and ultramicro-pores	4-10	17-20	12-16	16-21	12-17[+]	12-17	12-16
GW[3] or macro-pores	16-18	10-13	5-8	11-21	13-19	9-12	9-18
Approximate total porosity	20-25	40-45	55-60	71-83	67-81	76-84	65-70

[1]θ_{PWP}: soil water content at permanent wilting point; [2]PAWS: plant available water storage; [3]GW: gravitational water; **, [+] Significant differences between Andisols and Inceptisols at $p < 0.01$ and $p < 0.1$, respectively. [4]Source for soil textural class data: Rawls et al., 1982 and 2004.

The high soil water content at PWP in both Andisols and Inceptisols, implies that a high portion of the pore volume contains water that is not available to plants. Despite this high hygroscopic water content, both soil types have considerable values for GW and PAWS. The value of PAWS in Andisols under forest was similar to a typical loam soil, while the PAWS values for Andisols under pasture and Inceptisols under both land uses were similar to that reported for a typical clay soil. This relatively high PAWS is important for forage and crops, particularly in the El Chocho watershed (Inceptisol site), given the lower annual precipitation at this site. The values of GW in Andisols and Inceptisols under both land uses were intermediate between sandy and loam soils (Table 4.3), implying a considerable hydrological buffering capacity.

The high total soil porosity of both Andisols and Inceptisols relative to typical clay textured soils, may be due to high specific surface area (SSA) of the dominant colloids in the soils of the study sites. In particular allophane and imogolite (700-1500 m^2/g), ferrihydrite (220-560 m^2/g), Al and Fe oxides (90-140 m^2/g), and SOC (800-900 m^2/g) all have high SSA (Table 3.1) in comparison to clay minerals such as illite, chlorite and kaolinite, with SSA < 40 m^2/g.

The higher values of SWR in Andisols relative to Inceptisols (Appendix F), may be related to the type of high surface area colloids and their abundance. Allophane for example, has a nanoparticle size and a hollow spherical structure of 3.5 to 5 nm in diameter (Van Wambeke, 1992) that stores water within its structure (Wada, 1985). Similarly, imogolite has a hollow tubular structure of 2 nm outer diameter (Nanzyo, 2002). Furthermore, these soil colloids, in addition to their nano-particle size and high specific surface area, have positive and negative charges (Table 3.1), forming aggregates with silt and clay particles, increasing pore volume (Kaiser et al., 2011; Regelink et al., 2013; Arias et al., 1996; Sei et al., 2002; Regelink et al., 2015).

Comparing the Andisols of this study with other data from the Andes (Table 4.4) suggests that high organo-metallic compounds and high SOC (found in páramo ecosystems in non-allophanic soils) increase both macro and crypto-pore volume. The Andisol of this study, is predominantly allophanic with lower amounts of SOC and organo-metallic compounds relative to páramo ecosystems, but has considerable amount of SRO minerals, relatively lower gravitational and hygroscopic water content, and higher PAWS (Table 4.4). This suggests that Andisols, such as in this study, which have SOC $< 17\%$ by weight, but considerable amounts of SRO minerals (4-10% allophane), may have comparatively more PAWS. This comparison between Andisols in the Andes, highlights the importance of Andisols at mid-elevations, since they have both higher PAWS and considerable GW, which is important for food production and water supply. In Colombia, most Andisols are allophanic with a predominance of SRO minerals in the B horizon and low amounts of organo-metallic complexes in the A horizon.

Table 4.4 Water retention characteristics of Andisols of this study and other regional studies

Country	Ecosystem	θ_{PWP}[1] (cm^3/cm^3)	PAWS[2] (cm^3/cm^3)	GW[3] (cm^3/cm^3)	SOC[4] in A horizon (%)	Allophane (%)	Al_p/Al_o[5]	Reference
Colombia	**Natural forest**	**36-50**[6]	**16-21**	**11-21**	**10-15**	**4-7**	**0.07 - 0.16**	**This study**
	Pasture	**49-57**	**12-17**	**9-12**	**7-11**	**5-9**	**0.05 - 0.13**	
Ecuador	Páramo	48-59	-	-	32-37	-	0.9 – 1.11	Buytaert et al., 2006
Colombia	Páramo	68-69	8.8-9.7	18-33	35-38	-	-	Diaz and Paz, 2002
Colombia	Natural forest	45	8	29	**16**	-	-	Tobón et al., 2010
	Pasture	48	15	19	**8**	-	-	
Colombia	Coffee plantations	27-44	13-25	8-12	6-7	5-10	-	Hincapié, 2011

[1]θ_{PWP}: soil water content (θ) at permanent wilting point (PWP); [2]PAWS: plant available water storage; [3]GW: gravitational water; [4]SOC: soil organic carbon; [5]Al_p/Al_o: Indicator for determing allophanic or non-allophanic soils; [6]Results shown from this study are the first and third quartile in the A horizon

Inceptisols may develop on a variety of parent materials including volcanic ash. The Inceptisol in the study of Henao (2001), which has significant amounts of SRO minerals (Table 4.5) was developed on a volcanic ash, limiting the comparability to the Inceptisols of the El Chocho watershed sampled in my study. However, based on available research, it is possible that SWR characteristics of Inceptisols in the region, are related to SOC and the presence of SRO minerals such as allophane or ferrihydrite.

Table 4.5 Water retention characteristics of Inceptisols of this study and other regional studies

Country	Ecosystem	θ_{PWP}[1] (cm^3/cm^3)	PAWS[2] (cm^3/cm^3)	GW[3] (cm^3/cm^3)	SOC[4] in A horizon (%)	Allophane (%)	Reference
Colombia	**Natural forest**	**41-47**[5]	**12-17**	**13-19**	**5-10**	**1.2-3.6**	**This study**
	Pasture	**40-43**	**12-16**	**9-18**	**4-6**	**1.2-2.1**	
Colombia	Páramo	34-44	23-26	21-19	18	-	Daza et al., 2014
Colombia	Forest	-	18-33	-	-	-	Morales, 2008
Colombia	Coffee plantations	-	-	-	3.5	4-13	Henao, 2001

[1]θ_{PWP}: soil water content (θ) at permanent wilting point (PWP); [2]PAWS: plant available water storage; [3]GW: gravitational water; [4]SOC: soil organic carbon; [5] Results shown are the first and third quartile in A horizon

4.3.2 Relationships between soil water retention characteristics and soil properties

Correlations among SWR characteristics and soil properties for the two soils in this study are given in Appendix E, Table E2. There were few significant correlations using the complete data set. As the objective was to compare the two soil orders, correlations are presented for each soil separately comparing all horizons and each horizon (Table 4.6).

Andisols showed positive correlations between SWR characteristics and the clay size fraction, SOC, and Al and Fe associated with SOM (pyrophosphate extractable Al_p and Fe_p), when the complete dataset was used (Table 4.6a). In contrast, only SOC was positively correlated with SWR in Inceptisols. The only common factor in both soil orders was ρ_b, which was negatively correlated with SWR. In contrast to the complete data set where there were no correlations with SRO minerals and SWR, allophanes and ferrihyrite, presented significant positive correlations in A and/or B horizons in both soils (Table 4.6).

Table 4.6 Spearman´s Rho correlation coefficients (r) between soil water retention (SWR) characteristics and soil physical and chemical soil properties in all horizons and in A and B horizons in: a) Andisols; and b) Inceptisols

	θ_{Sat}[1] (%v/v)	θ_{FC}[1] (%v/v)	$\theta_{100\ kPa}$[1] (%v/v)	$\theta_{500\ kPa}$[1] (%v/v)	$\theta_{PWP\ kPa}$[1] (%v/v)	PAWS[2] (% v/v)	GW[3] (% v/v)	θ_{Sat}[1] (%v/v)	θ_{FC}[1] (%v/v)	$\theta_{100\ kPa}$[1] (%v/v)	$\theta_{500\ kPa}$[1] (%v/v)	$\theta_{PWP\ kPa}$[1] (%v/v)	PAWS[2] (% v/v)	GW[3] (% v/v)	θ_{Sat}[1] (%v/v)	θ_{FC}[1] (%v/v)	$\theta_{100\ kPa}$[1] (%v/v)	$\theta_{500\ kPa}$[1] (%v/v)	$\theta_{PWP\ kPa}$[1] (%v/v)	PAWS[2] (% v/v)	GW[3] (% v/v)
a) Andisols	All horizons (n= 44)							A horizon (n= 17)							B horizon (n= 19)						
Sand (%)		-0.53	-0.52	-0.54	-0.58				-0.56		-0.56	-0.64									
Silt (%)																					
Clay (%)	0.40	0.54	0.54	0.49	0.49			0.63	0.78	0.60	0.57										
SOC[4] (%)	0.70	0.51				0.65								0.48	0.88						
Al_p[5] (g/kg)	0.49	0.51				0.51															
Fe_p[5] (g/kg)	0.54	0.49				0.49															
Allophane (%)										0.60	0.54										
Ferrihydrite (%)															0.78						
ρ_b[6] (kg/m^3)	-0.84	-0.53				-0.53		-0.80					-0.66		-0.81						-0.47
b) Inceptisols	All horizons (n= 42)							A horizon (n= 18)							B horizon (n= 19)						
Sand (%)																					
Silt (%)																					
Clay (%)																					
SOC[4] (%)	0.44																				
Al_p[5] (g/kg)															0.49	0.67		0.50			
Fe_p[5] (g/kg)														0.49							
Allophane (%)																			0.46		
Ferrihydrite (%)																					
ρ_b[6] (kg/m^3)	-0.77					-0.50	-0.58	-0.84	-0.61	-0.51		-0.48	-0.65	-0.51	-0.63						-0.58

[1]θ_{Sat}, θ_{FC}, $\theta_{100\ kPa}$, $\theta_{500\ kPa}$, θ_{PWP}: soil water content (θ) at saturation (Sat), field capacity (FC), 100 kPa, 500 kPa and at permanent wilting point (PWP), respectively; [2]PAWS: plant available water storage; [3]GW: gravitational water; [4]SOC: soil organic carbon; [5]Pyrophosphate-extractable aluminum and iron (Al_p and Fe_p); [6]ρ_b: bulk density; correlations shown are the ones $r > 0.4$; Gray cells show correlations with $p < 0.01$ and white cells show correlations with $p < 0.05$

4.3.2.1 Relationships between soil water retention (SWR) characteristics and texture

The clay size fraction had an effect on SWR in the A horizons of Andisols. There were positive correlations between soil water content and the proportion of clay size fraction at tensions up to 500 kPa (Table 4.6a and Fig. 4.5), reflecting the high SWR characteristics of the clay fraction.

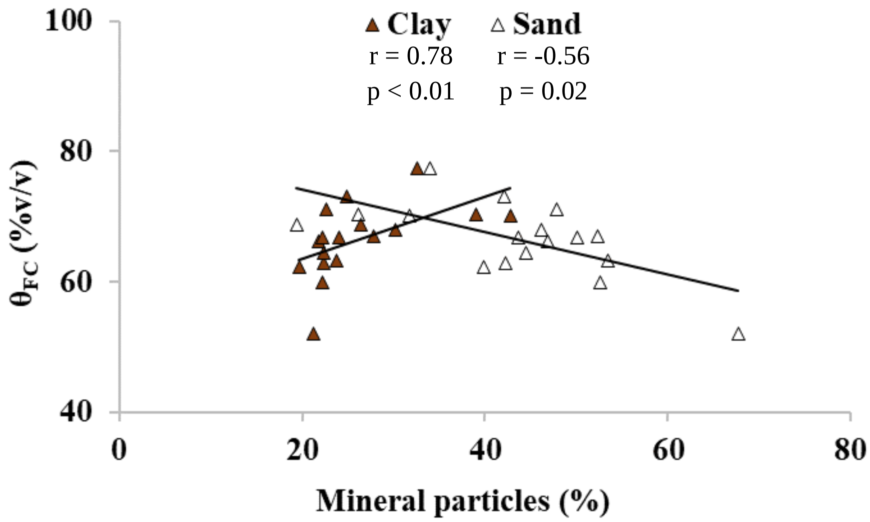


Figure 4.5 Relationship between proportion of size fractions of clay size (clay) and sand size (sand) with soil water retention at field capacity (θ_{FC}) in A horizon of Andisols, n= 17

While the texture of Andisols of the Sonora watershed were dominantly sandy loam and loam, Inceptisols of the El Chocho watershed have a clay texture, with clay size fraction >40% in the majority of the samples (Section 3.3.3.4). Due to the high specific surface area, the % clay size fraction contributes to the relatively high SWR of Inceptisols. However, there were no statistically significant correlations between texture and water retention in Inceptisols (Table 4.6b).

4.3.2.2 Relationships between soil water retention characteristics (SWR), bulk density (ρ_b) and soil organic carbon (SOC)

As expected, (ρ_b) was negatively correlated with soil water content in both soil orders. There were significant correlations in Andisols and Inceptisols between soil water content at saturation (θ_{Sat}) and bulk density (ρ_b) using the complete data set and also in A and B horizons (Table 4.6). In Andisols, a higher r-value was found, when all data was compared (Figure 4.6a); in Inceptisols the highest correlation was found in the A horizon (Fig. 4.6b).

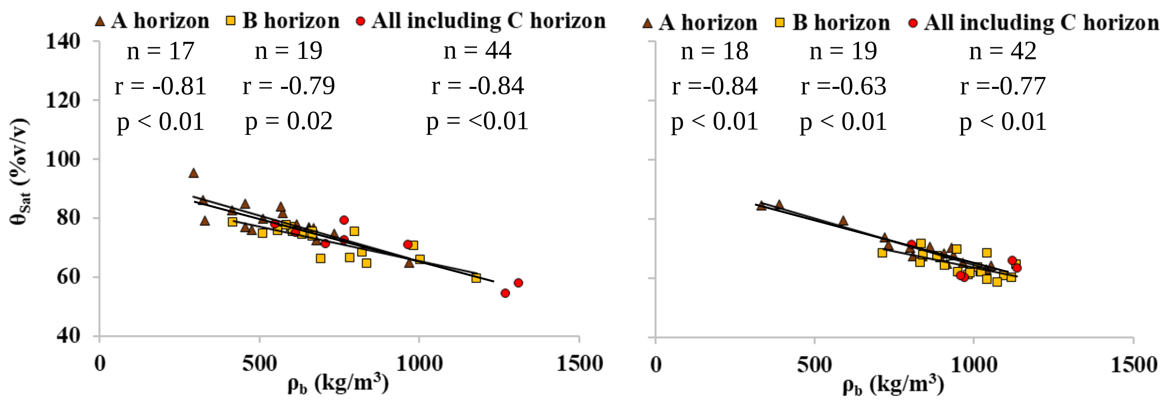


Figure 4.6 Relationships between soil water content at saturation (θ_{Sat}) and bulk density (ρ_b) in A, B and C horizons of: a) Andisols; and b) Inceptisols

The importance of SOC in enhancing SWR in both soils was shown in the B horizon of Andisols where there was a significant correlation between SOC and θ_{Sat}; and in Inceptisols with the complete data set (Fig. 4.7). In Andisols, although SOC was highest in the A horizon, there was no significant correlation between SOC and soil water content at any tension. This result leads to two observations: first, despite a lower concentration of SOC in the B horizon, SOC is an important property that increases the SWR; and second, the high correlation coefficient may be due the stabilizing effect of SRO on SOC in the B horizon (Section 3.3.3.2), which then suggests a synergistic effect of SRO and SOC that increases SWR in the B horizon.

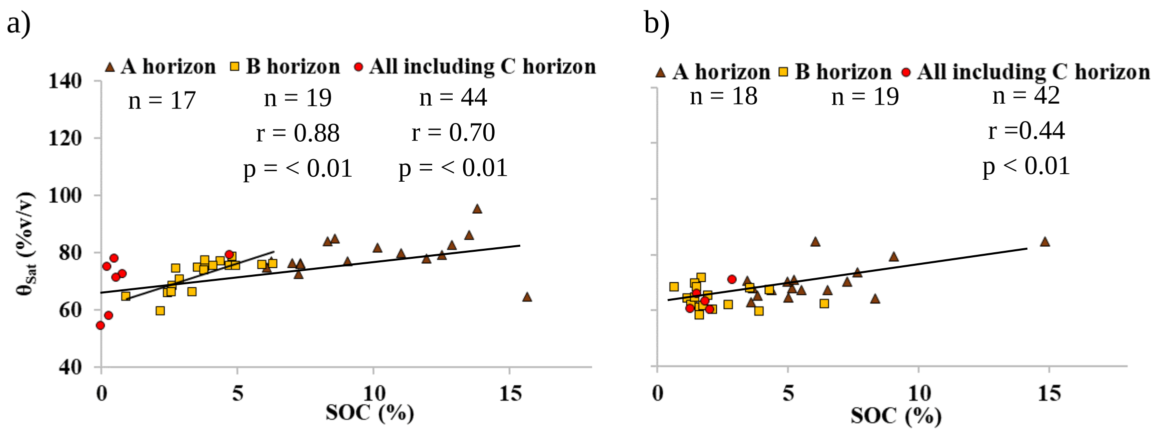


Figure 4.7 Relationships between soil water content at saturation (θ_{Sat}) and soil organic carbon (SOC) in A, B and C horizons of: a) Andisols; and b) Inceptisols

4.3.2.3 Relationships between soil water retention (SWR) characteristics and short-range order (SRO) minerals

Short-range order minerals, despite their low contribution to soil mass, had an influence on SWR characteristics. In the A horizon of Andisols there was a positive correlation between soil water content at 100 kPa (θ_{100kPa}) and allophane (Fig. 4.8b), and in the B horizon between θ_{Sat} and ferrihydrite (Fig. 4.8a). Ferrihydrite, even in lower amounts compared to allophane in Andisols, had the highest r-value with SWR. Ferrihydrite occurs mainly as coatings on soil separates, and the high number of functional groups increases SWR (Table 3.1). Additionally, the synergistic effect suggested previously between SOC and SRO minerals increasing SWR, is supported by these strong correlations found between ferrihydrite and θ_{Sat}, and ferrihydrite and SOC in B horizon of Andisols (Fig. 3.11). This role of ferrihydrite in stabilizing SOC is also reported in the literature (Kaiser et al., 2011; Regelink et al., 2013), and may further enhance SWR characteristics. Furthermore, the influence of SRO minerals on SWR characteristics is indicated by the higher PAWS in the B horizon of Andisols (Fig. 4.2b). In contrast, in the B horizon of Inceptisols, there was a significant correlation between soil water content at permanent wilting point (θ_{PWP}) and allophane (Fig 4.8c). Although allophane content was low in Inceptisols (median values in A and B horizons were 1.4 and 1.2%, respectively), allophane with its high specific surface area and hollow spherical structure, may have contributed to greater SWR at higher tensions (Table 3.1).

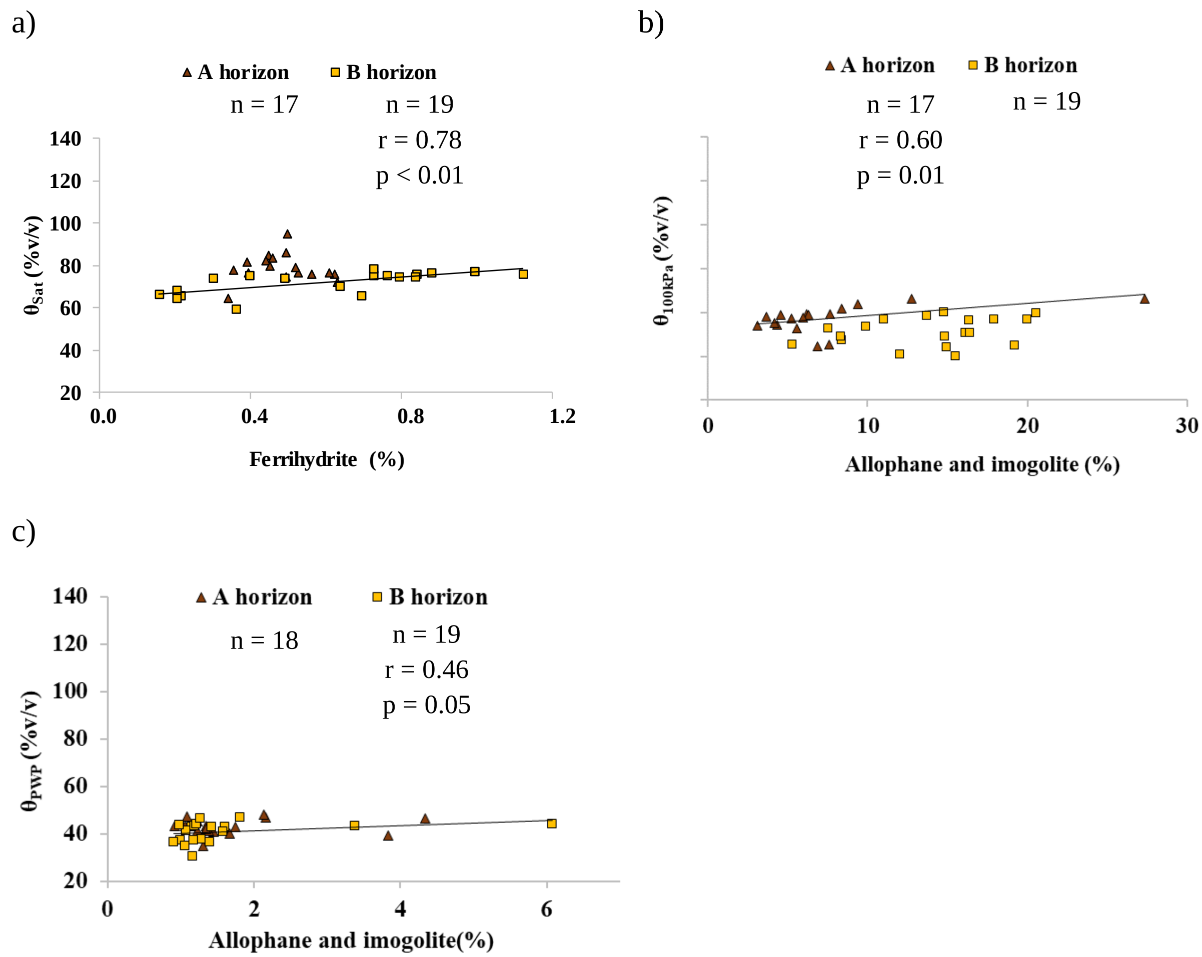


Figure 4.8 Relationships between short range order (SRO) minerals in A and B horizons of Andisols or Inceptisols: a) ferrihydrite and soil water content at saturation (θ_{Sat}) in Andisols; b) allophane and imogolite and soil water content at 100kPa (θ_{100kPa}) in Andisols; and c) allophane and imogolite and soil water content at PWP (θ_{PWP}) in Inceptisols

4.3.2.4 Relationships between soil water retention (SWR) characteristics and organo-metallic complexes

Although the influence of SOC was greater (Fig. 4.7), organo-metallic complexes had also an influence on SWR in Andisols. Positive correlations were found between Al_p and Fe_p with θ_{Sat} (r-values 0.49 and 0.54, respectively) (Table 4.6a), suggesting that organo-metalic complexes increase $\theta_{Sat.}$ However, SOC had a stronger correlation coefficient (r-value 0.70). Al_p found in the allophanic Andisols, from Sonora, was less than 3 g/kg, which is very low compared to the concentrations found in non-allophanic soils where Al_p may approach 30 g/kg (Shoji et al., 1993) and where Al-humus complexes are dominant over SRO minerals.

Typically, pyrophosphate extractable minerals are strongly correlated to SOC since pyrophosphate extracts Al and Fe complexed with organic materials, which was the case in Andisols of this study (Section 3.3.2.1). This suggests that Fe_p and Al_p are strongly associated with SOC and that poorly crystalline hydroxide phases are unlikely to have contributed significantly to the pyrophosphate extracts (Kaiser and Zech, 1996). However, this was not the case in Inceptisols (Table 3.5), indicating that Fe_p and Al_p may be associated with poorly crystalline hydroxides. Crystalline hydroxide may be Al and Fe oxides such as goethite, hematite, gibbsite, boehmite or ferrihydrite (Kaiser and Zech, 1996; Parfitt and Childs, 1988). X-ray analyses in Inceptisols (Section 3.3.1), showed the presence of hematite and boehmite in A and B horizons, boehmite, hematite and goethite in the C horizon, and ferrihydrite (by chemical extraction) was significantly higher in Inceptisols than Andisols in the A horizon. Therefore, in Inceptisols, the presence of minerals with high specific surface area, such as iron and aluminum oxides, may play an important role in increasing SWR characteristics, as shown by the correlation in the B horizon of Inceptisols, between θ_{FC} and Al_p (Fig. 4.9b). There was also a weak positive correlation between GW and Fe_p in the A horizon of Inceptisols (Fig. 4.9a).

a) b)

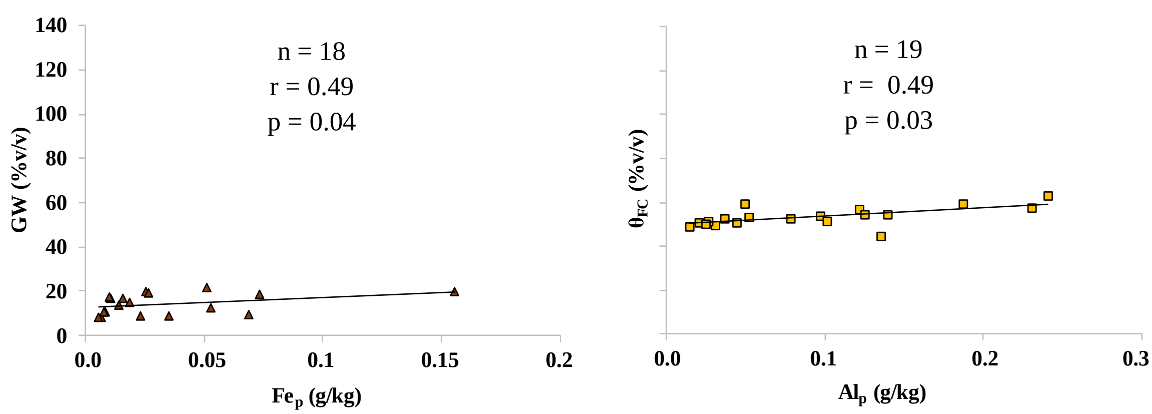


Figure 4.9 Relationships in Inceptisols between: a) pyrophosphate extractable Fe (Fe_p) and gravitational water (GW) in A horizon; and b) pyrophosphate extractable Al (Al_p) and soil water content at saturation (θ_{Sat}) in B horizon

Texture, ρ_b, SOC, ferrihydrite, allophane and imogolite and organo-metallic complexes all were correlated with SWR characteristics in Andisols (Table 4.6). In contrast, in Inceptisols, correlations with ρ_b, Fe and Al oxides, allophane and imogolite were found, but coefficient values were lower (Table 4.6). These results show the importance of SRO minerals and SOC on SWR in both soils, and the influence of organo-metallic complexes in Andisols. Allophane and imogolite were found in both soils, although concentrations were higher in Andisols. In Inceptisols, Fe and Al oxides influence SWR. Interestengly, ferrihydrite was the SRO in Andisols with the highest correlation with SWR characteristics, even at concentrations < 1%.

4.4 Conclusions

Both Andisols and Inceptisols have a high water retention capacity, particularly at high tensions (i.e., hygroscopic water). Despite the contrasting soil parent materials, climate and geographical conditions, Andisols and Inceptisols of this study share the presence of minerals with high specific surface area, that increase their ability to retain water. These minerals are allophane, imogolite, ferrihydrite and organo-metallic compounds in Andisols; and extractable ferrihydrite and other Al / Fe oxides in Inceptisols.

The SWR characteristics of Andisols and Inceptisols were significantly different in pasture, but not under natural forest. PWP was highest under pasture in Andisols (52%) and similar for Inceptisols and Andisols under natural forest (~43%). Having a high soil water content at PWP, implies that a high portion of the pore volume in both Andisols and Inceptisols was neither PAWS nor GW. Yet, despite this high hygroscopic water content, both soil types have considerable values of PAWS and GW, with no significant differences between soil orders.

In Andisols, positive correlations were found between soil water retention at different tensions and clay size fraction, SOC, ferrihydrite, allophane and imogolite, and organo-metallic compounds, which suggests that these soil properties increase soil water retention. There may also be a synergistic effect between ferrihydrite and SOC in the B horizon of Andisols that increases SWR characteristics.

In Inceptisols, positive correlations were found between soil water retention at different tensions with Al_p and Fe_p, allophane and imogolite, and SOC. Al_p and Fe_p in Inceptisols may be related to Al and Fe oxides, such as hematite, boehmite, goethite and ferrihydrite. These minerals, although present in low amounts may be increasing soil water retention in Inceptisols.

In comparison to studies from páramo ecosystems (Diaz and Paz, 2002; Buytaert et al., 2006), the results of this study suggest that non-allophanic soils (Andisols from páramo ecosystems) had greater volumes of hygroscopic and gravitational water, while allophanic soils (Andisol of this study), had higher PAWS.

Land management practices which maintain or increase soil organic matter are recommended for all soils, but particularly for soils containing SRO minerals, as SOC acts in conjunction with SRO minerals to enhance SWR characteristics. Thus, maintaining or increasing SOC in soils with SRO minerals is important for plant available water for both forest and rangeland productivity in the watersheds of this study. The relatively high PAWS in both soil orders is particularly important for forage and crop production in the El Choco watershed (Inceptisol site) due to the lower annual precipitation at this site. The high θ_{PWP} in both soil orders implies that soils retain water throughout the year. In the Sonora watershed (Andisol site), which has a wet climate, this implies that soils may be subject to compaction, especially under pasture grazed by cattle.

5. LAND USE IMPACTS ON SOIL WATER RETENTION CHARACTERISTICS OF ANDISOLS AND INCEPTISOLS AT TWO MID-ELEVATION SITES IN THE COLOMBIAN ANDES

5.1 Introduction

People living in the Colombian Andes rely on services provided by mountain ecosystems such as water supply, agriculture, biodiversity conservation and carbon storage (De Groot et al., 2002; Labrière et al., 2015; Buytaert et al., 2011). Particularly important for these ecosystem services are natural land covers such as forest, wetlands and páramos (Forsyth, 1996; Calder, 1999, 2002; Roa-García, 2009). However, as discussed in Chapter 1, these natural land cover types have been converted to pasture for cattle grazing and to agricultural crops, land uses which may not be appropriate on steeper slopes. The Colombian National Geographical Institute (IGAC) determined that within the Andean region 54% of the area has inappropriate land uses, 41% of the area being classified as overused and 13% as underused. IGAC classifies land use in three soil categories: Group I for soils adequate for intensive or semi-intensive agriculture and cattle grazing; Group II for soils adequate for agriculture, cattle grazing, forestry and agro-forestry and Group III for preservation, conservation and eco-tourism. Soils under a land use different than recommended, that causes lower benefits than expected are classified as underused soils, while soils under a land use that causes damages- mainly soil erosion- to vulnerable soils (particularly those of Group III) are classified as overused soils (IGAC, 2012).

Despite the relevance of the soil component in these ecosystems for water regulation, limited research has been conducted in the Andean region to assess the impacts of land use type on soil water retention (SWR) characteristics. The majority of studies that did evaluate the effects of land use on soil properties have been conducted in páramo ecosystems (elevation >3,500 m), which play an important role in regulating water for large cities in the Andes and in Colombia. For example, Diaz and Paz (2002) and Daza et al. (2014) reported that the conversion from natural vegetation to crops and pasture in the Colombian páramo reduced soil water content at field capacity (θ_{FC}), permanent wilting point (θ_{PWP}) and gravitational water (GW). Other studies in the Ecuadorian Andes, also found negative effects on soil characteristics such as a reduction in SOC, increased bulk density (ρ_b), and lower θ_{FC} (Buytaert et al., 2002; Buytaert et al., 2005b; Podwojewski et al., 2002). However, soils at these study sites are non-allophanic (organo-metallic complexes are predominant) and have different mineralogy and soil chemical and physical properties; hence, are not directly comparable to the soils of this study.

The objectives of this chapter were to (i) compare the effects of two common land uses (natural forest and pasture) on the SWR characteristics of Andisols and Inceptisols at two mid-elevation sites in the Colombian Andes, and (ii) determine the soil properties related to SRW characteristics.

5.2 Experimental conditions and laboratory analyses

The same experimental conditions and laboratory analyses as outlined in the previous chapter (Section 4.2) are of relevance for this chapter. From each of the two soil orders (Andisols and Inceptisols), 18 soil pits (6 under natural forest and 12 in pasture) were excavated and composite soil samples were taken by horizon. These composite soil samples were analyzed for: pH in H_2O and in $CaCl_2$, SOC, soil particle distribution, short-range order (SRO) minerals, soil bulk density (ρ_b), and soil particle density (ρ_s). In addition, soil water retention cores (45 cm^3) were taken from each soil horizon to 1.20 m depth. All cores sampled from the 18 pits were analyzed for the following soil water retention characteristics: soil water content (θ) at saturation (Sat), field capacity (FC), 100 kPa, 500 kPa, and 1,500 kPa or permanent wilting point (PWP). The number of soil samples collected on each soil order by land use and horizon are provided in Figure 5.1. Laboratory analyses are described in Sections 3.2.2 and 4.2.1.

5.2.1 Statistical analyses

Soil water retention (SWR) characteristics, including the measured values of θ_{Sat}, θ_{FC}, θ_{100kPa}, θ_{500kPa}, $\theta_{PWP,}$ and calculated values for plant available water storage (PAWS) and gravitational water (GW), were compared by horizon between natural forest and pasture to evaluate significant differences using Mann Whitney U test and probability values (p-value) of 0.01, 0.05, and 0.1 (Fig. 5.1a). In addition, data were separated into Andisols and

Incepisols to evaluate the differences between natural forest and pasture within the same soil order (Fig. 5.1a).

Relationships between SWR characteristics and soil physical and chemical properties were assessed utilizing the non-parametric Spearman's rank-order correlation. Spearman's Rho correlation coefficients (r) with values > 0.4 and probability values (p) of 0.01 and 0.05 were used to indicate notable relationships (Fig. 5.1b). Correlations were conducted for:

- Natural forest, all horizons
        - Natural forest by horizon (A, B and C horizons)
    - Natural forest in Andisol, all horizons
        - Natural forest in Andisol, by horizon (A and B horizons)
    - Natural forest in Inceptisol, all horizons
        - Natural forest in Inceptisol, by horizon (A and B horizons)
- Pasture, all horizons
        - Pasture by horizon (A, B and C horizons)
    - Pasture in Andisol, all horizons
        - Pasture in Andisol, by horizon (A and B horizons)
    - Pasture in Inceptisol, all horizons
        - Pasture in Inceptisol, by horizon (A and B horizons)

Correlations for C horizon data in individual soil orders were not assessed since there were less than three samples for the combination of land use and soil order with the exception of Andisols under pasture which had a total of seven samples.

Soil properties including soil particle size, organo-metallic complexes (Al_p and Fe_p), allophane, imogolite and ferrihydrite, and bulk density (ρ_b) were compared for each soil order by horizon for natural forest and pasture to evaluate any significant differences using Mann Whitney U test and probability values (p-value) of 0.01, 0.05, and 0.1 (Fig. 5.1c). Sample numbers for statistical analyses are provided in Figure 5.1.

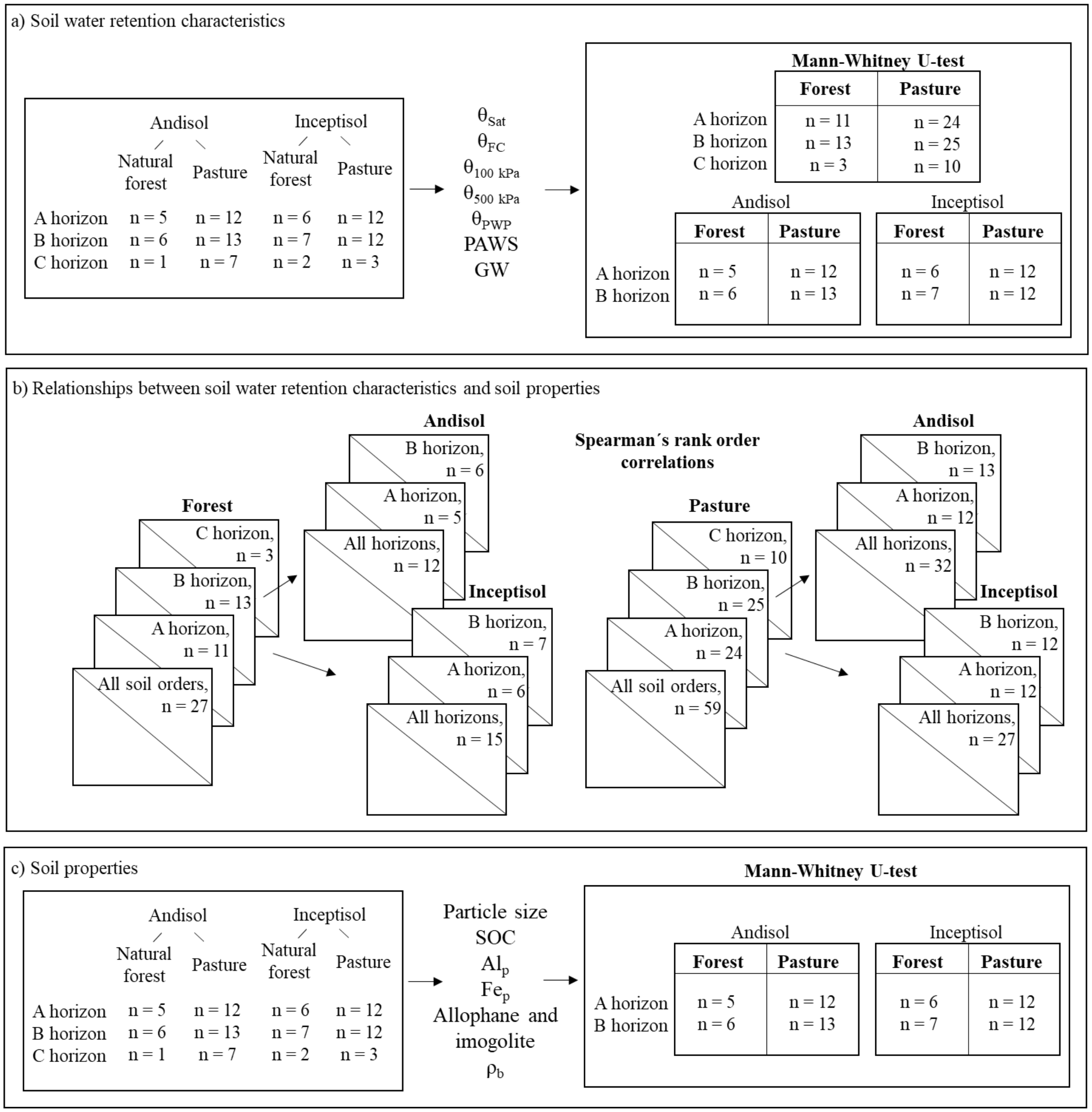


Figure 5.1 Overview samples collected to a) compare soil water retention (SWR) characteristics between natural forest and pasture in Andisols and Inceptisols; b) determine relationships between SWR characteristics and soil properties; and c) compare overall differences in soil properties between natural forest and pasture

5.3 Results and discussion

5.3.1 Soil water retention characteristics in Andisols and Inceptisols: differences between natural forest and pasture

Soil water retention characteristic curves under forest and pasture at the Andisol and Inceptisol study sites are shown in Figures 5.2 and 5.3. There was a marked difference in PWP in the A horizon under forest within the Andisols but no differences between land uses were seen at any tension in the Inceptisols (Fig. 5.2 and Table 5.2). In contrast, when comparing the SWR characteristics between natural forest and pasture in the B horizon, Inceptisols display the greater change (Fig. 5.3 and Table 5.2), with higher θ_{Sat} and θ_{FC} under forest.

a) Andisols b) Inceptisols

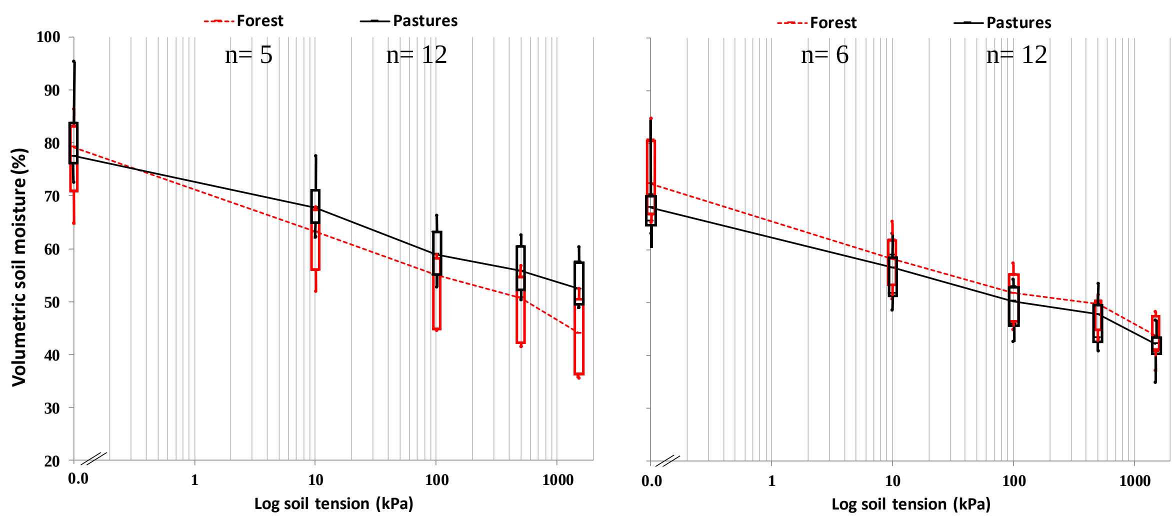


Figure 5.2 Median results and quartiles for soil water retention (SWR) curves in A horizon of natural forest and pasture for a) Andisols, and b) Inceptisols

a) Andisols b) Inceptisols

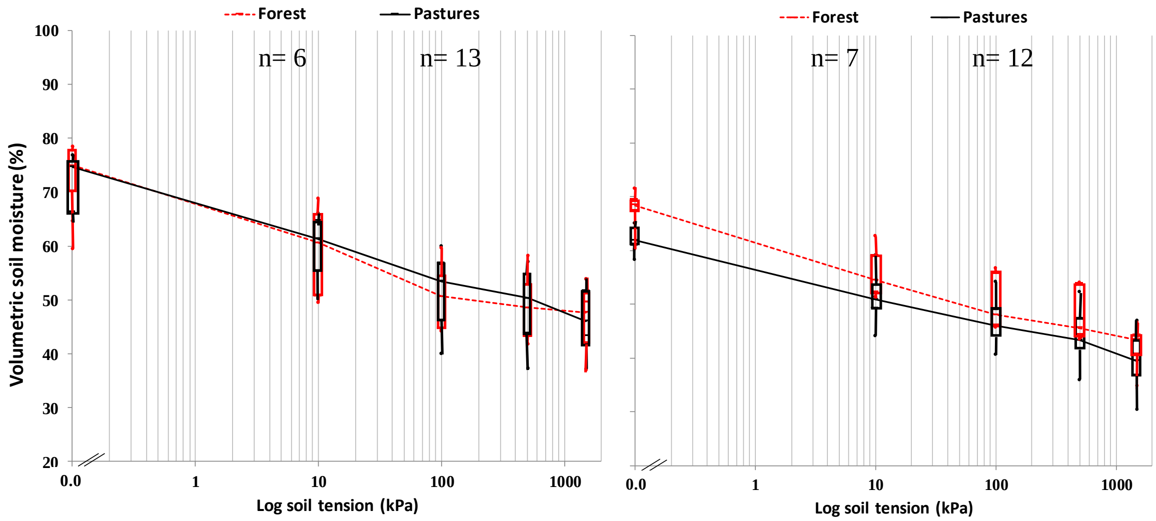


Figure 5.3 Median results and quartiles for soil water retention (SWR) curves in B horizon of natural forest and pasture for a) Andisols, and b) Inceptisols

Analyzing the combined dataset from both soil orders (Table 5.1), GW was significantly higher under natural forest than pasture. Higher GW represents a larger hydrological buffering capacity, implying a larger capacity of the soil to retain rainwater for one to two days after a rainfall event (Herron, 2001). This water will flow relatively slowly by gravity compared to overland flow as it percolates through soil macropores. This relationship, however did not hold when comparisons were made within the soil orders. Even in the A horizon of Andisols, where the median SWR curve was steeper under forest, there were no statistically significant differences between natural forest and pasture in PAWS or GW (Table 5.2).

Table 5.1 Median results of soil water retention (SWR) characteristics for forest and pasture in A and B horizons with all data for Andisols and Inceptisols

Horizon	Forest	Pasture
	$\theta_{Sat}{}^{1}$ (%v/v)	
A	77.0 (67.3-79.8)[2]	73.6 (67.9-80.8)
B	69.5 (67.6-74.9)	65.2 (61.9-74.9)
	$\theta_{FC}{}^{1}$ (%v/v)	
A	59.9 (54.1-65.4)	62.6 (56.3-68.3)
B	57.4 (51.8-62.6)	54.5 (50.5-61.7)
	$\theta_{100\ kPa}{}^{1}$ (%v/v)	
A	52.5 (45.3-57.5)	53.5 (50.0-59.0)
B	50.6 (45.9-54.3)	48.2 (44.7-55.3)
	$\theta_{500\ kPa}{}^{1}$ (%v/v)	
A	49.8 (43.1-51.5)	51.0 (47.7-55.9)
B	48.5 (44.1-52.6)	46.1 (42.2-52.1)
	$\theta_{PWP}{}^{1}$ (%v/v)	
A	44.1 (37.3-48.3)	47.8 (41.8-53.1)
B	43.9 (41.8-47.7)	43.3 (37.5-47.8)
	PAWS[3] (%v/v)	
A	16.4 (13.4-18.4)	14.0 (11.8-16.5)
B	13.5 (10.4-15.8)	12.2 (9.8-14.5)
	GW[4] (%v/v)	
A	16.7 (11.9-19.3)	10.9 (9.4-15.5)[+]
B	10.4 (8.9-15.4)	11.6 (7.8-13.1)

[1]θ_{Sat}, θ_{FC}, $\theta_{100\ kPa}$, $\theta_{500\ kPa}$, θ_{PWP}: soil water content (θ) at saturation (Sat), field capacity (FC), 100 kPa, 500 kPa and at permanent wilting point (PWP), respectively; [2]Values in parenthesis are first and third quartile, [3]PAWS: plant available water storage; [4]GW: gravitational water; Number of samples (n) for natural forest were 11 and 13, and for pasture were 24 and 25 for A and B horizons, respectively; [+] Significant difference between forest and pasture with Mann Whitney U test at $p < 0.1$.

Table 5.2 Median results of soil water retention (SWR) characteristics for forest and pasture in A and B horizons of Andisols and Inceptisols

	Andisols		Inceptisols	
Horizon	Forest	Pasture	Forest	Pasture
		θ_{Sat}[1] (%v/v)		
A	79.2 (70.9-83.1)[2]	77.5 (76.1-83.7)	72.4 (66.8-80.8)	67.9 (65.4-70.4)
B	74.9 (70.3-77.7)	74.7 (66.3-75.6)	68.4 (67.4-69.5)	61.9 (60.8-64.1)**
		θ_{FC}[1] (%v/v)		
A	63.2 (55.9-67.5)	67.8 (64.9-71.0)	58.2 (53.2-61.9)	56.6 (51.7-58.9)
B	60.6 (50.9-65.9)	61.4 (55.5-64.7)	54.5 (52.3-59.1)	50.8 (49.3-53.5)*
		$\theta_{100\ kPa}$[1] (%v/v)		
A	55.0 (45.0-58.2)	58.9 (55.1-63.2)$^{+}$	51.8 (46.5-55.4)	50.3 (46.0-53.1)
B	50.7 (44.9-54.5)	53.4 (46.2-56.8)	48.1 (46.2-55.9)	46.0 (44.1-49.0)
		$\theta_{500\ kPa}$[1] (%v/v)		
A	50.8 (42.2-54.7)	55.8 (52.2-60.5)*	49.8 (45.0-50.4)	47.7 (43.3-49.7)
B	48.6 (43.3-53.0)	50.4 (43.8-51.7)	45.6 (44.4-53.9)	43.3 (41.7-47.3)$^{+}$
		θ_{PWP}[1] (%v/v)		
A	44.1 (36.4-50.5)	52.5 (49.5-57.5)**	43.8 (40.9-47.5)	42.2 (40.2-43.5)
B	47.7 (42.1-49.7)	46.1 (43.4-51.7)	43.4 (40.9-44.2)	39.4 (36.8-43.2)
		PAWS[3] (%v/v)		
A	18.4 (15.9-20.9)	15.4 (11.8-17.3)	13.5 (12.1-16.9)	13.3 (11.9-15.7)
B	14.3 (10.1-15.4)	12.6 (10.3-15.1)	12.5 (10.2-19.5)	11.0 (9.3-13.5)
		GW[4] (%v/v)		
A	12.8 (10.9-21.2)	10.9 (9.5-12.4)	16.8 (12.9-18.9)	11.4 (8.9-18.1)
B	11.4 (8.9-18.5)	11.5 (8.4-14.4)	10.4 (8.8-15.1)	11.7 (7.3-12.8)

[1]θ_{Sat}, θ_{FC}, $\theta_{100\ kPa}$, $\theta_{500\ kPa}$, θ_{PWP}: soil water content (θ) at saturation (Sat), field capacity (FC), 100 kPa, 500 kPa and at permanent wilting point (PWP), respectively; [2]Values in parenthesis are first and third quartile, [3]PAWS: plant available water storage; [4]GW: gravitational water; Number of samples (n) in Andisols for natural forest were 5 and 6, and for pasture 12 and 13 for A and B horizons, respectively; in Inceptisols for natural forest were 6 and 7 and 12 and 12 for A and B horizons, respectively; $^{+}$, *, ** Significant differences between forest and pasture with Mann Whitney U test at $p < 0.1$, $p < 0.05$ and $p < 0.01$, respectively.

5.3.2 Soil water retention characteristics under natural forest and pasture as affected by soil properties

Correlations among SWR characteristics and soil properties are provided in Tables 5.3 through 5.5. Few significant correlations were found under natural forest using the complete data set; however, sand and clay size fractions, SOC, SRO and ρ_b were all correlated with SWR characteristics under pasture (Table 5.3). The lower number of samples under natural forest and the higher variability in SWR under forest (Fig. 4.3) relative to pasture (Fig. 4.4), may partially explain the lower number of significant correlations under natural forest.

5.3.2.1 Differences between land uses in Andisols

Similar correlation patterns as those presented in Chapter 4 (Table 4.6a) are seen in the A and B horizons of Andisols, but with distinct differences between land uses (Table 5.4). In the A horizon, SWR was correlated with sand size fraction, clay size fraction and organo-metallic compounds under natural forest, and with SOC and SRO under pasture. Comparison between land uses, showed a significantly higher SOC under natural forest in relation to pasture (Table 5.6). Numerous studies in the tropics (e.g., Van Noordwijk et al., 1997; Navarrete et al., 2016) have found that land cover change from forests to pasture may result in either higher or lower SOC, depending on land management practices such as grazing intensity and soil C loss due to erosion. Comparison between land uses also showed a significantly higher sand size fraction under natural forest in relation to pasture (Table 5.6). The higher SOC, the higher measured sand size fraction, and the positive correlation between SOC and the apparent sand fraction (Fig. 5.4) suggest aggregation, which may contribute to the steeper SWR curve under natural forest. In addition, the pH under natural forest was significantly lower than under pasture (Table 5.6). Since both SOC and SRO have dominantly pH dependent charge (Table 3.1), SWR may be lower under natural forest.

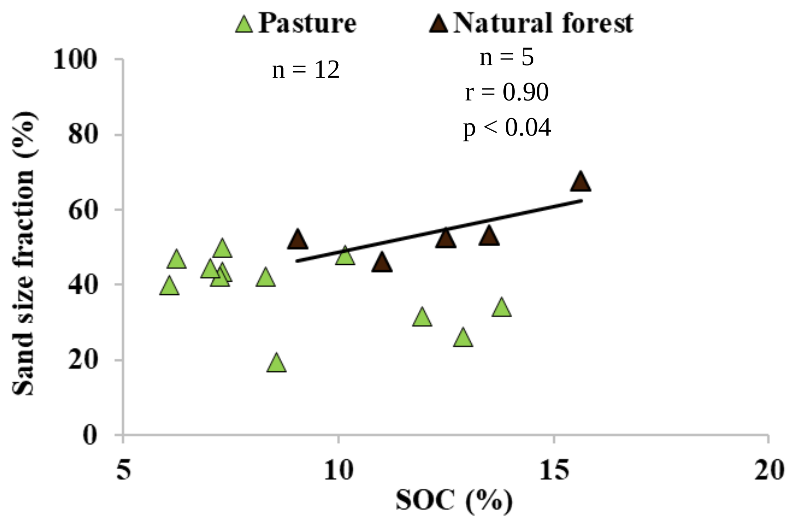


Figure 5.4 Relationship between soil organic carbon (SOC) and sand size fraction in A horizon of natural forest and pasture of Andisols

Regional studies which compared SWR characterstics between forest and pasture in Andisols are limited and suggest contrasting impacts on SWR in the A horizon (Table 5.7a). Tobón et al. (2010) found higher PAWS and lower GW under pasture than under natural forest, but similar θ_{PWP} values. In contrast, this study found no change in GW or PAWS but higher θ_{PWP} under pasture, while Roa et al. (2011) noted no significant differences in SWR between natural forest and pasture. All three of these sites were dominated by allophanic mineral soils. SOC was lower under pasture in this study consistent with Tobón et al. (2010). As noted earlier, forest conversion to pasture may result in lower SOC depending on management, particularly on sloping land were grazing and erosion may contribute to losses of soil C (Noordwijk et al., 1997; Navarrete et al., 2016).

In the B horizon of the Andisol site, SWR characteristics were similar between land uses (Fig. 5.3a), and no significant differences were noted in SOC, SRO or bulk density (Table 5.6). Tobón et al. (2010) also found limited differences in SOC and SWR characteristics in the B horizon (Table 5.7).

Table 5.3 Spearman´s Rho correlation coefficients (r) between soil water retention (SWR) characteristics and soil physical and chemical soil properties for both soil orders in all horizons and in A and B horizons in: a) natural forest; and b) pasture

	θ_{Sat}[1] (%v/v)	θ_{FC}[1] (%v/v)	$\theta_{100\ kPa}$[1] (%v/v)	$\theta_{500\ kPa}$[1] (%v/v)	$\theta_{PWP\ kPa}$[1] (%v/v)	PAWS[2] (% v/v)	GW[3] (% v/v)	θ_{Sat}[1] (%v/v)	θ_{FC}[1] (%v/v)	$\theta_{100\ kPa}$[1] (%v/v)	$\theta_{500\ kPa}$[1] (%v/v)	$\theta_{PWP\ kPa}$[1] (%v/v)	PAWS[2] (% v/v)	GW[3] (% v/v)	θ_{Sat}[1] (%v/v)	θ_{FC}[1] (%v/v)	$\theta_{100\ kPa}$[1] (%v/v)	$\theta_{500\ kPa}$[1] (%v/v)	$\theta_{PWP\ kPa}$[1] (%v/v)	PAWS[2] (% v/v)	GW[3] (% v/v)
a) Natural forest	All horizons (n = 27)							A horizon (n = 11)							B horizon (n = 13)						
Sand (%)													0.61								
Silt (%)																					
Clay (%)															-0.58						
SOC[4] (%)	0.53					0.41	0.50						0.71								
Al_p[5] (g/kg)																					
Fe_p[5] (g/kg)									0.68				0.63								
Allophane (%)															0.58				0.59		
Ferrihydrite (%)						-0.43							-0.61								
ρ_b[6] (kg/m^3)	-0.89	-0.54				-0.61	-0.58	-0.90	-0.74				-0.77	-0.61	-0.85						
b) Pasture	All horizons (n = 59)							A horizon (n = 24)							B horizon (n = 25)						
Sand (%)								0.52	0.64	0.66	0.63	0.66			0.67	0.46			0.41		
Silt (%)																					
Clay (%)								-0.51	-0.60	-0.60	-0.66	-0.69			-0.68	-0.47			-0.46		
SOC[4] (%)	0.59	0.49				0.50		0.68	0.77	0.70	0.71	0.76			0.60						
Al_p[5] (g/kg)	0.69	0.66	0.53	0.52	0.59			0.63	0.67	0.61	0.62	0.69			0.81	0.76	0.55	0.52	0.71		
Fe_p[5] (g/kg)	0.53	0.49		0.40		0.43		0.65	0.66	0.57	0.62	0.66									
Allophane (%)	0.56	0.49			0.51			0.77	0.80	0.79	0.75	0.82			0.80	0.61			0.58		
Ferrihydrite (%)								-0.70	-0.77	-0.74	-0.80	-0.76									
ρ_b[6] (kg/m^3)	-0.90	-0.75	-0.60	-0.60	-0.62	-0.45		-0.93	-0.89	-0.82	-0.76	-0.78	-0.50		-0.86	-0.47					

[1]θ_{Sat}, θ_{FC}, $\theta_{100\ kPa}$, $\theta_{500\ kPa}$, θ_{PWP}: soil water content (θ) at saturation (Sat), field capacity (FC), 100 kPa, 500 kPa and at permanent wilting point (PWP), respectively; [2]PAWS: plant available water storage; [3]GW: gravitational water; [4]SOC: soil organic carbon; [5]Pyrophosphate-extractable aluminum and iron (Al_p and Fe_p); [6]ρ_b: bulk density; correlations shown are the ones r > 0.4; Gray cells show correlations with p < 0.01 and white cells show correlations with p < 0.05

Table 5.4 Spearman´s Rho correlation coefficients (r) between soil water retention (SWR) characteristics and soil physical and chemical soil properties within Andisols in all horizons and in A and B horizons in: a) natural forest; and b) pasture

	θ_{Sat}[1] (%v/v)	θ_{FC}[1] (%v/v)	$\theta_{100\ kPa}$[1] (%v/v)	$\theta_{500\ kPa}$[1] (%v/v)	$\theta_{PWP\ kPa}$[1] (%v/v)	PAWS[2] (% v/v)	GW[3] (% v/v)	θ_{Sat}[1] (%v/v)	θ_{FC}[1] (%v/v)	$\theta_{100\ kPa}$[1] (%v/v)	$\theta_{500\ kPa}$[1] (%v/v)	$\theta_{PWP\ kPa}$[1] (%v/v)	PAWS[2] (% v/v)	GW[3] (% v/v)	θ_{Sat}[1] (%v/v)	θ_{FC}[1] (%v/v)	$\theta_{100\ kPa}$[1] (%v/v)	$\theta_{500\ kPa}$[1] (%v/v)	$\theta_{PWP\ kPa}$[1] (%v/v)	PAWS[2] (% v/v)	GW[3] (% v/v)
a) Natural forest	All horizons (n = 12)							A horizon (n = 5)							B horizon (n = 6)						
Sand (%)									-0.90			-0.90									
Silt (%)																					
Clay (%)						0.68			1.00		0.90	1.00									
SOC[4] (%)						0.69									0.89						
Al_p[5] (g/kg)											0.90		-0.90								
Fe_p[5] (g/kg)									0.90	0.90	1.00	0.90									
Allophane (%)									-0.90			-0.90									
Ferrihydrite (%)	0.68														0.83						
ρ_b[6] (kg/m^3)	-0.74														-0.83						
b) Pasture	All horizons (n = 32)							A horizon (n = 12)							B horizon (n = 13)						
Sand (%)	-0.55	-0.62	-0.57	-0.59	-0.62																
Silt (%)	0.47	0.41												0.62							
Clay (%)	0.50	0.60	0.61	0.56	0.59			0.69	0.73												
SOC[4] (%)	0.77	0.70	0.46	0.49	0.40	0.57		0.75	0.87	0.68	0.71				0.93						
Al_p[5] (g/kg)	0.58	0.62				0.55										0.56					
Fe_p[5] (g/kg)	0.60	0.61				0.55															
Allophane (%)								0.60	0.59	0.90	0.89	0.73									
Ferrihydrite (%)						0.41		-0.60		-0.59	-0.66				0.86						
ρ_b[6] (kg/m^3)	-0.85	-0.66	-0.55	-0.53	-0.44	-0.50		-0.81	-0.80	-0.66	-0.64		-0.65		-0.77						

[1]θ_{Sat}, θ_{FC}, $\theta_{100\ kPa}$, $\theta_{500\ kPa}$, θ_{PWP}: soil water content (θ) at saturation (Sat), field capacity (FC), 100 kPa, 500 kPa and at permanent wilting point (PWP), respectively; [2]PAWS: plant available water storage; [3]GW: gravitational water; [4]SOC: soil organic carbon; [5]Pyrophosphate-extractable aluminum and iron (Al_p and Fe_p); [6]ρ_b: bulk density; correlations shown are the ones r > 0.4; Gray cells show correlations with $p < 0.01$ and white cells show correlations with $p < 0.05$

Table 5.5 Spearman´s Rho correlation coefficients (r) between soil water retention (SWR) characteristics and soil physical and chemical soil properties within Inceptisols in all horizons and in A and B horizons in: a) natural forest; and b) pasture

	θ_{Sat}[1] (%v/v)	θ_{FC}[1] (%v/v)	$\theta_{100\ kPa}$[1] (%v/v)	$\theta_{500\ kPa}$[1] (%v/v)	$\theta_{PWP\ kPa}$[1] (%v/v)	PAWS[2] (% v/v)	GW[3] (% v/v)	θ_{Sat}[1] (%v/v)	θ_{FC}[1] (%v/v)	$\theta_{100\ kPa}$[1] (%v/v)	$\theta_{500\ kPa}$[1] (%v/v)	$\theta_{PWP\ kPa}$[1] (%v/v)	PAWS[2] (% v/v)	GW[3] (% v/v)	θ_{Sat}[1] (%v/v)	θ_{FC}[1] (%v/v)	$\theta_{100\ kPa}$[1] (%v/v)	$\theta_{500\ kPa}$[1] (%v/v)	$\theta_{PWP\ kPa}$[1] (%v/v)	PAWS[2] (% v/v)	GW[3] (% v/v)
a) Natural forest	All horizons (n = 15)							A horizon (n = 6)							B horizon (n = 7)						
Sand (%)																					
Silt (%)													-0.83								
Clay (%)													0.94			-0.79			-0.79		
SOC[4] (%)							0.60	0.94					0.89								
Al_p[5] (g/kg)					-0.51																
Fe_p[5] (g/kg)								0.89													
Allophane (%)																					
Ferrihydrite (%)						-0.54							-0.94								
ρ_b[6] (kg/m^3)	-0.77						-0.80	-1.00	-0.83	-0.83				-0.83							
b) Pasture	All horizons (n = 27)							A horizon (n = 12)							B horizon (n = 12)						
Sand (%)																					
Silt (%)																					
Clay (%)																					
SOC[4] (%)	0.50					0.43															
Al_p[5] (g/kg)														0.65							
Fe_p[5] (g/kg)	0.38																				
Allophane (%)																					
Ferrihydrite (%)	0.53																				
ρ_b[6] (kg/m^3)	-0.66					-0.52		-0.68	-0.64				-0.69								-0.59

[1]θ_{Sat}, θ_{FC}, $\theta_{100\ kPa}$, $\theta_{500\ kPa}$, θ_{PWP}: soil water content (θ) at saturation (Sat), field capacity (FC), 100 kPa, 500 kPa and at permanent wilting point (PWP), respectively; [2]PAWS: plant available water storage; [3]GW: gravitational water; [4]SOC: soil organic carbon; [5]Pyrophosphate-extractable aluminum and iron (Al_p and Fe_p); [6]ρ_b: bulk density; correlations shown are the ones r > 0.4; Gray cells show correlations with $p < 0.01$ and white cells show correlations with $p < 0.05$

Table 5.6 Median results of soil properties for natural forest and pasture in A and B horizons of Andisols and Inceptisols

	Andisols		Inceptisols	
Horizon	Forest	Pasture	Forest	Pasture
		pH H_2O		
A	4.6 (4.5-4.7)[1]	5.1 (5.0-5.2)**	5.6 (5.4-5.8)	5.6 (5.4-5.7)
B	5.5 (5.4-5.6)	5.7 (5.5-5.7)$^{+}$	5.1 (5.0-5.6)	5.5 (5.3-5.9)$^{+}$
		Sand (%)		
A	52.6 (49.3-60.6)	42.2 (32.3-46.3)**	14.2 (10.2-36.4)	13.6 (11.6-19.7)
B	60.0 (48.7-68.1)	55.1 (51.0-59.8)	20.0 (18.1-29.2)	18.9 (8.0-22.7)
		Clay (%)		
A	23.8 (21.7-29.0)	23.3 (22.3-31.1)	39.3 (27.0-52.6)	56.2 (50.2-60.1)*
B	14.6 (12.1-15.3)	15.9 (14.7-17.6)$^{+}$	30.6 (22.5-45.6)	53.2 (42.8-58.3)*
		SOC[2] (%)		
A	12.5 (10.0-14.6)	7.8 (7.1-11.5)*	7.1 (4.9-10.5)	5.0 (3.6-5.9)$^{+}$
B	3.8 (2.6-4.3)	3.5 (2.6-4.8)	1.7 (1.4-3.5)	1.6 (1.4-2.5)
		Al_p[3] (g/kg)		
A	1.40 (1.09-2.14)[1]	1.53 (1.07-1.72)	0.06 (0.05-0.08)	0.08 (0.04-0.21)
B	0.32 (0.22-0.57)	0.42 (0.27-0.55)	0.13 (0.08-0.23)	0.04 (0.03-0.12)*
		Fe_p[3] (g/kg)		
A	0.22 (0.14-0.39)	0.37 (0.15-0.50)	0.02 (0.01-0.03)	0.03 (0.01-0.06)
B	0.01 (0.01-0.03)	0.01 (0.01-0.04)	0.03 (0.01-0.04)	0.01 (0.00-0.03)
		Allophane and imogolite (%)		
A	6.0 (4.4-7.3)	6.3 (4.6-9.2)	1.5 (1.2-3.6)	1.4 (1.2-2.1)
B	15.5 (7.0-17.4)	14.8 (10.5-17.1)	1.6 (1.2-3.4)	1.2 (1.0-1.4)$^{+}$
		Ferrihydrite (%)		
A	0.45 (0.36-0.50)	0.49 (0.44-0.60)	0.83 (0.64-1.18)	1.2 (1.0-1.6)*
B	0.44 (0.35-0.79)	0.7 (0.2-0.8)	0.6 (0.4-1.2)	0.7 (0.5-1.0)
		ρ_b[4] (kg/m^3)		
A	455 (326-740)	594 (461-665)	727 (539-847)	900 (840-935)$^{+}$
B	650 (544-894)	668 (578-829)	887 (834-1041)	1016 (958-1067)

[1]Values in parenthesis are first and third quartile, [2]SOC: soil organic carbon; [3]Pyrophosphate-extractable aluminum and iron (Al_p and Fe_p); [4]ρ_b: bulk density; Number of samples (n) in Andisols were 5 and 6 in natural forest and 12 and 13 in pasture in A and B horizons respectively, in Inceptisols were 6 and 7 in natural forest and 12 and 12 in pasture in A and B horizons, respectively; $^{+}$, *, ** Significant differences between forest and pasture with Mann Whitney U test at $p < 0.1$, $p < 0.05$ and $p < 0.01$, respectively

Table 5.7 Soil water retention (SWR) characteristics and soil properties of Andisols of the Sonora watershed and other regional studies

a) A horizon

Land use	GW	PAWS[2]	θ_{Sat}[3]	θ_{FC}[3]	θ_{PWP}[3]	SOC[4] (%)	ρ_b[5] (kg/m^3)	Al_p[6] (g/kg)	Al_o[6] (g/kg)	Reference
			(cm^3/cm^3)							
						Allophanic soils				
Forest	**13**	**18**	**79**	**63**	**44**	**12**	**455**	**1.4**	**14**	**This study**
Pasture	**11**	**15**	**77**	**68**	**52**	**8**	**594**	**1.5**	**15**	
Forest	29	8	82	53	45	16	407	-	-	Tobón et al., 2010
Pasture	19	15	82	63	48	8	528	-	-	
Forest	-	7	-	61	53	-	600	-	-	Roa-García, et al., 2011
Pasture	-	8	-	60	52	-	700	-	-	
						Non-allophanic soils				
Humid Páramo	-	-	-	52	-	10	680	4	6	Podwojewski et al., 2002
Pasture	-	-	-	15	-	5	760	2	3	
Dry Páramo	-	-	-	20	-	7	740	2	4	
Pasture	-	-	-	15	-	4	990	1	2	

b) B horizon

Land use	GW	PAWS[2]	θ_{Sat}[3]	θ_{FC}[3]	θ_{PWP}[3]	SOC[4] (%)	ρ_b[5] (kg/m^3)	Al_p[6] (g/kg)	Al_o[6] (g/kg)	Reference
						Allophanic soils				
Forest	**11**	**14**	**75**	**61**	**48**	**3.8**	**650**	**0.3**	**39**	**This study**
Pasture	**11**	**13**	**75**	**61**	**46**	**3.5**	**668**	**0.4**	**35**	
Forest	19	16	74	55	39	7.8	612	-	-	Tobón et al., 2010
Pasture	19	16	80	61	45	9.2	627	-	-	
						Non-allophanic soils				
HumidPáramo	-	-	-	50	-	7	-	5	9	Podwojewski et al., 2002
Pasture	-	-	-	20	-	3	-	1	2.5	
Dry Páramo	-	-	-	30	-	5	930	2.5	4	
Pasture	-	-	-	14	-	2	-	0.4	2	

[1]GW: gravitational water; [2]PAWS: plant available water storage; [3]θ_{FC} and θ_{PWP}: soil water content (θ) at field capacity (FC) and at permanent wilting point (PWP); [4]SOC: soil organic carbon; [5]ρ_b: bulk density; [6]Al_p and Al_o: pyrophosphate and oxalate extractable aluminum (Al), respectively

5.3.2.2 Differences between land uses in Inceptisols

In the case of Inceptisols, SWR characteristics in the A horizon were similar between land uses (Fig. 5.2b and Table 5.2). Although SOC was lower in pasture (similar to the Andisol site), the clay fraction and ferrihydrite were higher (Table 5.6). Ferrihydrite, due to its high specific surface area and large number of functional groups, may partially compensate in SWR for the lower SOC in the A horizon under pasture, in spite of its small contribution to soil mass (<1%) (Regelink et al., 2015; Goldberg et al., 2012). Bulk density was negatively correlated with SWR for both land uses (Table 5.5), similar to relationships found in Chapter 4 (Table 4.6b). Bulk density was slightly higher in the A horizon of Inceptisols under pasture (Table 5.6). As noted by Daza et al. (2014) compaction due to cattle grazing may increase ρ_b and reduce GW in Inceptisols (Table 5.8), although no significant change in GW was found in this study (Table 5.2).

In the B horizon of Inceptisols, SWR was greater at low tensions under natural forest relative to pasture (Fig. 5.3b and Table 5.2). While SOC content was similar, Al_p, allophane and imogolite were higher under natural forest (Table 5.6). Allophane and imogolite due to their hollow structures, high specific surface area and large number of functional groups, as discussed in Chapter 3, contribute to higher SWR. Al_p may be an indicator of boehmite in Inceptisols, as explained in Section 3.3.3.1, and their relatively high specific surface area also contributes to SWR. Boehmite, allophane and imogolite may all contribute to aggregation and an increase in macro-pores, accounting for the increase in total porosity under natural forest.

Table 5.8 Soil water retention (SWR) characteristics and soil properties of Inceptisols of the El Chocho watershed and other regional studies

Land use	GW	PAWS[2]	θ_{Sat}[3] (cm^3/cm^3)	θ_{FC}[3]	θ_{PWP}[3]	SOC[4] (%)	ρ_b[5] (kg/m^3)	Al_p[6] (g/kg)	Allophanes (%)	Ferrihydrite (%)	Reference
a) A horizon											
							Allophanic soils				
Forest	**17**	**13**	**72**	**58**	**44**	**7**	**727**	**0.06**	**14**	**0.83**	**This study**
Pasture	**11**	**13**	**68**	**57**	**42**	**5**	**900**	**0.08**	**15**	**1.2**	
Páramo[6]	21	23	78	57	34	18	700	-	-	-	Daza et al., 2014
Pasture	15	17	57	42	25	10	830	-	-	-	
Potato crops	10	18	49	39	21	12	900	-	-	-	
b) B horizon											
Forest	**10**	**12**	**68**	**54**	**43**	**1.7**	**887**	**0.13**	**1.6**	**0.6**	**This study**
Pasture	**12**	**11**	**62**	**51**	**39**	**1.6**	**1016**	**0.04**	**1.2**	**0.7**	
Páramo[6]	19	37	100	81	44	13	1000	-	-	-	Daza et al., 2014
Pasture	15	29	64	50	21	11	1200	-	-	-	
Potato crops	13	23	63	50	24	1	1100	-	-	-	

[1]GW: gravitational water; [2]θ_{Sat}, θ_{FC} and θ_{PWP}: soil water content (θ) at saturation (Sat), field capacity (FC) and at permanent wilting point (PWP); [3]SOC: soil organic carbon; [4]ρ_b: bulk density; [5]Al_p and Al_o: pyrophosphate and oxalate extractable aluminum (Al), respectively; [6]Volumetric soil moisture was calculated with the published data of gravimetric soil moisture and bulk density

The effect of land use change on SWR has been shown to vary depending on site characteristics, management factors such as grazing intensity, and sampling design whether by horizon, as in this study, or by depth (Horel et al., 2015). Intensive land use commonly increases ρ_b and reduces SOC but research shows contrasting results in GW, PAWS and θ_{PWP} (Asghari et al., 2016; Pirastru et al., 2013), and may be a reflection of different inherent soil characteristics such as SRO, which are not appreciably influenced by land management. In mountainous regions, disturbance of the original land cover, may have a negative effect on soil structure and soil loss which are closely related with a reduction in SOC and SWR (Li et al., 2007). In this study, the conversion of natural forest to pasture, showed no changes in GW or PAWS in either soil. However, steeper SWR curves were noted under natural forest in the A horizon of Andisols and the B horizon of Inceptisols.

5.4 Conclusions

Land use effects on SWR characteristics in Andisols and Inceptisols appear limited, although SOC was lower under pasture than natural forest in both soils. Significant differences between pasture and natural forest were found only at PWP in the A horizon of Andisols, and θ_{Sat} and FC in the B horizon of Inceptisols.

In the Andisols of the Sonora watershed, as discussed earlier, aggregate formation gives rise to a pseudo-sand fraction that may be increasing the slope of the SWR curve in the A horizon under forest. In Inceptisols of the El Chocho watershed ferrihydrite appears to offset the effects of lower SOC under pasture in the A horizon resulting in no appreciable differences in SWR between the land uses.

The limited differences in SWR between natural forest and pasture appear to reflect the effects of SRO minerals and organo-metallic compounds on SWR. The high water retention capacity of SRO and organo-metallic compounds may compensate the lower SOC under pasture, resulting in similar SWR characteristics between land uses.

6. FIELD SATURATED HYDRAULIC CONDUCTIVITY DURING DRY AND WET SEASONS UNDER PASTURE ON ANDISOLS AND INCEPTISOLS AT TWO MID-ELEVATION SITES IN THE COLOMBIAN ANDES

6.1 Introduction

Field saturated hydraulic conductivity (Kfs) (quasi steady-state infiltration rate) is a key soil physical property that affects the partitioning of rainfall into infiltration and overland flow (OF) (Nimmo et al., 2009; Bonell, 1993). Kfs is dependent on soil properties such as texture, structure, soil organic matter, pore size distribution, and bulk density (ρ_b); it varies spatially due to the local geomorphology, topography and land cover, and temporally due to the antecedent soil water content (θ) (Bonell, 1993; Assouline, 2013). Consequently, a field-based measurement incorporating spatial and temporal variation is needed for an accurate determination of soil water movement (Diamond and Shanley, 2003).

In the Andes, pasture has been recognized as a particularly important land use with a direct impact on runoff. Studies such as Tobón et al. (2010) and Zimmermann and Elsenbeer (2008) found higher runoff in pasture relative to forest, and this increase in runoff is generally attributed to livestock trampling and reduced infiltration (Leitinger et al., 2010; Chaves et al., 2008). Greater runoff under pasture in comparison to natural forests has been found in the Central Colombian Andes (Suescún et al., 2017; García-Leoz et al., 2018) and in Ecuador (Molina et al., 2007). These studies also suggested a decrease in soil infiltration associated with pasture, although Kfs was not directly measured. In spite of the relevance of Kfs and associated soil properties, limited research has focused on the role of soils in runoff generation in both the Andes and the tropics (Bonell, 1993; Ilsted et al., 2007).

Runoff models, such as the Soil Water Assessment Tool (SWAT), require soil parameters including saturated hydraulic conductivity (K_{sat}) as input variables (Arnold et al., 2012). In Colombia, Ecuador and Perú, hydrological studies (Quintero et al., 2009; Uribe et al., 2013) have relied on soil texture for estimating K_{sat} values instead of the more accurate measured Kfs values. Modelling of runoff from watersheds could be improved with additional data on the main soil orders with consideration of spatial and temporal variability.

The objectives of this chapter were to compare the field saturated hydraulic conductivity (Kfs) under pasture in Andisols and Inceptisols in the Colombian Andes during the wet and dry seasons, and determine the factors affecting Kfs in these two soils. Kfs was then compared to rainfall intensity to provide a preliminary estimate of OF.

6.2 Experimental conditions and measurements

The experiment was designed to compare Kfs on pasture between two soil orders and between two seasons. Kfs was measured using double ring infiltrometers, and as indicated in Chapter 2, provides an index of quasi steady-state infiltration rate as measured in the field. Measurements were taken on flat slope positions only (slope <20%) and near the locations of the sampled soil pits discussed in earlier chapters of this thesis in both Andisol and Inceptisol study areas. Measurements were repeated in the dry and the wet seasons.

6.2.1 Measurement of field saturated hydraulic conductivity

Field saturated hydraulic conductivity (Kfs) was measured using double ring infiltrometers following the method developed by Bouwer (1986). Kfs was measured in duplicate at each site; a pair of double ring infiltrometers were used simultaneously approximately 10 m apart. Before every Kfs measurement, a soil sample was taken from the 0-15 cm depth, next to the site where the double ring was installed, for determination of the gravimetric soil water content (θ_{grav}). Dates when Kfs was measured in the dry and wet seasons are presented in Table 6.1.

Table 6.1 Dates when field saturated hydraulic conductivity (Kfs) were measured in the Sonora watershed (Andisol site) and in El Chocho watershed (Inceptisol site)

Watershed - soil order	Dry season	Wet season
Sonora - Andisol	August 28-31, 2013	November 19-22, 2013
El Chocho - Inceptisol	August 5-8, 2013	November 27-28, 2013

The double ring infiltrometer used for the measurements was 30 cm in height with sharpened bottom edges. The outer ring was 60 cm in diameter, while the inner ring was 30 cm in diameter. Rings were driven 15 cm into the soil. Inner and outer rings were filled with water (more than 7 cm above the ground level) prior to beginning the measurements. The infiltration rate was assessed by measuring the change in water level every 30 seconds for the first 5 minutes, every minute from 6 to 10 minutes, every 5 minutes from 15 to 45 minutes, and every 20 minutes until steady state. Outer and inner rings were periodically filled with water immediately after a water level measurement, to maintain the water level at a minimum of 7 cm above the ground level. The change of the water level was measured until steady state was reached; determined by an equal change in water level over at least two periods of 20 minutes. Steady state was reached in Andisols sites between 2 to 4 hours, while in Inceptisol sites, steady state was reached between 2 to 5 hours.

θ_{grav} was assessed gravimetrically by oven drying the soil sample at 105°C for 24 hours. Volumetric soil water content (θ_{vol}) was calculated using θ_{grav} and the median ρ_b in the A horizon from each of the pasture sites on flat slope position.

6.2.2 Estimation of overland flow

Overland flow will occur if the rainfall intensity exceeds the infiltration capacity of the soil; and Kfs defines a minimum absorption capacity, as the soil is capable of storing additional water, depending on the antecedent soil moisture conditions and micro-relief (Diamond and Shanley, 2003). Thus, estimating runoff as rainfall intensity > Kfs provides comparable results between sites but could result in an overestimation of the OF particularly in the dry season.

To estimate OF, the rainfall intensity at 10-minute intervals (RI_{10}) was compared to the median Kfs in the wet and the dry seasons ($Kfs_{wetseason}$ and $Kfs_{dryseason}$). Continuous precipitation data (every 0.2 mm), from within each watershed, was obtained from a research project (Roa and Brown, 2014); details are provided in Appendix G. Data was then organized for 10 minutes periods to obtain RI_{10}. The interval of 10 minutes for rainfall intensity was defined as half of the time used for determing the quasi steady state infiltration rate (Kfs) at the end of the infiltration measurements, and captures the most common rainfall events in the two watersheds (Fig. 6.3). For comparative purposes with other studies, the work of Pardo Gomez and Rodrígues Lopez (2014), was used to define low intensity events as the ones with $RI_{10} < 10$ mm/hr. Two years of precipitation data were utilized, allowing for the separation of wet and dry seasons. For each 10-minute interval within each season, RI_{10} was compared to Kfs and OF estimated as given in Table 6.2.

Table 6.2 Rationale for overland flow (OF) estimation comparing rainfall intensity every 10 minutes (RI_{10}) with field saturated hydraulic conductivity (Kfs)

	Dry season	Wet season
OF = 0 mm	$RI_{10} \leq Kfs_{dryseason}$	$RI_{10} \leq Kfs_{wetseason}$
OF = RI_{10} - Kfs	$RI_{10} > Kfs_{dryseason}$	$RI_{10} > Kfs_{wetseason}$

Organizing data by season during the two years for which data was available for both watersheds, allowed the estimation of the percentage of OF over total precipitation (OF/TP) by season, by year and over the two-year study period.

6.2.3 Statistical analyses

Field saturated hydraulic conductivity (Kfs), θ_{grav} and θ_{vol} were compared between Andisols and Inceptisols, over the entire study period and by season (Fig. 6.1a). In addition, data for Andisols and Inceptisols were evaluated separately to determine differences between dry and wet seasons within each soil order (Fig. 6.1a). The Mann Whitney U test and probability values (p-value) of 0.01, 0.05 and 0.1 were used for these comparisons.

Relationships between Kfs and θ_{grav} and θ_{vol} were assessed utilizing the non-parametric Spearman's rank-order correlation. Spearman's Rho correlation coefficients (r) with values > 0.4 and probability values (p) of 0.01 and 0.05 were used to indicate significant relationships (Fig. 6.1b). Correlations were conducted for:

- Andisol and Inceptisol, all seasons
    - Andisol and Inceptisol by season (dry and wet seasons)
  - Andisol only, all seasons
    - Andisol by season (dry and wet seasons)
  - Inceptisol only, all seasons
    - Inceptisol by seasons (dry and wet seasons)

Sample numbers for each analysis are provided in Figure 6.1

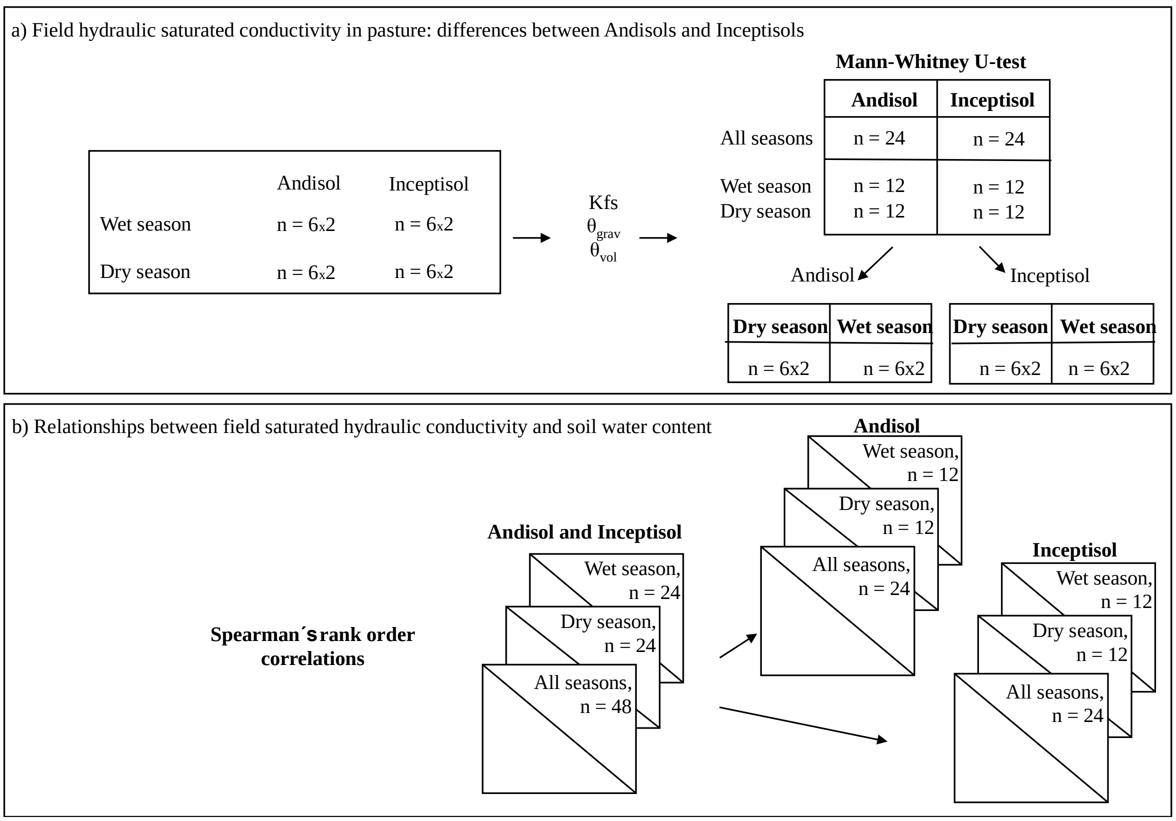


Figure 6.1 Overview of field measurements to a) compare field saturated hydraulic conductivity (Kfs) in pasture between Andisols and Inceptisols and b) determine relationships between Kfs and soil water content

6.3 Results and discussion

Steady infiltration state or saturated hydraulic conductivity is a key parameter in hydrological modelling to partition rainfall into runoff and infiltration, and is used in irrigation calculations to determine the rate at which water should be applied to avoid excess application and OF. Yet Kfs is challenging and time-consuming to measure in the field, and is often estimated from a more easily measured soil parameter such as textural class (NCSS, 1996). In the following sections Kfs values determined under pasture in Andisols and Inceptisols at two mid-elevation sites will be compared to each other, to infiltration categories based on soil texture, and to Kfs values reported in other studies conducted in the region. Seasonal variability and soil characteristics affecting Kfs will be discussed, followed by a first approximation of OF based on a comparison between Kfs and rainfall intensity.

6.3.1 Field saturated hydraulic conductivity (Kfs) in pasture: differences between Andisols and Inceptisols

Infiltration categories classified by soil texture are given in Table 6.3, with clay textured soils having lower Kfs values than sandy soils. In contrast, results from this study (Table 6.4) show that Inceptisols in the El Chocho watershed, which have a clay texture, had significantly higher Kfs values than Andisols in the Sonora watershed with dominantly sandy loam to loam texture. Median Kfs values for Andisols fell within the "slow" infiltration category, while Inceptisols ranked as "moderately slow".

Table 6.3 Infiltration categories and hydraulic conductivity relative to texture class adapted from NCSS (1996)

Infiltration category	Texture class	Hydraulic conductivity (mm/hr)
Very slow	Heavy clay	< 1
Slow	Clay, clay loam, silty clay, sandy clay loam	1 – 5
Moderately slow	Sandy clay, silty clay loam, clay loam, silt loam, silt, sandy clay loam	5 – 20
Moderate	Clay loam, silt, silt loam, very fine sandy loam, loam	20 – 60
Moderately rapid	Fine sandy loam, sandy loam	60 -125
Rapid	Loamy sand, fine sand	125 - 250
Very rapid	Medium sand	> 250

Table 6.4 Median field saturated hydraulic conductivity (Kfs) and soil water content (θ) in Andisols and Inceptisols

Andisols	Inceptisols
Kfs[1] (mm/hr)	
3 (0.1 - 7.1)[4]	9 (2 - 33)*
θ_{grav}[2] (g/g)	
102 (85-164)	57 (30 - 67)**
θ_{vol}[3] (cm^3/cm^3)	
0.51 (0.45-0.63)	0.47 (0.26 - 0.54)*

[1]Kfs: field saturated hydraulic conductivity; [2]θ_{grav}: field gravimetric soil water content; [3]θ_{vol}: calculated volumetric soil water content; [4]Values in parenthesis are first and third quartile; Number of samples (n) were 24 for Andisols and Inceptisols; *, ** Significant differences between Andisols and Inceptisols with Mann Whitney U test at $p < 0.05$ and $p < 0.01$, respectively

Kfs values in Andisols in the Sonora watershed were lower than what is commonly reported in the literature (Nanzyo et al., 1993; Perrin et al., 2001; Neris et al., 2012; Tobón et al., 2010). The pseudo-sandy texture of Andisols in this study (Section 3.3.3.4) may suggest high Kfs values; however, this was not observed. The low Kfs values of Andisols in this study may be explained by a combination of soil properties and antecedent soil moisture regime. The high volume of micro-pores (Section 4.5.1 and Table 4.2), and the high soil water content throughout the year (Fig. 6.2), are related to both the high SWR characteristics of these soils (Section 4.3.1) and high rainfall. The precipitation (~3,000 mm/year) is high enough in the Sonora watershed (Andisol site), that the majority of θ_{grav} was > 70% throughout the year (Fig. 6.2). The presence of volcanic ash layers and placic horizons (Sections 2.1.1; 2.1.3; and 2.1.4.1) may impede drainage and reduce measured Kfs values. Volcanic ash layers were found at 1 – 2 meters depth in the upper portion of the Sonora watershed, and a placic horizon was observed at approximately 2.8 meters in the lower watershed. No correlations were found in Andisols between Kfs and antecedent soil water content, even when high Kfs values are excluded (Tables 6.5 and 6.6). High SWR characteristics in Andisols in combination with the high precipitation in the Sonora watershed (~3,000 mm/year) maintain high θ_{grav} which combined with imperfect drainage impacts measured values of Kfs, reducing it even in the dry season to values close to 0 mm/hr (Fig. 6.2).

In general, the Kfs values for the Inceptisols (Table 6.8) were found to be slow in the wet season consistent with the values reported in Table 6.3. However, during the dry season the Kfs values were moderate, even though the texture class is clay, which should place the Kfs into the slow category of Table 6.3. These dry season values are also high in comparison to infiltration data reported by studies conducted in similar soils in the region (Table 6.5) (Zimmermann and Elsenbeer, 2008; Toohey et al., 2018). The seasonal effect in measured infiltration in the Inceptisols of this study is related to the lower antecedent soil water content during the dry season. Recall that precipitation in the El Chocho watershed (Inceptisol site), ~1400 mm/year, is about 60% lower than in the Sonora watershed (Section 2.1.2) and is also lower than the precipitation at regional studies sites (Table 6.7). Thus, the negative correlation between Kfs and antecedent soil moisture in Inceptisols observed in Figure 6.2 with the majority $\theta_{grav} < 70\%$ (Tables 6.5 and 6.6) may in part explain the higher values of Kfs in comparison to regional studies and expected Kfs based on texture alone.

Inconsistencies were found between measured Kfs values and Kfs predicted based on soil texture class for both Andisols and Inceptisols. Measured values of Kfs in Andisols were lower than predicted based on soil texture class, while Kfs measured in Inceptisols was higher than predicted, highlighting the importance of field data for use in hydrological modelling or agricultural practices.

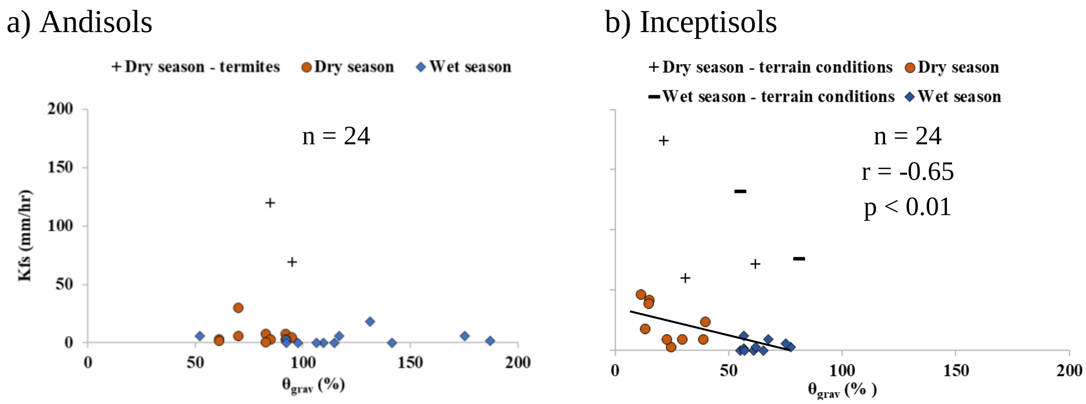


Figure 6.2 Gravimetric soil water content (θ_{grav}) vs field saturated hydraulic conductivity (Kfs) in the wet and dry seasons in: a) Andisols; and b) Inceptisols

Table 6.5 Spearman´s Rho correlation coefficients (r) between field saturated hydraulic conductivity (Kfs) and soil water content

	Kfs[1] (mm/hr)	Kfs (mm/hr)	Kfs (mm/hr)
a) Andisols and Inceptisols	All seasons (n = 48)	Dry season (n = 24)	Wet season (n = 24)
θ_{grav}[2] (g/g)	-0.42		
θ_{vol}[3] (cm^3/cm^3)	-0.39		
b) Andisols	All seasons (n = 24)	Dry season (n = 12)	Wet season (n = 12)
θ_{grav} (g/g)			
θ_{vol} (cm^3/cm^3)			
c) Inceptisols	All seasons (n = 24)	Dry season (n = 12)	Wet season (n = 12)
θ_{grav} (g/g)			
θ_{vol} (cm^3/cm^3)			

[1]Kfs: field hydraulic saturated conductivity; [2]θ_{grav}: gravimetric soil water content; [3]θ_{grav}: volumetric soil water content; gray cells show correlations with $p < 0.01$

Table 6.6 Spearman´s Rho correlation coefficients (r) between field saturated hydraulic conductivity (Kfs) and soil water content without high values (greater than 50mm/hr)

	Kfs[1] (mm/hr)	Kfs (mm/hr)	Kfs (mm/hr)
a) Andisols and Inceptisols	All seasons (n = 41)	Dry season (n = 19)	Wet season (n = 22)
θ_{grav}[2] (g/g)	-0.47	-0.66	
θ_{vol}[3] (cm^3/cm^3)	-0.49	-0.59	
b) Andisols	All seasons (n = 22)	Dry season (n = 10)	Wet season (n = 12)
θ_{grav} (g/g)			
θ_{vol} (cm^3/cm^3)			
c) Inceptisols	All seasons (n = 19)	Dry season (n = 9)	Wet season (n = 10)
θ_{grav} (g/g)	-0.65		
θ_{vol} (cm^3/cm^3)	-0.65		

[1]Kfs: field hydraulic saturated conductivity; [2]θ_{grav}: gravimetric soil water content; [3]θ_{grav}: volumetric soil water content; gray cells show correlations with $p < 0.01$

Table 6.7 Field saturated hydraulic conductivity (Kfs) values reported in other studies carried out in the tropics and in the Andes

Land cover	**Site/Country**	**Elevation (m)**	**Precipitation (mm/year)**	**Texture**	**Kfs[1] (mm/hr)**	**Method**	**Reference**
Pasture (Andisols)	**Sonora watershed, Colombia**	**2,088-2,331**	**2,955**	**Sandy loam, loam, sandy clay loam**	**Median dry – wet season 5 – 0.7**	**Double ring infiltrometer**	**This study**
Pasture (Inceptisols)	**El Chocho watershed, Colombia**	**1,768-2,111**	**1,393**	**Clay, silty clay, silty clay loam**	**31 – 3**		
Pasture (Andisols)	San Gerardo area, Costa Rica	1,520-1,620	4,400-6,000	Sandy loam, loam	Average 14.7 8.7 under cow trails	Guelph permeameter Tension infiltrometer Small-cores method	Tobón et al., 2010
Pasture (Inceptisols)	Reserva Biosfera de San Francisco, Ecuador	1,860	2,273	Silt loam	Median 3	Ammozemeter (constant head permeameter)	Zimmermann and Elsenbeer, 2008
Pasture (Inceptisols)	Catie[2] farm, near Turrialba, Costa Rica	650	2,500-3,000	Clay loam, loam	Average 12	Double ring infiltrometer	Toohey et al., 2018

[1]Kfs: field saturated hydraulic conductivity; [2] CATIE: Tropical Agricultural Research and Higher Education Center

When separating Kfs data of Andisols and Inceptisols of this study by season, significant differences between soil orders only occurred in the dry season (Table 6.8). In contrast, wet versus dry season Kfs values were significantly different in both soil orders (Table 6.9). In Andisols, median Kfs values were <5 mm/hr falling into the slow and very slow infiltration categories. In contrast, in Inceptisols the difference in Kfs between seasons was more pronounced (Table 6.9). Moderate Kfs values in Inceptisols only occurred in the dry season, while Kfs values were classed as slow in the wet season. Significant differences in Kfs between seasons are also reported in the literature (Diamond and Shanley, 2003; Jejurkar and Rajukar, 2012) with antecedent soil moisture contributing to this seasonal effect. θ_{grav} in the Andisol site was generally > 70% in contrast to θ_{grav} < 70% in the Inceptisol site. Note that zero infiltration was measured in six of the sites in Andisols and three of the sites in Inceptisols during the wet season, indicating imperfect drainage particularly in the Sonora watershed. Conversely, true steady-state infiltration rate may not have been achieved at all Inceptisol sites during the dry season. These results reflect infiltration rates in the field and suggest that the use of seasonally measured Kfs values in hydrological models may increase our understanding of the factors and mechanisms affecting OF and water dynamics in Andean watersheds.

Table 6.8 Median field saturated hydraulic conductivity (Kfs) and soil water content (θ) in Andisols and Inceptisols

Dry season		Wet season	
Andisols	Inceptisols	Andisols	Inceptisols
Kfs[1] (mm/hr)			
5 (3 - 24)[4]	31 (9 - 57)*	0.7 (0 - 6)	3 (0 - 11)
θ_{grav}[2] (g/g)			
84 (70 - 92)	24 (15 - 37)**	112 (94 - 139)	61 (57 - 73)**
θ_{vol}[3] (cm^3/cm^3)			
0.45 (0.38 - 0.49)	0.20 (0.13 - 0.32)**	0.60 (0.50 - 0.75)	0.53 (0.49 - 0.63)

[1]Kfs: field saturated hydraulic conductivity; [2]θ_{grav}: field gravimetric soil water content; θ_{vol}: calculated volumetric soil water content; [4]Values in parenthesis are first and third quartile; Number of measurements were 12 for each soil order in each season; *, ** Significant differences between Andisols and Inceptisols with Mann Whitney U test at p < 0.05 and p < 0.01, respectively

Table 6.9 Median saturated hydraulic conductivity (Kfs), and soil water content (θ) by season in Andisols and Inceptisols

Andisols		Inceptisols	
Dry season	Wet season	Dry season	Wet season
Kfs[1] (mm/hr)			
5 (3 - 24)[4]	0.7 (0 - 6)*	31 (9 - 57)	3 (0 - 11)*
θ_{grav}[2] (g/g)			
84 (70 - 92)	112 (94 - 139)**	24 (15 - 37)	61 (57 - 73)**
θ_{vol}[3] (cm^3/cm^3)			
0.45 (0.38 - 0.49)	0.60 (0.50 - 0.75)**	0.20 (0.13 - 0.32)	0.53 (0.49 - 0.63)**

[1] Kfs: field saturated hydraulic conductivity; [2] θ_{grav}: field gravimetric soil water content; [3] θ_{vol}: calculated volumetric soil water content; [4] Values in parenthesis are first and third quartile; Number of measurements were 12 for each soil order in each season *, ** Significant differences between the dry and the wet season with Mann Whitney U test at $p < 0.05$ and $p < 0.01$, respectively

High Kfs values (lines and crosses in Figure 6.2) were measured in both soil orders. These Kfs values > 50 mm/hr, may have been affected by site conditions. In the case of Andisols, as discussed in Chapter 2 (Section 2.1.3), high values may be the result of the random distribution of termites. Also, as discussed in Chapter 2 (Section 2.1.3), the high Kfs values of Inceptisols, may be the result of rocks associated with the deposition of materials from road construction and localized land subsidence. Regardless whether considering geographically isolated areas with high Kfs values, there were significantly higher Kfs values in Inceptisols relative to Andisols, and significantly higher Kfs values in the dry season relative to the wet season in both soil orders, highlighting the importance of measuring infiltration seasonally. See Appendix H, Tables H1 and H2 for the differences between soil orders and seasons with extreme values excluded. High Kfs values indicate the inherent soil variability encountered in the field, and thus should be considered when determing Kfs values for hydrological or other models.

The variability of Kfs spatially and temporaly highlights the importance of field measurements which incorporate a larger surface area, to represent field conditions. The double ring infiltrometer, due to the large soil contact area, incorporates macro-pores and is thus representative of field conditions (Davis et al., 1999). This method; however, is labour intensive and requires time to obtain reliable measurements (Diamond and Shanley, 2003).

6.3.2 Estimation of overland flow

Overland flow (OF) is largely regulated by the soil infiltration rate, rainfall intensity, antecedent soil water content and slope (Bonell, 1993). High OF may lead to floods in lowlands and to water scarcity in upper and mid-watersheds, as water is rapidly lost from watersheds. If OF is low, rain water can remain in the watershed, be stored in the soils, drain slowly to streams by gravity, be taken up by plants, or contribute to groundwater recharge. Thus, retaining water within soils is a key factor for communities facing water scarcity, climatic variability and population growth, especially in the Colombian Andes, where it is projected that 70% of urban municipalities will be affected by water scarcity by 2025 (IDEAM, 2000).

The precipitation regime of the two watersheds is described in Table 6.10. In both watersheds, the majority of the rainfall events are of low intensity (RI_{10}< 10 mm/hr) represented by 87% of the rainy days in the Andisol site and 93% of the rainy days in the Inceptisol site. These low intensity events accounted for 43% and 59% of total precipitation (TP) during the monitored years in Andisol and Inceptisol sites, respectively. Despite this similarity in the distribution of rainfall intensity, there is a large difference in the total precipitation between the sites. During the two years evaluated, precipitation in the Andisol site was 2.6 times greater than that of the Inceptisol site, and the number of days with precipitation was double at the Andisol site.

Table 6.10 Rainfall intensity classes for Sonora a) and El Chocho b) watersheds

a) Sonora watershed (Andisol site)

Rain intensity class (mm/hr)	**No. Of days**	**% days with rain**	**Precipitation (mm)**	**% of total precipitation**
0-9.99	42.3	86.8	2698	43
10-19.99	3.6	7.3	1224	19
20-29.99	1.4	2.9	810	13
30-29.99	0.7	1.5	609	10
40-39.99	0.3	0.6	293	5
50-39.99	0.2	0.4	282	4
60-49.99	0.1	0.3	205	3
70-69.99	<0.1	0.1	86	1
80-79.99	<0.1	<0.1	41	1
90-99.99	<0.1	0.1	63	1
100-109.99	<0.1	<0.1	18	<1
110-119.99	-	0.0	-	0
120-129.99	-	0.0	-	0
Total	48.8	100	6331	100

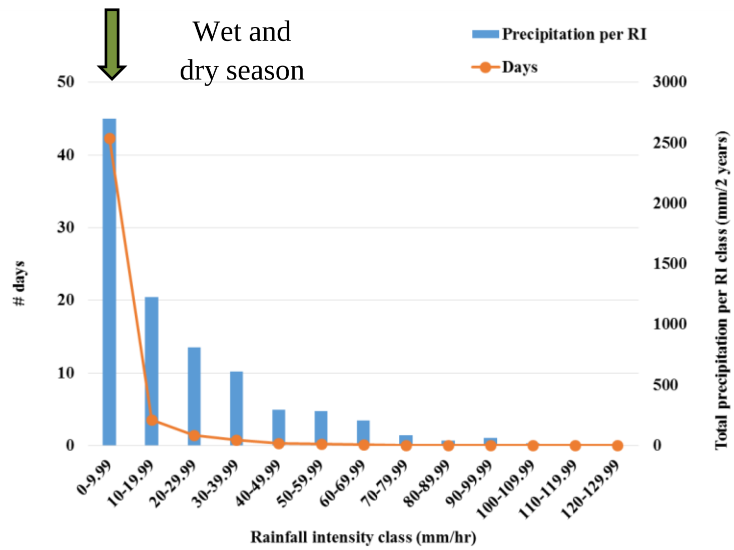
b) El Chocho watershed (Inceptisol site)

Rain intensity class (mm/hr)	**No. Of days**	**% days with rain**	**Precipitation (mm)**	**% of total precipitation**
0-9.99	24.7	93.3	1384	59
10-19.99	1.0	3.8	337	14
20-29.99	0.4	1.6	237	10
30-29.99	0.2	0.7	139	6
40-39.99	<0.1	0.2	66	3
50-39.99	<0.1	0.2	53	2
60-49.99	<0.1	0.1	44	2
70-69.99	<0.1	0.1	37	2
80-79.99	<0.1	<0.1	14	1
90-99.99	<0.1	0.1	32	1
100-109.99	-	0.0	-	0
110-119.99	-	0.0	-	0
120-129.99	<0.1	<0.1	20	<0.1
Total	26.5	1	2365	100

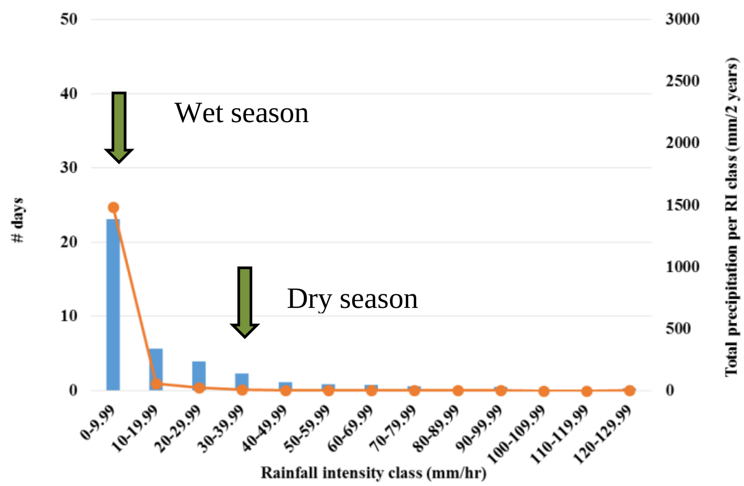
The majority of precipitation in both watersheds has a low RI_{10} (<10 mm/hr). Figure 6.3 graphically compares Kfs to RI_{10} and indicates the amount of precipitation that may be partitioned to OF. Arrows represent the Kfs values in the dry and wet seasons for both soil orders, and precipitation is shown by the blue bars. Precipitation categories to the right of the green arrows (Fig. 6.3) are more likely to be partitioned to OF, as RI_{10} is higher than Kfs. Thus, more rainfall events in the wet season of both soils will be partitioned into OF.

In the El Chocho watershed (Inceptisols), Figure 6.3b suggests that during the dry season when Kfs> 30 mm/hr, OF would be reduced. This graphical representation, shows a higher chance of occurrence of OF in Andisols in both seasons. In Inceptisols, OF may also occur in the wet season, but may be lower in the dry season since the infiltration rate in this season is faster.

a) Sonora watershed (Andisol site)



b) El Chocho watershed (Inceptisol site)



Arrows represent Kfs values for pasture

Figure 6.3 Number of days and total precipitation (TP) for each rain intensity (RI) class in: a) Andisol site; and b) Inceptisol site

The ratio OF/TP was used to estimate the percentage of precipitation that results in OF. The results, given in Table 6.11, suggest that 75% of total precipitation in the Andisols site (~2,400 mm/year) would result in OF, in comparison to only 30% in the Inceptisol site (~350 mm/year). Note that in the wet season OF/TP was higher; around 89% and 36% in Andisol and Inceptisol sites, respectively, in comparison to 50% and 15% in the dry season. Suescún et al. (2017) measured OF in the Central region of the Colombian Andes and found values OF/TP < 3% in pasture on slopes of 18-22%, while Molina et al. (2007) in Ecuador found runoff coefficients (OF/simulated rainfall) between 36 and 98% under a land use (abandoned land) similar to pasture with slopes of 15-25%. These opposing results suggest that direct OF measurements are necessary to confirm the estimations of this study. However, during field measurements in the wet season in the Andisols site, runoff was observed during rainfall events which provides some confidence for the OF estimations at this site. In the Andisol site, high OF/TP is a concern for community water providers, as they are interested in conserving or increasing baseflows in the local streams, which are reliant on GW from the soil. In order to increase Kfs, reforestation and/or natural forest regeneration of pasture sites is recommended. The literature suggests that forest coverage has consistently higher Kfs than non-forest lands (Zimmerman et al., 2006, 2010; Germer et al., 2010). In addition, there is increasing evidence that soil infiltrability increases with time during natural forest regrowth (Deuchars et al., 1999; Ziegler et al., 2004; Zimmerman et al., 2006; Hassler et al., 2011) and with reforestation (Gilmour et al., 1987; Ilstedt et al., 2007).

Table 6.11 Estimation of overland flow (OF) over total precipitation in: a) the Andisol site; and b) Inceptisol site

a) Sonora watershed - Andisols

Year	Season	Months	Monitored rainfall (mm)	% monitored time	Total rainfall TP[1] (mm)	Estimated OF (mm)	OF/TP (%)
Year 1 2012-2013	Wet 1	Oct-Dec/12	1021	100	1021	912	89
	Dry 1	Jan-Feb/13	569	100	569	302	53
	Wet 2	Mar-May/13	1007	100	1007	893	89
	Dry 2	Jun-Sep/13	611	100	611	295	48
		Year 1 2012-2013	**3208**		**3208**	**2403**	**75**
Year 2 2013-2014	Wet 1	Oct-Dec/13	1209	99	1209	1077	89
	Dry 1	Jan-Feb/14	511	100	511	290	57
	Wet 2	Mar-May/14	867	100	867	751	87
	Dry 2	Jun-Sep/14	536	100	536	248	46
		Year 2 2013-2014	**3123**		**3123**	**2365**	**76**

b) El Chocho watershed - Inceptisols

Year	Season	Months	Monitored rainfall (mm)	% monitored time	Total rainfall TP[1] (mm)	Estimated OF (mm)	OF/TP (%)
Year 1 2011-2012	Dry 1	Aug-Sep/11	135	100	135	15	11
	Wet 1	Oct-Dec/11	507	100	507	173	34
	Dry 2	Jan-Feb/12	181	75	212	27	13
	Wet 2	Mar-May/12	422	84	464	169	36
	Dry 3	Jun-Jul/12	110	94	110	8	7
		Year 1 2011-2012	**1355**		**1428**	**393**	**29**
Year 2 2012-2013	Dry 1	Aug-Sep/12	156	100	156	31	20
	Wet 1	Oct-Dec/12	226	100	226	88	39
	Dry 2	Jan-Feb/13	173	60	201	25	13
	Wet 2	Mar-May/13	392	92	414	151	36
	Dry 3	Jun-Jul/13	64	100	64	7	12
		Year 2 2012-2013	**1010**		**1061**	**302**	**30**

[1] Total rainfall was estimated based on the monitored rainfall as explained in Appendix G

6.4 Conclusions

Significant differences were found in quasi steady-state infiltration rate in each soil type between the wet and the dry seasons, highlighting the importance of field measurements of Kfs and soil water content, in order to obtain data that represent temporal variations. Kfs under pasture in Andisols was classified in the very slow and slow categories, in the wet and in the dry seasons, respectively; while in Inceptisols, Kfs classified in slow and moderate categories, in the wet and in the dry seasons.

The low Kfs in Andisols may be the result of soil properties and conditions within the Sonora watershed, specifically: high micro-pore volume, high soil water content even in the dry season, high precipitation in the watershed, and the presence of thick layers of volcanic ash and placic layers at depth that impede infiltration. Higher Kfs values in Inceptisols than in Andisols may be explained by lower precipitation in the El Chocho watershed that contributes to a range in θ_{grav} from 20% to 85%, and a significant correlation between Kfs and θ.

In Andisols of this study, spatial variability in Kfs was most likely related to termites, while in Inceptisols, land subsidence and rocks depositions associated with road construction likely contributed to variability. A map of Kfs values related to site conditions could be created, to identify regions with similar Kfs. Data separated by soil type, season and site conditions could then be used as input values in hydrological modelling to more accurately represent field conditions.

Preliminary estimations of OF/TP during the two years of this study were found to be higher in the wet season in both Andisols and Inceptisols. Over 70% of rainfall was estimated to be partitioned into OF in the Sonora watershed (Andisols), indicating that management practices to increase infiltration should be implemented.

7. GENERAL DISCUSSION AND CONCLUSIONS

7.1 Overview

Within a watershed context at mid-elevation (1,700-2,300 m) in the Colombian Andes, the goal of this research was to assess soil properties of the two most common soil types, as they affect soil water dynamics. The studied Andisols are located in the Central mountain range and Inceptisols are located in the Western mountain range. The colloidal fraction of the two soils are dominated by high surface area minerals and organic matter, and have similar soil water retention (SWR) characteristics even though the composition of the colloidal fraction is different.

The specific objectives of the research were to:

- Determine the mineralogy of the soils and relate these properties to water retention characteristics
- Determine the soil water retention (SWR) characteristics of the A and B horizons
- Compare the effects of natural forest and pasture land uses on SWR characteristics, and
- Determine and compare field saturated hydraulic conductivity (Kfs) during dry and wet seasons under pasture, as it was not possible to compare to natural forest.

The soils of this study, are located in different mountain ranges of the Colombian Andes, with different climate and parent materials, but are located in watersheds with similar elevation (1,700-2,300 m) and land uses (natural forest and pasture). Both watersheds drain to the Cauca River which flows north to the Atlantic Ocean, and both are the source of water for peri-urban communities. The two selected watersheds the Sonora and the El Chocho, are dominanted by Andisol and Inceptisol soils, respectively.

7.2 Summary

Andisols and Inceptisols of this study have large total porosity, GW, θ_{FC} and θ_{PWP} in comparison to values reported for clay soils in the literature. Andisols in the Sonora watershed, even though they have a loamy texture, displayed high SWR. In contrast, the

Inceptisols of the El Chocho watershed were clay texture, yet SWR values in both A and B horizons of Andisols were greater than values for Inceptisols at every tension. Both soils however, have similar values of PAW and GW. Despite having different parent materials and climatic conditions, the soils of this study share the presence of colloids with high specific surface area, that increase their ability to retain water. These colloids contribute to the high hygroscopic water content of the two soils, aggregate formation and a wide range in pore size distribution. The inorganic-colloidal fraction is dominated by allophane, imogolite and organo-metallic compounds in Andisols, and ferrihydrite and Al/ Fe oxides in Inceptisols.

Land use effects on SWR characteristics in Andisols and Inceptisols appear to be minimal. Although SOC was significantly lower under pasture relative to natural forest in the A horizon of both soils, significant differences in SWR were found only for PWP of Andisols. The similarity in SWR between natural forest and pasture may reflect the cumulative and integrative effects of SOC and SRO on SWR.

Significant differences were found in Kfs in each soil between the wet and the dry seasons, highlighting the importance of seasonal, *in situ* field measurements of Kfs. Quasi steady-state infiltration or Kfs under pasture in Andisols was classified in the very slow (<1 mm/hr) and slow categories (5 mm/hr), in the wet and in the dry seasons, respectively. While in Inceptisols, Kfs was classified in the slow (3 mm/hr) and moderate categories (31 mm/hr), in the wet and in the dry seasons. The low Kfs in Andisols throughout the year was attributed to impermeable layers at depth, specifically volcanic ash and/or placic horizons. Higher values in Inceptisols were attributed to deep soils, and a pronounced seasonal effect on measured infiltration rates, reflected by a negative correlation between Kfs and antecedent soil moisture content.

Preliminary estimations of overland flow (OF), determined from the ratio of OF to total precipitation, suggest that up to 88% of precipitation in the Sonora watershed (Andisol site) may be partitioned to OF in the wet season. In contrast, only 28% of precipitation is expected to form runoff in the El Chocho watershed (Inceptisol site). These results highlight the high OF in the Andisol site, and the need for a shift in management practices to increase infiltration in the watershed.

7.3 Significance

This study makes an important contribution to our understanding of both soil types in the Colombian Andes, as it included mineralogical properties in the evaluation of factors affecting water retention characteristics, in addition to physical and chemical properties. Analyses of these properties by horizon facilitates a better understanding of the factors influencing water retention. For example, in the case of the dominant soil group of the Sonora watershed, it was found that this allophanic Andisol, had high amounts of SRO minerals in the B horizon, and low amounts of organo-metallic compounds in the A horizon, but a significant amount of organic matter in the surface and B horizons. In contrast, in the Inceptisols of the El Chocho watershed, the water retention is affected by minerals such as oxides and hydroxides of Fe (goethite and ferrihydrite) and Al (boehmite). These minerals with large specific surface areas, despite being present at small concentrations, as in the case of ferrihydrite, contribute to the high volume of micro-pores and moderate values of plant available water storage (PAWS) and gravitational water (GW). The presence of ferriyhidrite in Inceptisols, helped to explain the similarities between the two soils in terms of their water retention characteristics.

Short-range order minerals contribute in two different ways in relation to SWR characteristics: they stabilize SOC and they increase the apparent sand size fraction. In Andisols, SRO minerals and SOC may have a synergistic effect increasing SWR characteristics. The increase in the apparent sand size fraction may be a reflection of aggregate formation, which increases macro-pores and GW.

Hydrological modellers working in the Andean region commonly utilize texture to estimate soil water retention and hydraulic conductivity. This research has shown that soil texture is a poor surrogate for these estimations in soils with SRO minerals such as the Andisols and Inceptisols of this study. The apparent sand size fraction reflects the presence of aggregates rather than disaggregated soil particles. SWR of both soils was high. And soil water movement, in the Andisol site in particular, was impacted by a restrictive layer at depth resulting in imperfect drainage. Thus, the use of texture alone to predict soil water dynamics would not accurately represent watershed conditions.

This study contributes to the knowledge on SWR characteristics and the relationships with soil properties at mid-elevation in the Andes as most studies reported in the literature have focused on high elevation páramo ecosystems. This information is important as a large proportion of the Andean population live at these elevations and communities living in peri-urban and urban zones are dependent on these ecosystems for their water supply and livelihoods.

7.4 Implications for land use management

Both Andisols and Inceptisols have unique SWR characteristics: although they retain significant water in their micro-pores, they have moderate PAWS and macro-pore volume (GW). Soils under pasture had significantly lower SOC in both watersheds. Thus, for communities interested in source water protection, a recommendation is to increase SOM in order to enhance both the hydrological buffering capacity of the soil and PAWS. Higher SOC will not only contribute to source water protection, but also provides carbon storage within the watersheds. The addition of organic matter to soils with SRO minerals, may foster carbon stabilization, aggregate formation and increase SWR characteristics.

In Andisols, where OF was high, reforestation is recommended. With reforestation Kfs may increase and OF decrease, as suggested by the literature. Despite an increase in evapotranspiration (ET) with reforestation, the reduced OF, could compensate for the higher ET, and may result in higher dry season base flows in local streams. In the El Chocho watershed (Inceptisol site), precipitation is significantly lower, <1,400 mm/yr, and irrigation rates should be carefully controlled to avoid OF.

7.5 Suggestions for future research

To improve our understanding of the role of soils in supporting crop production and regulating stream flow in the Sonora and El Chocho watersheds, the next step could be a hydrological study that includes a water balance, estimates of base flow in the dry seasons, water yield evaluation and modelling of stream flow under different climatic scenarios. The data of this study provides input variables for soil properties, which combined with hydrological monitoring and modelling would support local communities in their efforts to adapt to climatic variability.

Further analysis of the differences between land uses is needed to better understand the effect of land use change on SOC and changes in pore size distribution. While this study found limited differences in SWR between natural forests and pasture, and suggests that SRO minerals may play a role in mitigating impacts, additional detail on pasture management practices, erosion and characteristics of the forest floor would further our understanding about the relationships between land use and SWR.

Since SOC found in Andisols and Inceptisols of this study was relatively high (~ 8% in Andisols and ~ 5% in Inceptisols) and SOC lability may be low in soils with SRO minerals as proposed by Bruun et al. (2010), the role of these soils as carbon sinks is important in the context of climate change (Lal, 2013). Therefore, a study of lability, turnover, and residence time of SOC in these soils is of interest.

As aggregate dispersion in Andisols is problematic, the Bouyucous method conducted on samples at field water content (as opposed to air dried) is recommended. These data will provide more reliable texture information that may correlate with SWR characteristics and would be interesting for comparison purposes with the standard Bouyucous test results on air dried samples on both soil orders. To fully investigate the difference in SWR of soils containing SRO minerals, analysis of specific surface area, could be a more suitable approach, than texture analysis.

Few studies of Inceptisols in Colombia have been conducted. Thus, additional characterization of these soils, including SWR, parent material and mineralogy will provide a better understanding of the range in water retention and related soil characteristics found in these soils. In particular, further research on the effect of ferrihydrite in moderating changes in SWR in surface horizons of Inceptisols, would be of interest.

Future research on Andisols and Inceptisols in the Andes under a range of climate and ecosystems will contribute to an improved understanding of the factors affecting SWR characteristics and to developing regionally relevant data. In addition, exploration of suitable methods for measuring infiltration in natural forest on slopes is recommended, in order to further study the differences of soil water dynamics between land uses.

The contribution of this study was to give a complete analysis of the soil characteristics, including chemical, physical and mineralogical properties that affect SWR characteristics, of two great groups of the two most common soil orders in the Colombian Andes, Andisols and Inceptisols, at mid-elevations.

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APPENDICES

Appendix A. General characteristics of Andisols and Inceptisols

The Andisol order is relatively a new soil order that was added in 1990 to the Soil Taxonomy (Soil Survey Staff, 2014). The radical “andi” comes from the Japanese word ando, meaning dark soil, which connotes the color being the typifying characteristic of volcanic ash soils (Van Wambeke, 1992). The vast majority of Andisols are formed from pyroclastic deposits (volcanic ejecta) such as ash, pumice, cinders and lava. Rapid cooling of the molten materials upon ejection prevents crystallization of minerals with long range order, and the resulting product is vitric material or volcanic glass, which are dominated by amorphous or short-range order (SRO) minerals (Grunwald, 2012).

Term “short-range order (SRO) minerals” refers to a class of material that are noncrystalline or at best, poorly crystalline, although they consist of tightly bonded silicon, aluminum and oxygen atoms. The two principal clay minerals of this type are allophane and imogolite that are commonly formed from volcanic ash (often found in Andisols) and from organic matter and aluminum accumulation (found in Spodozols) (Huang, 1991). The molecular structure of allophane consists of incomplete 1:1 phyllosilicate layers that contain aluminum both in octahedral and tetrahedral positions with the formula Al_2O_3 $(SiO_2)_{1.3\text{-}2}$ (2.5-3) H_2O. Defects produce hollow spherules of 3.5 to 5 nm in diameter (Van Wambeke, 1992). Imogolite $Al_2SiO_3(OH_4)$, is also a nanoparticle of tubular structure with an inner diameter of 1 nm and outer diameter of 2 nm (Nanzyo, 2002). The hollow spheres and tubes of allophane and imogolite of nanoparticle size (1-100 nm), result in micrococsopic pores that can store water within the structure (Wada, 1985). The form and size of these SRO minerals are related to their high water absorbing capacity and the high water content at high moisture tension (Buytaert et al., 2002).

The high specific surface area of SRO minerals (Eusterhues et al., 2005) (Table A.1) and the presence of positive and negative charges (pH dependent charge), allow SRO minerals to bond organic compounds and participate in aggregate formation. Within the formed aggregates, soil organic carbon (SOC) is preserved from decomposition or microbial attack through physical protection (i.e., SOC inaccessibility and/or the existence of temporary water saturated conditions) (Broadbent et al., 1964; Dahlgren et al., 2004; Egli et al., 2008; Parfitt, 2008). Therefore, it is not surprising that Andisols often have high organic matter content.

The combination of SRO minerals, stable aggregates and high organic matter content, affects soil water characteristics in Andisols by enabling:

- low soil bulk density (ρ_b), especially when higher SOC content is present in both non-allophanic soils (where organo-metalic compounds are predominant) and allophanic soils (where allophane and imogolite are predominant) (Nanzyo, 2002). Lower ρ_b indicate higher porosity, which in turn may increase soil water content.
- wide range in pore size distribution. In mature Andisols, where SRO mineral concentrations are high, the proportion of macro-pores decreases and that of micro-pores increases. However, the proportion of macro-pores could remain around 10% (Nanzyo, 2002).
- high permeability and rapid rainfall infiltration (Warkentin and Maeda, 1980; Shoji et al., 1993; Tejedor et al., 2012).

Andisols may have the pseudo-sandy texture that is likely the product of aggregate formation (Shoji et al., 1993) when a complete dispersion of aggregates is virtually impossible because each of the inorganic colloids shows a different point of zero net charge (Shoji et al., 1993). Therefore, there is no available technique that accurately measures the texture of Andisols due to their strong soil aggregate structure (Shoji et al., 1993).

Inceptisols are soils that are in the incipient (i.e., early) stages of formation toward mature soil orders but have not yet fully developed their diagnostic properties. Conceptually, Inceptisols are transitional soils with minimum or no appreciable development (Entisols) and to soils of various orders that have been accepted by pedologists as carrying the marks of well-defined soil-forming processes (Van Wambeke, 1992). In Inceptisols of the tropics it is common to find a cambic horizon, which is a noncemented subsurface horizon in which the marks of original rocks structures or thin bedding have been obliterated in at least one-half of their volume. Texture of Inceptisols is typically of very fine sand or finer (Van Wambeke, 1992). It is also common that one or more horizons are affected by weathering of primary minerals, which releases free iron oxides and/or produces clays that give subsurface horizons stronger chromas or redder hues that the underlying horizons (Van Wambeke, 1992).

Iron and aluminum oxides are produced from the weathering of primary and secondary silicate minerals. The iron and aluminum atoms are coordinated with oxygen atoms (the latter are associated with hydrogen ions to make hydroxyl groups). Some minerals such as gibbsite (an Al-oxide) and goethite (an Fe-oxide) consist of crystalline sheets, while ferrihydrite (an Fe-hydroxide $5Fe_2O_3\ 9H_2O$) is noncrystalline (Goldberg et al., 2012). Ferrihydrite structure is still been debated (Manceau, 2011; Faivre, 2016).

Iron and aluminum oxides also play a significant role in soil water characteristics as they enhance aggregation. Films of gibbsite, goethite and hematite, and the amorphous hydroxide ferrihydrite coat and cement soil aggregates preventing their breakdown (Goldberg et al., 2012). Crystalline Fe-oxides and hydroxides are of less importance in enhancing aggregation than the amorphous oxides such as ferrihydrite (Duiker et al., 2003; Regelink et al., 2015) despite their small contribution to soil mass (<1%) (Regelink et al., 2015). Ferrihydrite dominates the surface area available for sorption of SOC, stabilizing it and forming organo-mineral assemblages (Kaiser et al., 2011; Regelink et al., 2013). In addition, ferrihydrite binds soil particles, silt and sand, which in association with soil organic matter creates secondary aggregates (Arias et al., 1996; Sei et al., 2002). This can be explained by smaller size of ferrihydrite particles (diameter <10 nm) and their high specific surface area (Table A.1).

In terms of infiltration, Inceptisols tend to have intermediate values compared to other soil orders, influenced by a balanced set of soil properties such as a moderate level of aggregation and moderate structural stability, loam texture and moderate bulk density (Tejedor, et al., 2012).

Soil organic matter content and composition affect soil structure and adsorption properties (Rawls et al., 2003). Organic matter helps stabilize soil structure and aggregates (Feller and Beare, 1997; Boix-Fayos et al., 2011), which in turn contribute to a significant total pore volume and a wide pore size distribution (Barral et al., 1998). Soil humic substances such as humic acid, fulvic acid, and humin are nanoparticles (Bakshi et al., 2015) with high specific surface area (Table A.1). An increase in soil organic carbon in a fine textured soil results in an increase in water retention (Rawls et al., 2003). The stability of microaggregates is enhanced by multivalent cations, which act as bridges between organic colloids and clays, and by the binding action of polysaccharides, mainly mucilages produced by bacteria, but also by plant roots and fungal hyphae (Oades, 1984).

Appendix B. Characteristics of soil profiles of Andisols (great group Hapludands) and Inceptisols (great group Dystrudepts) included in this study

Table B.1 General characteristics of soil profiles in Andisols watershed (great group Hapludands)

Sonora watershed - Andisols

Site	Horizon	Elevation (m)	Slope	Depth (m)	Air dried color	pH[1] H_2O	pH $CaCl_2$	SOC[2] (%)	Bulk density (kg/m^3)	Sand (%)	Silt (%)	Clay (%)	Texture
						Pasture							
P1	A	2148	Slope 33%	0.0-0.2	10YR 4/2	5.0	4.0	12.0	617	32	26	43	Clay
	B			0.2-0.6	10YR 6/3	5.7	4.9	2.4	1005	53	29	18	Sandy loam
	C			0.6-1.1+	10YR 7/2	5.8	4.9	0.0	1270	62	20	18	Sandy loam
P2	A	2141	Flat <20%	0.0-0.2	10YR 4/2	5.1	4.2	10.2	572	48	29	23	Loam[3]
	B			0.2-0.9	10YR 6/3	5.7	4.9	2.6	821	59	32	9	Sandy loam[3]
	C			0.9-1.2+	10YR 7/2	5.7	4.9	0.3	1312	69	22	9	Sandy loam[3]
P3	A	2228	Slope 59%	0.0-0.2	10YR 5/4	5.4	4.5	6.2	655	47	31	22	Loam
	B			0.6-1.1	10YR 7/6	5.8	5.4	2.9	984	50	33	17	Loam
P4	A	2222	Flat <20%	0.0-0.5	10YR 5/3	5.2	4.1	8.6	455	19	54	26	Silt loam
	B1			0.5-2.7	10YR 5/4	5.6	4.7	6.3	557	52	33	15	Loam
	B2			2.7-2.9	10YR 7/2	5.5	5.1	0.9	837	57	26	17	Sandy loam
	C			3.1+	10YR 8/3	5.4	4.5	0.5	550	41	29	30	Clay loam
P5	A	2235	Slope 37%	0.0-0.3	10YR 5/3	5.0	4.1	7.3	656	44	34	22	Loam
	B			0.5-1.5+	10YR 6/4	5.5	4.8	3.5	510	53	30	17	Sandy loam
P6	A	2230	Flat <20%	0.0-0.2	10YR 5/3	5.2	4.2	6.1	733	40	40	20	Loam
	B			0.8+	10YR 6/4	5.7	5.2	3.8	654	43	38	20	Loam
P7	A	2205	Flat <20%	0.0-0.2	10YR 4/3	5.4	4.3	7.3	477	50	26	24	Sandy clay loam
	B			0.3-1.5+	10YR 5/4	5.5	4.8	4.4	598	45	33	22	Loam
P8	A	2233	Slope 24%	0.0-0.2	10YR 5/3	4.9	4.2	8.3	566	42	33	25	Loam
	B			0.6-1.1+	10YR 6/6	5.6	5.3	4.7	668	60	28	12	Sandy loam
P9	A	2216	Slope 44%	0.0-0.2	10YR 3/4	4.8	3.8	12.9	414	26	35	39	Clay loam
	B			1.0-1.7	10YR 7/4	5.7	5.2	2.6	693	63	21	16	Sandy loam
	C			1.7-2.1+	7.5YR 8/1	4.9	3.6	0.6	709	11	24	65	Clay
P10	A	2151	Flat <20%	0.0-0.15	10YR 4/2	5.3	5.1	13.8	293	34	33	33	Clay loam
	B			0.25-0.40	10YR 6/4	5.3	4.6	3.3	784	55	30	15	Sandy loam
P11	A	2179	Slope 29%	0.0-0.3	10YR 4/2	5.0	4.0	7.2	677	42	35	22	Loam
	B			0.3-1.2+	10YR 6/3	5.7	5.1	4.9	606	60	25	15	Sandy loam
P12	A	2144	Flat <20%	0.0-0.2	10YR 4/2	5.2	4.1	7.0	669	45	33	22	Loam
	B			02-1.5+	10YR 5/4	5.7	5.0	5.9	558	63	23	15	Sandy loam
	C	-	-	-	10YR 8/1	4.9	4.0	0.8	768	53	23	25	Sandy clay loam
	C	-	-	-	10YR 8/1	5.2	4.3	0.2	613	39	14	47	Clay
	C	-	-	-	10YR 8/1	4.9	3.9	0.0	965	2	13	85	Clay
						Natural forest							
B1	A	2104	Slope 59%	0.0-0.3	10YR 3/2	4.5	3.5	15.6	969	68	11	21	Clay
	B			0.3-1.2	10YR 6/3	5.3	4.6	2.2	1181	48	38	15	Loam
B2	A	2131	Slope 53%	0.0-0.3	10YR 3/4	4.6	3.7	11.0	511	46	24	30	Sandy clay loam
	B			0.3-1.2+	10YR 6/6	5.5	5.1	3.8	586	63	23	15	Sandy loam
B3	A	2217	Slope 47%	0.0-0.3	10YR 4/2	4.6	3.7	9.0	455	52	20	28	Sandy clay loam
	B			0.3-1.2	10YR 6/3	5.4	4.5	4.1	798	49	34	17	Loam
	C			1.2-1.7+	10YR 5/4	5.5	5.1	4.7	765	59	28	14	Sandy loam
B4	A	2153	Slope 88%	0.0-0.2	10YR 4/3	4.9	3.7	12.5	329	53	25	22	Sandy clay loam
	B			0.2-0.6	10YR 5/4	5.5	5.0	4.8	418	68	20	12	Sandy loam
B5	B	2077	Slope 73%	0.55-1.2+	10YR 6/4	5.7	4.9	3.8	667	57	28	15	Sandy loam
B6	A	2129	Slope 34%	0.0-0.15	10YR 4/2	4.6	3.6	13.5	323	53	23	24	Sandy clay loam
	B			0.25-0.9+	10YR 6/4	5.6	5.1	2.7	633	69	19	12	Sandy loam

[1] pH determination in samples with SOC>12%, liquid volume was doubled; [2]SOC: Soil organic carbon; [3] texture samples analyzed with Kettler method. Note**:** Based on filed observations there was 0% coarse fragments (2 – 75 mm in diameter) in A, B and C horizons.

Table B.2 General characteristics of soil profiles in Inceptisols watershed (great group Dystrudepts)

El Chocho watershed - Inceptisols													
Site	**Horizon**	**Elevation (m)**	**Slope**	**Depth (m)**	**Air dried color**	**pH[1] H_2O**	**pH $CaCl_2$**	**SOC[2] (%)**	**Bulk density (kg/m^3)**	**Sand (%)**	**Silt (%)**	**Clay (%)**	**Texture**
						Pasture							
P1	A	1850	Slope 45%	0.0-0.3	10YR 3/4	5.6	4.8	8.3	1053	13	32	55	Clay
	B			0.3-1.0+	YR 4/6	5.4	4.6	6.4	1020	6	27	66	Clay
	C			0.95+	7.5YR 5/8	5.4	4.1	1.5	1122	44	43	13	Clay
P2	A	1798	Flat < 20%	0.0-0.3	10YR 4/4	5.4	4.4	6.0	333	14	28	58	Clay
	B			0.5-0.8	10YR 6/6	5.3	4.0	1.9	832	21	20	58	Loam
P3	A	1861	Slope 40%	0.0-0.3	10YR 4/4	5.7	4.5	3.6	906	19	17	64	Clay
	B			0.3-0.9+	5YR 4/6	5.6	4.1	1.4	1011	8	36	56	Clay
P4	A	1830	Flat < 20%	0.0-0.4	10YR 4/3	5.9	4.9	5.0	916	25	48	27	Clay loam
	B			0.6-1.2+	10YR 6/6	5.7	4.8	1.6	984	25	32	43	Clay
P5	A	1912	Slope 47%	0.0-0.1	10YR 3/2	5.7	4.8	5.5	839	13	26	61	Clay
	B1			0.1-0.6	10YR 5/6	6.0	5.2	1.6	1096	23	54	23	Silt loam
	B2			0.6-1.1+	10.5YR 5/6	5.3	4.2	1.2	909	15	47	38	Silt clay loam
P6	A	1863	Flat < 20%	0.0-0.4	10YR 5/4	5.5	4.6	3.6	1039	20	22	58	Clay
	B			0.4-0.9+	7.5YR 5/6	5.7	4.7	2.7	1025	20	21	58	Clay
P7	A	1876	Slope 40%	0.0-0.15	10YR 4/3	5.6	4.7	7.3	799	11	39	50	Clay[3]
	B			0.4-0.6	7.5YR 5/6	6.0	5.1	3.9	1041	9	35	56	Clay
	C			0.75-1.0+	10R 5/6	6.1	5.0	2.0	972	14	21	65	Clay
P8	A	1844	Flat < 20%	0.0-0.3	5YR 5/4	5.7	4.8	3.7	936	12	44	44	Silty clay
	B			0.7-1.0	7.5YR 6/6	5.9	4.9	1.3	949	19	30	51	Clay
P9	A	1851	Slope 47%	0.0-0.2	10YR 5/4	5.3	4.3	5.1	842	11	31	58	Clay
	C			0.4-2.5+	10R 5/6	4.9	3.6	1.3	959	9	35	55	Clay
P10	A	1714	Flat < 20%	0.0-0.2	7.5YR 4/4	5.7	4.9	3.5	861	16	32	52	Clay
	B			0.5-0.6+	7.5YR 5/6	5.4	4.4	1.6	1075	19	35	46	Clay
P11	A	1891	Slope 47%	0-0.1	10R 3/2	5.4	4.1	4.4	893	12	13	76	Clay
	B			0.3-0.9+	10R 5/8	5.2	3.7	1.4	1134	4	34	62	Clay
P12	A	1844	Flat < 20%	0-0.2	10YR 4/2	5.5	4.5	5.0	931	26	21	53	Clay
	B			0.5-0.8+	10YR 5/2	5.4	4.2	1.8	990	35	22	43	Clay
						Natural forest							
B1	A	1932	Slope 34%	0.0-0.7	10R 3/1	5.5	4.6	6.5	807	47	23	31	Sandy clay loam
	B			0.75-0.9+	10R 4/3	5.1	4.0	3.5	840	66	11	23	Sandy clay loam
B2	A	1928	Slope 48%	0-0.05	10YR 3/1	5.7	4.9	14.9	388	33	15	52	Clay
	B			0.05-0.2	5YR 4/3	5.8	4.9	4.3	887	29	25	46	Clay
	C			0.2-0.55+	5YR 5/4	5.3	4.1	2.9	805	64	13	23	Sandy clay loam
B3	A	1959	Slope 48%	0-0.03	10R 3/1	6.0	5.1	9.0	590	9	43	48	Silty clay[3]
	B			0.06-0.80+	10R 5/6	5.6	4.7	1.7	834	20	50	30	Clay loam[3]
B4	A	1971	Slope 48%	0-0.1	5YR 3/3	5.8	5.1	7.7	721	12	32	56	Clay[3]
	B1			0.3-0.7	10R 6/8	4.8	3.4	1.4	947	23	46	31	Clay loam[3]
	B2			0.7-0.9+	7.5YR 6/6	5.0	3.5	0.6	714	18	47	35	Silty clay loam[3]
B5	A	1902	Slope 26%	0-0.35	10YR 5/2	5.5	4.4	3.8	964	16	56	28	Silty clay loam
	B			0.4-0.6+	7.5YR 5/6	4.9	4.5	1.5	1041	17	62	22	Silt loam
B6	A	1919	Slope 49%	0-0.17	10YR 4/2	5.4	4.3	5.2	733	11	65	24	Silt loam
	B			0.17-0.4	10YR 5/4	5.6	4.6	2.1	1117	19	28	53	Clay
	C			0.5-0.6+	7.5YR 5/3	5.5	4.4	1.8	1137	59	15	25	Sandy clay loam

[1] pH determination in samples with SOC>12%, liquid volume was doubled; [2]SOC: Soil organic carbon; [3] texture samples analyzed with Kettler method. Note: Based on field observations, there were 5% coarse fragments (2 – 75 mm in diameter) in A horizon, 10% in B horizon and 15% in C horizon

Appendix C. Family, species and Importance Value Index (IVI) of vegetation found in natural forest of Sonora (Andisol site) and El Chocho (Inceptisol site) watersheds

Table C.1 Family, species and Importance Value Index (IVI) of vegetation found in the Andisols watershed

Family	Species	Individuals	Relative density	Relative frequency	Relative coverage	IVI
Cyatheaceae	*Cnemidaria horrida*	37	0,14	0,06	0,17	0,37
Arecaceae	*Wettinia kalbreyeri*	27	0,10	0,07	0,11	0,29
Cyatheaceae	*Alsophila cuspidata*	13	0,05	0,06	0,07	0,18
Melastomataceae	*Tibouchina lepidota*	8	0,03	0,04	0,11	0,17
Rubiaceae	*Guettarda crispiflora sabiceoides*	16	0,06	0,04	0,07	0,17
Arecaceae	*Geonoma undata*	11	0,04	0,04	0,04	0,13
Solanaceae	*Cuatresia riparia*	19	0,07	0,02	0,03	0,13
Rubiaceae	*Palicourea angustifolia*	14	0,05	0,04	0,02	0,11
Arecaceae	*Chamaedorea linearis*	8	0,03	0,04	0,02	0,09
Rubiaceae	*Guettarda hirsuta*	8	0,03	0,02	0,02	0,07
Melastomataceae	*Miconia sp.4*	6	0,02	0,03	0,02	0,07
Symplocaceae	*Symplocos quindiuensis*	3	0,01	0,02	0,03	0,06
Rubiaceae	*Elaeagia karstenii*	5	0,02	0,03	0,01	0,06
Rubiaceae	*Palicourea acetosoides*	7	0,03	0,01	0,01	0,06
Araliaceae	*Oreopanax floribundum*	5	0,02	0,02	0,01	0,05
Rubiaceae	*Ladenbergia macrocarpa*	3	0,01	0,02	0,01	0,05
Clusicaceae	*Chrysochlamys colombiana*	4	0,02	0,02	0,01	0,04
Fabaceae	*Inga sierrae*	2	0,01	0,01	0,02	0,04
Bignoniaceae	*Tecoma stans var. velutina*	3	0,01	0,02	0,00	0,04
Lauraceae	*Ocotea sp.1*	1	0,00	0,01	0,03	0,04
Piperaceae	*Piper aff. imperialis*	4	0,02	0,01	0,01	0,04
Hippocastanaceae	*Billia columbiana*	2	0,01	0,01	0,01	0,03
Myrtaceae	*Myrcia popayanensis*	3	0,01	0,01	0,01	0,03
Primulaceae	*Geissanthus francoae*	3	0,01	0,01	0,00	0,03
Sapindaceae	*Pouteria torta tuberculata*	1	0,00	0,01	0,02	0,03
Euphorbiaceae	*Alchornea glandulosa*	1	0,00	0,01	0,02	0,03
Melastomataceae	*Miconia curvipetiolata*	2	0,01	0,01	0,01	0,03
Verbenaceae	*Aegiphila grandis*	2	0,01	0,01	0,00	0,03
Sabiaceae	*Meliosma violacea*	2	0,01	0,01	0,00	0,03
Sapindaceae	*Allophyllus mollis*	2	0,01	0,01	0,00	0,02
Lauraceae	*Nectandra lineatifolia*	2	0,01	0,01	0,00	0,02
Lauraceae	*Ocotea insularis*	2	0,01	0,01	0,01	0,02
Melastomataceae	*Miconia smaragdina*	3	0,01	0,01	0,00	0,02
Melastomataceae	*Miconia theaezans*	2	0,01	0,01	0,01	0,02
Nyctaginaceae	*Guapira myrtiflora*	2	0,01	0,01	0,01	0,02
Lauraceae	*Ocotea lentii*	1	0,00	0,01	0,01	0,02
Melastomataceae	*Meriania speciosa*	1	0,00	0,01	0,01	0,02
Melastomataceae	*Miconia aff. coronata*	2	0,01	0,01	0,00	0,02
Rubiaceae	*Notopleura cf. capacifolia*	2	0,01	0,01	0,00	0,02
Melastomataceae	*Miconia sp.6*	2	0,01	0,01	0,00	0,02
Poaceae	*Chusquea latifolia*	2	0,01	0,01	0,00	0,02
Boraginaceae	*Cordia af. lucidula*	1	0,00	0,01	0,01	0,02
Clusicaeae	*Clusia crenata*	1	0,00	0,01	0,00	0,01
Cyatheaceae	*Trichipteris conjugata*	1	0,00	0,01	0,00	0,01
Solanaceae	*Solanaceae*	1	0,00	0,01	0,00	0,01
Staphylaceae	*Turpinia occidentalis*	1	0,00	0,01	0,00	0,01
Clusicaceae	*Chrysochlamys dependens*	1	0,00	0,01	0,00	0,01
Rubiaceae	*Ladenbergia oblongifolia*	1	0,00	0,01	0,00	0,01
Melastomataceae	*Miconia aff. acuminifera*	1	0,00	0,01	0,00	0,01
Rubiaceae	*Cinchona pusbences*	1	0,00	0,01	0,00	0,01
Melastomataceae	*Miconia sp.5*	1	0,00	0,01	0,00	0,01
Rubiaceae	*Palicourea calophlebia*	1	0,00	0,01	0,00	0,01
Rubiaceae	*Palicourea ovalis*	1	0,00	0,01	0,00	0,01
Solanaceae	*Solanum aphyodendron*	1	0,00	0,01	0,00	0,01
Meliaceae	*Trichilia martiana*	1	0,00	0,01	0,00	0,01
Ericaceae	*Cavendishia bracteata*	1	0,00	0,01	0,00	0,01
Pentaphylacaceae	*Freziera nervosa*	1	0,00	0,01	0,00	0,01
Euphorbiaceae	*Hyeronima macrocarpa*	1	0,00	0,01	0,00	0,01
Lauraceae	*Ocotea macrophylla*	1	0,00	0,01	0,00	0,01
Rubiaceae	*Palicourea cuatrecasasii (sp1)*	1	0,00	0,01	0,00	0,01
Rubiaceae	*Psychotria hazenii*	1	0,00	0,01	0,00	0,01
Annonaceae	*Guatteria crassipes*	1	0,00	0,01	0,00	0,01
		264	1	1	1	3

IVI: Importance Value Index

Table C.2 Family, species and Importance Value Index (IVI) of vegetation found in the Inceptisols watershed

Family	Species	Individuals	Relative density	Relative frequency	Relative coverage	IVI
Heliconiaceae	*Heliconia griggsiana*	75	0,18	0,04	0,16	0,38
Arecaceae	*Prestoea acuminata*	30	0,07	0,03	0,06	0,16
Piperaceae	*Piper sp. 3*	30	0,07	0,01	0,04	0,13
Piperaceae	*Piper sp. 2*	26	0,06	0,03	0,03	0,12
Moraceae	*Clarisia biflora*	9	0,02	0,03	0,07	0,12
Actinidiaceae	*Saurauia cuatrecasana*	12	0,03	0,04	0,04	0,11
Meliaceae	*Cedrela montana*	3	0,01	0,02	0,07	0,09
Anacardiaceae	*Toxicodendron striatum*	9	0,02	0,03	0,04	0,09
Tiliaceae	*Helicocarpus americanus*	9	0,02	0,03	0,04	0,09
Rubiaceae	*Palicourea thyrsiflora*	14	0,03	0,03	0,02	0,09
Siparunaceae	*Siparuna lepidota*	14	0,03	0,03	0,03	0,08
Myrsinaceae	*Myrsine guianensis*	11	0,03	0,03	0,02	0,08
Asteraceae	*Verbesina arborea*	7	0,02	0,03	0,02	0,06
Melastomataceae	*Miconia ochracea*	9	0,02	0,02	0,02	0,06
Poaceae	*Guadua angustifolia*	13	0,03	0,01	0,02	0,06
Nyctaginaceae	*Guapira costaricana*	7	0,02	0,02	0,01	0,05
Mimosaceae	*Inga coruscans*	3	0,01	0,02	0,02	0,04
Rubiaceae	*Palicourea sp. 1*	6	0,01	0,02	0,01	0,04
Heliconiaceae	*Heliconia huilensis*	9	0,02	0,01	0,01	0,04
Cyatheaceae	*Cyatheaceae 1*	5	0,01	0,01	0,01	0,04
Clusiaceae	*Vismia guianensis*	2	0,00	0,01	0,02	0,04
Boraginaceae	*Cordia cilindrosthachya*	5	0,01	0,01	0,01	0,04
Lauraceae	*Ocotea macrophylla*	4	0,01	0,02	0,01	0,03
Flacourtiaceae	*Hasseltia floribunda*	4	0,01	0,01	0,01	0,03
Meliaceae	*Ruagea glabra*	2	0,00	0,01	0,01	0,03
Sapindaceae	*Cupania americana*	3	0,01	0,01	0,01	0,03
Clusiaceae	*Chrysochlamys colombiana*	4	0,01	0,01	0,01	0,03
Flacourtiaceae	*Casearia megacarpa*	2	0,00	0,01	0,01	0,03
Urticaceae	*Myriocarpa stipitata*	3	0,01	0,01	0,01	0,03
Lauraceae	*Lauraceae 3*	1	0,00	0,01	0,02	0,02
Ulmaceae	*Trema micrantha*	2	0,00	0,01	0,01	0,02
Mimosaceae	*Zygia lehmannii*	3	0,01	0,01	0,00	0,02
Siparunaceae	*Siparuna laurifolia*	3	0,01	0,01	0,00	0,02
Piperaceae	*Piper sp. 1*	3	0,01	0,01	0,00	0,02
Melastomataceae	*Miconia lehmannii*	3	0,01	0,01	0,00	0,02
Lauraceae	*Ocotea lentii*	1	0,00	0,01	0,01	0,02
Euphorbiaceae	*Alchornea glandulosa*	3	0,01	0,01	0,00	0,02
Solanaceae	*Cuatresia riparia*	4	0,01	0,01	0,01	0,02
Lauraceae	*Beilschmiedia costaricensis*	1	0,00	0,01	0,01	0,02
Rubiaceae	*Guettarda crispiflora sabiceoides*	2	0,00	0,01	0,00	0,02
Siparunaceae	*Siparuna aspera*	2	0,00	0,01	0,00	0,02
Passifloraceae	*Passiflora arborea*	2	0,00	0,01	0,01	0,02
Boraginaceae	*Tournefortia scabrida*	2	0,00	0,01	0,01	0,02
Bignoniaceae	*Tecoma stans*	2	0,00	0,01	0,00	0,02
Euphorbiaceae	*Acalypha macrostachya*	2	0,00	0,01	0,00	0,02
Rubiaceae	*Palicourea sp. 2*	3	0,01	0,01	0,01	0,02
Melastomataceae	*Miconia sp. 3*	2	0,00	0,01	0,00	0,02
Euphorbiaceae	*Hyeronima scabrida*	2	0,00	0,01	0,00	0,02
Cyatheaceae	*Cyatheaceae 3*	2	0,00	0,01	0,01	0,02
Lauraceae	*Lauraceae 4*	2	0,00	0,01	0,00	0,01
Mimosaceae	*Inga sp. 2*	1	0,00	0,01	0,01	0,01
Rhamnaceae	*Rhamnus sphaerocarpa*	2	0,00	0,01	0,00	0,01
Euphorbiaceae	*Croton magdalenensis*	1	0,00	0,01	0,00	0,01
Melastomataceae	*Miconia minutiflora*	2	0,00	0,01	0,00	0,01
Boraginaceae	*Cordia sp.*	1	0,00	0,01	0,00	0,01
Lauraceae	*Ocotea sp. 2*	2	0,00	0,01	0,00	0,01
Bombacaceae	*Spirotheca rhodostyla*	1	0,00	0,01	0,00	0,01
Cyatheaceae	*Cyatheaceae 2*	1	0,00	0,01	0,00	0,01
Lauraceae	*Nectandra sp. 2*	1	0,00	0,01	0,00	0,01
Melastomataceae	*Miconia sp. 1*	1	0,00	0,01	0,00	0,01
Rosaceae	*Prunus carolinae*	1	0,00	0,01	0,00	0,01
Actinidiaceae	*Saurauia ursina*	1	0,00	0,01	0,00	0,01
Lauraceae	*Nectandra sp. 1*	1	0,00	0,01	0,00	0,01
Lauraceae	*Lauraceae 1*	1	0,00	0,01	0,00	0,01
Piperaceae	*Piper sp. 4*	1	0,00	0,01	0,00	0,01
Lauraceae	*Ocotea sp. 1*	1	0,00	0,01	0,00	0,01
Lauraceae	*Lauraceae 5*	1	0,00	0,01	0,00	0,01
Melastomataceae	*Miconia notabilis*	1	0,00	0,01	0,00	0,01
Rubiaceae	*Palicourea angustifolia*	1	0,00	0,01	0,00	0,01
Sabiaceae	*Meliosma sp.*	1	0,00	0,01	0,00	0,01
Annonaceae	*Raimondia sp.*	1	0,00	0,01	0,00	0,01
Euphorbiaceae	*Sapium stylare*	1	0,00	0,01	0,00	0,01
Lauraceae	*Lauraceae 2*	1	0,00	0,01	0,00	0,01
Melastomataceae	*Miconia sp. 2*	1	0,00	0,01	0,00	0,01
Mimosaceae	*Inga sp. 1*	1	0,00	0,01	0,00	0,01
Mimosaceae	*Inga densiflora*	1	0,00	0,01	0,00	0,01
Monimiaceae	*Mollinedia repanda*	1	0,00	0,01	0,00	0,01
Monimiaceae	*Mollinedia campanulacea*	1	0,00	0,01	0,00	0,01
Rubiaceae	*Ladenbergia oblongifolia*	1	0,00	0,01	0,00	0,01
Rubiaceae	*Coffea arabiga*	1	0,00	0,01	0,00	0,01
Zingiberaceae	*Renealmia ligulata*	1	0,00	0,01	0,00	0,01
		411	1	1	1	3

IVI: Importance Value Index

Appendix D. Presence and intensities of crystalline minerals in Andisols and Inceptisols

Table D.1 Presence and intensities of crystalline minerals in Andisols

Profile	Horizon	Primary minerals									Secondary minerals				
		Hydro biotite	Illite or micas	Amphiboles	Chrysotile and Antigorite	Chrysotile and Antigorite	Cristobalite	K feldspar	Na feldspars	Quartz	Chlorite or vermiculite	Kaolinite, meta halloysite	Ca and Mg carbo-nates	Magnetite (Fe_3O_4)	Hematite (αFe_2O_3)
		d=11.68, 3.87, 3.44	d=9.93	d=8.37, 3.12, 2.70	d=7.52, 3.59	d= 7.05, 3.63	d=4.04	d=3.25	d=3.74, 3.19	d=4.24, 3.33	d=14.06	d=4.41, 3.52	d=2.93, 2.84	d=2.55	d=2.48
P4	**A**	1	-	1	-	1	4	1	2	4	1	-	1	-	-
	B1	3	-	2	-	2	3	1	3	4	3	1	1	-	-
	C	-	1	1	2	-	4	1	-	1	-	4	1	1	1
B3	**A**	1	-	1	-	-	4	-	3	3	1	-	1	-	1
	B	1	-	1	-	-	4	-	3	3	1	-	1	-	1
	C	1	-	1	-	-	4	-	2	2	1	-	1	-	1

Abundance of soil minerals = 1: traces (intensities <10%), 2: present (<10% intensities <20%), 3: significant (<20% intensities <40%), 4: dominant (<40% intensities <100%)

Table D.2 Presence and intensities of crystalline minerals in Inceptisols

		Primary minerals						Secondary minerals							
Profile	Horizon	Chlorite or vermiculite d=14.17, 7.12, 3.54	Musco-vite d=4.94	Na feldspars d=4.05, 3.19	Chrysotile and Antigorite d= 3.63	Horn-blende d= 3.13	Quartz d=4.24, 3.33, 1.81	Partially dehydrated halloysite d=7.28	Kaolinite, meta halloysite d=4.42, 3.56	Ca and Mg carbonates d=2.99, 2.93, 2.89, 2.23, 2.01	Ca and Mg carbonates d=2.28, 2.12, 1.97	Magnetite (Fe_3O_4) d=2.55	Hematite (αFe_2O_3) d=2.66, 2.51	Goethite (αFeO(OH)) d=4.15, 2.45	Boehmite (γ-AlO(OH)) d=2.34
	A	-	-	1	-	-	4	2	4	1	2	1	-	1	-
P7	**B**	-	-	2	-	-	4	2	3	-	1	1	-	1	-
	C	-	-	1	-	-	4	2	3	-	1	1	1	1	-
	A	-	-	-	-	-	4	2	3	1	1	2	1	3	1
B4	**B1**	-	-	-	-	-	4	2	3	1	1	2	3	3	1
	B2	1	-	-	-	-	1	2	4	1	1	3	1	3	1

Abundance of soil minerals = 1: traces (intensities <10%), 2: present (<10% intensities <20%), 3: significant (<20% intensities <40%), 4: dominant (<40% intensities <100%)

Appendix E. Correlations between short-range order minerals and soil water retention characteristics with soil physical and chemical properties with all data of Andisols and Inceptisols

Table E.1 Correlations between short-range order (SRO) minerals and indices and soil physical and chemical properties

	All horizons (n= 86)				A horizon (n= 35)			
	Al_p[1] (g/kg)	Fe_p[1] (g/kg)	Allophane (%)	Ferrihydrite (%)	Al_p[1] (g/kg)	Fe_p[1] (g/kg)	Allophane (%)	Ferrihydrite (%)
pH H_2O	-0.46				-0.79	-0.75	-0.59	0.69
pH $CaCl_2$					-0.70	-0.60	-0.46	0.58
Sand (%)	0.49		0.75		0.71	0.60	0.75	-0.64
Silt (%)								
Clay (%)	-0.45		-0.72		-0.59	-0.55	-0.57	0.52
SOC[2] (%)	0.48	0.66			0.46	0.53	0.52	-0.75
ρ_s[3] (kg/m^3)	-0.42							
ρ_b[3] (kg/m^3)	-0.55	-0.41	-0.52		-0.48	-0.57	-0.53	0.51

	B horizon (n= 38)				C horizon (n= 13)			
pH H_2O								
pH $CaCl_2$			0.56					
Sand (%)	0.59		0.84					
Silt (%)								
Clay (%)	-0.61		-0.82					
SOC[2] (%)	0.43		0.59					0.88
ρ_s[3] (kg/m^3)	-0.55		-0.61					
ρ_b[3] (kg/m^3)	-0.52		-0.71					

[1]Pyrophosphate-extractable aluminum (Al) and iron (Fe) (Al_p and Fe_p); [2]SOC: soil organic carbon; [3]ρ_s and ρ_b: particle and bulk density; correlations shown are the ones r > 0.4; Gray cells show correlations with $p < 0.01$ and white cells show correlations with $p < 0.05$

Table E.2 Correlations between soil water retention (SWR) characteristics and soil physical and chemical properties

	All horizons (n= 86)							A horizon (n= 35)						
	θ_{Sat}[1] (%v/v)	θ_{FC}[1] (%v/v)	$\theta_{100\ kPa}$[1] (%v/v)	$\theta_{500\ kPa}$[1] (%v/v)	$\theta_{PWP\ kPa}$[1] (%v/v)	PAWS[2] (% v/v)	GW[3] (% v/v)	θ_{Sat}[1] (%v/v)	θ_{FC}[1] (%v/v)	$\theta_{100\ kPa}$[1] (%v/v)	$\theta_{500\ kPa}$[1] (%v/v)	$\theta_{PWP\ kPa}$[1] (%v/v)	PAWS[2] (% v/v)	GW[3] (% v/v)
Sand (%)									0.42					
Silt (%)														
Clay (%)														
SOC[4] (%)	0.60	0.43				0.50		0.64	0.59	0.48	0.42		0.44	
Al_p[5] (g/kg)	0.58	0.58	0.43	0.43	0.48			0.46	0.59	0.48	0.51	0.55		
Fe_p[5] (g/kg)	0.47	0.41						0.57	0.67	0.55	0.60	0.61		
Allophane (%)	0.49	0.43			0.44			0.52	0.56	0.47	0.45	0.49		
Ferrihydrite (%)								-0.56	-0.65	-0.55	-0.58	-0.52		
ρ_b[6] (kg/m^3)	-0.91	-0.69	-0.51	-0.47	-0.50	-0.51		-0.94	-0.79	-0.67	-0.58	-0.59	-0.59	
	B horizon (n= 38)							C horizon (n= 13)						
Sand (%)	0.61	0.40			0.41									
Silt (%)														
Clay (%)	-0.63	-0.41			-0.48									
SOC[4] (%)	0.57													
Al_p[5] (g/kg)	0.64	0.66	0.50	0.50	0.66									
Fe_p[5] (g/kg)														
Allophane (%)	0.71	0.57			0.60									
Ferrihydrite (%)														
ρ_s[2] (kg/m^3)	-0.48													
ρ_b[6] (kg/m^3)	-0.87	-0.46				-0.40	-0.43	-0.89	-0.83	-0.85	-0.83	-0.80		

[1] θ_{Sat}, θ_{FC}, $\theta_{100\ kPa,}$ $\theta_{500\ kPa}$, θ_{PWP}: soil water content (θ) at saturation (Sat), field capacity (FC), 100 kPa, 500 kPa and at permanent wilting point (PWP), respectively; [2]PAWS: plant available water storage; [3]GW: gravitational water; [4]SOC: soil organic carbon; [5]Pyrophosphate-extractable aluminum (Al) and iron (Fe) (Al_p and Fe_p); [6]ρ_b: bulk density; correlations shown are the ones r > 0.4; Gray cells show correlations with p < 0.01 and white cells show correlations with p <0.05

Appendix F. Comparison of median values of soil water retention characteristics (SWR) between Andisols and Inceptisols

Horizon	Andisols	Inceptisols
	θ_{Sat} [1] (%v/v)	
A	78.0 (76.1-83.4)[2]	68.2 (66.7-71.8)**
B	74.7 (66.3-75.9)	63.6 (60.9-67.8)**
C	71.9 (61.2-77.3)	63.3 (60.4-68.5)
	θ_{FC} [1] (%v/v)	
A	66.8 (63.1-70.3)	57.4 (51.7-59.5)**
B	61.4 (54.5-64.9)	52.3 (50.4-56.7)**
C	62.1 (51.1-67.7)	53.0 (50.2-55.7)
	$\theta_{100\ kPa}$ [1] (%v/v)	
A	58.2 (54.1-60.4)	50.9 (46.5-53.2)**
B	50.8 (45.2-56.8)	47.7 (45.1-51.8) $^{+}$
C	57.0 (45.0-61.3)	47.8 (45.8-50.8)
	$\theta_{500\ kPa}$ [1] (%v/v)	
A	55.1 (51.0-58.3)	48.2 (44.2-49.9)**
B	48.6 (43.8-54.8)	44.7 (43.0-48.6)$^{+}$
C	54.0 (42.4-56.7)	46.2 (43.8-47.9)
	$\theta_{PWP\ kPa}$ [1] (%v/v)	
A	50.7 (48.7-54.0)	42.7 (40.6-45.6)**
B	47.3 (43.8-51.2)	42.7 (37.4-43.5)**
C	51.3 (41.9-53.5)	43.2 (40.0-45.8)
	PAWS [3] (%v/v)	
A	16.4 (12.4-18.8)	13.5 (12.1-16.0)$^{+}$
B	13.9 (10.8-14.9)	11.6 (9.4-13.5)
C	11.1 (9.2-14.0)	10.9 (8.4-11.2)
	GW [4] (%v/v)	
A	11.9 (9.8-14.5)	13.9 (9.2-18.6)
B	11.5 (9.1-15.1)	11.6 (8.6-13.2)
C	10.1 (9.4-12.0)	10.7 (8.3-14.6)

[1] θ_{Sat}, θ_{FC}, $\theta_{100\ kPa}$, $\theta_{500\ kPa}$, θ_{PWP}: soil water content (θ) at saturation (Sat), field capacity (FC), 100 kPa, 500 kPa and at permanent wilting point (PWP), respectively; [2]Values in parenthesis are first and third quartile, [3]PAWS: plant available water storage; [4]GW: gravitational water; Number of samples (n) for Andisols were 17, 19 and 8 and for Inceptisols 18, 19 and 5 for A, B and C horizons, respectively; **, *, $^{+}$ Significant differences between Andisols and Inceptisols with Mann Whitney U test at $p < 0.01$, $p < 0.05$ and $p < 0.1$, respectively

Appendix G. Precipitation for a) Sonora and b) El Chocho watersheds during the overland flow assessment period (mm)

a)

Season	Year	2012	2013
Dry season 1	January		238
	February		332
Wet season 2	March		216
	April		363
	May		428
Dry season 2	June		178
	July		54
	August		159
	September		220
Wet season 1	October	414	326
	November	305	490
	December	302	393

b)

Season	Year	2011	2012
Dry season 1	January		124
	February		57
Wet season 2	March		64
	April		287
	May		70
Dry season 2	June		80
	July		30
	August	77	84
	September	58	72
Wet season 1	October	144	109
	November	184	77
	December	179	39

Incomplete data

Source: Roa and Brown, 2014. To infill gaps in daily precipitation (February 15 to March 14, 2012; June 1 to 5, 2012 and February 6 to March 7, 2013) in the Inceptisol site, a regression through the origin was assessed with SPSS software (IBM, 2011) using the daily precipitation data of the nearby station Villa Aracelly, managed by the local environmental authority Corporación Autónoma Regional del Valle del Cauca (CVC).

Appendix H. Results of field saturated hydraulic conductivity (Kfs) and soil water content in Andisols and Inceptisols without high values (>50mm/hr)

Kfs data excluded from Andisols were two from the dry season; then, n= 12 for the wet season and 10 for the dry season. Data excluded from Inceptisols were three from the dry season and two from the wet season; then, n= 9 from the dry season and n =10 from the wet season.

Table H.1 Field saturated hydraulic conductivity (Kfs) and soil water content comparison between soil orders

Dry season		Wet season	
Andisols	Inceptisols	Andisols	Inceptisols
Kfs[1] (mm/hr)			
4 (3 - 8)[4]	18 (9 - 40)**	1 (0 - 6)	2 (0 - 7)
θ_{grav}[2] (g/g)			
84 (70 - 92)	24 (15 - 37)**	112 (94 - 139)	61 (57 - 73)**
θ_{vol}[3] (cm^3/cm^3)			
0.45 (0.38 - 0.50)	0.20 (0.13 - 0.32)**	0.6 (0.5 - 0.7)	0.53 (0.49 - 0.63)

[1] Kfs: field saturated hydraulic conductivity; [2]θ_{grav}: field gravimetric soil water content; [3] θ_{vol}: Calculated volumetric soil water content; [4]Values in parenthesis are first and third quartile; ** Significant differences between Andisols and Inceptisols in the dry and wet season in pasture with Mann Whitney U test at $p < 0.01$

Table H.2 Field saturated hydraulic conductivity (Kfs) and soil water content comparison between seasons

Andisols		Inceptisols	
Dry season	Wet season	Dry season	Wet season
Kfs[1] (mm/hr)			
4 (3 - 8)[4]	1 (0 - 6)[+]	18 (9 - 40)	2 (0 - 7)**
θ_{grav}[2] (g/g)			
84 (70 - 92)	112 (94 - 139)**	24 (15 - 37)	61 (57 - 73)**
θ_{vol}[3] (cm^3/cm^3)			
0.45 (0.38 - 0.50)	0.60 (0.50 - 0.75)**	0.20 (0.13 - 0.32)	0.53 (0.49 - 0.63)**

[1] Kfs: field saturated hydraulic conductivity; [2]θ_{grav}: field gravimetric soil moisture; [3] θ_{vol}: Calculated volumetric moisture; [4]Values in parenthesis are first and third quartile; [+], ** Significant differences between dry and wet season in pasture of Andisols and Inceptisols with Mann Whitney U test at $p < 0.1$ and $p < 0.01$, respectively