Influence of land use on hydro-physical soil properties of Andean páramos and its effect on streamflow buffering

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Abstract

The *páramos* biome of the northern Andes is a collection of tropical grassland ecosystems that provides important ecosystem services including hydrological buffering and water supply. Human activities in these ecosystems transform vegetation cover and soil hydro-physical properties, affecting their hydrological performance and water quality and quantity. Here, we conducted a systematic review on the influence of land use (agriculture, livestock grazing, and afforestation) on the hydro-physical properties of páramo soils and analyzed its implications for streamflow buffering. Our review protocol identified 32 relevant papers, from which key hydro-physical properties linked to streamflow variability were available: soil organic matter (SOM), soil organic carbon (SOC), porosity, bulk density, saturated hydraulic conductivity, and water retention capacity (WRC). The analysis shows that soils with native cover are characterized by a porous structure that allows a high WRC and SOM content. Agriculture increases macroporosity but it leads to bare fallow plots that promote loss of nutrients and SOM. Burning generates hydrophobic aggregates that affect WRC. Livestock grazing produces soil compaction and increases bulk density, reducing infiltration and WRC. Lastly, afforestation with exotic species (e.g. pines, eucalyptus) decreases SOM and WRC by changing soil structure. In general, the analyzed land-use activities generate hydrophobic aggregates, increase bulk density, promote erosion and runoff, and impair hydrological buffering capacity. This integrated evidence from multiple empirical studies can be used to effectively communicate the effects of different land use practices on páramo soils, provide information for modelling in data-scarce situations, and contribute to decision making processes for land use planning and conservation.

Keywords: hydrological services; soil hydrology; edaphology; hydrological regulation; natural infrastructure

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1. Introduction

The *páramos* are a biome consisting of a collection of high-mountain humid grassland ecosystems dominated by herbaceous and shrub vegetation (Tovar et al., 2013). They extend mainly over the northern Andes of South America at elevations above the forest line (3,000 to 3,500 m above sea level, m a.s.l.) (Marulanda and Villa, 2016; Podwojewski et al., 2002). Páramos generally feature a cold climate, and experience a high spatiotemporal variability in annual rainfall (e.g., between 700 and 3,000 mm yr^{-1}, depending on their location) (Buytaert et al., 2002; Ochoa-Tocachi et al., 2016). Their high humidity gives origin to a variety of lakes and peat bogs and has a considerable influence on their soil development (Camargo-García et al., 2012).

Páramos are regionally and globally important because of the extensive range of ecosystem services that they provide (Buytaert and Beven, 2011; Farley et al., 2013; Flores-López et al., 2016; Llambí et al., 2019). Mountain ecosystems are recognized as one of the global priorities for conservation as part of the SDG 15 of the United Nations 2030 Sustainable Development Goals (UN, 2014). Páramos are exceptionally diverse ecosystems featuring spatially distinct environments and discontinuous configuration (Flores-López et al., 2016), exceptional biodiversity (Bremer et al., 2014; Llambí et al., 2019), and outstandingly rich plant species with a high level of endemism (Cuesta et al., 2017; Sarmiento et al., 2003). Páramo soils have a considerable carbon accumulation capacity (Bremer et al., 2014; Llambí et al., 2019), which is globally important for climate change mitigation and adaptation (Farley et al., 2013).

Water supply is usually considered the most important ecosystem services provided by páramos (Buytaert and Beven, 2011). Páramos have a crucial role in regional *water provision* for the Andean highlands of Venezuela, Colombia, Ecuador, extensive parts of the adjacent lowlands, and the arid coastal plains of Northern Peru (Bremer et al., 2014; Buytaert et al., 2006a). They collect, store, and provide a large and sustained base flow and good water quality constituting the main water source for agricultural use, urban water supply, and hydropower generation for local communities and downstream users (Buytaert and Beven, 2011; Flores-López et al., 2016; Llambí et al., 2019). These contributions are remarkable in contrast to the area they occupy (Buytaert et al., 2006a; Farley et al., 2004). By 2016, it was estimated that water sources from páramo ecosystems supported around 100 million people, projected to increase to 135 million by 2050 (Flores-López et al., 2016).

Páramo soils play a key role in water provision by modulating the streamflow and fostering a high base flow (Harden, 2006). This ability of a terrestrial ecosystem to provide a seasonal buffer of streamflow, i.e., to store water during the wet seasons and to sustain streamflow during the dry seasons, is sometimes referred to as *streamflow buffering* or *hydrological regulation* (Minaya et al., 2018). Soil cover and land-use practices govern the dynamics of this process. General characteristics of páramo soils have been described as a predominately open, crumbly and granular structure (Buytaert et al., 2006b), and a high organic matter content that results in high porosity (Buytaert et al., 2002). The highly porous soils provide the conditions for high water storage and buffering capacities that sustain and regulate water flows, thus contributing to streamflow buffering (Buytaert et al., 2002).

For centuries, páramos have been inhabited by small-scale farmers and livestock keepers (Hofstede, 2013), who have transformed the natural vegetation cover and changed soil characteristics, for example, via burning, tillage, fertilization, agriculture, and grazing (Lis, 2015; Quichimbo et al., 2012). These activities have increased after the colonial period and have intensified, sometimes to unsustainable levels, in the last decades (Ochoa-Tocachi et al., 2016). Land-use activities modify the hydro-physical properties of soils, including their structure, porosity, water retention capacity, and organic matter content (Avellaneda-Torres et al., 2018; Dorel et al., 2000). The modification of these properties affects hydrological processes (Buytaert et al., 2006a). For example, soil structure degradation and compaction decrease water retention capacity, increase runoff occurrence, and reduce natural discharge (Poulenard et al., 2001). Removal of the natural vegetation cover also affects evapotranspiration and soil structure (Cárdenas-Agudelo, 2016).

Despite the importance of the ecosystem services provided by páramos, this is still a region that requires more studies and better scientific descriptions (Correa et al., 2020; Farley et al., 2013; Flores-López et al., 2016). Due to the geophysical diversity within the páramos and limited data availability, their hydrological processes remain unclear (Flores-López et al., 2016). Research on the effects of land-use changes over soil properties and streamflow buffering is relatively scarce in the Andes and the few available scientific studies have been derived from investigations at the local scale (Marín et al., 2018).

The article addresses the effects of land use on streamflow buffering using hydro-physical soil properties as a proxy. Soils play a key role in streamflow buffering, alongside many other factors (deeper subsurface flows, geology, landscape connectivity, etc.) and in ways that are still poorly understood. For example, other peat soils worldwide have many similar properties than those of páramo soils yet very different "regulation". One of the reasons to study those properties is to understand the key controls of streamflow buffering of the páramos, which remains unclear. Of specific interest is the fact that páramo soils behave hydrologically very different from other wetland and peatland soils despite having similar hydro-physical properties (Holden et al., 2006). Therefore, understanding and comparing them is key to understanding the link between pedon-scale soil characteristics and catchment scale hydrological response.

This paper reviews and integrates results obtained from studies that analyze the behavior of different soil hydro-physical properties in relation to the most common land-use types in Andean páramos (agriculture, afforestation, livestock farming, and natural vegetation). These relationships are then linked to the impacts on the streamflow buffering capacity of páramo ecosystems. To the best of our knowledge, there are no papers that integrate and analyze results from different studies on this topic in the last decade. The information compiled here provides reference values that can be used for regional comparisons and analyses, to fill missing data to overcome the challenge to understand, model, and predict the hydrological response in theses ecosystems, and to support policy makers and local water and land owners about the impacts of land-use change on páramo soil properties. We envisage that this will contribute to the conservation of the ecosystem services provided by páramos that are linked to their soil conditions.

2. Regional context

2.1 General aspects of páramos

Páramos are a collection of tropical Andean wet- and grasslands, at elevations above the upper forest limit (approximately at 3,000 to 3,500 m a.s.l.) to the permanent snow line (4,500 to 5,000 m a.s.l.) (Ochoa-Tocachi et al., 2016). They cover an area of approximately 35,000 km^2, extending from the Mérida range in western Venezuela to the Huancabamba depression in northern Peru (Hofstede et al., 2003). Generally, páramos are characterized by a cold and humid climate, shrub and herbaceous vegetation, lack of dense forest formations, high solar radiation and peat soil. From a hydrological perspective, páramos feature an extremely high runoff ratio that distinguishes them from adjacent ecosystems (Hofstede, 2013). The dominant vegetation type in páramos is herbaceous: tussock grasses locally known as *pajonal*. These are typically relatively compact shrub formations that can exceed 2 m in height. Many species within páramo vegetation have developed different physiological adaptations to face its extreme climate (Hedberg and Hedberg, 1979). For example, rosette forms serve as a protection against cold and wind; dwarf shrubs and leathery leaves reduce water lost through transpiration; hairy covers on leaves catch rainwater, dew or fog; dead leaves on the plant stems protect them against low temperatures and radiation, trap organic waste, and store water; and tillers trap organic matter and water (Salamanca, 1986). This often has hydrological consequences, such as a considerable storage of water, and effective trap of fog, and very low evapotranspiration rates.

2.2 Hydro-physical soil properties of the páramos

Páramo soils are generally humid, acidic, rich in humus, dark brown with a low concentration of nutrients, moldy, and have a low organic decomposition that allows the accumulation of organic matter on the surface (Guhl, 1982). They often form in conjunction with volcanic ashes; however, páramo soils exist that lack a layer of volcanic ash (Poulenard et al., 2003). Páramo soils are relatively young and underdeveloped, featuring thin profiles (< 50 cm) –although several active volcanic areas can host deeper soil profiles (Favier et al., 2008)–, and showing roughly indistinguishable horizons. Consequently, the classes, subclasses, and groups of soils have common characteristics across different elevations, and are less diverse than other soils of the high and middle Andean mountains with forest covers (Hosftede et al., 2014).

In general, páramo soils can be classified in four groups according to the Food and Agriculture Organization of the United Nations (FAO) (IUSS, 2007) classification; the correspondent order according to the United States Agricultural Department (USDA and NRCS, 2014) is specified in parenthesis: Andosol (Andisol), Regasol (Entisol), Umbrisol (Inceptisol), Histosol (Histosol). According to this taxonomy, Andosols are developed from volcanic ashes, while Histosols are developed from organic vegetable waste that contains high water content and low ash content. Typically, Andosols are found in the steep slopes of the Andean páramo landscapes, and Histosols are present in the valley bottoms beneath wetlands (Mosquera et al., 2015).

Andosols have a high water retention capacity (WRC) because of the presence of amorphous clay minerals such as allophane and imogolite (Rousseaux and Warkentin, 1976; Shoji and Fujiwara, 1984; Shoji et al., 1993). The particular climate and the organometallic complexation result in soil organic matter (SOM) and hydro-physical properties that are similar to those of a soil with allophane. The interaction between textural porosity and organic colloids result in a high WRC at different suctions (Buytaert et al., 2005b). Appendix A includes a summary of the main hydro-physical properties of páramo soils for different surface horizons under natural conditions.

2.3 *Land use change in the páramos*

The spatial and temporal analysis of land-use change in páramo soils is limited (Curatola Fernández et al., 2015). For example, the complex topography and atmospheric conditions limit the acquisition of good quality satellite imagery to analyze these processes remotely (Colby and Keating, 1998; Conese and Maselli, 1991). In contrast, there are local studies that analyze these processes, especially in Colombia and Ecuador. Hofstede et al. (2002) argue that the Ecuadorian páramo have had the largest land-use change in the Andean region. In central Ecuador, páramos have experienced an annual reduction of 0.8% of their area between 1963 and 1991 (Balthazar et al., 2015). In southern Ecuador, Curatola Fernández et al. (2015) found an increase in pasture areas and a fragmentation of natural cover between 1975 and 2001. Ross et al. (2017) reported an annual loss rate of 0.4% of páramo areas between 1979 and 2014 in the Chambo watershed in central Ecuador. In addition, they found that only 22% of the páramo ecosystem in this watershed remains intact. The main drivers of land-use change in páramo ecosystems have been linked to the Agrarian Reform and Colonization (1950) and to aggressive afforestation policies (Ross et al., 2017).

In Colombia, the intervened páramo landscape is dominated by pastures and crop mosaics (Cabrera and Ramírez, 2014). By 2002, it was estimated that an additional 24.9% of páramo areas were cultivated (Hincapié et al., 2002). In central Colombia, between 1979 and 1990, páramo

Laguna-Verde experienced an increase of 106% in agricultural lands, 164% in pastures, and a reduction of native cover of 32% (Van der Hammen et al., 2002). In the Berlin páramo of eastern Colombia, agriculture and grazing increased by 49%, whereas riparian vegetation decreased by 94% between 1997 and 2015 (Macías and Omaña, 2018). Other páramos are less affected by land conversion, such as Paja Blanca (7.5% of land-use change) (Muñoz-Guerrero, 2017), Guanacas-Puracé-Conucos (7.34%), Chilí-Barragán (6.89%), and Chingaza (6.72%) (Cabrera and Ramírez, 2014).

Compared to other tropical ecosystems, páramos can be easily adapted for agricultural activities by burning (Morales-Rivas et al., 2007), despite the substantial interventions required to make soils favorable for crops (Hofstede et al., 2003). The rapid soil abatement and its posterior abandonment push the agricultural border upslope (Sandoval, 2004). Land use policies, deforestation, urbanization, and people migration have been the main drivers of páramo degradation (Peters et al., 2013).

3. Methods

We followed a systematic literature review method (Pullin and Stewart, 2006) with the aim of evaluating the effect of different land-use types over soil hydro-physical properties and the potential consequences on streamflow buffering in páramo ecosystems. We relied on the academic databases Web of Science®, Scopus® and Scielo®.

3.1 Search strategy, inclusion and exclusion criteria

Key search terms were organized in three groups and used to produce search Boolean equations: i) Group 1: land use change, land use cover, soil use; ii) Group 2: páramo, peatland, Andes; and iii) Group 3: cultivation/crop, livestock, afforestation/forestry, burn, tillage. The search was expanded by tracking the references of articles identified as influential. As a result, 1,411 papers were retrieved using the search terms, from which 549 papers were filtered out following the criteria indicated below. These filters were conservative, and we retained studies in case of doubt.

i. hydro-physical properties of soil are the primary or secondary topic;
ii. search terms appear in at least one of the main fields (title, keywords, or abstract);
iii. the research has been published in a peer-reviewed journal or by a recognized academic institution;
iv. publication year is between 1980 and June 2019;
v. language is either English or Spanish.

We then identified the most relevant documents according to its research focus and reduced the set as follows (Figure 1):

i. 136 papers were duplicated records.
ii. 316 papers were removed based on the title.
iii. 37 papers were removed based on the abstract.
iv. 12 papers were removed based on a cursory reading.
v. 16 papers were removed based on a detailed reading (6 papers related to another type of ecosystem, 4 papers that reported information with the same dataset, 5 papers whose units could not be transformed, and 1 paper that did not clearly specify land-use types).

The altitudinal range of the study areas was used to identify if the reported sites correspond to páramo ecosystems (between 3,000–3,500 m a.s.l. and 4,500–5,000 m a.s.l.) (Buytaert et al., 2006a). If this information was unavailable, we checked the description of the reported natural vegetation to corroborate that it related to páramo. This procedure concluded in the selection of 32 studies for detailed analysis (Figure 1).

3.2 Organization and systematization

The selected 32 papers were read in full, from which we extracted data on the physical and hydrological characteristics of the studied areas, including location, elevation, soil type, average annual rainfall, land-use type and history, among others. Additionally, the main investigated variables, sampling techniques, and quantification methods related to soil hydro-physical properties were identified and extracted (Table 1).

Our study addressed the four predominant land-use types in páramo ecosystems (Hofstede, 2001): i) natural vegetation; ii) agriculture (preparation and cultivation); iii) livestock farming (grazing); and vi) afforestation (exotic tree plantation). Hofstede (2001) describes these activities as follows:

- Natural vegetation: páramo vegetation (*pajonal*) is shrubby, characterized by a matrix of straw within which bushes, rosettes, mosses, and lichens grow.
- Agriculture: climatic conditions of páramo ecosystems are not the most suitable for agricultural activities; however, crops massively extend over Andean páramos. The main crops are potato (*Solanum tuberosum*), barley (*Hordeum vulgari*), broad beans (*Vicia faba*), and to a lesser extent ocas (*Oxalis tuberosa*), mashuas or cubios (*Tropaeolum tuberosum*), and mecollos or chuguas or ullucos (*Ullucus tuberosum*).

Cultivation activities include burning and ploughing for land preparation.

- Livestock farming: it involves extensive grazing of cattle and sheep. Generally, this activity is associated with burning large páramo areas to promote the growth of tender shoots. This land-use type also includes planted grass used for livestock farming.
- Afforestation: planting of rapid-growth trees aiming at increasing biomass, vegetation cover, and SOM. In the Andes, this activity has used mainly exotic species such as pine (*pinaceae*) and eucalyptus (*myrtaceae*) (Bonnesoeur et al., 2019).

Table 2 shows the 32 selected papers, location of study areas, studied soil hydro-physical properties, main sampling characteristics, and applied statistical tests. Figure 2 presents a map of the Andean páramo where the study areas are located.

3.3 Data analysis

We extracted quantitative data of soil hydro-physical properties from the selected papers, focusing on surface horizons (O and A) or less than 40 cm deep, according to land-use type. Horizon C was not considered in this review because few studies report information on horizon C and several authors (e.g., Benavides et al., 2018) agree that the largest amount of water is stored in the upper soil layer (Horizons O and A). Additionally, land use generally does not influence Horizon C which, in addition to the low SOM in Horizon C has a lower contribution to streamflow buffering as indicated by some authors (Iñiguez et al., 2008). We extracted data from the text, tables, supplementary materials, and figures using the graph digitizer “engauge-digitizer” (Mitchell et al., 2017). The data were tabulated, and units were homogenized for each parameter (see Table 1). We identified information related to the study areas (location, elevation, average annual rainfall, soil type, among others), sampling techniques, and statistical tests used in the studies (Table 2). Furthermore, the quality of the investigations was assessed by inspection of the methodologies used to quantify the soil hydro-physical properties in aspects such as: sampling design; type, number and depth of samples; equipment and/or method used, and statistical treatment of the collected data.

The studied sites were compared in terms of country, average annual rainfall, soil type, land-use types, and the methods used for collecting soil samples such as depth, type, and number of samples. Variables of soil hydro-physical properties were statistically characterized using boxplots and frequency analyses. The boxplots were employed to compare the effects of different land-use types (natural vegetation, livestock, afforestation, and agriculture) on páramo soil hydro-physical properties using measures of central tendency (mean and median). In addition, the interquartile range (IQR) and the presence and amount of outlier data outside the limits of the diagram (± 1.5 IQR) were used to characterize variable dispersion. Lastly, the effect caused by the change from natural páramo to the studied land-use types and its potential impact on streamflow buffering was qualitatively compared.

We identified papers that explicitly establish relationships between land-use types to soil hydro-physical properties along with whether the reported relationships were positive (+) or negative (–) using conventions from the field of System Dynamics (Sterman, 2002). On the one hand, a positive relationship (+) represents a positive correlation: an increase (decrease) in a particular land-use type would result in an increase (decrease) in a soil hydro-physical property. On the other hand, a negative relation (–) represents a negative correlation: an increase (decrease) in a land-use type would result in a decrease (increase) in a soil hydro-physical property. The same positive and negative relationships were identified for soil hydro-physical properties and streamflow buffering. This information was summarized through tables and using a causal diagram representing the relationships and their polarity (+ or –). The causal diagram was complemented including the coefficient of determination (Gutiérrez and de la Vara, 2012) for those relationships in which papers reported data for variables linked in the causal diagram. This was possible as long as the paper included variables that were measured from the same soil sample to ensure that the properties were directly related. However, from the information reported in the papers, it was not possible to develop further and more thorough statistical analyses.

4 Results and discussion

4.1 Research trends and current status

The growth of research about hydro-physical properties of páramo soils is notable after 1998 (Appendix B), suggesting an increased interest towards understanding the characteristics of páramo soils and their relationships with the water cycle. Publications on this topic were practically inexistent before the 2000s, probably because páramos were not yet sufficiently recognized as paramount water providers and flow regulators at that time (Baptiste and Ruggiero, 2012; MMA, 2002). In contrast, the increase in publications has been prominent in the last five years.

The results of the scanning process highlight the lack of studies about hydrological services of páramos and their association with soil hydro-physical properties (9 of the 32 selected papers). Land use change research in the páramos has focused on agriculture (48%) and livestock (41%), with afforestation present in only 10% of the studies. The country dominance of research in páramo soils is also skewed, with Ecuador (53%) and Colombia

(44%) dominating the scene. Soil hydrology research from Peru is practically inexistent (Appendix B).

Andosols, a typical taxonomy found in the páramos (Buytaert et al., 2006b), was the most studied soil type (46%), whereas soil taxonomy was not reported in 38% of the studies (Appendix B). In addition, 47% of the analyzed studies are concentrated in semi-humid and humid páramo, and another 31% of the studies were conducted in dry páramos, i.e., average annual rainfall less than 1,196 mm yr^{-1} (Rangel, 2000).

A pedon scale was used in 71% of the studies, representing land units with similar characteristics. This allows more representative comparisons between studies that analyzed different land uses in the same soil units, providing a perspective of the impact of land use on the studied hydro-physical properties.

4.2 Effect of land use on soil hydro-physical properties

The hydro-physical properties of páramo soils (i.e. Soil Organic Carbon (SOC); Soil Organic Matter (SOM); Porosity; Bulk density (Bd); saturated hydraulic conductivity (K); and water retention capacity (WRC)) provide the conditions for high water storage and buffering capacities that sustain and regulate river flows and thus contribute to streamflow buffering (Buytaert et al., 2002). The following sections summarize empirical evidence on how these properties are altered as a consequence of land-use change.

4.2.1 Soil organic Matter (SOM) and Soil Organic Content (SOC)

Páramo soils are characterized by their high Soil Organic Carbon (SOC) content developed by the low degradation rate of SOM as a result of low temperatures and high water content

(Podwojewski et al., 2002). According to Buytaert et al. (2007a), SOC can be as high as 40% in humid regions (> 900 mm yr^{-1}), while in dry regions (< 600 mm yr^{-1}), SOC can be around 7% (Podwojewski et al., 2002). Figure 3 summarizes the evidence found in this review and shows SOM and SOC according to land-use type. The natural vegetation has, on average, the highest SOM and SOC values at 43% and 20%, respectively. In the case of SOM (Figure 3-a), data for natural vegetation range between 20 and 66% and is noticeably higher compared to the anthropic uses considered. This gives evidence of the important effect that land use change has over this property. Agricultural practices such as burning and ploughing increase the amount of SOM available. However, the direct exposition of soils to environmental factors and the extreme páramo climatic conditions favor oxidization of SOM and release it into the atmosphere in the form of CO_2, resulting in a progressive overall loss (Peña-Quemba et al., 2016). This is in line with observations of a lower SOM (Figure 2a) in uses where the soil is directly exposed to atmospheric conditions (agriculture and livestock farming); in the case of SOC (Figure 2b), the results regarding agriculture are variable and a clear decrease is not observed in contrast to the evident reduction for livestock farming. In Figure 3-b, the SOC distribution is similar between agricultural and natural vegetation; however, natural vegetation shows a wider range and higher values outside the IQR (29–54%) compared to agriculture (28–36%). Livestock grazing and afforestation have lower values of SOC, the lowest being from the latter (0.1%).

Sites with natural vegetation show higher SOM and SOC average values than those intervened, which has been associated to an also higher protection of soils that reduces physical degradation and improves conservation (Tonneijck et al., 2010). Likewise, natural vegetation provides biomass residues which support decomposition and stabilization of SOM.

The protection provided by natural vegetation prevents soil crusting by natural or mechanical processes.

In preparation for cultivation, natural vegetation is manually removed or burned, and soils are uncovered. Soils are then ploughed deep, tilled, and turned, aiming for the reorganization of the soil surface. This leads to an exchange between deeper soil layers and surface soil layers, which are more acidic and have low availability of interchangeable bases. These preparation activities promote the generation of hydrophobic aggregates (Golchin et al., 1997; Piccolo and Mbagwu, 1999; Valat et al., 1991), along with nutrient and SOM leakage that produce high crop yields during the first harvests (Hofstede, 2001). This frequent practice of turning, drying, and cultivating, leads to an overexploitation of páramo soils, which deteriorates their hydro-physical properties (López-Sandoval, 2004). Lastly, the analyzed papers regarding afforestation in páramo using pine and eucalyptus agree on the fact that these species dry the soils (reduce water content) and decrease the SOM, especially during the growth stage (Bonnesoeur et al., 2019; Buytaert et al., 2007a). The plant species used for afforestation in the páramo, especially during their growth stage, have high water demand (reduce water content). Although plants do not deplete SOM directly and, on the contrary, the faster they grow, the more organic matter they produce. The main process in these conditions is that fast plant growth produces drier soils, and drier soils favor accelerated SOM decomposition. This changes the soil conditions such as pore size distribution, reduction of macro and micro porosity, favoring the mineralization of SOM (aggravating the state of the soil) that finally decreases WRC. This promotes hydrophobicity, which is induced when SOM is exposed to direct sun radiation and dries out vigorously (e.g., from ploughing). The organic matter produced by pine may be more hydrophobic, adding another process altogether.

Hydrophobicity reduces water content. All these processes lead to a positive feedback that further decrease WRC. According to the literature, afforestation does not favor aeration but tends to increase Bd (decrease in aeration), which is probably the result of decreasing SOM (Farley et al., 2004). Plants used in afforestation favor the mineralization of organic matter when water is replaced by air in drier soils. Due to this lower organic matter content soil structure is compromised, affecting its porosity and water retention capacity. Furthermore, the organic components from afforestation could generate hydrophobicity, which can be exacerbated if the soil is continuously subject to dry out (Poulenard et al., 2004).

4.2.2 Soil porosity

Figure 4-a shows soil porosity in páramo soils according to land-use type. The average soil porosity under natural vegetation is particularly high (75%), which is associated to its granular structure and high SOM. Agriculture, afforestation, and livestock farming all produce soil compaction and thus reduce porosity. Livestock farming produces a greater change in soil porosity (values as low as 7% are reported) compared to agriculture (the lowest reported value is 29%) (Hofstede, 1995b), likewise a decrease in infiltration capacity (Podwojewski et al., 2002). This is attributed to livestock trampling compressing the soil and increasing its density, and to animal farming preventing the regeneration of the vegetable cover (Hofstede, 1995a). Afforestation, in turn, dries out the soil and reduces MOS which changes its macroporosity and influences other properties decreasing WRC, aeration, and K. Agriculture activities such as tillage, planting, and harvesting, often performed with heavy machinery or animal traction, also affect soil structure and porosity negatively (Strudley et al., 2008). Similarly, frequent tillage can generate a change in the pore distribution and

influence other properties such as saturated hydraulic conductivity (Camargo-García et al., 2012) and WRC (Farley et al., 2004).

4.2.3 Bulk density (Bd)

In páramo soils, bulk density (Bd) is highly variable and depends on local moisture conditions (Buytaert et al., 2005a). For instance, according to Buytaert et al. (2006a), in humid páramo (rainfall above 1800 mm), observed Bd values are around 0.15-0.6 g cm-3, while in dry páramo (rainfall below 1200 mm), observed Bd values are around 0.6-0.9 g cm-3. Figure 4-b shows Bd in páramo soils according to land use-type. Data reveal that afforestation and livestock grazing show average Bd values of 0.69 and 0.62 gr cm^{-3}, respectively which are higher compared to the average Bd values reported for natural vegetation (0.36 g cm^{-3}). This is attributed to compaction caused by forestry activities, which use high water demand species, and by trampling from livestock, which decreases macroporosity. On the other hand, cultivation (including soil preparation) feature lower Bd compared to other anthropic uses, which can be related to tilling practices such as deep ploughing during soil preparation that destroy soil structure and disaggregate particles. However, frequent tilling at the same depth can produce a type of compaction known as "plough pan" over time (Strudley et al., 2008). This may lead to increase Bd as has been observed in fallow plots (Daza-Torres et al., 2014). The change in Bd linked to soil porosity affects WRC, which leads to an increase in overland runoff during storm events. This effect is more critical for livestock farming and afforestation than to cultivation.

4.2.4 Saturated hydraulic conductivity (K)

Páramo soils have a high saturated hydraulic conductivity (K) that varies with depth. Buytaert et al. (2005b) observed that K rapidly reduces with depth, being 5.3 mm h-1 at 3 cm, and 0.52

mm h-1 at 15 cm. Figure 4-c shows K in páramo soils according to land–use type. Sites under natural vegetation feature values of K that exceed 100 mm h^{-1}. This is a result of the high macroporosity and undisturbed structure and texture (mostly sandy, with sand content greater than 50%) in natural páramo soils (Buytaert et al., 2007b). The greatest negative effects on K are seen under agriculture and livestock farming. These activities break soil aggregates, reduce macroporosity, and increase direct soil exposure to environmental conditions, because of the removal of natural vegetation, which can reduce K, associated to pore clogging by cattle trampling (Podwojewski et al., 2002) or an increase in clay dispersion due to agriculture (Poulenard et al., 2004), which could lead to a reduction of WRC. Agriculture features higher K (>50 mm h^{-1}) than other anthropic uses, possibly because of soil ploughing before cultivation which prepares the soils for plant growth in contrast to the soil compaction observed under livestock farming and tree plantations.

4.2.5 Water retention capacity (WRC)

The high porosity and low Bd of páramo soils, in addition to the local climatic conditions, provide a strong potential for storing water and minimizing surface runoff (Harden, 2001; Hofstede, 2001; Sarmiento, 2000; Serrano and Galarraga, 2015). Figure 5 shows WRC in páramo soils according to land–use type at different suctions (0, 10, 33, 1500 kPa). Several authors (Camargo-García et al., 2012; Cárdenas-Agudelo, 2016; Daza-Torres et al., 2014; Farley et al., 2004; Quichimbo et al., 2012) reported a higher degradation in WRC at high suctions compared to low suctions. Natural vegetation, agriculture, and livestock farming feature large WRC dispersion at 1500 kPa. This result, associated to the breakdown of soil aggregates could be linked to the increase of clay dispersion (Jaramillo, 2002) that leads to pore blockage and limits WRC (Dorel et al., 2000). Several data in this review originate from the analysis of Andosol soils with histic horizons, high SOM content, and low bulk density, which increases variability (Buytaert et al., 2002; Buytaert et al., 2006b; Buytaert et al., 2007b; Poulenard et al., 2003). These soils can retain large quantities of water above their weight, which causes a considerable skew on the data. This situation is similar for WRC at 0 kPa under natural vegetation (Figure 6). However, this characteristic is not observed for suctions 10 and 33 kPa since the previously mentioned studies conducted in histic andosols did not include data at these suctions.

Three methods were reported to quantify WRC: plates (57%), pressure membrane extractor (36%), and one-step outflow method (7%). Generally, for the selected tensions, the plate pressure method is considered most adequate. The water retention curve in andosols is influenced by the soil and management practices, since it changes the dynamics of the organic matter content which ultimately defines soil structure and porosity (Salcedo-Pérez et al., 2004). Most páramo soils are andosols, which contain organo-mineral complexes between clay minerals and organic matter. It has been shown that when these soils are exposed to strong drying conditions and radiation, hydrophobic conditions are generated (Poulenard et al., 2004).

In general, afforestation had the lowest values for WRC among anthropic uses, which could be related to a change in pore size distribution (Farley et al., 2004). Authors such as Farley et al. (2004) report a decline in the hydrophysical properties (e.g. decrease in water content, SOM and increase in Bd) leading to increased aggregation, in areas where natural vegetation has been transformed to pine and eucalyptus plantations. This decline could lead to a loss of soil stability evidenced in a reduction on the meso- and micro-porosity (Shoji et al., 1993), which promotes a decrease in WRC.

Figure 6 shows WRC curves at different suctions according to land-use type. At suctions of 10 kPa and 33 kPa, WRC in agricultural sites has a similar data distribution compared to natural vegetation sites. However, WRC in agricultural sites is slightly higher than that of natural vegetation, possibly because of the increase in macroporosity associated with activities such as ploughing, which can improve soil aeration, due to the rise of large pores, causing an increase of WRC at low suctions (0-33 kPa). In contrast, the water retention at Permanent Wilting Point (PWP) tends to decrease (Camargo-García et al., 2012; Cárdenas-Agudelo, 2016; Daza-Torres et al., 2014; Quichimbo et al., 2012), possibly due to the rapid oxidation of SOM which deteriorates soil structure (Lal and Shukla, 2004) and changes pore size distribution (Dick and Gregorich, 2004). This may be exacerbated by an increase of dispersed clays that can cause pore blockage and limit WRC at high suctions (Dorel et al., 2000). In general, except for the skew in the data described above, the highest WRC conditions occur in natural vegetation, as well as the largest variability derived from the analyzed data. Afforestation is the land use that affects adversely WRC the most.

The water retention curve reflects the distribution of pore size (Leij et al., 2002). In this case, agriculture and livestock farming have a similar pore size distribution, with differences at low suctions (0-33 kPa). For instance, livestock farming shows a higher slope compared to agriculture at this range of suctions, possibly due to an impairment in soil macroporosity associated to cattle trampling. On the other hand, afforestation substantially affects pore size distribution possibly due to the reduction of SOM and water content, key properties to preserve soil structure (Dexter, 2004). This is evident in a gentle slope in the water retention curve, with water content in the range of 50 and 10% between saturation and the PWP.

4.3 Effect of land use on streamflow buffering

Natural vegetation and agriculture are the most studied land-use types, while research on afforestation is sub represented in the analyzed literature (Table 3; see also Bonnesoeur et al.

(2019)). SOM and SOC are the hydro-physical properties that have been most analyzed in relation to streamflow buffering (15 papers) because of their clearer relationship. For example, water storage is a main driver of hydrological buffering and SOM, particularly, can store up to 22 times its weight in water (Shaxson and Barber, 2005). The high capacity of páramo soils to store SOM and the influence of this property on others such as micro-porosity is key (Buytaert et al., 2005b; Daza-Torres et al., 2014). High porosity and saturated hydraulic conductivity restrain the ability of the soil to store water in its structure which might promote rapid drainage and impair streamflow buffering. Activities such as ploughing break soil structure, increase its macro-porosity, and facilitate water infiltration. However, water is not retained efficiently in a ploughed soil structure and, therefore, river discharge will increase following rainfall events (Buytaert et al., 2005b; Lazo et al., 2019).

Most of the reviewed papers focus on the effect of land use change on the soil properties as a one-way causal relation. However, it is likely that substantial feedback mechanisms exist. Figure 7 represents those relationships using a systemic perspective to integrate land-use types, soil hydro-physical properties, and streamflow buffering.

Páramo soils have a substantial capacity to modulate water flows due to their favorable soil hydro-physical properties (Harden, 2001; Poulenard et al., 2003). The high SOM is associated to several good characteristics in páramo soils: open structure, high porosity, low Bd, high infiltration capacity, and large WRC (Buytaert et al., 2007b). Figure 7 shows the strong correlation between several hydro-physical properties and SOM, which reflects also on its large influence on streamflow buffering. Other variables have a weak correlation, such PWP and WRC with an $r^2 = 0.011$, although the PWP can be highly influenced by texture, SOM, or Bd, which demands further study. Similar results were found by Buytaert et al. (2007b). However, microporosity can also contribute to water storage and hydrological buffering, as long as the associated suction is below the PWP (15 bar) (water retained by capillary action). This has a positive effect on the streamflow buffering of páramo soils in the long term (Buytaert et al., 2002; Buytaert et al., 2007b; Farley et al., 2004), associated to the streamflow buffering capacity and the maintenance of base flow. The low climate seasonality and the uniform rainfall distribution through the year might explain the sustained base flow in rivers whose headwaters are located in páramo regions (Célleri et al., 2010). In addition, topography acts as a water regulator itself (e.g., Hungerbühler et al. (2002) and Kehrer and Kaaden (1980)). In páramo areas, wetlands and lakes contribute to water storage, boosting their hydrological buffering capacity (Hribljan et al., 2016). A particular relationship exists between the considerable infiltration capacity of páramo soils and the low rainfall intensity in páramo areas. This results in a virtually inexistent infiltration excess surface runoff (Ochoa-Tocachi et al., 2016). In consequence, overland flow, if existent, originates from saturation excess, which contrast with the more typical infiltration excess runoff in other ecosystems worldwide with less developed soils and subject to high intensity rainfall events (Calder, 1998).

Although agriculture seems to affect soil porosity and infiltration the least and afforestation with exotic species increase soil biomass, the collected literature data suggest that the three analyzed land-use types reduce WRC and SOM in páramo soils. Additionally, afforestation and livestock farming decrease porosity and infiltration capacity. The three analyzed land-use types generate hydrophobic aggregates, increase bulk density, and enhance surface runoff, thus compromising the streamflow buffering capacity.

Buytaert (2004), Buytaert et al. (2007), and Ochoa-Tocachi et al., (2016) report the effect of agriculture on the discharge of small catchments. They found that the ratio between peak flow and base flow in catchments of around 2 km^2 was 5 for a catchment with natural vegetation and up to

11.9 for a catchment with crops. Soil preparation activities for cultivation decrease soil roughness, create artificial drainages which connect surface depressions, accelerate runoff, and interrupt water storage, all leading to a raise in peak flows (Buytaert et al., 2006a). Given the effect on the hydro-physical properties of soils (e.g., porosity), Buytaert et al. (2005b) compared hydrological buffering capacity in a cultivated catchment against a catchment with natural vegetation, and observed a decline up to 40% in the streamflow buffering capacity of the former.

The mechanic compaction of soils as a consequence of intensive livestock trampling and soil exposure has a direct effect on soil infiltration capacity and saturated hydraulic conductivity. These two variables control surface runoff, and thus an increase in overland flow will result in a decrease in streamflow buffering. Runoff has been reported to increase in up to 300% in páramos with natural vegetation converted to livestock farming (Poulenard et al., 2001).

Few studies report infiltration characteristics, whose measuring difficulty is not necessarily high, but indeed highly variable in space (less so in time). However, the plot scale effect of infiltration can be observed in surface runoff, which might be more difficult to measure than infiltration, but provides an aggregated picture of the process. The indirect analysis of hydrographs and surface runoff data allow evidencing the effects on streamflow buffering at catchment scale (Antoine et al., 2011).

Despite the documented effects of land use on streamflow buffering, this area of research should be further developed. Some studies report that no significant differences exist in the soil infiltration capacity after the introduction of crops (Hofstede, 1995a), or that differences in runoff may be less than 2% in catchments with agriculture compared to catchments with natural vegetation (Sarmiento, 2000). Therefore, further research is needed to understand these relationships better, particularly with the installation of robust, representative, and sustainable monitoring systems that comprehensively integrate variables regarding climate, water flows, soil hydro-physical properties, and plant-water relations (Ochoa-Tocachi et al., 2018).

We believe this review appropriately integrates information on the effects of land-use change over the hydro-physical properties of páramo soils that have previously been dispersed. This can inform policy decisions and professional practice, for instance, contributing to overcome challenges associated with model conceptualization, calibration, and simulation particularly in ungauged or poorly monitored páramo regions (Flores-López et al., 2016; Ochoa-Tocachi et al., 2016). Currently, data from páramos are sparse, and the extreme variety of meteorological conditions, vegetation types, soils, geology and topography complicates hydrological modelling in these ecosystems (Flores-López et al., 2016; Ochoa-Tocachi et al., 2016). The use of average values obtained from the literature and the consideration of expected uncertainty ranges can be a way to ease the difficulties of data scarcity, whereas data from recent monitoring efforts can allow models capture the hydrological response to specific events (e.g. Flores-López et al., 2016). In addition to modelling, this integrated data from multiple empirical studies can be used to effectively communicate to stakeholders about the effects of different land-use alternatives on the ecosystem service of hydrological regulation, and contribute to decision making processes for land-use planning that may ensure the provision of key hydrological ecosystem services originated in the páramo regions in the long term.

5 Conclusions

Páramo soils have a high capacity to regulate water flows due to their favourable hydro-physical properties, which typically feature an open structure, high porosity, soil organic matter, water retention capacity, infiltration rate, and saturated hydraulic conductivity.

The information reviewed in this study shows that agriculture, afforestation and livestock farming affect different soil hydro-physical properties. Livestock farming mainly decrease porosity and infiltration capacity because of soil compaction. Associated land-use activities (i.e., burning, tillage, trampling, etc.) change these soil hydro-physical properties, increasing bulk density, decreasing water retention capacity, and promoting runoff, which compromise streamflow buffering and increase erosive processes. These findings were obtained from data reported in the literature regarding superficial soil horizons (A and O).

Further study on the hydro-physical properties of páramo soils and their relation to land use is required to understand the effects over hydrological ecosystem services for people depending on these fragile ecosystems. In order to achieve this, monitoring systems that comprehensively integrate variables regarding climate, water flows, soil hydro-physical properties, and plant-water relations are urgently needed.

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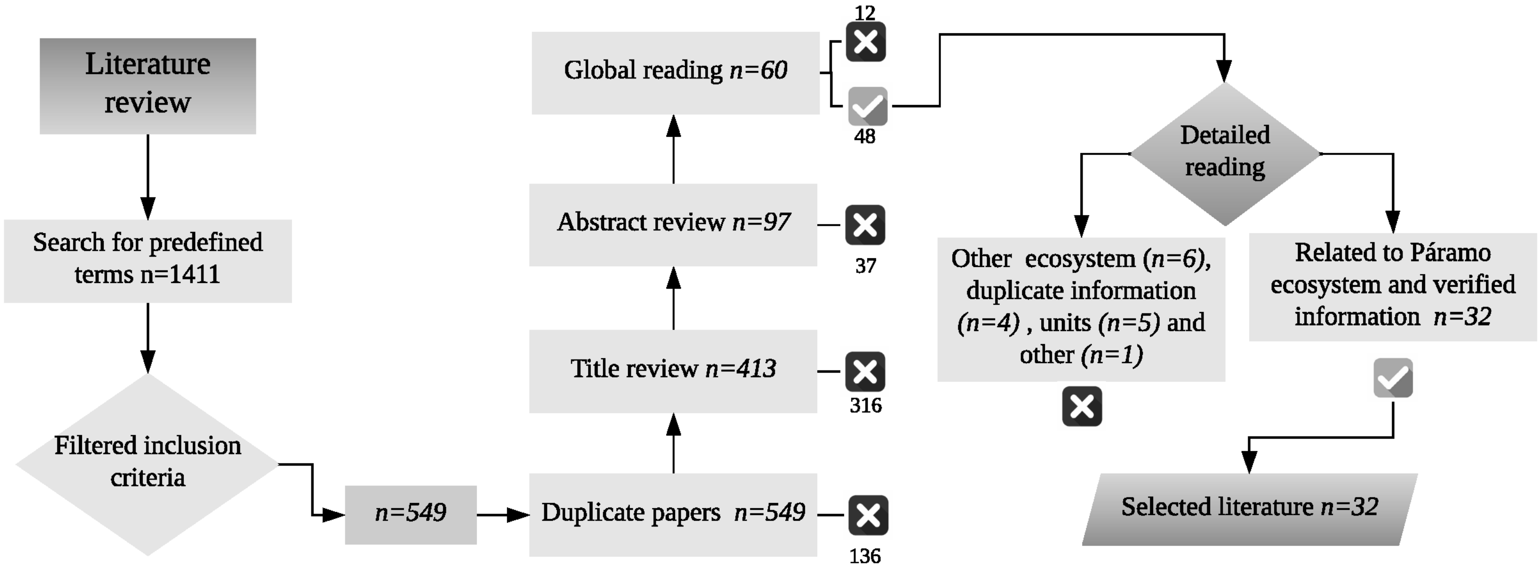
Figure 1


Literature review
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Abstract review n=97
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12
48
Detailed reading
Other ecosystem (n=6), duplicate information (n=4) , units (n=5) and other (n=1)
Related to Páramo ecosystem and verified information n=32
Selected literature n=32

Figure 2


85°0′O
80°0′O
75°0′O
70°0′O
65°0′O
10°0′N
5°0′N
0°0′
5°0′S
10°0′S
Caribbean Sea
Sierra Nevada de Santa Marta
COSTA RICA
PANAMÁ
Talamanca Mountain range
VENEZUELA
Mérida Mountain range
Central and Western Mountain ranges
Eastern Mountain range
COLOMBIA
PACIFIC OCEAN
ECUADOR
Eastern and Western Mountain ranges
PERÚ
Legend
Country boundaries
Páramo complexes
Study sites
0
250
500 km
Andean Mountain range
SOUTH AMERICA
0
500
1000 km

Figure 3

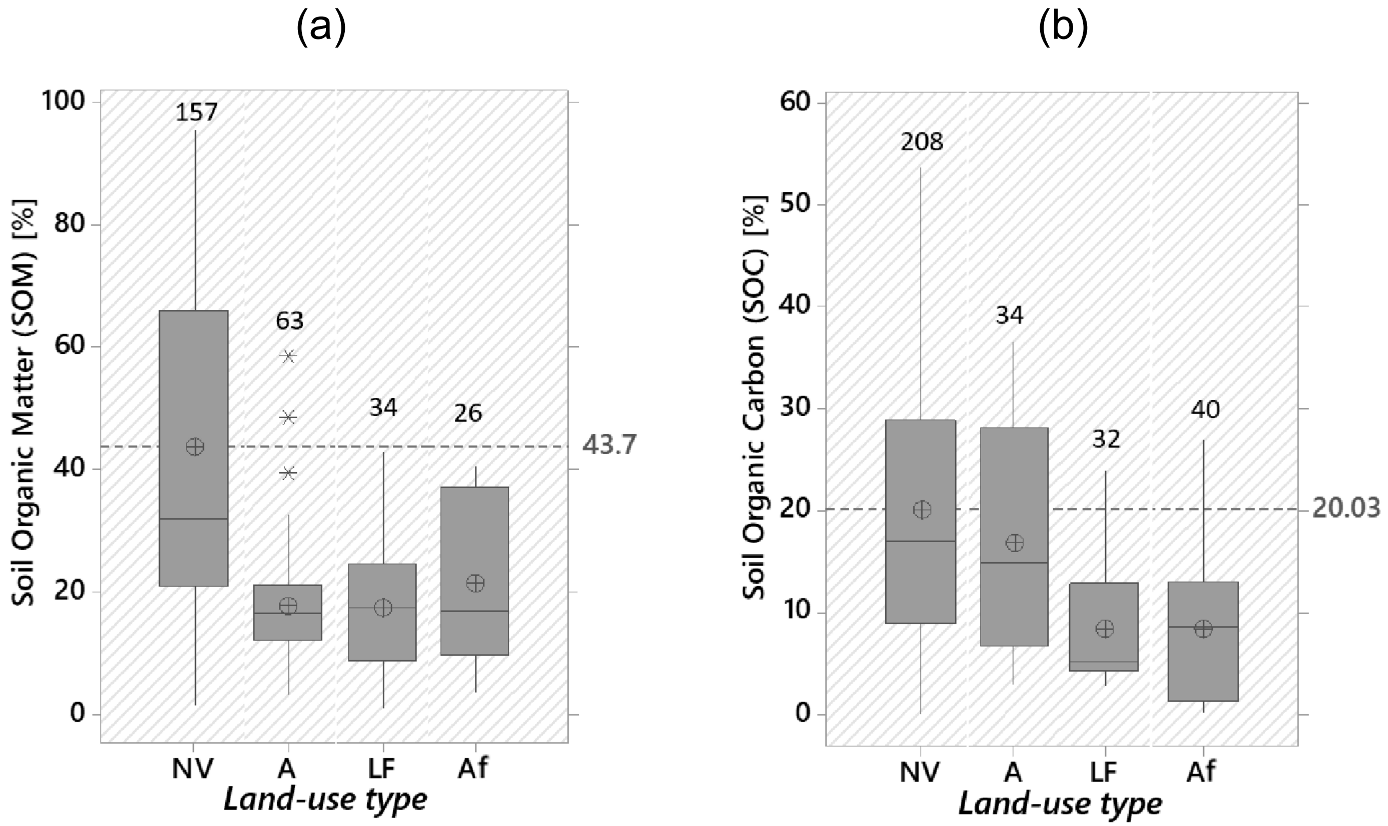
(a)
Soil Organic Matter (SOM) [%]
100
80
60
40
20
0
157
63
34
26
43.7
NV
A
LF
Af
Land-use type
(b)
Soil Organic Carbon (SOC) [%]
60
50
40
30
20
10
0
208
34
32
40
20.03
NV
A
LF
Af
Land-use type

Figure 4

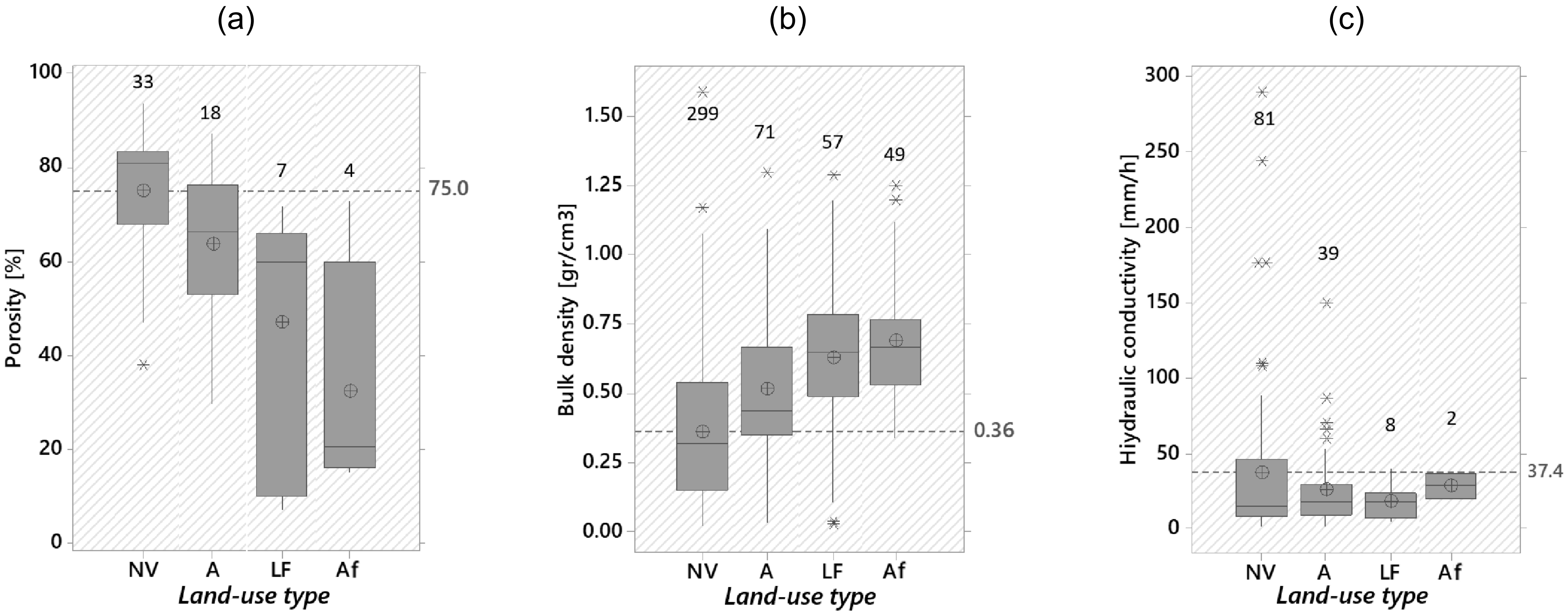
(a)
Porosity [%]
100
80
60
40
20
0
33
18
7
4
75.0
NV
A
LF
Af
Land-use type
(b)
Bulk density [gr/cm3]
1.50
1.25
1.00
0.75
0.50
0.25
0.00
299
71
57
49
0.36
NV
A
LF
Af
Land-use type
(c)
Hydraulic conductivity [mm/h]
300
250
200
150
100
50
0
81
39
8
2
37.4
NV
A
LF
Af
Land-use type

Figure 5

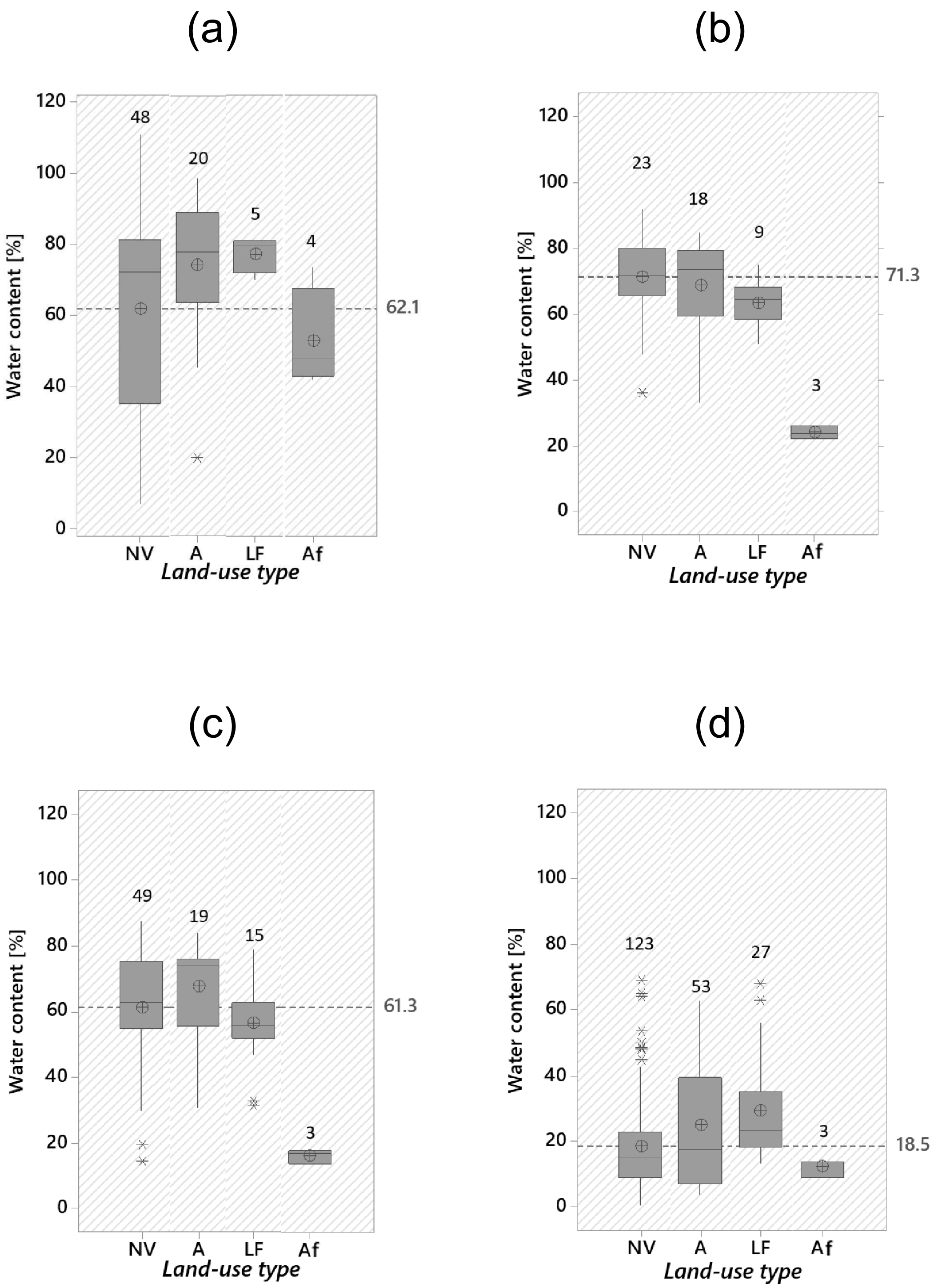
(a)
(b)
(c)
(d)
Water content [%]
Land-use type
NV
A
LF
Af
0
20
40
60
80
100
120
48
20
5
4
62.1
23
18
9
3
71.3
49
19
15
3
61.3
123
53
27
3
18.5

Figure 6

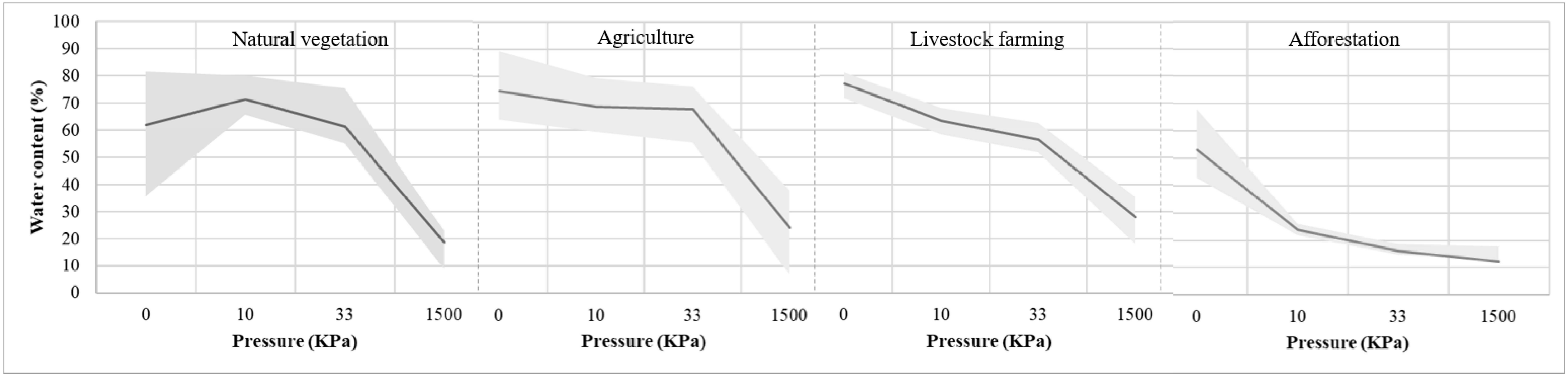
Natural vegetation
Agriculture
Livestock farming
Afforestation
Water content (%)
100
90
80
70
60
50
40
30
20
10
0
0
10
33
1500
Pressure (KPa)

Figure 7

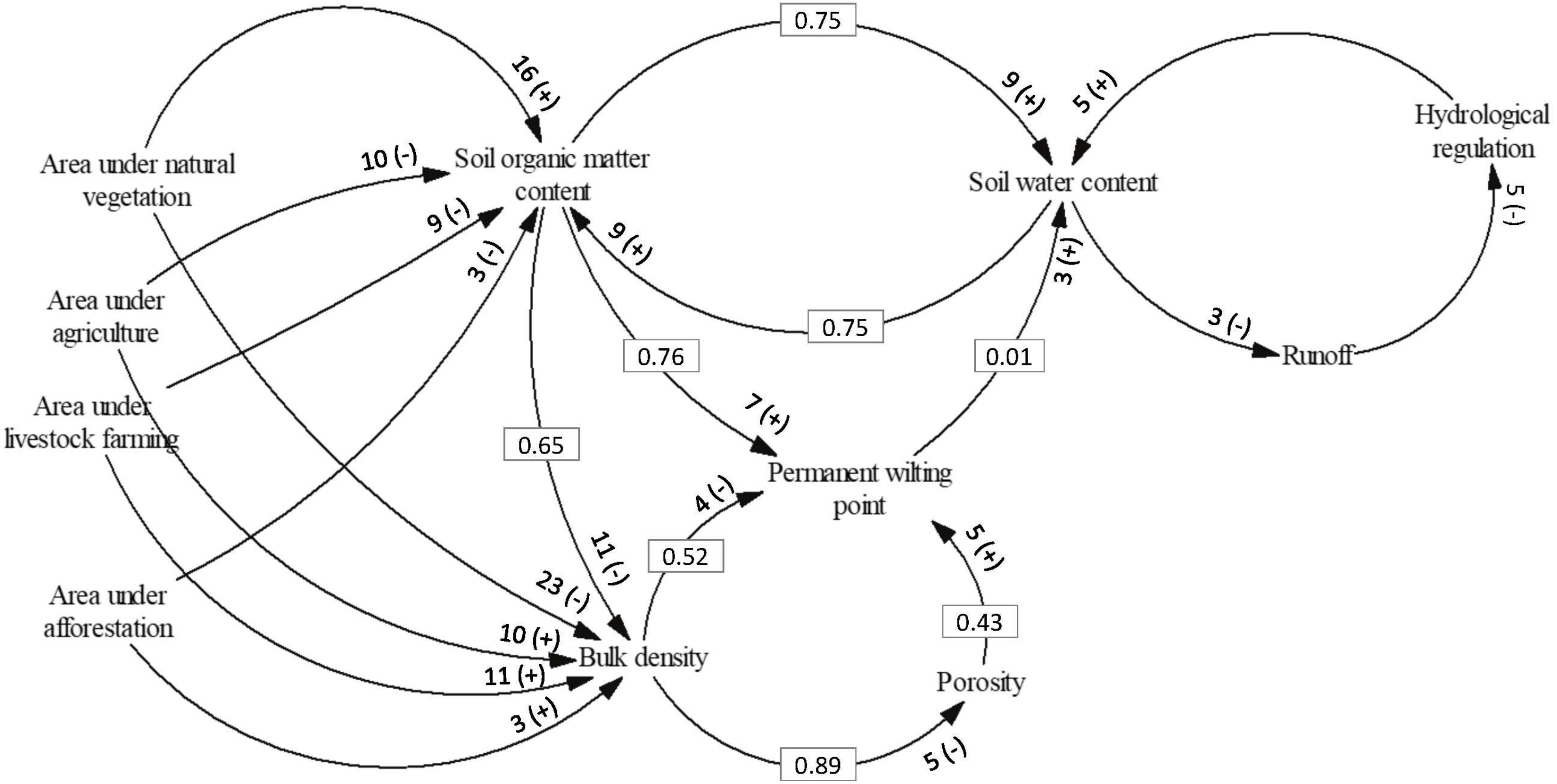
0.75
16 (+)
9 (+)
5 (+)
Hydrological regulation
Area under natural vegetation
10 (-)
Soil organic matter content
Soil water content
5 (-)
9 (-)
9 (+)
3 (-)
3 (+)
Area under agriculture
0.75
3 (-)
0.76
0.01
Runoff
Area under livestock farming
7 (+)
0.65
Permanent wilting point
4 (-)
11 (-)
0.52
5 (+)
23 (-)
Area under afforestation
0.43
10 (+)
Bulk density
11 (+)
Porosity
3 (+)
0.89
5 (-)

Figure captions:

Figure 1. Stages of the systematic review process, exclusion, and selection of studies. n is the number of publications retained at each stage.

Figure 2. Extent of the Andean páramo and location of the reviewed study sites.

Figure 3. (a) Soil organic matter (SOM) content and (b) soil organic carbon (SOC) content according to land-use type. 43% of the papers included in the review reported SOM, 40% SOC, and 17% both. NV: natural vegetation; A: agriculture; LF; livestock farming; Af: afforestation; *: outlier; ⊕: average; —: median; --: natural vegetation average; number above the box diagrams are the data points found for each use in the literature review.

Figure 4. (a) Porosity and (b) Bulk density (Bd) and (c) Hydraulic conductivity (K) according to land-use type. NV: natural vegetation; A: agriculture; LF; livestock farming; Af: afforestation; *: outlier; ⊕: average; —: median; --: natural vegetation average; number above the box diagrams are the data points found for each use in the literature review.

Figure 5. Water retention capacity (WRC) according to land-use type at (a) 0 kPa, (b) 10 kPa, (c) 33 kPa, and (d) 1500 kPa. NV: natural vegetation; A: agriculture; LF; livestock farming; Af: afforestation; *: outlier; ⊕: average; —: median; --: natural vegetation average; number above the box diagrams are the data points found for each use in the literature review.

Figure 6. WRC curves at different suctions according to land-use type. The bold line represents average WRC and the shade represents the variability expressed using the interquartile range (IQR).

Figure 7. Synthesis of the effect of land-use type on the hydro-physical properties of páramo soils and streamflow buffering (hydrological regulation). The numbers show the quantity of papers that explicitly addressed relationships between the variables. A positive sign (+) means an increase (decrease) in a particular variable would result in an increase (decrease) in the linked variable. A negative sign (–) means that an increase (decrease) in a variable would result in a decrease (increase) in the linked variable. The numbers within the rectangles are the coefficients of determination between properties. For simplicity, porosity only refers to microporosity, which is the type of porosity associated to the permanent wilting point. The relations focused on microporosity (high suctions), since this characteristic is responsible for water storage in the long term (streamflow buffering). At the same time, this property is highly influenced by the Soil Organic Matter (SOM). The reviewed literature mostly reported SOM and only in few cases macroporosity or

texture. Therefore, the correlations in the diagram were produced with the available information. When a naturally vegetated soil is first transformed to agriculture, bulk density may decrease; however, on the long term, agricultural activities increase bulk density.

Table 1. Commonly reported variables in studies on land-use change in páramo ecosystems

Group	*Variable*	*Type*	*Unit of measurement*	*Description*
1	Country	Qualitative	-	Variables characterizing the study area
	Elevation	Quantitative	m a.s.l.	
	Area	Quantitative	m^2	
	Annual average rainfall	Quantitative	mm yr^{-1}	
	Soil type	Qualitative	-	
	Vegetation type	Qualitative	-	
	Land-use type	Qualitative	-	
	Time under use	Qualitative	yr	
2	Methodology	Qualitative	-	Variables describing the methodology used
	Number of samples	Quantitative	-	
	Type of sample	Qualitative	-	
	Scale	Qualitative	-	
	Depth	Quantitative	m	
3	WC	Quantitative	%	Variables linked to the hydro-physical properties of soil
	SOC	Quantitative	%	
	SOM	Quantitative	%	
	PWP	Quantitative	%	
	FC	Quantitative	%	
	K	Quantitative	mm h^{-1}	
	Ks	Quantitative	mm h^{-1}	
	Bd	Quantitative	g cm^{-3}	
	Pd	Quantitative	g cm^{-3}	
	WRC	Quantitative	%	
	Soil texture	Quantitative	%	

Notes: *m a.s.l.: m above sea level; WC: water content; SOC: Soil Organic Carbon; SOM: Soil Organic Matter; PWP: permanent wilting point; FC: field capacity; K: hydraulic conductivity; Ks: saturated hydraulic conductivity; Bd: Bulk density; Pd: particle density; WRC: water retention capacity. Water content (WC) captures specific spatiotemporal conditions that can be affected by water regime, weather conditions, among other factors, and thus it was not included in a comparative analysis.*

Table 2. Selected studies, site characteristics, and soil hydro-physical properties analyzed in the systematic review

Study site	*Coordinates*		*Elevation [m a.s.l]*	*Reference*	*Study aim*	*Land-use types*	*Soil hydro-physical properties*	*Sampling*				*Statistical tests*
	Latitude	*Longitude*						*Type (scale)*	*Depth*	*Condition*	*Samples*	
Sumapaz páramo, CO	3°45'-4°10' N	74°10'-74°30' W	3550	Daza-Torres et al. (2014)	1	NV, A, LF	WRC, Bd, P, SOM	Area (pedon)	S	Ud	48	Uv
Cotopaxi province, EC	0°40' S	78°30' W	3400-3500	Farley et al. (2004)	2	NV, Af	WRC, Bd, SOC	Area (pedon)	S, Sb	Ud	100	Uv
Cajas national park, EC	2°50' S	79°08' W	3000-4300	Harden (2006)	1	NV, A	WC, Bd, SOM	Area (catchment)	S	Ud	46	____
Guerrero páramo, CO	5°8' N	73°57' W	3325-3640	Peña-Quemba et al. (2016)	3	NV, A	WC, SOM	Transect (catchment)	S, Sb	Ud	108	Uv, Mv
Pichincha & Province of Carchi, EC	0°10' S and 0°37' N	78°36' and 77°56' W	3200-3640	Poulenard et al. (2001)	2	NV, A, LF	P, WRC, Bd, Ks, SOC	Area (pedon)	S, Sb	____	____	____
Paute catchment, EC	3°11' S	78°57' W	3000-3300	Buytaert et al. (2002)	1	NV, A	WRC, Bd, SOM, WC	Point (pedon)	S, Sb	D, Ud	64	Uv
Sumapaz páramo, CO	4°19' N	74°12' W	3573-3590	Montes-Pulido et al. (2017)	3	NV, A	Bd, SOM, WRC	Area (pedon)	S, Sb	D, Ud	30	Uv, Ca
Ecuadorian Andes, EC	0°46' N-3°40' S	77°51'-79°21' W	3000-4000	Hofstede et al. (2002b)	1	NV, Af	WRC, Bd, SOM, WC	Area (pedon)	S, Sb	Ud	95	Uv, Ca
Paute catchment, EC	2°48 S	78°51' W	>3300	Buytaert et al. (2007b)	1	NV, A	WRC, Bd, Ks, SOC	Transect (Andean	S, Sb	D, Ud	108	Uv

								mountain range)				
Páramos: Cuenca, Azogues and El Ángel, EC	0°41' N, 2°57' S and 2°38' S	77°54', 79°13' and 78°46' W	3250-3700	Poulenard et al. (2003)	3	NV	Bd, WRC, SOC, Pt	Area (pedon)	Sb	Ud	___	____
Anaime páramo, CO	4°15' N	75°33' W	3200-3750	Andrade Castañeda et al. (2014)	3	NV, LF	Bd, SOC	Area (pedon)	S, Sb	D, Ud	18	Uv, Ca
Nevados national park, CO	4°44' N	75°26' W	3432-3769	Avellaneda-Torres et al. (2018)	1	NV, A, LF	WC, Bd, SOC, SOM	Area and transect (pedon)	S, Sb	Ud	102	Uv
Catchments: Huagrahuma, Soroche and Queseras, EC	2°15' - 3°00' S	78°80'- 79°00' W	3500-4500	Buytaert et al. (2005b)	2	NV, A	WRC, Ks, Bd, SOM	Point (pedon)	S	D, Ud	162	Uv
Cayambe-Coca national park, EC	0°19' S	78°10' W	3950-4250	Comas et al. (2017)	3	NV	Bd, SOC, SOM	Point (pedon)	S, Sb	Ud	132	____
Guandera biological station, EC	0°35 N	77°39'- 77°42' W	3330-3990	Tonneijck et al. (2010)	3	NV	Bd, Pt, SOC, WRC	Area and transect (pedon)	___	D, Ud	____	Uv, Ca
Belmira páramo, CO	6°40' N	75°40' W	3200	Urbina and Benavides (2015)	1	NV, LF	Bd, WC	Area (pedon)	S, Sb	Ud	27	Uv, Mv
Paja Blanca páramo, CO	0°59' N	77°37' W	3000	Benavides et al. (2018)	2	NV, A, LF	WC, Bd, SOC, SOM, Ks	Area (catchment)	S, Sb	D	72	Uv, Ca
Cayambe-Coca	0°04' and	77°50' and	3919-	Hribljan et al. (2016)	3	NV, LF	Bd, SOC	Point	S,	Ud	53	____

national park, EC	0°33' S	78°09' W	4880					(pedon)	Sb			
Iguaque national park, CO	5°41' N	73°25' W	2500 - 3800	Benavides (2015)	3	NV	Bd, SOM, WC	Area (pedon)	S, Sb	Ud	9	Uv
Quimsacocha páramo, EC	3°05' S	79°30' W	3400-3900	Quichimbo et al. (2012)	1	NV, A, LF, AF	Bd, WRC, Ks, SOM, SOC, EC	Area and transect (catchment)	S, Sb	Ud	___	Mv
Nevados national park, CO	04°46' N	75°24' W	3900	Camargo-García et al. (2012)	1	NV, A	Bd, Pt, Ks, WRC, SS, SOM	Area (pedon)	S, Sb	Ud	48	Uv, Ca
Macujabí páramo, VE	8°47' N	70°49' W	3500-3750	Azócar and Monasterio (1980)	1	NV	WC	Point and transect (pedon)	S, Sb	____	54	_____
Cruz verde páramo, CO	4°33' N	74°02' W	3300-3400	Schnetter et al. (1976)	2	NV	WRC, SOC, WC	Point (pedon)	S, Sb	Ud	72	____
La Cortadera páramo, CO	05°32' N	73°06' W	3300-3815	Cuervo-Barahona et al. (2016)	3	NV, A, LF	SOC	Point (pedon)	S, Sb	D, Ud	___	Uv
Huagrahuma and Ningar, EC	2°44' S	78°50' W	3350-3900	Buytaert et al. (2006b)	1	NV	WRC, Ks, SOM, Pt, Bd	Transect (catchment)	S, Sb	UD	140	Mv
Tungurahua province, EC	1°15' S	78°37' W	3800-4200	Podwojewski et al. (2002)	2	NV, LF	Bd, SOC, WC	Area (pedon)	S, Sb	____		_____
Santa Inés páramo, CO	06°40' N	75°40' W	3200	Marulanda and Villa (2016)	3	NV	Bd, SOM	Point (pedon)	S, Sb	Ud	165	Uv
Páramos: Berlina,Chingaza and	04°39' - 06°39' N	73°50' - 75°40' W	3060-3770	Cárdenas-Agudelo (2016)	2	NV, LF	Bd, SOM, WRC, Pt	Area (catchment)	S, Sb	Ud	6	____

Romerales, CO												
Río Guandoque microcatchment, Tausa, CO	5°12' N	74°00' W	_____	Lis (2015)	3	NV, A, LF	SOC, SOM, Bd, WC	Area and transect (catchment)	S, Sb	Ud	225	___
Antisana ecological reserve, EC	0°30' S	78°11' W	4010-5300	Minaya et al. (2018)	2	NV	SOC	Area (catchment)	S, Sb	Ud	100	Uv
Ecuador highlands, EC	2°40'-3°20' S	78°40'-79°20' W	3032-3035	Chacón et al. (2009)	1	NV, Af	SOC, SOM	Area (pedon)	S	___	117	Uv, Mv
Zhurucay Echohydrological Observatory, EC	3°03’S	79°13’	3400-3900	Lazo et al. (2019)	2	NV	WRC	Area and transect (catchment)	S, Sb	D, Ud	68	Uy, My

***Notes:** *m a.s.l.: m above sea level; S: Superficial; Sb: Subsuperficial; Uv: Univariate; Mv: Multivariate; Ca: Correlation analysis; D: Disturbed; Ud: Undisturbed; NV: natural vegetation; A: agriculture; LF: livestock farming; Af: afforestation. Study aim: 1: To assess soil hydro-physical properties as result of land use change; 2: To compare the state of the hydrological services provided by páramo natural vegetation in contrast with anthropic land use (i.e. agriculture, livestock, afforestation); 3: To study carbon storage in soils. SOC: Soil Organic Carbon, SOM: Soil Organic Matter, Ks: saturated hydraulic conductivity, Bd: Bulk density, WRC: water retention capacity; P: porosity; Pt: Total Porosity; EC: electrical conductivity; SS: structural stability; WC: water content*.

Table 3

Table 3. Synthesis of relations between soil hydro-physical properties, land-use type, and streamflow buffering. The numbers refer to the quantity of papers that include explicit references to those relationships in their results or conclusions.

	Number of papers and relationships							
Area under afforestation	3 (-)	1 (-)	3 (+)	1 (-)	3 (-)	2 (-)	3 (-)	
Area under livestock farming	9 (-)	2 (-)	11 (+)	3 (-)	6 (-)	5 (-)	4 (-)	
Area under agriculture	10 (-)	3 (+)	10 (+)	6 (+)	6 (-)	5 (+)	7 (-)	
Area under natural vegetation	16 (+)	4 (+)	23 (-)	7 (+)	14 (+)	9 (+)	13 (+)	
Land-use type / **Soil hydro-physical properties**	Soil Organic Carbon / Organic Matter	Porosity	Bulk density	Hydraulic conductivity	Water Content	Water Retention Capacity (<100 KPa)	Water Retention Capacity (>100 KPa)	
	15 (+)	3 (-)	3 (-)	3 (-)	5 (+)	4 (-)	3 (+)	**Streamflow buffering**
	Number of papers and relationships							