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Variability of Soil Surface Characteristics in A Mountainous Watershed in Valle Del Cauca, Colombia: Implications for Runoff, Erosion, and Conservation

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Abstract

Understanding catchment sediment or solute transport frequently relies on understanding of soil nutrient conditions and physical properties. This study investigates hydropedological patterns in a tropical catchment by understanding soil nutrient and soil surface changes. Soil nutrient concentrations and hydraulic properties were measured from the La Vega micro watershed in the southwestern Colombian Andes at 16 distributed locations in four elevation ranges (between 1450 - 1700 m a.s.l.). The site is a part of a conservation partnerships which implements programs and monitor impacts. Soil samples were analyzed for total nitrogen (TN), Bray II- available phosphorus, exchangeable cations, pH, organic matter, and texture. Soil hydraulic conductivities at two depths (0 to 5 cm and 5 to 10 cm) were determined in conservation implementation areas (enclosures and natural regrowth). In the upper elevation range, regrowth of natural vegetation was found on deep soils (~3 m) with moderate infiltration (26 cm hr^{-1}), the lowest bulk density (0.92 g cm^{-3}), and the highest TN (0.4%). The lowest elevation (mixed land use of grazing and riparian forests with deep profiles) had the lowest infiltration (4 cm hr^{-1}), highest bulk density (1.02 g cm^{-3}), and the lowest TN (0.26%). In the middle elevation ranges, conserved tropical forest vegetation were located on shallow soil depths with high organic matter (~6%) and high infiltration (86 cm hr^{-1}). The lowest infiltration rate average (2.3 cm hr^{-1}) exceeded the estimated erosive regional precipitation intensity (~2.5 cm hr^{-1}) about 60% of the time, while the median infiltration rate (10 cm hr^{-1}) exceeded rainfall intensities 94 % of the time, indicating that infiltration excess and saturation excess runoff mechanisms are both present. Coupling data with sediment concentration and solute concentration patterns can help discern correlations between scales and will help to monitor effectiveness of conservation programs aimed at sustaining ecosystem services.

Keywords: *saturated hydraulic conductivity, soil nutrient gradients, Colombian Andes*

1. Introduction

The intertwined nature of soil and water dynamics, referred to as hydropedology (Ma et al., 2017), show how each component is important for mapping, monitoring, and modeling in watershed studies. As conservation programs gain awareness and support among downstream users and industries interested in mitigating their impact on natural resources, research on hydropedology and these intertwined ecosystem services is increasing (Naeem et al., 2015), with attention often focused on short-term soil functioning and long-term soil pedogenic processes (Bouwer et al., 2015; de Lima et al., 2019; Hamel et al., 2018; Ma et al., 2017). Two of these main dynamics that conservation programs intend on remediating are related to the soil nutrients and hydraulic properties recharging shallow and deep aquifers (Buytaert et al, 2004). In 2014, a large agreement was reached between an NGO (The Nature Conservancy) and Latin American institutions in order to catalyze partnerships between water users and community stewards that promote conservation projects designed to help enhance watershed ecosystem services (The Nature Conservancy, 2014, Ponette-González et al., 2015). Empirical findings in these projects on the conditions of the soils (main determinant of these watershed ecosystem services) are limited but emerging recently and demonstrating the unique patterns in the humid tropics (Ponnette-González et al., 2014; Wohl et al., 2012; Hoyos-Villada et al., 2016).

For mountainous humid tropics, conservation projects must contend with the fact that soil nutrients are known to be spatially heterogeneous and dependent on local climate, land use, topography, and parent material (Guzman et al., 2017b; Tebebu et al., 2017). Additionally, the humid tropics are regions where leaching of nitrate and accompanying plant nutrients quickly increase in a positive feedback loop after shifting from humid forest cover to cultivated land cover

(Wong and Rowell, 1994) indicating that empirical findings are static snapshots in dynamic processes changing over time.

Soil hydraulic properties similarly are not only highly dependent on soil surface characteristics but also land use. Previous researchers have measured strong influences of land use and topography on the infiltration patterns of tropical soils (Bayabil et al., 2010, 2019; Buytaert et al., 2004; Hoyos et al., 2005; Brauman et al., 2012; Brauman, 2015; Da Silva et al., 2016a,b; Tilahun et al., 2016; Guzman et al., 2017b; Zimale et al., 2017). Generally, forested land use patterns were found to have conditions of greater infiltration than what is measured on areas with altered anthropological use (Tebebu et al., 2017). Recently, studies have shown the dependence of saturated hydraulic conductivity on the textural heterogeneity of soils (García-Gutiérrez et al., 2018), and others have noted that in mountainous regions, cultivated lands are capable of much lower runoff coefficients than trails, unpaved roads, abandoned or fallow lands (Harden, 2001; Hanson et al., 2004). The susceptibility of these land uses to degradation and subsequent hardpan and runoff are tied to the moisture availability and productivity of the soils (Harden, 2001; Hanson et al., 2004). In order to maximize the ecosystem services provided by the diverse soil qualities, indicators of conditions enhancing soil quality such as vegetation cover (forests) are being studied and promoted among several conservation organizations (Barrios et al., 2006; Bonnesoeur et al., 2019; Bruijnzeel, 2004; de Lima et al., 2019; Ponette-González et al., 2014; Naeem et al., 2015).

It is important to better understand these variations and expected impacts on hydrology as hydropedology suggests (Ma et al., 2017). Le Bissonnais et al. (2005) determined the variability of soil surface characteristics to be an important part of understanding where runoff and sediment concentration would increase in loess soils, where Hortonian flow processes (Horton, 1933) are dominant. This variability needs to be considered in climates and soil conditions where saturation excess flow (Beven and Kirkby, 1979; Dunne and Black, 1970; Dunne, 1983; Kirkby, 1997; Steenhuis et al., 2013) may be more important. Humid tropical mountainous watersheds, with volcanic, clay soils and high moisture, are likely regions where soil surface conditions enable various mixtures of Horton and saturation excess flow processes to be occurring, resulting in implications for watershed conservation programs. The Southwest Colombian Andes is a part of the Andean mountain range and produces headwaters for several important rivers in Colombia's economic and municipal sectors. The Rio Bolo, in particular, receives waters from Paramo (high altitude tropical wetlands) and high elevation watersheds that have been changing in land use and in their weather patterns. A sub-watershed of a nested study site within the Rio Bolo drainage network was chosen for work on soil surface characteristics to complement ongoing watershed ecosystem services research (Hoyos-Villada et al., 2016).

The objective of this study is to investigate the emergent characteristics of a sub-humid tropical watershed to better understand the changes in soil surface characteristics that will have the most impact on sediment transport, soil quality, and changes in vadose zone hydrological processes. Specifically, the land use and hillslope positions will be used as indicators of expected factors influence hydraulic properties (saturated hydraulic conductivity, K_s; bulk density, ρ_b; texture) and chemical properties (nutrients, organic matter, pH). At the nascent stage of shifting land use, we ask: are reforestation initiatives likely to promote soil characteristic changes that could have significant impact on increasing recharge and decreasing sediment and solute transport? Some hypotheses we posit are that soil properties (saturated hydraulic conductivity, bulk density, texture) in the tropics enable sufficiently high percolation (high K_s, low ρ_b) in most zones of the highland watersheds such that water from most storms is able to infiltrate and that soil quality indicators are greatest in (re)forested regions.

2. Methods

2.1 Study site

The 75-ha La Vega is a sub-watershed in the Rio Bolo watershed within the Cauca Valley in the southwestern Colombian Andes located at 76°11'42.687"W 3°29'55.541"N (Fig. 1). The five year mean annual rainfall as measured at the International Center for Tropical Agriculture (25 km away from La Vega) from 2010 to 2014 was 1005 mm, distributed over two periods (October to January and February to May) with periods of dryness in between. The climate is influenced by the El Niño Southern Oscillation (ENSO) which can bring significant conditions of drought (negative anomalies of rainfall and discharge) during the warming phase of ENSO (El Niño), and positive anomalies during the cold phase (La Niña) (de Lima et al., 2017; Hoyos et al., 2005; Poveda et al., 2001;). In addition, the Pacific Decadal Oscillation affects the arrival of drought and flooding periods (Mantau and Hare, 2002). High intensity of precipitation can range from 1.0 cm hr^{-1} to over 2.5 cm hr^{-1} (Hoyos et al., 2005; Ruppenthal et al., 1996; Sonder, 2004). Around 40 to 49% of the rainfall intensities in this region have been previously measured to exceed 2.5 cm hr^{-1} (Ruppenthal., 1996), in contrast to the expected 5% of rainfall intensities exceeding this threshold in temperate regions (Hudson, 1971). Soils in this region of Colombia have been mapped by the Geographic Institute Agustín Codazzi (IGAC) and are categorized as Dystrudepts, Udorthents, Eutrudepts, Hapludolls with outcroppings (IGAC Code 47fg2). Due to the coarse resolution of this mapping, the soil unit (Code 47fg2) is a combination of these soil types for the region covering La Vega. The study investigates 16 sites spatially distributed across land use and elevation ranges in the La Vega sub-watershed (Fig. 2). These distributed sites are positioned to inform effects on erosion and hydrologic recharge. Eight study points are located on the western portion of the watershed and eight are located on the eastern portion (two for each elevation range within the two portions).

Four of the sampled sites are located in the "downslope area" (elevation is ~1450 m; sites 1,2,3,4) very close to a small forested area with grazing land surrounding the stream sides and outlet (Fig. 2). Point 2 and 3 appear to be within the fenced area that is mapped as conserved forest (Fig. 2b), however they are physically slightly outside of the actual forest land use and are in fact in open regions where occasional cattle grazing occurs. In the middle part of the slope, two transects were differentiated (four sampling sites within each elevation range); the first ("midslope 1 area") is located at a lower elevation range, closer to the watershed outlet (~1500 m; 5,6,7,8). The western side of this range is located in grazing land and the eastern portion is located in forage and plantain cultivation areas. The second of the midslope ranges ("midslope 2") is higher in elevation (~1600 m; 9,10,11,12), and is predominantly covered in forested land with mixed uses for coffee cultivation (arabica), banana (*Musa* sp., *Musaceae*) and pine and tropical forests containing various flora (Yarumo, Balsa, Oak, Cedar, Walnut, Fern, Palm, Comino, Gualanday, Alder, Croton, and Epiphytes). The sites at the highest elevations (~1700 m; 13, 14, 15,16) were located in range land with regrowth of natural vegetation and trees.

2.2 Soil sampling and analysis

Sixteen pvc-type monitoring wells were installed with manual soil augers to determine depth of soil thickness and water levels (Fig. 3). In the initial baseline water level measurement, water tables were only present at point 15 (in the upper slope) and at point 2 (in the downslope area). Most piezometers were installed to depths of 3 m. There were several locations (for example in the midslope forested region where the parent material was near the soil surface) that were only installed to a depth of 1 m due to difficulty drilling through the rock layer.

Three soil sampling periods were established (beginning of February, late February, and late-March of 2015) to measure primary nutrients, total nitrogen (TN), available phosphorus (AP), and potassium (K^{+}), as well as soil surface properties such as organic matter (OM), pH, and measurement of secondary nutrients magnesium (Mg^{2+}) and calcium (Ca^{2+}). At each of the sixteen sampling points a set of split-core samplers were used to collect composite soil samples (made up of about three combined samples to achieve 1 kg) to a depth of 30 cm below the surface (Fig. 4). Total nitrogen was analyzed using the UV/visible spectrometry technique and available phosphorus was analyzed by the Bray II method, while exchangeable cations where estimated using the atomic absorption method. Organic matter estimation was analyzed by the Walkley-Black method. Finally, particle size analysis was performed to determine soil texture class using the Bouyoucos hydrometer method (Bouyoucos, 1962). Composite disturbed soil samples were analyzed in the Laboratory of Analytical Services in the International Center for Tropical Agriculture (CIAT) in Colombia.

To determine saturated hydraulic conductivity, K_s, laboratory measurements were conducted on six replicates of undisturbed soil samples (Fig. 5) collected in metallic cylinders of 5 cm diameter and at two depths (three replicates at 0-5 cm and three replicates at 5-10 cm). While a variety of in situ field measurements are available (e.g. double ring infiltrometer, Guelph permeameter, and tension permeameters), each has its own drawback in comparison to benchmark steady deep flow rates (Morbidelli et al., 2017). In the absence of readily available large volumes of water for these or other controlled methods, the undisturbed soil core method (Klute and Dirkson, 1986; Reynolds et al., 2000) was used as an initial starting benchmark for K_s

measurements in the catchment. These undisturbed samples were analyzed in the Physical Soil Laboratory in the International Center for Tropical Agriculture (CIAT) using the constant head method (Klute and Dirkson, 1986) and then oven-dried at 105°C for 24 hours to determine bulk density (ρ_b). Pedotransfer functions were used to compare methods of estimating K_s from soil texture and bulk density data (Eq. 1, Cosby et al., 1984; Eq. 2, Puckett et al., 1985; Eq. 3, Jabro, 1992; Eq. 4, Saxton and Rawls, 2006; Van Looy et al., 2017).

$$K_s\ (cm\ hr^{-1}) = 2.54\ \times 10^{(-.6+0.0126\ \times Sa - 0.0064\ \times Cl)} \quad (1)$$

$$K_s\ (cm\ hr^{-1}) = 15.696 \times\ e^{-0.1975\times\ Cl} \quad (2)$$

$$\log(K_s(cm\ hr^{-1})) = 9.56 - 0.81\ \times \log Si - 1.09 \times \log Cl - 4.64\ \times\ \rho_b \quad (3)$$

$$K_s\ (cm\ hr^{-1}) = 19.30 \times\ (\theta_s - \theta_{33})^{(3-\lambda)} \quad (4)$$

where *Sa*, *Si*, and *Cl* are %Sand, % Silt, and %Clay respectively and ρ_b is bulk density in g cm^{-3}. For Eq 4., θ_s is the saturated moisture content, θ_{33} is the moisture content at field capacity, and λ is the slope of logarithmic tension vs. moisture plot (Refer to Supplementary materials and Saxton and Rawls, (2006) for full equations describing these variables). Statistical analysis of differences between spatial and temporal samples were conducted with student t-tests for normally distributed data and with non-parametric tests for non-normally distributed data. Bartlett's test was used to determine homogeneity of variances (Bartlett and Fowler, 1937).

3. Results

3.1 Spatial and topographical differences in soil physical properties

PVC monitoring wells, intended to measure water table dynamics, captured very little patterns due to the low frequency of visits and apparent deep or dry status of the soil profiles. Only at the nearest points to the stream were water tables present within the depths of the installed wells.

This indicates extremely well drained soils within the profile above bedrock and potentially that some of the 3 m depth wells had not reached bedrock. Nevertheless, important information regarding soil profiles was discovered. The western portion of the sub-watershed had deep soil profiles (>3 m deep) as revealed through the augering. Calculated texture averages for this western portion of sampling sitesfound higher percentages of clay in the top 0-5 cm, and 5-10 cm (25% compared to 15% for eastern portion sampling points) west of the stream. The eastern part of the watershed had variable soil profile depths, some areas exceeded 3 m, while others had a high content of stones and rocks (Fig. 4). In both sides of the sub-watershed, the areas with greatest forest cover contained the darkest soils signifying high organic matter content (Table 1). These regions (broadly in the upslope and midslope 2 zones) also contained the highest sand content and the lowest clay content in contrast to the lower regions which had the inverse texture relationship (Table 1). In the upper elevation range , regrowth of natural vegetation was found on deep soils (~3 m) with moderately high K_s (26 cm hr^{-1}) and the lowest bulk density (0.92 g cm^{-3}). Soil in the lowest elevation range, in mixed land use of grazing and riparian forests with deep profiles, had the lowest K_s (4 cm hr^{-1}), and highest bulk density (1.02 g cm^{-3}). In the middle elevation ranges, conserved tropical forest vegetation were located on soils of shallow depths with high organic matter and high K_s (86 cm hr^{-1}). When compared with regional precipitation (~1005 mm yr^{-1}) the lowest infiltration rate is exceeded about 50% of the time, while the average and median infiltration rates were not exceeded. The second depths of measurements (5-10 cm) showed mostly lower *Ks* than the first depth layer measurement except for at the upslope region (first layer: 26 cm hr^{-1}, second layer: 28 cm hr^{-1}). The coefficient of variation for these soils (CV= 0.68 to 1.8) indicate that there is high variability across all slope positions according to the classification of Wilding and Drees (1983): low variability for CV < .15; moderate variability for 0.15 < CV < 0.35; and high variability for CV > .35. Very high CV was similarly found for Oxisols in São Paulo State, Brazil for laboratory experiments investigating solute transport and *Ks* spatial variability (Godoy et al., 2019).

Though most of the saturated hydraulic conductivity tests tended to be highest in the upslope forested areas (upslope and midslope 2), within one site of the midslope 1 region (in plantain cultivation landcover) there was an instance where the measured K_s for the first 5 cm was very high (79 cm hr^{-1}). High K_s results were similar in areas with high rock content due to the lower bulk density resulting from the larger void spaces caused by the presence of the rocks. These void spaces in the profile provide quick flow paths for water to infiltrate. High biological activity was observed in various parts of the watershed represented by the macro soil fauna (earthworms, beetles, larvae among other observations) in addition to soil profiles with distinctly darker surface soil layers (black) in comparison to deeper soil layers.

3.2 Spatio-temporal nutrient variation

Soil nutrient properties are varied throughout the watershed with each interacting with the differing fluxes from slope positions and land use (Table 2). The upper elevation zones had the highest TN (0.4%) and organic matter (OM; 6.9%), with soil organic carbon (SOC) approximately 3.5 – 4% (Pribyl, 2010). Soils in the lowest elevation zone had the lowest TN (0.26%), OM (4.8%), and SOC (2.4 – 2.8 %). Forested areas have greater levels of TN, AP, Ca^{2+}, and K^{+}. Forested regions (e.g. TN_f) showed higher nutrients and lower acidity than in the actively used altered regions (e.g. TN_a). All comparisons except Mg^{2+} were significant ($p<0.05$) (Fig. 6). These land use types corresponded to slope regions as well (i.e. Revegetated and natural forested areas were upslope and at midslope-2 regions, while actively used lands were at midslope-1 and lower slope regions). Calcium concentrations are the greatest (statistically significant, $p<0.01$) in the midslope-2 position, where the greatest proportion of native forest vegetation is found.

Soils tend to be modestly shifting over time and only depleting in certain locations for certain nutrients such as TN and K^+. For example, for TN, trends for midslope and downslope regions shift slightly lower from the beginning of February till the end of March however this is only statistically significant for K+ and TN in the midslope 1 zone ($p<0.05$), and near significant for TN ($p = 0.053$) in the downslope zone. The trend of change overall for the remaining nutrients (AP, Ca^{2+} and Mg^{2+}) is less sharp for the upslope regions than for midslope and downslope, but overall the pattern seems to be decreasing, though high variability means that these are not statistically significant (Fig. 7). AP trends decrease in midslope 1 ($p=0.53$) and downslope regions ($p=0.12$), while they increase upslope ($p=0.19$). Ca^{2+} and Mg^{2+} decrease most notably in the downslope regions ($p=0.26$ and $p=0.55$, respectively).

4. Discussion

Hydropedology considers the feedbacks between water and soil dynamics. As can be seen through these results and in other studies, topography, and land use show controls on the development of soil infiltration, bulk density, and nutrient conditions (Bean et al., 2015; Price et al., 2010; Siltecho et al., 2015; Zimmerman et al., 2006). The soil characteristics that developed in this watershed denote two soil (hydraulic and nutrient) dynamics and some future needs.

4.1 Soils are compacted and less permeable in non-forested conditions

Soil compaction as measured through bulk density shows an influence of land use and with an additional control being induced by topography. Differences in soil texture class due to elevation has been observed previously in tropical agricultural watersheds (Taye et al., 2018) and elsewhere (Papanicolaou et al., 2015; Riebe et al., 2015). Still, whether these texture difference have occurred as a result of land use change and management or whether this relates to geological and climatic differences may require further investigation. Field studies indicate that the production of fine sediments may be enhanced at lower elevations and inhibited at higher elevations for an alpine catchment in the High Sierra, California, however, these elevation differences are on the scale of kilometers rather than hundreds of meters (Riebe et al., 2015). Studies investigating contrasting textures along a topographic sequence of Thailand rice fields have pointed to the translocation of clays down the soil profile as the primary mechanism for differences (Boivin et al., 2004). In comparison to studies at nearby CIAT research stations, the proportion of clay (between 14 and 26%) was much lower than that found in bare fallow fields of Quilichao (75%) and Mondomo (64%) experimental fields (Ruppenthal., 1996). However, as mapped by the IGAC (IGAC Code 47fg2) for the coarse areal average, this study found similar results, with slightly higher silt and clay fractions than reported for the average of the combination of soils found in this code: Dystrudepts, Udorthents, Eutrudepts, Hapludolls (65% Sand, 20% Silt, 15% Clay). While slightly different proportions of sand, silt, and clay are found for the different regions, organic matter (OM) appears to be higher at the higher elevation ranges in this study (upslope and midslope 2). In addition to its relationship to decreased bulk density, higher OM could lead to soil storage recovery through nutrients provided and establishment of vegetation. Both are effects that can potentially reduce runoff through increased capture and storage of water (Bean et al., 2014).

Saturated hydraulic conductivity, K_s, measurements here are determined through laboratory analysis, but do not correspond to other measurements that may be determined in the field that are capable of capturing larger characteristics such as macropores, greater depths, or other soil heterogeneities (Bean et al., 2015; Morbidelli et al., 2017; Reynolds et al., 2000). The Guelph permeameter, for example, is one approach that might provide a more holistic measurement of the subsoil infiltration dynamics, however after several attempts logistical challenges made repeated measurements difficult. Furthermore, tests have sometimes demonstrated that the Guelph permeameter can overestimate laboratory controlled experimental soil infiltration rates and underestimate those in natural soil at study plots (Morbidelli et al., 2017), as it measures the conductivity of the matrix and may have a lower probability of measuring macropore flow (Mohanty et al., 1994). While some modifications to the Guelph permeameter are available to make it more representative of different porous media types (Reynolds and Lewis, 2012), other methods more suited to forested and mountainous conditions may be needed such as single (or double) ring infiltrometers or soil monolith sampling in cylindrical containers (Ilek and Kucza, 2014; Ilek et al, 2019). Hence, the data presented here provide a starting point for estimation of infiltration dynamics that could be assumed to be underestimating hydrological subsurface processes at several of the locations.

Brooks et al., (2004) noted that in field experiments and modeling exercises, point estimates of vertical and lateral hydraulic conductivity can be 10 to 100 times smaller than actual hillslope scale K_s due in part to macropores and biological activity. Lateral flow is also shown to be important as it erodes soil structure internally and thereby increases the conductivity (Mendoza and Steenhuis., 2002). In comparison to pedotransfer functions (Cosby et al., 1984; Puckett et al., 1985, Jabro, 1992; Saxton and Rawls, 2006), the data in fact were largely underestimated, indicating that transfer functions may even be assuming lower conductivities than laboratory measurements capture for their estimate of natural conditions in tropical watersheds of the Andes

(Fig. 8). The pedotransfer function developed by Jabro (1992) was the only empirical formula that actually overestimated the K_s by a factor of between 25 to 40. This equation (Eq. 3) was derived from 350 silt-loam soil samples originating in southeastern Pennsylvania with high bulk density and a well-drained nature (and high silt fraction). The lower bulk densities and silt fractions measured in these Andean soils result in estimated values that are much higher than observed values mainly due to the assumptions formulated by the contextually scaled empirical inverse relationship between silt fraction (or bulk density) and K_s. The remaining pedotransfer functions also rely on US-based soil properties to define the relationships between soil texture, bulk density, and K_s but underestimate the value. Saxton and Rawls (2006) use 2000 samples from the USDA NRCS Soil Survey, Puckett et al. (1985) used samples from the Lower Coastal Plain of Alabama, and Cosby et al. (1984) use data from samples obtained over 35 localities in 23 states of the US. Cosby et al (1984) note that their database did not originally include particle size distribution but rather had percentage sand, silt, and clay assigned through mid-point of soil texture class. Each of these particular features of the original derived equations show the region-specific nature of the equations.

Ramírez et al. (2017) also found that for their study in the Orinoco River Basin (Colombia), the Rosetta pedotransfer function (Schaap et al., 2001) likely underestimated K_s by a factor of 10, as had similarly been the case in studies for Ecuador, Costa Rica, and Jamaica (Hafkenscheid, 2000, Huwe et al., 2008; Tobón et al., 2011). These volcanic soils tend to have much greater conductivity than other soils in similar texture classes upon which pedotransfer functions were developed. Moreover, the value obtained from the reference information for these regional soils mapped by the Geographic Institute Agustín Codazzi (IGAC Code 47fg2) was also much lower (3.3 cm hr^{-1}).

Another important finding is the demonstration of vertical non-uniformity in saturated hydraulic conductivity. Though previously understood that upper layers of soil may be more permeable than soils beneath the surface, and that a decreasing trend with depth may be observed (Brooks et al., 2004; Morbidelli et al., 2018), this has not been as widely researched in these mountainous soils. Some researchers have found hard pan layers in soils ranging from 0.15 m to 0.6 m from the surface of the soil in degraded mountainous regions (Tebebu et al., 2017). More findings describing these variable depth profiles will help to integrate the tropical dynamics into modeling practices describing runoff from tropical hilly watersheds.

4.2 Nutrients are lower in non-forested conditions.

The concentration of total nitrogen, available phosphorus, and exchangeable cations demonstrate low availability in non-forested, compacted areas in the lower portions of the watershed (downslope). These areas experience more disruption and have processes that could lead to depletion of the nutrients as has been found in other mountainous regions (Guzman et al., 2017b). Tebebu et al. (2017) furthermore found that the depletion of nutrients and organic matter is indicative of degradation processes that increase the disaggregation of soils and later leads to clogged macropore networks and development of hardpan slowly permeable regions.

Temporal nutrient dynamics (Fig. 7) could be influenced by the changing hydraulic structure of the soils due to forest-conversion to agriculture or pasture land uses, however, these dynamics are not always straightforward in the tropics (Ponette-Gonzalez et al., 2014). Studies have found that nitrogen could be leached at higher rates after conversion, yet the effects may be dampened due to different proportions of nitrogen input from wet, fog, and dry deposition (Weathers and Ponette-González, 2011), or the effects could be inverted due to microbial nitrification (Ponette-González et al., 2014). Finally, studies investigating high-altitude vs lower-altitude forest cover show that water reaching the forest floor (which would influence leaching and other processes) may depend on the interception and throughfall differences caused by tree size, crown cover, density, understorey vegetation, and epiphytes coverage (Crockford and Richardson, 2000). Given that these data are only available in a short time period, they currently provide a baseline of conditions in the initial phases of these projects rather than a full study on the majority of the annual climatic/hydrological variability in the site. Interestingly, Bonnesoeur et al. (2019) indicate that forestation in the Andean regions tends to increase infiltration rates by a factor of 8, within 14 – 20 years and allows for improved erosion control. Recent laboratory studies on the times scale of weeks have shown that soils leached with varying levels of cations may be behind some of these physical changes. For instance, Mg^{2+} leaching through soils in excess can lead to disaggregation of soil structure and reduced K_s (Zhu et al., 2019), while excess K^+ has been shown to decrease soil hydraulic conductivity through dispersion of clays, and reduced porosity and pore connectivity, thereby increasing bulk density and leading to soil structural degradation (Marchuk and Marchuk, 2018).

4.3 Conservation implementation: where should erosion processes be a concern?

Soils in tropical Andean watersheds can be quite permeable and may counteract the intensity of precipitation (Ruppenthal et al., 1996; Janeau et al. 2015), leading to a disconnect between theory and evidence of runoff and erosion processes (Dagnew et al., 2016, 2017). Harden (2000) showed that for plowed fields in the soils of the Rio Paute basin of southern Andean Ecuador, little runoff was observed. All rainfall was absorbed for the frequently observed intensities in the beginning of the season and even later when fields were more compacted, there was rarely evidence for soil washed out of a cultivated field (Harden, 2001). Moreover, endemic vegetation may be able to provide an additional benefit over short-cycle crops of enhanced water transmission to the root zone after rainfall (Janeau et al., 2015), preserving macrostructure and soil moisture. Models must take into account that roads, trails, and compacted lands can contribute a disproportionate amount of runoff and sediment compared to their presence in the landscape (Guzman et al., 2017a; Harden, 2001). Frequently, estimates of erosivity and erodibility in tropical climates are deduced from USLE (Wischmeier and Smith, 1978; or modified versions of the USLE i.e. RUSLE) to map and identify where erosion could be a concern and highlight particular zones or management practices to implement (Guzman et al., 2018; Hoyos et al., 2005; Hoyos, 2006; Quintero et al., 2009; Ochoa-Cueva et al., 2015; Stocking, 1995). However, Ponette-González et al., (2015) argue that rather than relying on this assumed relationship between land cover and hydrological flux, research should be targeted towards accounting for structural and ecological characteristics of the certain land covers and key mediators of the hydrologic flux of concern. Particularly, the infiltration rate changes should be investigated and of primary concern.

The data presented in this study has demonstrated an expected link from compacted soils (through land use change) which can influence how infiltration rates can decrease, potentially leading to greater surface runoff and subsequently erosion, nutrient transport, and decreased baseflow (Bean et al., 2014). However, upslope regions do not appear to be as large a concern as typically argued. Whether these hydraulic properties develop geomorphologically, or due to the vegetative changes will need further investigation, however high K_s was measured in most of the higher elevation regions (26 – 86 cm hr^{-1}) and much lower K_s were found in areas closest to the lower regions near the access road and stream valley (likely experiencing much more disturbance) (1 – 14 cm hr^{-1}). Ruppenthal et al. (1995) and Sonder (2004) find that regional precipitation tends to have a much higher percentage (40%) of storm events that can be considered erosive precipitation intensities (2.5 cm hr^{-1}) than temperate regions (5%) (Hoyos et al., 2005). For the 140 storms measured by Sonder (2004), 62% were lower than 2.5 cm hr^{-1}, 80% lower than 5 cm hr^{-1}, roughly 90% lower than 7.5 cm hr^{-1}, and 94% were less than 10 cm hr^{-1}. This means that the average K_s for the samples in the downslope region for both depth measurements (2.3 cm hr^{-1}) roughly exceeds storm intensities 60% of the time, while midslope 2 and upslope measurements almost always exceed this intensity (Table 1; Fig. 9). The median K_s (10 cm hr^{-1}) for all measured samples coincides with the intensity that is 90% greater than all storm intensities (Sonder, 2004). The maximum measured rainfall intensity was 47 cm hr^{-1}, exceeded mostly by samples in the midslope 2 (forested) region.

Investments in watershed services (IWS) have targeted the enhancement of the natural for the benefit of human populations (Ponette-Gonzalez et al., 2015; Vogl et al., 2017). Beyond the difficulty of identifying the most vulnerable areas in watershed or the most critical target areas to invest in, some scholars argue that only tackling gaps in scientific knowledge will not solve the effectiveness issue for Payment for Ecosystem Services (de Lima et al., 2017, 2019). Uncertainties in the assumptions involved in assessing ecosystem services and in the links between land use and ecosystem services present challenges for expectations and assessment of impacts (de Lima et al., 2017).

4.4. Future research needs for soil hydraulic properties and ecosystem services

Researchers and community partners are continuing to build databases in these sub-catchments (Hoyos-Villada et al., 2016; Rodriguez de Francisco, 2013; de Lima et al 2017, 2019) to fill in the knowledge gaps in baseline information and the impacts of new interventions.

Complexities that need to be address in ecosystem services research have been described by de Lima et al (2017) as falling into three main dimensions: "(a) the complexity of human-environment systems (HES); (b) the limits of knowledge about these systems; and (c) practical constraints, such as the high cost of measuring and monitoring system variables". These complexities are described below as opportunities for response time analysis, cross-disciplinary collaborations, and support structures for future research on soil hydraulic properties and watershed hydrological services in tropical climates.

4.4.1 The complexity of human-environment systems (HES)

The complexity of the human-environment system means that effects can be masked in ongoing unreported or unknown physical or social processes. In addition, addressing the low flow problem and the time lag between upland conservation activities and downslope sediment concentration patterns require further research in tropical forested regions (Bruijnzeel, 2004). Within a short period of time there have been some recent trends emerging. In this watershed, the Water Fund project (Agua por La Vida y Sostenibilidad/ Water for Life and Sustainability) measured flow and total suspended solids from November 2013 to May 2015 (Hoyos-Villada et al., 2016). Starting in April 2014, conservation activities were implemented in about 60% of the watershed, primarily composed of fencing and enclosing areas off from agricultural or grazing use (mostly in midslope-2 and upslope regions). Most of the peaks for these measured dynamics of flow and total suspended solids occur during March to May and between the months of November to December (Hoyos-Villada et al., 2016).

Two indicators of flow regulation were reported as having some notable changes in the brief monitoring period of La Vega. The first flow indicator for high flows was set with a threshold of 5% exceedance and resulted in a value of 0.012 m^3s^{-1} (1,037 m^3d^{-1}) before conservation activities were enacted. Post-implementation, this 5% exceedance resulted in a value of 0.067 m^3s^{-1} (5,789 m^3d^{-1}; Supplementary Materials Fig. S1). Similarly, the low flow indicator (flows equal to or exceeded 95% of the time) had a value of 0.007 m^3s^{-1} (605 m^3d^{-1}) before conservation activities and 0.034 m^3s^{-1} (2,938 m^3d^{-1}) post-implementation (Hoyos-Villada et al., 2016). For sediment monitoring, the sediment load per day was calculated based on suspended solids measured with automatic sensors (Sonda Solitax). Thresholds for sediment loads equaled or exceeded 5% of the time were found to be 20.5 t y^{-1} (4,110 kg d^{-1}) before conservation activities and 12.9 t y^{-1} (2,651 kg d^{-1}) post-implementation (Supplementary Materials Fig. S2). Both flow and sediment data presented in the graphs are aggregated from 15 min data (Hoyos-Villada et al., 2016). These findings have provided initial evidence for emerging patterns and will offer future opportunities to connect intervention impacts to the patterns in other parts of the Andes concerning reforestation and conservation techniques (Bonnesoeur et al., 2019).

4.4.2 The limits of knowledge about these systems

As these databases emerge, further linkages will be needed to between hydrologists, ecologists, and biogeochemists to begin synthesizing and making progress towards reducing uncertainties in ecosystem service assessment and impact measurement (Bouwer et al., 2015; Hamel et al., 2018). Ponette-Gonzalez et al., (2014,2015) report a summary of findings from tropical watersheds with expected changes in nutrient fluxes and also unexpected or complex changes resulting from conversion of forest cover to non-forest land uses. These interdisciplinary analyses of vegetation changes, hydrological fluxes, hydraulic impacts, and nutrient fluxes will be increasingly needed to help develop more understanding and build on the important field work and theoretical formulation developed for tropical regions (Bruijnzeel, 2004).

A physically-based reasoning behind how some of these presented soil physical and chemical observation may have emerged would be the ultimate goal of successive field campaigns and a sustained research program that could help indicate the mechanisms of change over time. For example, soil moisture dynamics, weathering, water table fluctuations, and acidification are a mixture of hydropedological processes influenced by water fluxes which Bouwer et al. (2015) suggest could be used to construct hydrological response models based on accessible soil data. In their study, Bouwer et al. (2015) offer a soilscape that relates recent soil water regime, flowpaths, and storage mechanics (as indicated by soil chemistry) to ancient soil water regime (as indicated by morphology) and current soil water regime indicated by hydrometric field measurements. Hydrochemical and ecohydrological studies are still only recently uncovering dynamics that have previously been overlooked in the analysis of runoff generation, infiltration, and preferential deep water flow (Bonnesoeur et al., 2019; Bouwer et al., 2015; Hamel et al., 2018; Marchuk and Marchuk, 2018; Tebebu et al., 2017; Zhu et al., 2019). Penna et al. (2018) and Hamel et al. (2018) review a series of opportunities for interdisciplinary work in tracing ecosystem water fluxes that help initiate future agenda in research partnerships in the tropical Andes.

4.4.3 Practical constraints: high costs of measuring and monitoring system variables

Finally, there are practical constraints which have shifted the field of hydrology from field work to modeling (Burt and McDonnell, 2016; Vidon, 2015) leading there to be issues with assumptions and validity in the analysis and compilation of field data and patterns (Stocking, 1995; Boardman, 2006). While pedotransfer functions and hydrological models could help evaluate changes in landscapes without spending the associated costs needed for soil sampling, current estimates may not yet be at the point where soil characteristics can be reliably interpolated or scaled across watersheds due to the variability and differing topographical, soil origin, and climatic impacts. More base-line level field studies providing empirical data, such as that which have gone into developing models (e.g the 10,000 plot years for the Universal Soil Loss Equation and hundreds of samples for various pedotransfer functions) in North America, will be needed to develop this reliability in understanding. In these subwatersheds in particular, further tests on the soil hydraulic properties in deeper soil horizons, in addition to repeating measurements after certain periods of time or regular intervals will be needed to gain a more representative understanding of the hydrological system. Similarly, these studies will need the partnerships and sustained financial resources that have funded previous work in the U.S. (e.g. USGS, USDA, NSF) in order to ensure that these studies on soil and hydrological processes develop into theoretical foundations for sediment transport and watershed landscape changes. Digital soil mapping, for instance, has been developing methods of using terrain attributes to estimate continuous maps of soil types and properties beyond simply using statistical techniques (Da Silva et al., 2016b). Lastly, longer term evaluation and continuing cooperative agreements with stakeholders will be needed to ensure that conservation mechanisms garner local support and obtain the maintenance required to ensure that conditions do not return to pre-conservation levels (Boardman et al., 2003; de Lima et al., 2019; Guzman et al., 2017c).

5. Conclusion

Soils in tropical sub-watersheds have varied soil nutrient and hydraulic properties, resulting from a combination of extreme weather influences (e.g. El Niño Southern Oscillation) and land use changes (e.g. grazing, agroforestry, etc). Recently, payments for ecosystem services (PES) schemes and investment in watershed services (IWS) have been developing conservation projects that aim to quantify and enhance the natural capacity of mountainous and forested regions to provide sustainable supplies of water (de Lima et al., 2017). These PES schemes have developed into innovative partnerships that employ "Water Funds" to encourage farmers and watershed community stakeholders to participate in conservation techniques (e.g. enclosures near riparian zones, reforestation) to reduce erosion rates and improve soil infiltration in degraded areas. In an effort to provide insights into some of the extant conditions in a watershed as it undergoes ecosystem service management, the estimation of hydraulic properties and soil nutrient conditions were measured in this Southwestern Andean catchment (75 ha). Greater saturated hydraulic conductivity rates (K_s) and lower bulk densities (ρ_b) are measured throughout the upper parts of the watershed. Lower K_s and greater bulk densities are measured throughout the lower parts of the watershed. Forested and enclosed revegetated regions coincide with these higher hydraulic properties as well as higher soil nutrients for most of the measured parameters. These findings indicate the variability within the watershed across land uses and in different slope positions, revealing patterns that should be considered for hydrological modeling in tropical mountainous watersheds, especially as it pertains to models that strongly assume slope gradient is the greatest determinant of runoff or erosion. Particularly important is that soils are highly permeable in certain forested upslope regions, but there may be converted areas in lower regions of the watershed nearer to streams, where rain and surface water runoff is not infiltrating as readily. Hydropedological feedback cycles may be present in these lower and midslope regions where anthropogenic land use patterns have decreased nutrients, organic matter, and pH that can further alter infiltration and runoff to produce conditions that increase erosion. Greater attention should be given to these biogeochemical changes, especially organic matter and nutrient loss, in an effort to improve ecosystem services related to landscape hydrology. Further field studies assessing the main differences between conserved regions of headwater catchments will be needed for reduction of uncertainties in ecosystem service evaluation and for future research and stakeholder support.

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Table 1. Mean values of physical properties of the surface soil at two depths ("1": 0-5 cm and "2": 5-10 cm) and chemical properties (from 0-30 cm) at the different slope positions in La Vega sub-watershed. Coefficient of variation (CV) for each slope position saturated hydraulic conductivity (K_S) are provided demonstrating measure of variability.

Slope position	Sand	Silt %	Clay	Soil texture class	K_{s_1} cm hr^{-1}	CV_1	K_{s_2} cm hr^{-1}	CV_2	Bulk Density ρ_b g cm^{-3}	Organic matter %	pH
Upslope	53	28	19	Sandy Loam	26	1.1	28	1.1	0.92	6.9	5.5
Midslope 2	60	26	14	Sandy Loam	86	0.68	66	0.76	0.96	6.6	6.2
Midslope 1	44	30	26	Loam	14	1.74	8	1.81	1.01	5.9	5.3
Downslope	47	32	21	Loam	4*	1.36	1*	1.62	1.02	4.8	5.4

*Only 1 of the three replicates taken for samples from points 3 and 4 in the downslope region were able to saturate due to a very low permeability of the samples. Downslope mainly consist of averages from points 1 and 2, which very low values obtain for one sample at each of points 3 and 4.

Table 2. Soil nutrients of the topsoil (0-30 cm) at the different land use and slope positions.

Sample date	Land use	Slope position	pH (H2O)		AP	Exchange complex (cmol (+)/ kg)			TN
2015			1:1	OM	mg/kg	Ca	Mg	K	%
5-Feb									
	grazing	downslope	5.15	5.08	0.80	17.3	17.0	0.13	0.27
	mixed	midslope-1	5.29	6.64	0.61	14.4	17.2	0.17	0.38
	forest	midslope-2	6.23	7.00	3.03	28.7	19.7	0.36	0.35
	regenerated	upslope	5.31	6.61	0.54	17.6	9.8	0.27	0.41
25-Feb									
	grazing	downslope	5.39	4.4	0.53	21.8	15.8	0.09	0.29
	mixed	midslope-1	5.21	5.7	0.59	17.6	13.4	0.12	0.34
	forest	midslope-2	6.06	7.1	1.90	31.7	17.8	0.21	0.41
	regenerated	upslope	5.27	7.0	0.71	19.3	10.1	0.19	0.38
20-Mar									
	grazing	downslope	5.59	5.10	0.42	11.8	14.6	0.10	0.20
	mixed	midslope-1	5.37	5.33	0.50	15.8	14.3	0.11	0.22
	forest	midslope-2	6.27	5.80	2.34	30.3	21.6	0.25	0.33
	regenerated	upslope	5.53	7.09	0.71	16.7	9.3	0.27	0.43

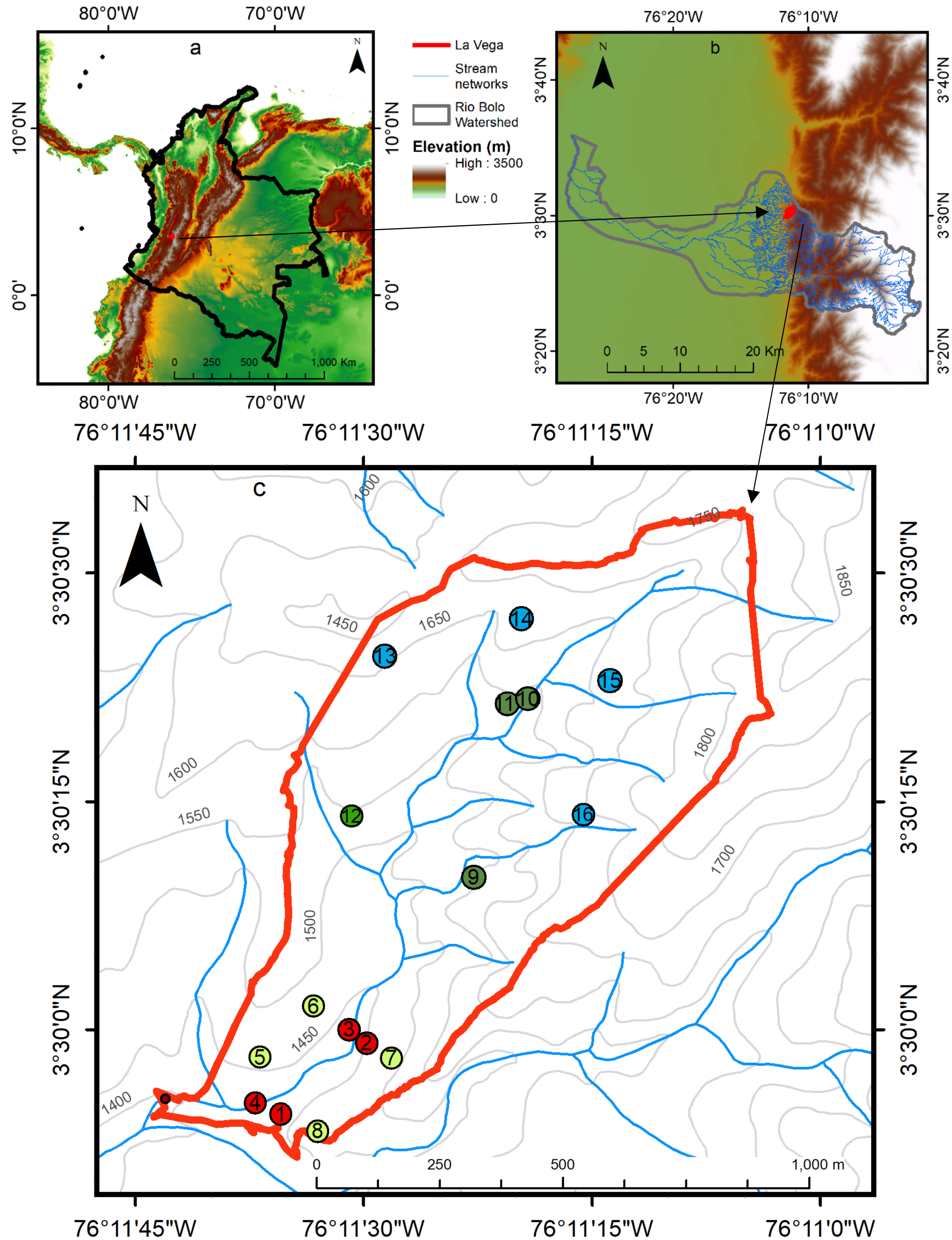


Figure 1: The southwestern Colombian Andes site (a) is located within the Rio Bolo watershed (b) that contributes to the Cauca River. The Aguaclara sub-watershed contains within it the several sub-watersheds, with the current focus being on La Vega sub-watershed (c). Points of measurement are indicated for four locations in each elevation gradient (blue= upslope; dark green = midslope 2; light green = midslope 1; downslope = red; total of 16).

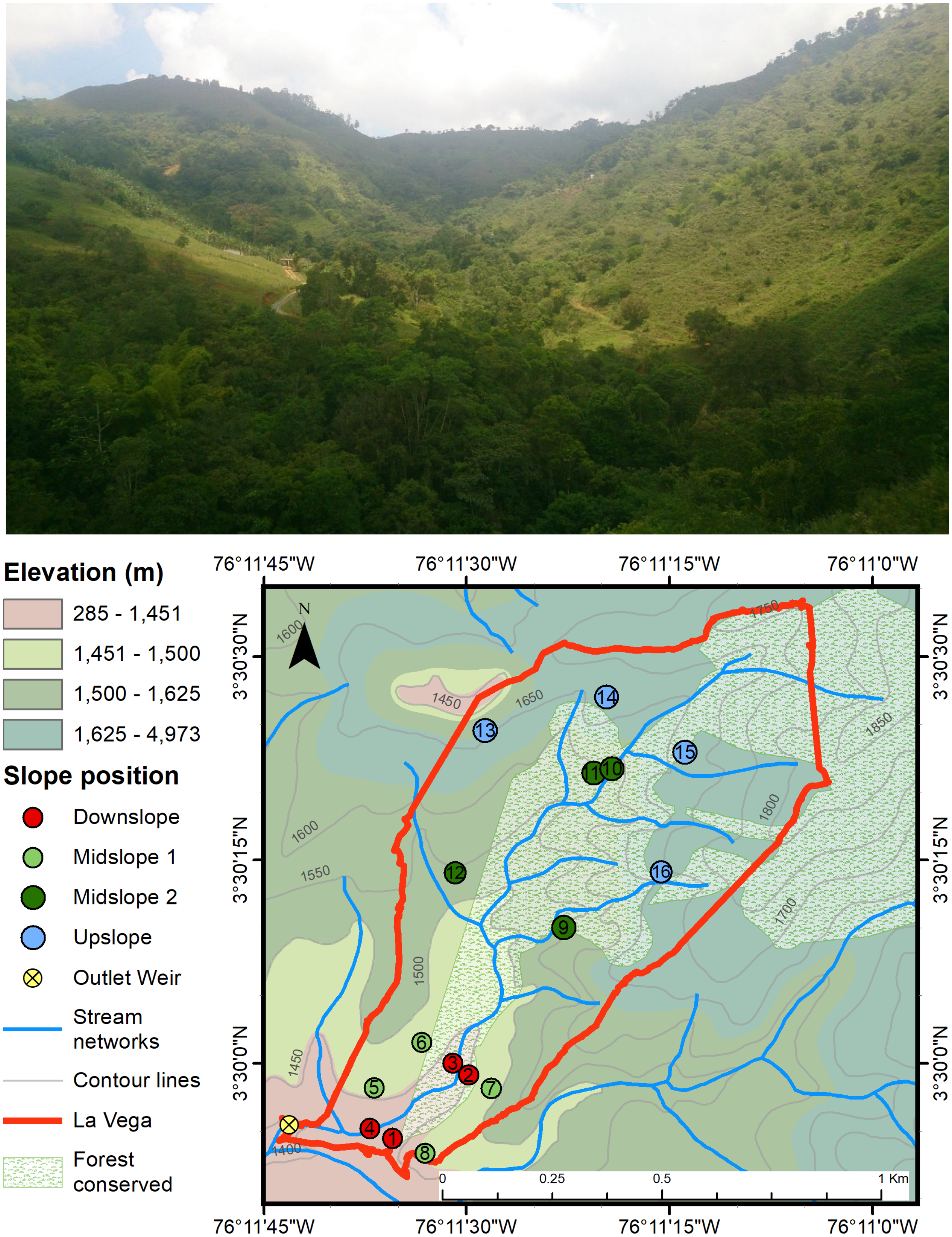


Figure 2: (a) View of La Vega sub-watershed facing northeastward and (b) map illustrating indications for piezometer locations and soil sampling transects (blue= upslope; dark green = midslope 2; light green = midslope 1; downslope = red; total of 16). Outlet weir symbol indicates watershed hydrological monitoring station.

Figure 3. Photos of (a) pvc-monitoring wells, (b) installation with auger, and (c) soil profile to rock layer.

Figure 4. Photos of (a) upland disturbed composite soil samples at 30 cm depths with rocks (point 16) in the upper part of the watershed and (b)disturbed composite soil sample at 30 cm depth with high clay content (point 4) in the downslope part of the watershed.

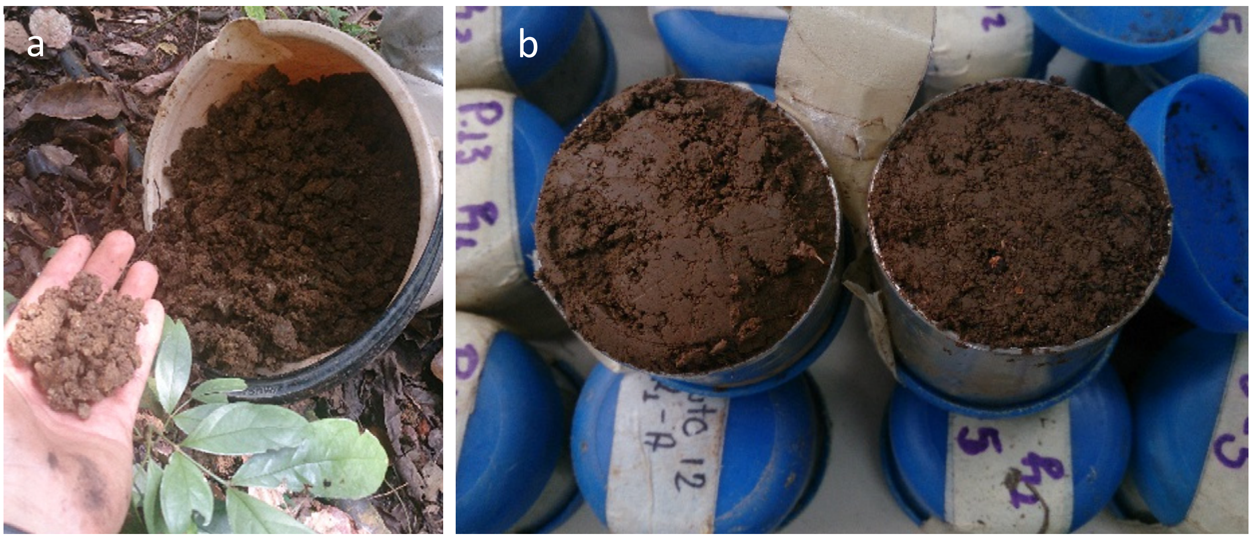


Figure 5. (a) Composite soil sample at each point and (b) fixed volume un-disturbed soil samples in 5 cm-diameter metallic cylinders

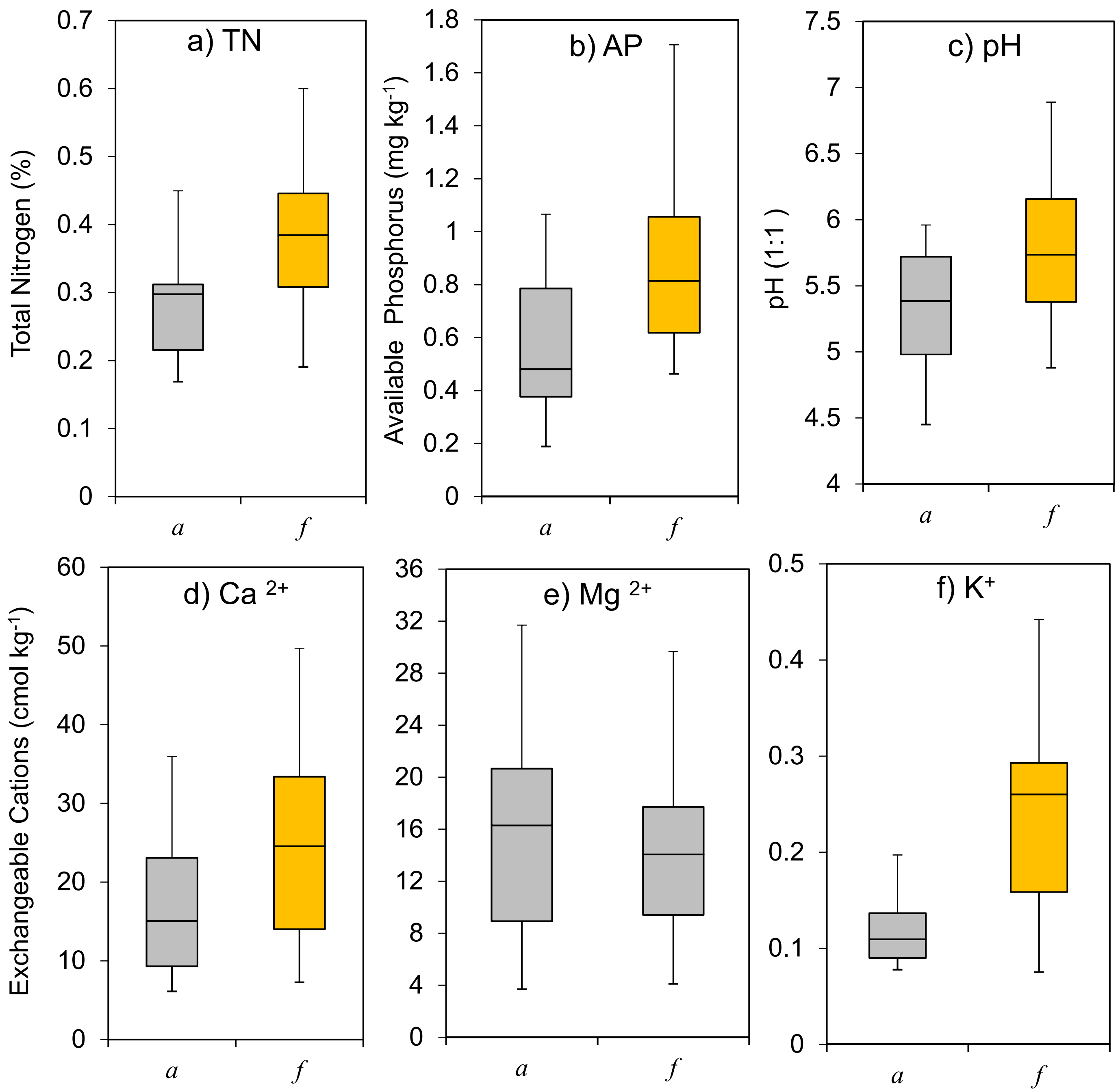


Figure 6. Boxplots of soil properties in forested regions (subscript "*f*", e.g. TN_f) and actively used altered regions (subscript "*a*", e.g. TN_a) for (a) total nitrogen (TN), (b) available phosphorus (AP), (c) soil acidity (pH), (d) calcium (Ca^{2+}), (e) magnesium (Mg^{2+}), and (f) potassium (K+). Yellow shading indicates a statistically significant difference ($p<0.05$) between land use types.

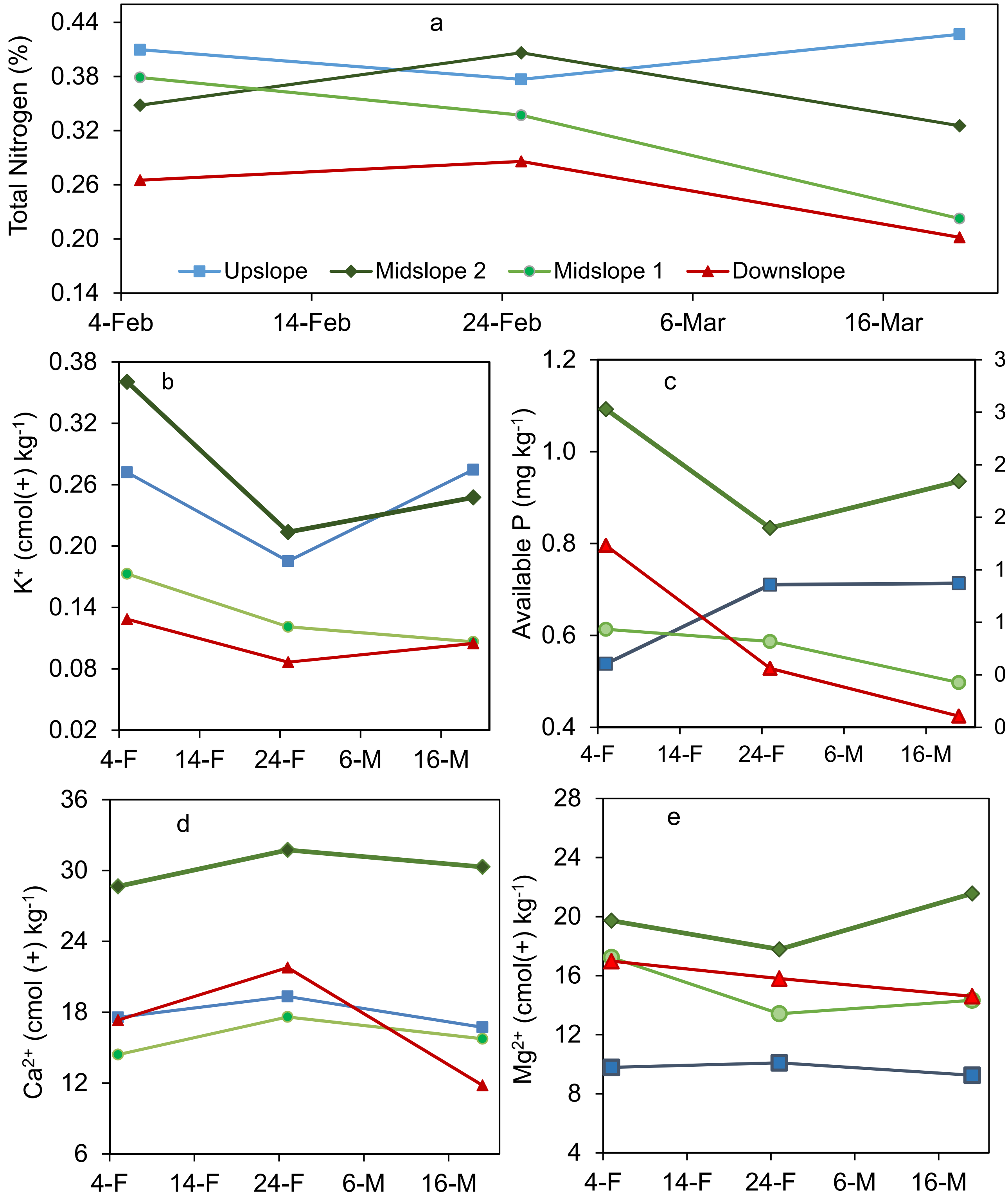


Figure 7. Measurement of soil nutrient parameters for (a) total nitrogen (TN), (b) potassium (K+), (c) available phosphorus (AP), (d) calcium (Ca^{2+}), (e) magnesium (Mg^{2+}) from samples taken on 5-Feb (F), 25-Feb (F), and 20-Mar (M) of 2015. Midslope 2 for AP is plotted on the secondary y-axis. Trends are only significant for decreases in TN ($p<0.05$) and K^+ ($p<0.05$) in midslope 1 regions and near significant for decreases in the downslope region (p=0.053).

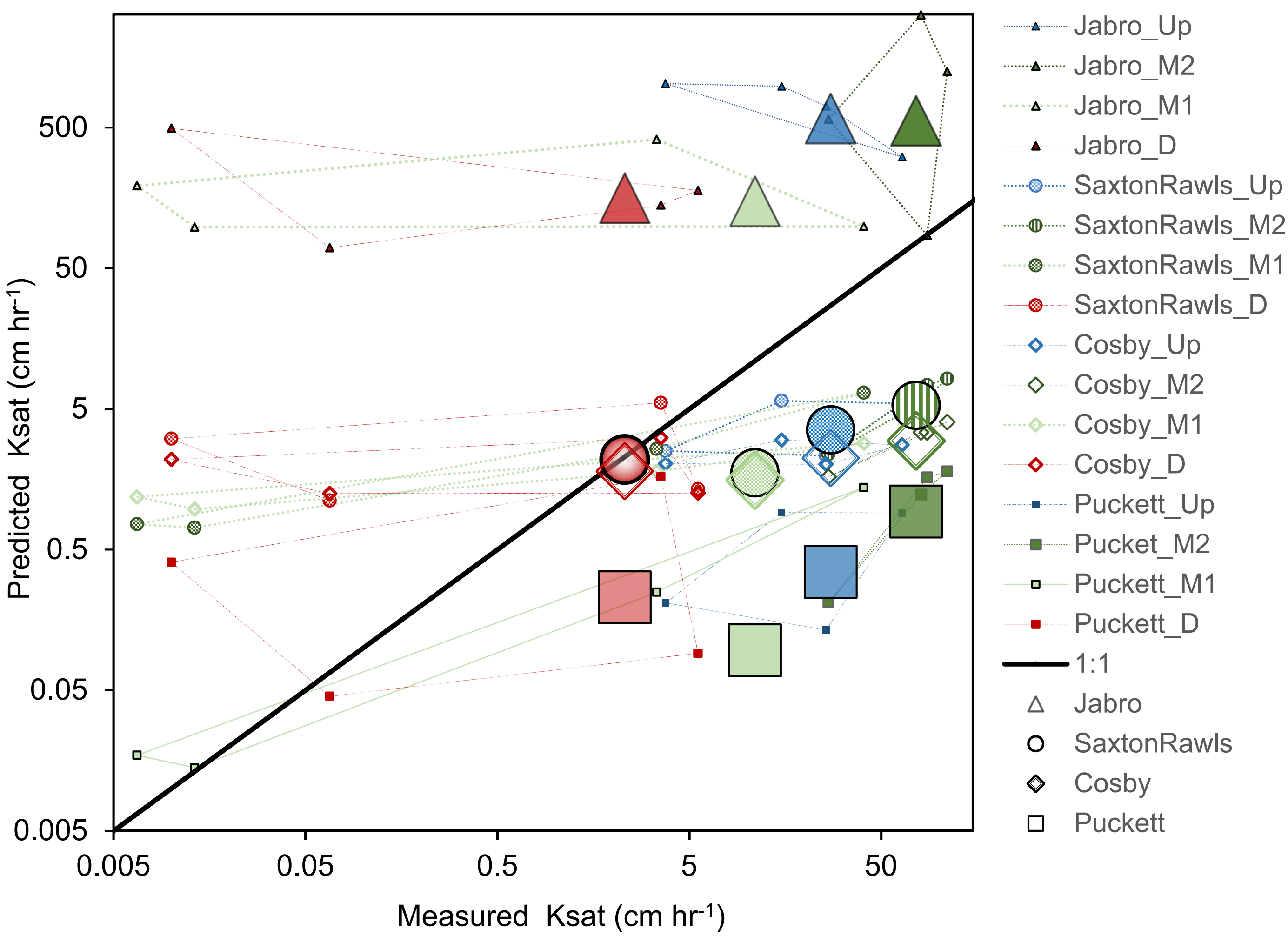


Figure 8. Pedotransfer functions by Cosby et al. (1984), Puckett et al. (1985), Jabro (1992), Saxton and Rawls (2006), and their predicted values based on the measured soil texture percentages, bulk density, and organic matter.

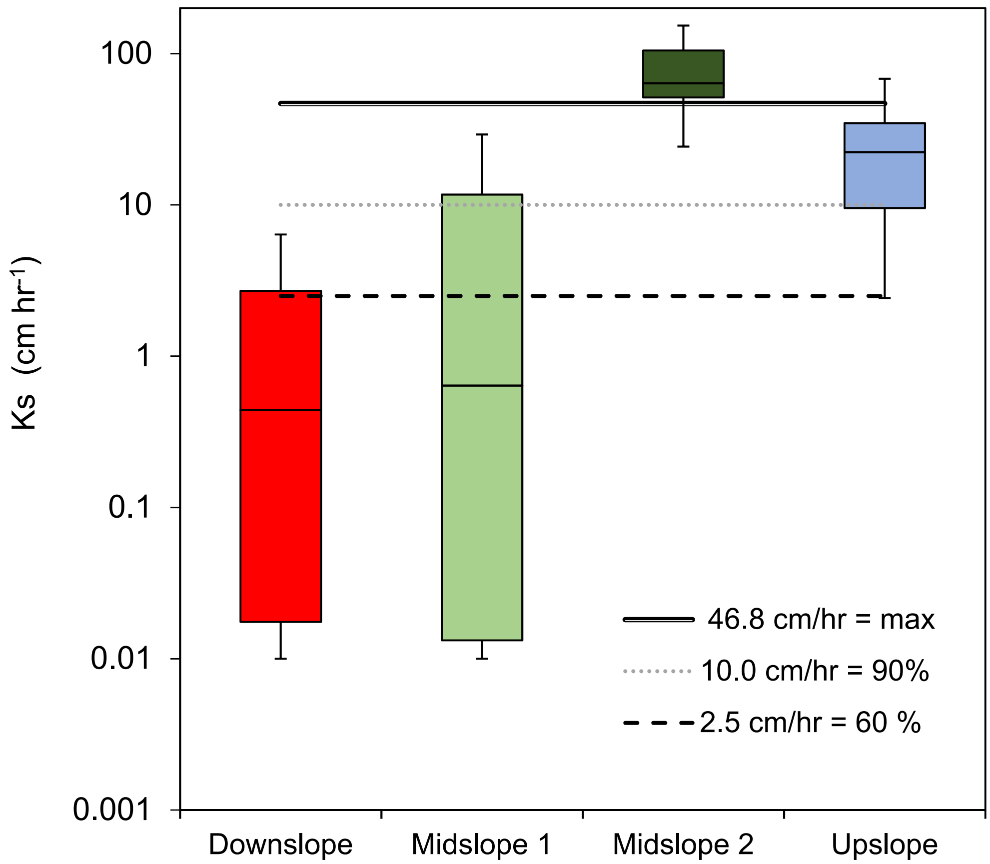
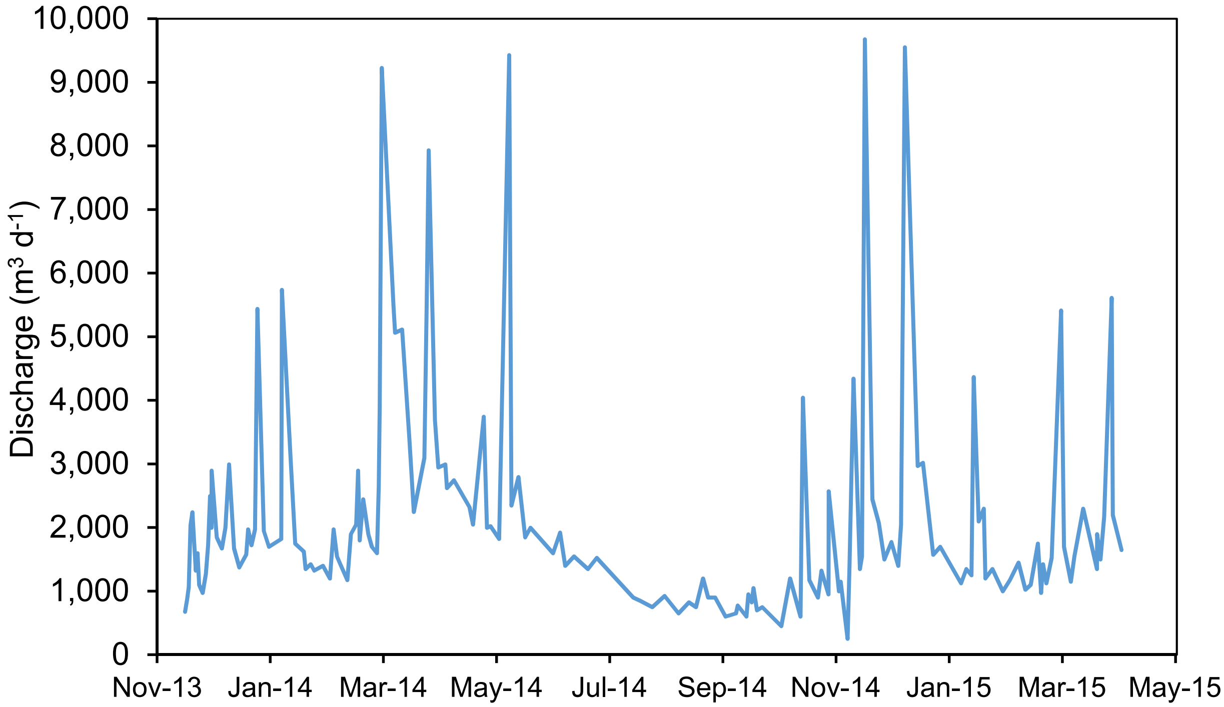
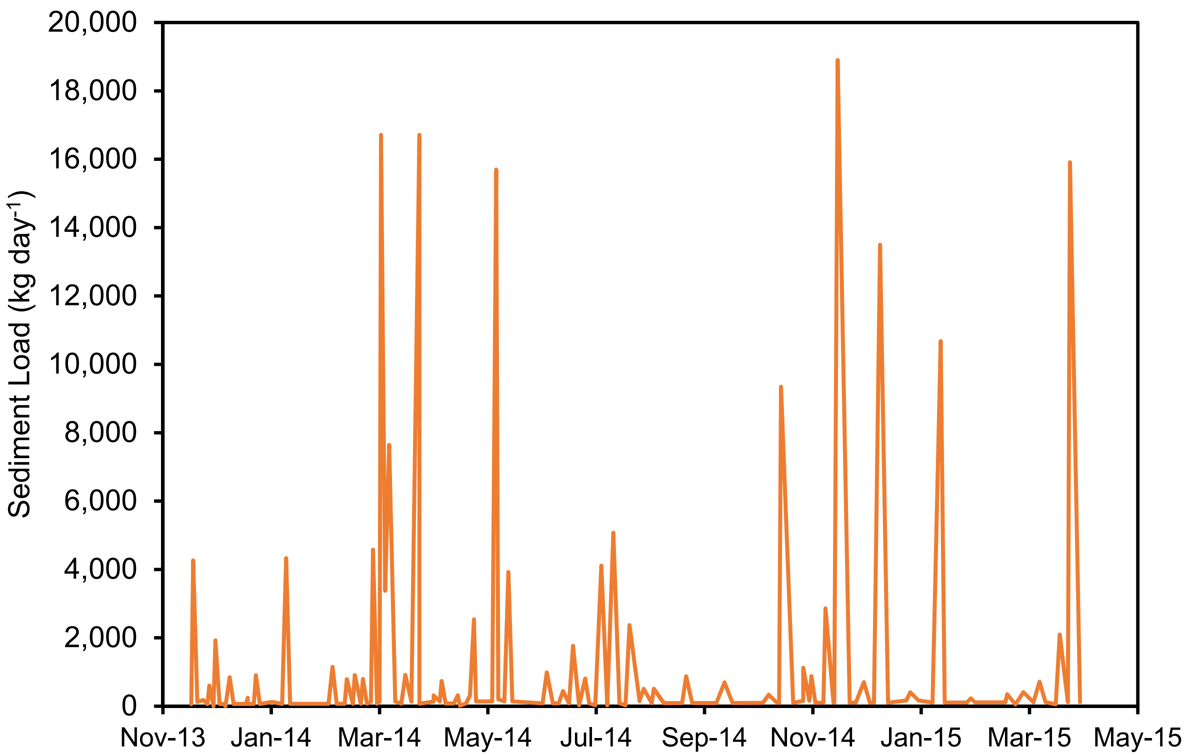


Figure 9. Boxplot of the saturated hydraulic conductivity measurements for two depths (0 – 5 cm, 5 – 10 cm) at different elevation ranges (red = Downslope, light green = Midslope 1, dark green = Midslope 2, blue = Upslope). Thresholds showing precipitation intensity rates (cm hr^{-1}) as measured by Sonder (2004) indicate percentage of storms below listed intensities.



Supplementary Figure S1. Streamflow at the La Vega Subwatershed recorded from November 2013 to April 2015 (digitized from Hoyos-Villada et al., 2016).



Supplementary Figure S2. Sediment load measured at the outlet of the La Vega Subwatershed recorded from November 2013 to April 2015 (digitized from Hoyos-Villada et al., 2016).

Supplementary Materials S3. Equations from Saxton and Rawls (2006)

S1a.) $\theta_{33} = \theta_{33a} + 1.283 \times (\theta_{33a})^2 - 0.374 \times (\theta_{33a}) - 015$

S1b.) $\theta_{33a} = -0.251 \times Sa + 0.195 \times Cl + 0.011 \times OM + 0.006 \times Sa \times OM$
$- 0.027 \times Cl \times OM + 0.452 \times Sa \times Cl + 0.299$

S2a.) $\theta_{1500} = \theta_{1500a} + (0.14 \times \theta_{1500a} - 0.02)$

S2b.) $\theta_{1500a} = -0.024 \times Sa + 0.487 \times Cl + 0.006 \times OM + 0.005 \times Sa \times OM$
$- 0.013 \times Cl \times OM + 0.068 \times Sa \times Cl + 0.031$

S3a.) $\theta_{S\text{-}33} = \theta_{(S\text{-}33)t} + (0.636 \times \theta_{(S\text{-}33)t} - 0.107)$

S3b.) $\theta_{(S\text{-}33)t} = 0.278 \times Sa + 0.034 \times Cl + 0.022 \times OM - 0.018 \times Sa \times OM$
$- 0.027 \times Cl \times OM - 0.584 \times Sa \times Cl + 0.078$

S4.) $\theta_s = \theta_{33} + \theta_{(S\text{-}33)} - 0.097S + 0.043$

S5) $B = [\ln(1500) - \ln(33)] / [\ln(\theta_{33}) - \ln(\theta_{1500})]$

S6) $\boldsymbol{\lambda} = 1/B$

θ_{33} is field capacity (33 kPa); θ_{1500} permanent wilting point (1500 kPa); θ_s saturated moisture content (0 kPa); $\theta_{s\text{-}33}$ is the soil moisture content from 0-33 kPa.