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Spatial prediction of soil water retention in a Páramo landscape: Methodological insight into machine learning using random forest

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ABSTRACT

Soils of Páramo ecosystems regulate the water supply to many Andean populations. In spite of being a necessary input to distributed hydrological models, regionalized soil water retention data from these areas are currently not available. The investigated catchment of the Quinuas River has a size of about 90 km^2 and comprises parts of the Cajas National Park in southern Ecuador. It is dominated by soils with high organic carbon contents, which display characteristics of volcanic influence. Besides providing spatial predictions of soil water retention at the catchment scale, the study presents a detailed methodological insight to model setup and validation of the underlying machine learning approach with random forest. The developed models performed well predicting volumetric water contents between 0.55 and 0.9 $cm^3\,cm^{-3}$. Among the predictors derived from a digital elevation model and a Landsat image, altitude and several vegetation indices provided the most information content. The regionalized maps show particularly low water retention values in the lower Quinuas valley, which go along with high prediction uncertainties. Due to the small size of the dataset, mineral soils could not be separated from organic soils, leading to a high prediction uncertainty in the lower part of the valley, where the soils are influenced by anthropogenic land use.

1. Introduction

Páramo ecosystems are found between 11°N to 8°S in the South American Andes, forming a discontinuous belt between Venezuela and northern Peru (Arroyo et al., 2013; Buytaert et al., 2006a). They are providing water-related ecosystem services to Andean communities (Asbjornsen et al., 2017; Viviroli et al., 2007) and are referred to as sentinels for climate change (Dangles et al., 2017). Páramo soils are identified as one of the most important biophysical components in order to maintain hydrological services and understand the ecohydrological functioning of the system (Mosquera et al., 2015; Schneider et al., 2016).

The soils which are described as volcanic ash soils with high organic matter contents (Buytaert et al., 2007) have commonly high water retention values (Buytaert et al., 2006a). Information regarding the spatial heterogeneity of these soils' water retention curves (WRC) in the form of high-resolution maps, including uncertainty estimates, is necessary for understanding, modeling, and management of these ecosystems (e.g. Horta et al., 2014).

The WRC describes the volumetric soil water content (θ) at equilibrium at different matric potentials (from here on, reported as the logarithm of the height of the water column, pF). It is related to the size and connectedness of pore spaces, soil structure, and texture, and to the soil's composition (e.g. organic matter content, soil minerals) (Rezanezhad et al., 2016; Tuller and Or, 2005). Knowledge of the WRC is necessary to characterize the distribution and transport of water in soils, which are both required for hydrological modeling.

Several methods that spatially interpolate and/or extrapolate from point measurements are commonly applied. Most of the studies, that regionalized soil data, focus on either of three approaches (Herbst and Diekkru, 2006): regression approaches including multiple linear regression as well as machine learning algorithms (e.g. Hengl et al., 2017; Ließ et al., 2016), geostatistical approaches (e.g. Goulard and Voltz, 1993; Sinowski et al., 1997; Voltz and Goulard, 1994), and hybrid approaches (e.g. Haghverdi et al., 2015; Herbst and Diekkru, 2006).

In the case of the WRC, the regionalized variables are either single retention values of the curve (e.g. at field capacity and permanent wilting point, as in Haghverdi et al., 2015) or parameters of functions used to describe the WRC (e.g. in Yang et al., 2015), like the van Genuchten, Brooks-Corey or Campbell water retention functions (e.g.

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Khlosi et al., 2008; Too et al., 2014). An advantage of the latter is that the employed function - and its predicted parameter values - can easily be incorporated into simulation models (Wösten et al., 2001). Specific functions have been successful for certain parts of the WRC, certain soil types or regions of the world, but none of them is universal (Botula et al., 2014; Too et al., 2014). With the available information, the selection of the appropriate function is at present largely determined by convenience of the researcher (Too et al., 2014) and, therefore, represents itself a problem that is out of the scope of this study.

The objectives of this study are to present new water retention data of Páramo soils and to set up a model to regionalize point measurements of the WRC at common pF values at the catchment scale using the random forest algorithm (Breiman, 2001). In digital soil mapping it has been used for manifold applications regarding different soil properties (Grimm et al., 2008; Guo et al., 2015; Hengl et al., 2015; Ließ et al., 2016; Wiesmeier et al., 2011). Whereas, to our knowledge, random forest has not been used to spatially predict the water retention of soils, before. Thus, we take this opportunity to investigate its performance in this regard and to estimate the relative importance of predictor variables, which correlate with hydrological properties of soils (e.g. Thompson et al., 2012). We are not aware of the existence of any other studies that aimed to regionalize the WRC of Páramo soils, before.

2. Methods

2.1. Research area

The Quinuas Catchment (Fig. 1) is located in the western part of the Paute river basin and covers an area of approximately 93 km^2 comprising part of the Cajas National Park. Located at around 2.8°S and 79.2°W between 3000 and 4400 m.a.s.l. (Ließ, 2015), the catchment's conditions match that of the wet Páramo ecosystem (Arroyo et al., 2013; Hofstede et al., 2003).

Due to its location in an inner Andean valley close to the Equator and due to the relatively narrow transversal section of the Andes at these latitudes, the climate of the catchment is influenced by air masses coming from both the Pacific ocean and the Amazon basin (Buytaert et al., 2006b; Celleri et al., 2007). Mean annual temperature in the catchment varies between 5.3 and 8.7 °C without seasonality, while total solar radiation, wind speed, and rainfall vary seasonally (Carrillo-Rojas et al., 2016; Córdova et al., 2016). Mean annual precipitation ranges from 900 to 1600 mm between 2980 and 4100 m.a.s.l. (Crespo et al., 2011); year-round drizzle, accounts for 29% of the total annual rainfall amount (Padrón et al., 2015). Rainfall is characterized by a bimodal pattern with one early peak March/May, and the other in October (Celleri et al., 2007; Padrón et al., 2015); following the October rainfall peak, increased solar radiation in November leads to a relative decrease of humidity. Because of the humid and cold conditions of the Páramo, along with volcanic ash inputs from the Quaternary volcanic activity (Barberi et al., 1988; Buytaert et al., 2007), low density, porous soils rich in organic material developed across the Paute basin (Buytaert et al., 2007; Poulenard et al., 2003). The soils have a high water storage capacity and a high saturated hydraulic conductivity (Buytaert et al., 2006c). The prevailing vegetation in the catchment is tussock grass (*Calamagrostis* sp. and *Festuca sp.*), which is present in > 70% of the area and coexists with cushion plants (e.g. *Plantago sp., Valeriana* sp. and *Gentian sp.*), small forest patches of *Polylepis* sp. and *Gynoxis* sp. and low shrubs like *Weinnmannia sp.* (Carrillo-Rojas et al., 2016). The occurrence of cushion plants increases above 4000 m.a.s.l. (Sklenář and Jørgensen, 1999).

2.2. Dataset

2.2.1. Soil data

Undisturbed soil samples were collected with 100 cm^3 steel cores of 4 cm height during a field campaign in 2014. The sampling design, explained in detail by Ließ (2015), was based on the following tenets: 1) stratified random sampling according to landscape characteristics and 2) accessibility of the area and sampling costs, while following the concept that similar landscape positions carry similar soils with similar soil properties. We used the "QC-arLUS" sampling design among the four suggested designs in Ließ (2015) but sampled only two of the selected points in each landscape unit due to the time-consuming laboratory work in determining water retention curves. This resulted into 48 sampling locations. Samples were taken at 7 cm depth from the surface (steel core sample from 5 to 9 cm) to avoid the root felt.

θ at pF 0, 0.5, 1.5 and 2.5 was measured by placing the water

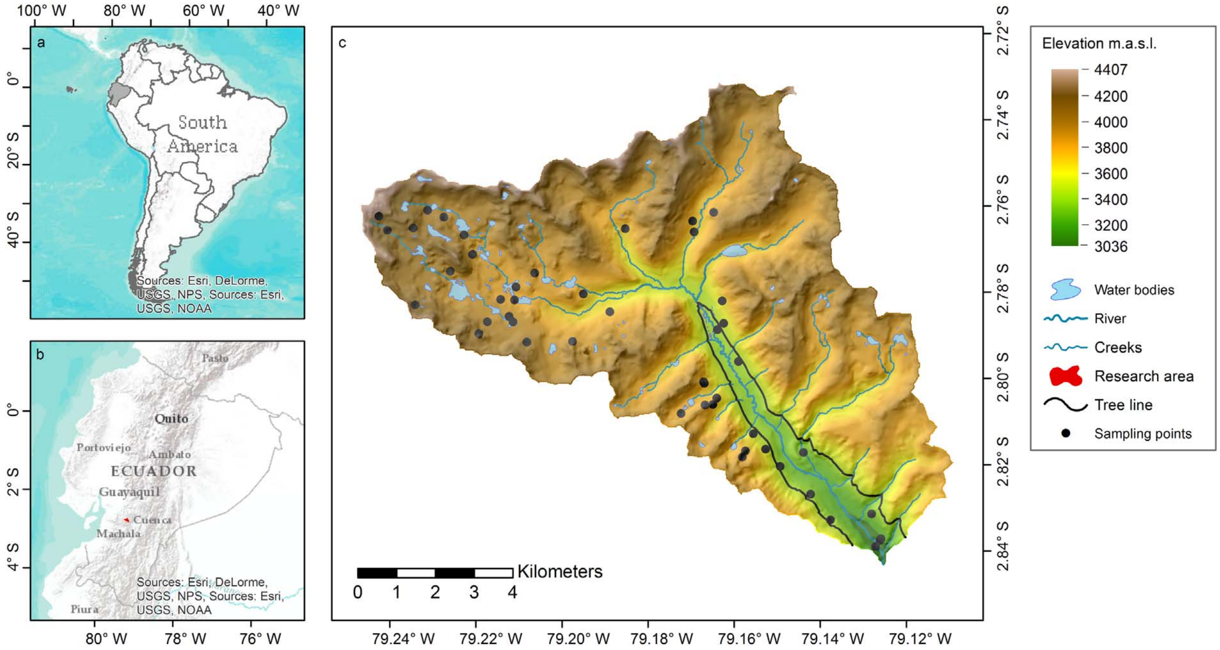

Fig. 1. Research area and sampling locations. a) Ecuador in South America, b) Research area within Ecuador, c) Location of sampling points within the research area (Overlaid hillshading with light source from North-West). Topographical data use with permission from the Ecuadorian Geographical Institute (2013, national base, scale 1:50.000).

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