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Tropical Montane Cloud Forests in the Orinoco river basin: The role of soil organic layers in water storage and release

Beatriz H. Ramírez [a,b,*], Martine van der Ploeg [c], Adriaan J. Teuling [d], Laurens Ganzeveld [e], Rik Leemans [f]

[a] Water Systems and Global Change Group, Wageningen University & Research, Netherlands
[b] Centro de Estudios Ambientales de la Orinoquia, Asociación de Becarios de Casanare, Colombia
[c] Soil Physics and Land Management Group, Wageningen University & Research, Netherlands
[d] Hydrology and Quantitative Water Management Group, Wageningen University & Research, Netherlands
[e] Meteorology and Air Quality Group, Wageningen University & Research, Netherlands
[f] Environmental Systems Analysis Group, Wageningen University & Research, Netherlands

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ABSTRACT

The Tropical Montane Cloud Forest (TMCF) is a hydrologically unique and highly vulnerable ecosystem to changes in land-use and climate. Assessing the impacts of these changes needs to consider soil-water dynamics. In particular, the organic layer and its functioning requires attention because its difference in water retention characteristics and root density compared to the underlying mineral soils. A higher root density and a higher water storage capacity of the organic layer compared to the mineral soils suggests that most nutrient and water uptake occurs in this layer. However, hydraulic properties of mineral soils and their impact on hydrology of TMCFs have been poorly studied. Here we provide organic layer water retention curves for TMCF soils that were measured in the laboratory. With these data we assessed the potential land-use and climate change impacts on TMCF soil moisture dynamics. From the land-use change perspective, we estimated the water storage capacity loss by slash-and-burn deforestation practices. These estimates show that the storage loss ranges from 35 to 59 mm when TMCFs are converted to pastures. This is several times higher than the estimated TMCF canopy storage capacity (2 to 5 mm). Therefore, the higher peak flow observations in deforested catchments might not only be explained by a decreasing canopy water storage but also likely due to a decreasing soil water storage. From the climate change perspective, we evaluated the effect of contrasting dry season conditions on soil moisture and transpiration using a 1-D water-flow model, and assessed the sensitivity of these hydrological variables to uncertainties in saturated hydraulic conductivity. Although transpiration was not limited by soil moisture during the mild dry season, it was affected during the severe dry season and continued to decline under expected climate change with the prolongation of dry spells. Our results show that the organic layer is a key element in TMCF's hydrological functioning and call for an increased focus on the role of organic soils when evaluating effects of land-use change.

1. Introduction

Understanding the consequences of changes in land-use and climate for hydrologic processes is a major scientific challenge (DeFries and Eshleman, 2004; Hooke and Martín-Duque, 2012; Wagener et al., 2010). The implications of these changes on the water cycle and ultimately water availability at variable spatial and temporal scales are subject to much debate and research (e.g. Bonell, 2010; Ellison et al., 2012). From an ecological perspective, native vegetation which is a unique species assemblage, is well adapted to site-specific water, nutrient and energy availability (Knapp et al., 2008; Reichstein et al., 2014). Simultaneously, this vegetation dynamically controls water fluxes between the atmosphere and the soil (Rodriguez-Iturbe, 2000). Both vegetation and its hydrology are affected in the short and the long-term by changes in land-use and climate. The initial short-term hydrological land-use change impacts are caused by structural and physical modifications of vegetation and soils (Zhao et al., 2012), while the long-term impacts depend on a new equilibrium between the interacting soils, the modified land covers and the atmosphere (Brown et al., 2005). Climate change alters the water-energy balances and plant-water processes and these eventually cause shifts in species composition (Beniston, 2003; Eller et al., 2015; Walther et al., 2002). In order for land-use and water resource management plans to be sustainable, these plans have to consider land-use change and climate change impacts.

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* Corresponding author at: Water Systems and Global Change Group, Wageningen University & Research, Lumen Building 100, Droevendaalsesteeg 3, 6708PB Wageningen, Netherlands.
E-mail address: dir.biodiversidad@abccolombia.org (B.H. Ramírez).

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Tropical Montane Cloud Forest (TMCF) is a hydrologically unique but highly vulnerable ecosystem to both climate and land-use changes (Scatena et al., 2011). TMCF's hydrology is tightly linked to the occurrence of fog and its effect on: 1) reducing evapotranspiration (Eller et al., 2015; Letts and Mulligan, 2005; Reinhardt and Smith, 2008), 2) adding a source of water to the system through fog interception (Zadroga, 1981), and 3) enabling foliar water uptake (Eller et al., 2013; Gotsch et al., 2014). Therefore, an increase in cloud- base altitude (Still et al., 1999) and in the frequency of extreme dry events (Magrin et al., 2014) due to climate change could severely affect TMCF's hydrology. Oliveira et al. (2014) showed that TMCF species are vulnerable to atmospheric drought due to hydraulic failure. However, seasonal TMCF's soil moisture dynamics and the potential impacts on root water uptake by soil moisture deficits are poorly understood. TMCFs can be found on various soil types (Roman et al., 2011), but regardless of the soil type they often have thick top organic soil horizons that can be >1 m deep. These layers consist of decomposing organic material with a dense fine root network (Hafkenscheid, 2000; Tanner et al., 1998). Root density is typically higher in this organic horizon than in the underlying mineral horizon, indicating that most of the water and nutrient uptake occurs in this layer (Leuschner et al., 2006). Therefore, understanding the organic layer's hydrological dynamics is important to assess potential climate-change impacts on TMCFs.

In addition to climate-change impacts, land-use change also poses a major threat as more than half of TMCFs world-wide were converted to other land use types by the year 2000 (Mulligan, 2011). Studies assessing the deforestation impact on the rainfall-streamflow responses in TMCF catchments, have shown higher peak flows in deforested catchments (e.g. Muñoz-Villers and McDonnell, 2013; Roa-García et al., 2011). These increases are generally attributed to a reduced rainfall canopy interception and reduced infiltration rates in grasslands compared to TMCFs. However, the impact of the loss of the organic during and after deforestation has not been considered yet. After deforestation, the organic layer and its water storage capacity are irreversibly lost. This occurs rapidly in areas, like the Andes, where slash-and-burn practices are common (Lambin et al., 2001). Data on the water storage capacity of these organic layers have only been established in Jamaican TMCF (Kapos and Tanner, 1985).

Organic layers have high water retention capacities (Yang et al., 2014) and likely are the major source for transpiration. Transpiration and wet canopy evaporation tend to equally contribute to the total evaporative water loss in TMCFs (Bruijnzeel et al., 2011). Water uptake in the root zone area implies that the organic layer acts as a highly dynamic systemic water storage component. The organic layers generally also present high infiltration rates that reduce runoff (Hartanto et al., 2003). Yet, infiltration rates are governed by the saturated hydraulic conductivity (K^*), which is a strongly scale-dependent variable (Hu et al., 2012), especially in organic soils (Van der Ploeg et al., 2012). Additionally, K^* depends on its quantification method (Fodor et al., 2011; Schellekens et al., 2004). This means that K^* variability needs to be considered when evaluating the organic layer's role in TMCF soil moisture dynamics. The vegetation's water use is constrained by the soil plant available water (PAW), the amount of water that plants can extract from the soil column to fulfil evapotranspiration demands. PAW is estimated by the difference between the water content at field capacity (θFC) and at wilting point (θWP) (Dunne and Willmott, 1996) over the root zone. θFC and θWP are defined from water retention curves (WRC) and to estimate the WRC from soil texture by using pedo-transfer functions is well possible because large data sets are available for mineral soils (Minasny and Hartemink, 2011; Wösten et al., 2001). However, K^* values can be underestimated due to preferential flows caused by gravel content in the soils and biological activity (Beckers et al., 2016; Bogner et al., 2008; Ravina and Magier, 1984). In contrast, such pedo-transfer functions cannot be used to estimate the organic layer's WRC because these layers consist of decomposing organic material that lack mineral soil particles. Hence, to evaluate climate and land-use change impacts on TMCFs we need to obtain data on the WRC of organic layers and improve our understanding on TMCF's soil moisture dynamics.

Our study area, located in the northern eastern Andes (Colombia) provides a unique opportunity to evaluate land-use and climate change impacts on TMCFs. First, it comprises three neighbouring catchments with contrasting TMCF covers. The catchment with larger grassland extents generates stronger wet season rainfall-streamflow responses. This likely reflects a reduction in its water storage capacity. Second, our observations show that during the dry season rainfall at the low elevation (1554 m asl) was lower (2.7 mm d^{-1}) than at the high elevation (2048 m asl: 6.5 mm d^{-1}), suggesting that dry season rainfall at the higher elevation is very important in sustaining high soil moisture levels and streamflow. Therefore extreme dry seasons could potentially lead to soil moisture deficits.

The characteristics of our study area enabled us to pursue the following objectives: 1) quantify the loss of water storage due to organic layer removal and 2) evaluate seasonal TMCF's soil moisture dynamics under observed and hypothetical extreme dry seasons. We measured the organic layers' WRC in the laboratory from core samples and inferred the mineral layer WRC from their soil texture. We also measured in the field the organic layers' K^*. To achieve the first objective we determined the organic layer PAW and its water storage capacity. We then estimated the total water storage loss in a per catchment basis based on the extent of their deforested areas. To achieve the second research objective we analysed soil moisture data and parameterized the Hydrus1D water-flow model (Šimůnek et al., 2013) to simulate soil moisture dynamics under several observed contrasting dry seasons, including one influenced by the record 2015 El Niño (Jiménez-Muñoz et al., 2016), and under a hypothetical longer dry season. We also assessed the sensitivity of these hydrological parameters to uncertainties in K^*.

2. Methods

2.1. Study area

The three neighbouring catchments that we studied are located on the eastern slope of the eastern Andean Cordillera (Fig. 1) at the municipality of Chámeza (Colombia). These catchments are fourth-order tributaries of the Orinoco River, and have different forest cover percentages: a deforested catchment (DEF) with 71% forest cover; an intermediate catchment (INT) with 84% forest cover; and a forested catchment (FOR) with 99% forest cover. Table 1 provides an overview of the catchments and their main characteristics.

The eastern Andes are dominated by young mountains with steep slopes and sharp summits (Stallard et al., 1991). Our study area is located on two formations belonging to the Caqueza Group of Cretaceous origin: Las Juntas formation and Macanal formation (IGAC, 2014). The Las Juntas formation consists of black shales and sandstones, and the Macanal formation consists of black shales and siltstones (Mejía, 2008). Soils at the study area are classified following USDA (2010) into two associations: Typic dystrudepts-Typic udorthents (Entisol) and Lithic udorthent (Entisol)-Typic dystrudept (Inceptisol) (IGAC, 2014). Lithic refers to shallow soils (<50 cm of depth) limited by bedrock contact (USDA, 2010). Inceptisols and Entisols generally undergo weak or very weak soil formation processes, respectively (Bockheim and Gennadiyev, 2000). The study area's current land cover consists of mature and old growth secondary forests (>10 yr) and grasslands (Table 1). Most forests in the region are subjected to selective logging. Slash-and-burn is the common local technique to transform these forests, first into annual crops and then into permanent grasslands (Lambin et al., 2001).

Climate data from April 2014 to April 2016 showed a mean daily temperature of 16.5 °C and 14.5 °C at 1850 m asl and at 2048 m asl respectively. Mean annual rainfall ranged between 4283 mm at 1550 m