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Water balances of old-growth and regenerating montane cloud forests in central Veracruz, Mexico

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SUMMARY

This paper compares the water budgets of two adjacent micro-catchments covered by mature (MAT) and 20-year-old secondary (SEC) lower montane cloud forests, respectively, in central Veracruz, Mexico over a 2-year period. Rainfall (*P*) and streamflow (*Q*) were measured continuously, whereas dry canopy evaporation (transpiration E_t), wet canopy evaporation (rainfall interception *I*), and cloud water interception (*CWI*) were quantified using a combination of field measurements and modeling. Mean annual *P* was 3467 mm, of which typically 80% fell during the wet season (May–October). Fog interception occurred exclusively during the dry season (November–April), and was ⩽2% of annual *P* for both forests. Rainfall interception loss was dominated by post-event evaporation of intercepted water rather than by within-event evaporation. Therefore, the higher overall *I* (i.e. including *CWI*) by the MAT (16% of *P* vs. 8% for the SEC) reflects a higher canopy storage capacity, related in turn to higher leaf area index and greater epiphyte biomass. Annual E_t totals derived from sapflow measurements were nearly equal for the MAT and SEC (~790 mm each). Total annual water yield calculated as *P* minus (E_t + *I*) was somewhat higher for the SEC (2441 mm) than for the MAT (2077 mm), and mainly reflects the difference in *I*. Mean annual *Q* was also higher for the SEC (1527 mm) than for the MAT (1338 mm), and consisted mostly of baseflow (~90%). Baseflow recession rates were nearly equal between the two forests, as were stormflow coefficients (4% and 5% for MAT and SEC, respectively). The very low runoff response to rainfall is attributed to the high infiltration and water retention capacities of the volcanic soils throughout the ~2 m deep profile. The water budget results indicate that ~875 and 700 mm year^{-1} leave the SEC and MAT as deep groundwater leakage, which is considered plausible given the fractured geology in the study area. It is concluded that 20 years of natural regeneration following cloud forest disturbance in central-eastern Mexico is capable of producing near-original hydrological behavior.

1. Introduction

Although tropical montane cloud forests (TMCF) cover only 1.4% (215,000 km^2) of the world's tropical forests (Scatena et al., 2010), their location in mountain regions exposed to frequent fog and high rainfall, together with the associated low evaporative losses, typically results in much higher water yields compared to non-cloud-affected forests (Zadroga, 1981; Bruijnzeel, 2001). However, much of the original TMCF have disappeared, and many of the remaining cloud forests are threatened by local and regional climatic warming effects such as a rising cloud base or reduced overall cloud incidence (Still et al., 1999; Lawton et al., 2001; Karmalkar et al., 2008; Mulligan, 2010).

Knowledge of TMCF hydrological functioning has increased considerably in the last 15 years (recently summarized by Bruijnzeel et al., 2010), with most published work focusing on single processes, mostly rainfall and cloud water interception and, to a lesser extent, evaporation. However, studies of the impact of TMCF conversion to pasture or cropping, or of cloud forest regeneration on streamflow are almost non-existent (Bruijnzeel, 2005, 2006; cf. Ingwersen, 1985).

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The effect of cloud forest conversion or regrowth on water yield is likely to reflect a trade-off between the loss of the extra water formerly gained via cloud water interception and the difference in water use (rainfall interception plus transpiration) between the old and new vegetation (Zadroga, 1981; Ingwersen, 1985; Bruijnzeel, 2005). A possible negative effect on streamflow is likely to be most pronounced during the dry season, when inputs of cloud water are typically of greater importance (Harr, 1982; Holder, 2003; Garcia-Santos, 2007). The effect may be further enhanced by advanced degeneration of the soil's infiltration capacity after forest clearing due to compaction by cattle or machinery. Under such conditions, recharge of soil and groundwater reserves during the rainy season may become impaired to the extent that dry season flows are reduced (Bruijnzeel, 2004).

To date, only two studies have addressed these questions in some detail. According to Ingwersen (1985), partial clearing of Douglas fir forest in the Pacific Northwest of the US, an area subject to heavy fog incidence (Harr, 1982), caused a temporary decrease in baseflows during the dry summer months. Interestingly, the effect gradually disappeared after 5–6 years when the regenerating trees were apparently effective at capturing sufficient amounts of cloud water (Ingwersen, 1985). Conversely, under the very wet conditions prevailing in northern Costa Rica, a process-based modeling approach (Schellekens, 2006) indicated that cloud forest conversion to pasture did not lead to significant decreases or increases in annual and seasonal water yields because the 'loss' of the former fog water input was compensated by lower water use of the pasture (Bruijnzeel, 2006). However, to properly assess the effects of land use and climate change on TMCF hydrology, additional information is required for different cloud forest settings around the world, particularly for areas experiencing a well-developed dry season, as potentially negative impacts might be greatest under these conditions (Ingwersen, 1985; Bruijnzeel, 2005).

Similarly, although secondary forests are currently more widespread than old-growth forests in many tropical environments (Uhl et al., 1988; Xu et al., 1999; Fox et al., 2000), this is not reflected in the volume of hydrological research conducted in regenerating tropical forests (e.g. Fritsch, 1992, 1993; Giambelluca, 2002; Bruijnzeel, 2004; Hölscher et al., 2005). The rate of forest (and soil) recovery after abandonment of pasture or agricultural land is strongly influenced by previous land management (Uhl et al., 1988; Hölscher et al., 2005; Zimmermann et al., 2006; Aide et al., 2010). As such, different stages of cloud forest development reflecting different land use histories may well exhibit different site water balances (cf. Ingwersen, 1985) but, again, information is extremely scarce (cf. Takahashi et al., 2010).

In Mexico, TMCFs cover less than 1% of the country's territory, but they harbor 10% of the country's plant biodiversity (Rzedowski, 1996). Although many have been disturbed or converted to other land uses (mostly pasture, coffee plantations, and agricultural land: Muñoz-Villers and López-Blanco, 2007), the hydrological effects of these changes are essentially unknown. This type of information is urgently needed as the recognition of the value of TMCFs as local providers of high-quality water continues to increase throughout Mexico, as evidenced by a series of nationwide conservation initiatives that have emerged in the last decade (Muñoz-Piña et al., 2008). The present study aims to partly fill this gap in knowledge by quantifying the hydrological effects of montane cloud forest disturbance and regeneration in a seasonally dry setting in central Veracruz State (central-eastern Mexico), using a combination of hydrological (rainfall and cloud water interception, and streamflow dynamics) and ecophysiological (tree water uptake) field measurements and modeling. The central research questions of the investigation were: (1) How does the hydrological behavior of a 20-year-old naturally regenerating cloud forest compare to that of an old-growth cloud forest? (2) What are the key variables controlling the water fluxes in this TMCF ecosystem? and (3) How does the seasonal climate affect the water balances of these forests?

2. Study area

The research was carried out in two adjacent headwater catchments covered by mature (hereafter called MAT; 24.6 ha) and regenerating (hereafter called SEC; 11.9 ha) lower montane cloud forests (LMCF), locally called *bosque mesófilo de montaña* (García-Franco et al., 2008). The micro-catchments are located at 97°02′W and 19°29′N at an average altitude of 2170 m a.s.l. on the eastern (windward) slopes of the Cofre de Perote volcano, and around the La Cortadura Forest Reserve of the municipality of Coatepec (central Veracruz State, Mexico; Fig. 1). The MAT and SEC catchments are part of the 38 km^2 basin of the Los Gavilanes river, which forms the principal water supply for the city of Coatepec and surrounding villages (García-Coll et al., 2004).

Site characteristics are listed in Table 1. The forest catchments have steep slopes and deeply incised valleys; slopes ranging from 20° to 45° cover more than half the area of each catchment (Muñoz-Villers, 2008). The streams draining the catchments are perennial. The volcanic soils were classified as Umbric Andosols (Campos, 2008; FAO-UNESCO, 1997). Deep (~2.5 m) and multi-layered soil profiles characterize the middle and upper portions of the hillslopes, whereas much shallower soils (~0.6 m) are found closer to the streams (Marín-Castro, 2010). The soils are characterized by a silt loam texture, relatively low bulk densities, high porosity, high organic matter content, and high water retention capacity (Geris, 2007; Table 1). The volcanic soils are overlying a semi-permeable, moderately weathered andesitic breccia, underlain, in turn, by weathered and fractured andesitic to basaltic rocks from the Oligocene–Neogene period (D. Geissert personal communication).

According to the Köppen classification modified by Garcia (1988), the climate between 2000 and 3000 m elevation in this region is 'temperate humid with abundant rains during the summer C(m)(w)', with average temperatures and annual rainfall between 12 and 18 °C and 2000 and 3000 mm, respectively. The climate at this latitude is influenced by the trade winds and the subtropical high pressure belt (Metcalfe, 1987). In the northern hemisphere winter, the proximity of the subtropical high leads to stable, dry weather but the occasional passage of cold fronts produces light rains and/or drizzle for 1–3 days per event (Baez et al., 1997). With the northward movement of the Inter-Tropical Convergence Zone in the summer, the region comes under the influence of the easterly trade winds that bring humid conditions with frequent showers and thunderstorms (Baez et al., 1997). Hence, the climate can be divided into two seasons: a relatively dry season (November–April) and a wet season (May–October). A more detailed description of the local weather will be given below.

The MAT forest is a well-conserved, old-growth lower montane cloud forest, with an average canopy height of about 27 m, and emergent trees up to 40 m (García-Franco et al., 2008). The forest is composed of deciduous (*Quercus ocoteoifolia, Quercus corrugata*, *Clethra macrophylla*) and evergreen broadleaf (*Miconia glaberrima*, *Parathesis melanosticta*, and *Alchornea latifolia*) species; the forest is also rich in vascular epiphytes of the family *Bromeliaceae* (García-Franco et al., 2008). The leaf area index (*LAI*) was estimated at 6.3 from measurements of annual leaf litter production and leaf specific area. Approximately half of the SEC forest is dominated by deciduous alder stands (*Alnus jorullensis*), with an average canopy height of about 20 m and an *LAI* of 5.2; this forest regenerated following a wild-fire occurring ~20 years ago (Gómez-Cárdenas, in preparation). Aerial photo analysis showed that the other half of the SEC forest regenerated from pasture land that was abandoned