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Suppression of transpiration due to cloud immersion in a seasonally dry Mexican weeping pine plantation

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ABSTRACT

Cloud immersion affects the water budget of fog-affected forests not only by introducing an additional source of water (via cloud water interception by the canopy), but also by suppressing plant transpiration. The latter effect is often overlooked and not routinely quantified, restricting a complete understanding of the net hydrological effect of cloud immersion and the possible consequences of projected reductions in cloud immersion under drier and warmer climates in tropical montane regions in the coming decades. This paper describes an approach to quantify the suppression of stand-level tree transpiration (E_t) due to cloud immersion using measurements of sapflow, fog occurrence (visibility), leaf wetness, and near-surface climate. Estimates of fog-induced E_t suppression in a 10-year-old *Pinus patula* plantation in the montane cloud belt of central Veracruz, Mexico, are presented for two contrasting dry seasons and a wet season. Fog occurred for 32% of the total study period, although showing pronounced seasonal variation (e.g. 44% during the second dry season). When fog occurred it was accompanied by rainfall during three quarters of the total time. Although the canopy was wet for almost a third of the time, fog-induced canopy wetness constituted only a very small portion of this total (2%). Relative to sunny conditions, E_t was suppressed by $90 \pm 7\%$ under conditions of dense fog versus $83 \pm 7\%$ under light fog and $78 \pm 10\%$ during overcast conditions. Quantification of the potential change in annual E_t associated with two scenarios for future cloud immersion at the study site revealed that: (i) when all fog occurrence is replaced by overcast conditions, mean annual E_t (645 ± 50 mm) is likely to increase by only $2 \pm 1\%$; and (ii) when sunny conditions replace all foggy conditions, the likely increase in annual E_t is $17 \pm 3\%$. As the rise in the regional lifting condensation level is likely to be on the order of only a couple of hundred meters and will probably result in a shift to overcast rather than clear-sky conditions, the present results suggest that the corresponding impact on E_t may be relatively small. Consequently, a climate change-related reduction in dry-season precipitation, through the associated potential reductions in soil water reserves, presents a more worrisome prospect for plant–water relations and water yield from headwater catchments than diminishing cloud immersion alone. The present results highlight the need for better projections of climate change-related alterations in cloud cover and immersion, as well as rainfall patterns for tropical montane regions.

1. Introduction

Frequent immersion in ground-level clouds, or fog, is the defining characteristic of cloud forests, which are widely regarded as biodiversity ‘hot spots’ and ‘water towers’, yet are among the most endangered terrestrial ecosystems in the world (Bruijnzeel et al., 2010; Viviroli et al., 2007). Projected future drier and warmer regional climate in many montane cloud belts world-wide is likely to cause an increase in the lifting condensation level (LCL) (Barradas et al., 2010; Karmalkar et al., 2008; Lawton et al., 2001; Nair et al., 2003; Ray et al., 2006; Richardson et al., 2003; Still et al., 1999; Van der Molen et al., 2006; Williams et al., 2007). This would reduce the frequency of fog occurrence and/or its liquid water content, and might, in turn, impact such vital ecosystem services provided by tropical montane cloud forests, as the stable supply of dry-season baseflows (Brown et al., 1996; Zadroga, 1981; cf. Muñoz-Villers and

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McDonnell, 2013). This rise in LCL has been suggested to be in the order of a few hundred meters in Costa Rica (Karmalkar et al., 2008). Hence, it is likely that many montane cloud belt zones will experience a shift in prevailing conditions from frequent cloud immersion to mostly overcast conditions. It must be noted, however, that there are no reliable projections to date for the trajectory of the LCL and the associated changes in cloud immersion occurrence and frequency under future climate scenarios (Bruijnzeel et al., 2011; Karmalkar et al., 2011; Williams et al., 2007).

Cloud immersion is known to affect the site water budget of a forest ecosystem directly via the capture of cloud water (i.e. fog) by the canopy, producing drip to the forest floor once the canopy's storage capacity is exceeded and increasing soil water availability above that maintained by rainfall alone (Bruijnzeel et al., 2011; Giambelluca and Gerold, 2011). The direct hydrometeorological effect of cloud immersion has attracted most attention (García-Santos and Bruijnzeel, 2011; Giambelluca et al., 2011; Gómez-Peralta et al., 2008; Haeger and Dohrenbusch, 2011; Holder, 2003; Holwerda et al., 2010; Hutley et al., 1997; Ingraham and Matthews, 1988; Juvik et al., 2011; Vogelmann, 1973), but the indirect hydrological effects of foggy conditions produced by the reduction of evaporative demand (through attenuation of incoming solar radiation plus increased atmospheric humidity) and increased canopy wetness, have become acknowledged only comparatively recently. These indirect effects include, firstly, the suppression of transpiration (Burgess and Dawson, 2004; Chu et al., 2012; Johnson and Smith, 2008; Reinhardt and Smith, 2008; Ritter et al., 2009), and, to a lesser extent, foliar absorption of cloud water accumulated on the canopy (Dawson, 1998; cf. Goldsmith, 2013; Gotsch et al., 2013; Limm et al., 2009; Simonin et al., 2009). Such indirect effects may be of greater importance for the water budget of fog-affected ecosystems in places where cloud-induced drip from the canopy contributes less to soil water reserves compared to rainfall (Dawson, 1998; García-Santos, 2007; Hildebrandt et al., 2007). Thus, a substantial reduction in soil water uptake due to cloud immersion may be highly relevant in producing the high streamflow volumes reported to emanate from catchments covered by tropical montane cloud forests (Brown et al., 1996; Bruijnzeel et al., 2011; Muñoz-Villers and McDonnell, 2013; Muñoz-Villers et al., 2012; Zadroga, 1981). Indeed, a growing number of studies have demonstrated that the occurrence of fog in fog-affected forests, including TMCF, results in strong instantaneous reductions of transpiration rates compared to those under sunny conditions (Burgess and Dawson, 2004; Chu et al., 2012; García-Santos, 2012; Hildebrandt et al., 2007; Hutley et al., 1997; Johnson and Smith, 2008; Reinhardt and Smith, 2008; Ritter et al., 2009). However, the associated decreases in seasonal and annual transpiration totals have not been quantified. Moreover, whilst the effect of fog on transpiration is usually evaluated by comparing transpiration under foggy conditions with rates observed during clear-sky conditions (e.g. Ritter et al., 2009), an arguably more realistic evaluation of the influence of diminished cloud immersion would be to compare against overcast conditions, as these are more likely to replace foggy conditions in future (cf. Karmalkar et al., 2008).

The quantification of changes in seasonal transpiration totals is especially relevant in seasonally dry regions experiencing not only changes in climate but also in land-use patterns, such as the expansion of planted forests observed in many fog-affected tropical headwater areas (Carabias et al., 2007; Evans, 1999; FAO, 2010; Muñoz-Villers and López-Blanco, 2008) that supply water to lower-lying towns, agroecosystems and industries (Muñoz-Piña et al., 2008). In the case of Mexico, the most widely used tree species in reforestation projects are conifers, and in the seasonal montane cloud belt of central Veracruz (eastern Mexico), this includes the Mexican weeping pine (*Pinus patula*) (Sánchez-Velásquez et al., 2009; Valtierra Pacheco et al., 2008).

Table 1
Characteristics of the *Pinus patula* plantation under study. LAI = leaf area index. DS09 and DS10 correspond to the two dry seasons under study: November 2008–April 2009 and November 2009–April 2010, respectively. DBH = diameter at breast height. Standard deviations are given after the ± symbol where available.

Elevation [m a.s.l.]	2180
Area [ha]	~1
Canopy height [m][a]	7 ± 1.5
LAI [$m^2\ m^{-2}$]	DS09: 6.0 ± 0.6[b]
	DS10: 6.5 ± 0.2;[b] 5.2 ± 0.1[c]
Tree density [stems ha^{-1}][a]	3783 ± 652
Basal area [$m^2\ ha^{-1}$][a]	34.3 ± 9.6
Number of sample trees	8
DBH range [cm][d]	7.3–11.8

[a] Hernández Hernández (2010) and Alvarado-Barrientos (2013).
[b] Estimated from photosynthetically active radiation measurements above and below the canopy for clear-sky conditions from 11:00 to 14:00 (Alvarado-Barrientos, 2013) and the Beer–Lambert Law with an extinction coefficient of 0.52 (Pierce and Running, 1988).
[c] Measured with a LI-COR LAI-2000 canopy analyzer throughout DS10 and a correction factor of 1.6 (Alvarado-Barrientos, 2013).
[d] As of 2010.

This paper examines the effect of ground-level cloud occurrence (fog) on stand-level tree transpiration (E_t) for a young *P. patula* plantation, as well as the implications of a projected rise in LCL within the seasonal montane cloud belt of central Veracruz, Mexico, by analyzing sapflow dynamics and concurring meteorological conditions over a 1.5-year period (November 2008–April 2010). Specific objectives were to:

- Characterize the local fog climatology and dynamics of leaf wetness in relation to fog occurrence and rainfall;
- Compare rates of E_t and the controlling meteorological variables for sunny versus overcast and foggy conditions; and
- Quantify the seasonal and annual degree of suppression of E_t by fog relative to overcast and sunny conditions.

2. Materials and methods

2.1. Study site

The present study was carried out in a young *P. patula* plantation (see Table 1 for stand characteristics), located within the La Cortadura Forest Reserve owned by the municipality of Coatepec (19.4931° N, 97.0422° W; 2180 m a.s.l.). The plantation was established in the year 2000 and had not received any thinning treatments prior to the study. The site was formerly covered with mature lower montane cloud forest, locally known as '*bosque mesófilo de montaña*' (García-Franco et al., 2008). The seasonally dry montane cloud belt of central Veracruz ranges from ~1200 to ~3000 m elevation. As such, the investigated pine plantation is situated in the upper part of the cloud belt and near the level of the inversion layer marking the transition toward the (mostly coniferous) upper montane forest zone (Rzedowski, 1978). The climate between 2000 and 3000 m elevation in this region is 'temperate humid with abundant rains during the summer', with average annual temperatures between 12 and 18 °C and mean annual precipitation totals (MAP) between 2000 and 3000 mm, respectively (García, 1973). The region has a seasonal rainfall and cloud immersion regime, with a wet season between May and October, during which approximately 80% of MAP falls, and a relatively dry season between November and April. Rainfall in the wet season is mostly of convective origin and brought by frequent showers and thunderstorms, while the dry season is characterized by an alternation of stable dry weather conditions and cloud immersion events, often accompanied by rain and/or drizzle (Holwerda et al., 2010; Muñoz-Villers et al., 2012). Additional information on the site's climate,