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Surface energy exchange in a tropical montane cloud forest environment: Flux partitioning, and seasonal and land cover-related variations

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ABSTRACT

Relationships between seasonal climate, land cover and surface energy exchange in tropical montane cloud forest environments are poorly understood. The goal of this study was to investigate the seasonality of flux partitioning in lower montane cloud forest (LMCF), shaded coffee (CO) and sugarcane (SU) in central Veracruz, Mexico, as well as to evaluate the changes in surface energy exchange associated with the conversion of LMCF to CO or SU. Sensible (H) and latent heat (λE) fluxes were measured during the late dry and wet seasons using eddy covariance (CO and SU) and sap flow (LMCF) methods. Other measurements included: meteorological parameters, radiation balance, soil heat flux, soil moisture and vegetation characteristics. During the wet-season month of July, average midday Bowen ratios (βs) for sunny conditions were lowest and least variable among land covers: 0.4 ± 0.2 (SE) in LMCF, 0.5 ± 0.1 in SU and 0.7 ± 0.1 in CO. In contrast, during the late dry-season months of March and April, βs were higher (i.e. higher H and lower λE) and more variable. The highest values of β were observed in LMCF, reflecting effects of partial leaf-shedding by dominant deciduous species (2.4 ± 0.8, March) and increased stomatal control (1.4 ± 0.3, April). There was also evidence of stomatal limitation of λE in CO and SU, having βs of up to 1.0 ± 0.1 in April and March, respectively. As compared to LMCF, the average midday available energy (A_e) for sunny conditions was very similar in CO (-3 ± 7%) and 15 ± 8% lower in SU. Although not all results were statistically significant, they suggest that for the wet season conversion of LMCF to shaded coffee or sugarcane led to a decrease of 15 ± 14% or 15 ± 17% in midday λE under sunny conditions, respectively, whereas corresponding values of H increased by 37 ± 38% or remained about the same (-4 ± 40%). In contrast, for the late dry season, conversion of LMCF to shaded coffee or sugarcane appears to have resulted in higher λE and lower H, with changes of, respectively, +79 (±32)%/−45 (±16)% (CO) or +39 (±32)%/−43 (±16)% (SU) for a partially leafless LMCF in March, and +17 (±16)%/−11 (±16)% (CO) for a fully-leafed LMCF in April. In order to more accurately quantify the changes in surface energy fluxes associated with LMCF conversion, future work should focus on reducing the errors in the flux estimates. Nevertheless, for sunny days during the wet season, potential changes in the moisture and heat content of the local atmosphere due to the conversion of LMCF to CO or SU seem to have been in the same direction as those induced by increased greenhouse gases (drying and warming), whereas for the late dry season the effects appear to have been opposite (moistening and cooling).

1. Introduction

Tropical Montane Cloud Forests (TMCFs) are among the most biodiverse ecosystems of the world, with often exceptional levels of plant and animal endemism (Rzedowski, 1996; Bruijnzeel et al., 2010). They are also important hydrologically because of their generally high water yield, resulting from abundant rainfall in combination with lower evapotranspiration (i.e. latent heat flux, λE) and additional moisture inputs from fog (Zadroga, 1981; Hamilton et al., 1995; Bruijnzeel et al., 2010, 2011). As such, TMCFs provide critical ecosystem services to the rapidly increasing populations in tropical montane areas (Martínez et al., 2009; Bruijnzeel et al., 2010; Ponette-González and Fry, 2014).

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Nevertheless, worldwide, TMCFs are threatened by land use and climate change (Doumenge et al., 1995; Bubb et al., 2004; Bruijnzeel et al., 2010). It was estimated that by the year 2000 almost half of the global TMCFs had been converted to other land covers (Bruijnzeel et al., 2010; Scatena et al., 2010). TMCFs are considered highly vulnerable to climate change because of their fragmented nature, small geographic range, high endemism and dependence on specific climatic conditions (Bruijnzeel, 2004; Bruijnzeel et al., 2010; Oliveira et al., 2014).

Modeling studies suggest that global warming due to anthropogenic greenhouse gas emissions will cause a reduction of fog occurrence in TMCF zones (Still et al., 1999; Foster, 2001; Karmalkar et al., 2008). Some observational evidence for this scenario comes from the Monteverde TMCF in Costa Rica, where decreases in fog frequency and increases in air temperature were found to be related to increases in the equatorial Pacific sea surface temperature (Pounds et al., 1999). The drier and warmer conditions in the Monteverde TMCF are already causing important changes in biodiversity (Pounds et al., 1999, 2006; Feeley et al., 2013), something which is projected to occur in other TMCFs as well (Rojas-Soto et al., 2012; Ponce-Reyes et al., 2013). Moreover, the reduction in cloud immersion, and the associated drying and warming are expected to negatively affect TMCF water yield (Still et al., 1999; Bruijnzeel et al., 2010, 2011; Alvarado-Barrientos et al., 2014) and plant functioning (Eller et al., 2013; Goldsmith et al., 2013).

In addition, changes in local and regional climatic conditions are to be expected from the large-scale deforestation in TMCF and adjacent areas (cf. Pielke et al., 1998, 2011; Salazar et al., 2015). However, to date, the empirical evidence for this is scarce and comes almost exclusively from remote sensing and modeling studies (Lawton et al., 2001; Nair et al., 2003; Ray et al., 2006). Hence, to properly evaluate the potential effects of deforestation, there is an urgent need for field studies to quantify the surface energy exchange of TMCF and replacement land covers. Subsequently, these data serve as input for atmospheric models to investigate the impacts of deforestation on local and regional climate (cf. Van der Molen et al., 2006).

Work of this kind carried out in Amazonia has shown that the conversion of lowland evergreen rain forest (LERF) to pasture generally results in a decrease in λE and a corresponding increase in sensible heat flux (H), particularly during the dry season when the grass has reduced access to soil moisture due to shallower rooting depth (Von Randow et al., 2004; Van der Molen et al., 2006; cf. Jipp et al., 1998). Furthermore, radiosonde measurements and model simulations have shown that deforestation in Amazonia leads to a drier and warmer boundary layer, changes in cloud formation patterns, as well as lower precipitation (Shukla et al., 1990; Henderson-Sellers et al., 1993; Gash and Nobre, 1997; Fisch et al., 2004; Sampaio et al., 2007; Wang et al., 2009). Moreover, drying and warming in Amazonia is predicted to be strengthened by vegetation feedbacks, such as forest dieback and reduced transpiration, E_t (Mayle et al., 2004; Malhi et al., 2008; Hilker et al., 2014).

However, the findings for LERFs are not necessarily applicable to TMCFs, as there are important biophysical differences between these ecosystems. TMCFs are cooler, more humid and often wetter as compared to LERFs (Bruijnzeel et al., 2010; Jarvis and Mulligan, 2011). Likewise, TMCFs usually experience a less pronounced dry season, partly due to the frequent occurrence of fog during that time of year (Holder, 2004; Holwerda et al., 2010; Bruijnzeel et al., 2011). However, the influence of these specific environmental conditions on the surface energy exchange of TMCFs remains poorly understood (Oliveira et al., 2014). In a review of the limited data available, Bruijnzeel et al. (2011) showed that TMCFs use on average a smaller fraction of net radiation (R_n) for E_t than LERFs. These authors also noted differences between cloud forest types, with upper montane cloud forests (UMCFs) of intermediate stature (1.5–18 m) and exposed to high fog incidence having on average lower E_t/R_n ratios than tall (15–33 m) lower montane cloud forests (LMCFs) subject to low to moderate fog incidence. They suggested that the lower E_t/R_n ratios in UMCF could be related to unfavorable soil conditions associated with waterlogging (cf. Santiago et al., 2000), and (to a lesser extent) to suppression of E_t by fog and/or prolonged canopy wetness (cf. Alvarado-Barrientos et al., 2014). On the other hand, there is some evidence that the more conservative water use by TMCF vegetation reflects ecophysiological adjustments, possibly in response to increased vulnerability to drought (Oliveira et al., 2014; Rosado et al., 2015). Finally, research so far has shown that E_t of TMCF is generally not limited by soil moisture during the dry season (Tanaka et al., 2003; Giambelluca et al., 2009; Wallace and McJannet, 2010). Nevertheless, the scarcity of information available underscores the need for more field observations on the relationships between (seasonal) climate, land cover and surface energy exchange in TMCF environments, in order to better understand the impacts of land use and climate change on these unique ecosystems.

In central Veracruz, Mexico, lower montane cloud forest (LMCF) occurs between 1100 and 2500 m asl. However, due to continued deforestation, the LMCF has been decimated and agricultural land now dominates the landscape (Muñoz-Villers and López-Blanco, 2008). The goal of this study was to determine the surface energy balance for LMCF, as well as for shaded coffee (CO) and sugarcane (SU), two important agricultural land uses in the lower part of the cloud forest zone, which together now occupy a similar proportion of the landscape (24%) as the remaining forest fragments (21%; Muñoz-Villers and López-Blanco, 2008). Measurements were made during the late dry and wet seasons of 2014 in order to investigate: (i) the seasonality of flux partitioning in each land cover type; and (ii) the changes in H and λE associated with the conversion of LMCF to CO or SU under conditions of low and high soil and atmospheric moisture content. This study follows up on the work of Holwerda et al. (2013), who determined total annual evapotranspiration and its components for the same coffee plantation studied here, and compared the results with previously published data for mature and secondary LMCF at higher elevation in this study region.

2. Methods

2.1. Analysis framework and methodological considerations

Measurement equipment could not be left unattended at all field sites because of the high risk of theft or vandalism. Hence, the present analysis is based on data collected on selected, sunny days during the late dry-season months of March (8, 9, 12, 14, 15, 27, 28) and April (1, 2, 12, 13, 14, 24, 25, 26), and the wet-season month of July (10, 11, 14, 19, 21, 22, 25, 26) 2014, respectively (see below for further details). Sunny days were preferred because any differences in energy partitioning between land covers and between seasons would be more pronounced during such days. Furthermore, the current analysis focused on the midday period (1100–1400 h), as this is when the fluxes were greatest and contributions of the evaporation of intercepted rain, fog or dew water were probably negligible (see below).

The vegetation underwent the following changes during the study period: (i) due to phenology, the LMCF was partly without leaves in March, and fully in leaf in April and July; and (ii) the sugarcane was mature in March, harvested at the beginning of April, and in the development stage in July (Table 1). No measurements were made in sugarcane in April. Hence, the comparisons in this analysis included: (1) surface energy balance between seasons for each land cover type; and comparisons between the surface energy balance of (2) partly leafless LMCF, shaded coffee and sugarcane under dry