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Area-wide evapotranspiration monitoring at the crown level of a tropical mountain rain forest

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ABSTRACT

Ecosystem water regulation couples energy and water balance, depends on the integrity of the ecosystem, and responds to changes in climate. Changes in tree-water relationships in the biodiversity hotspot of the tropical Andes in southern Ecuador might be potentially observed at the level of individual trees, thus providing an efficient ecosystem monitoring method with applications in forest management and conservation at the tree and landscape levels. In this study, we combine area-average measurements from a laser scintillometer above the forest with optical satellite data at high spatial resolution to obtain area-wide evapotranspiration data. The processing of field data includes the calculation of energy storage in forest biomass and the partitioning of evapotranspiration into transpiration and evaporation. Satellite-based estimates are calibrated by using tower flux measurements and meteorological data within periods of humid and less-humid atmosphere. The annual evapotranspiration was 1316 mm, of which 1086 mm per year corresponds to the forest transpiration at the study site. Average values of 4.7 and 4.1 mm d^{-1} per tree crown are observed under humid and less-humid atmospheric conditions, respectively, when applying high-resolution area-wide evapotranspiration in individual crown analysis. Approximately 24% of the observed crowns show a positive monthly change in ET, and 51% of the crowns show a significant change in the daily ET, which can be considered sensitive individuals concerning water relationships. The limitations in the area-wide evapotranspiration at the crown level can be explained by considering the spectral responses of the crown individuals. The presented method can be robustly deployed in the ecological monitoring of mountain forests.

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1. Introduction

Tropical mountain forests harbor a unique diversity of tree species and complex structural patterns, which have not yet been fully understood (Bendix et al., 2013). While functional traits and tree diversity were found to correlate with edaphic conditions (e.g., eastern Andes, Homeier et al., 2010), the response of vegetation to climate was mostly investigated from a broad perspective and rarely reached an individual- or species-level approach (Condit et al., 2013). At the same time, land use change threatens biodiversity and modifies the environment, so the functional variability within a forest is forced to adapt or restitute the optimal natural conditions. Consequently, the conservation and management of natural forests depend on an efficient assessment of ecosystem dynamics (e.g., growth, acclimation), which in turn requires monitoring ecosystem indicators in a systematic manner across a range of scales (Lawley et al., 2016).

A key indicator of an ecosystem's state and function is evapotranspiration (ET) (Nagler et al., 2009a) because ET represents both the water flow and energy balance of an ecosystem (Müller, 2005). Two consolidated methods are used to estimate ET by remote sensing. The first approach calculates ET as the residual of the surface energy balance, where the solar radiation is obtained by astronomical calculations, the ground heat flux is empirically based on the surface albedo, and the sensible heat flux depends on the radiometric surface temperature. The surface temperature requires thermal sensors, which exhibit coarse granularity and are thus applied to investigate the hydrological regulation of crop compartments or forest patches at the lowest level (Bastiaanssen et al., 1998; Gonzalez-Dugo et al., 2009). The second approach relates a vegetation index (VI) to a reference or potential ET. This reference or potential ET requires the field meteorology and assumes a known reference or water-saturated surface. One advantage of this approach is that the surface reflectance that is used to calculate the VI relies on optical sensors with high radiometric performance (Glenn et al., 2010; Yebra et al., 2013), thus reaching lower levels than forest patches.

Global ET products are available at spatial resolutions of 0.05 and 1.0 degrees (Jung et al., 2010; Liu et al., 2011; Mu et al., 2011) and can be estimated at up to 100-m ground sampling (Roy et al., 2014). However, none of the available products can be used to directly extract information at the individual crown level. The large number of tree crown

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detection approaches in the literature reveals the interest of forestry and ecology communities in deploying emerging remote sensing technologies at the crown level (Chadwick and Asner, 2016; Dalponte et al., 2014; Hyyppä et al., 2008; Wulder, 1998). Common to these studies is that remote sensing improves the regionalization of biophysical and forest inventory elements (e.g., density and biomass) and that trees can be analyzed individually in terms of crown traits or their physiological response to environmental changes. Consequently, knowledge at the crown level empowers forest management institutions in high biodiversity environments by combining taxonomic and indicator-specific analyses at the landscape level. In addition to costly field and aerial campaigns (Chadwick and Asner, 2016), solid advancement in mapping spectral traits at the tree-crown level can be achieved by using currently operating satellites at high granularity (McGraw et al., 1998). To our knowledge, no research exists on monitoring evapotranspiration (ET) at the level of individual trees by satellite remote sensing. In terms of the VI-based approach, any uncertainties in area-wide ET are mainly related to the illumination geometry and radiometric processing of satellite data and to the constraints and parameterization of the potential ET model. Different VI-based approaches have been published in recent decades, with the potential ET model incorporating either only atmospheric terms or also including aerodynamic and surface resistance terms (Choudhury et al., 1994; Glenn et al., 2011; Nouri et al., 2016). Following these authors, a calibration coefficient is used to adjust the potential ET model to a specific vegetation surface to obtain the actual ET. However, none of these previous studies has been implemented at the level of individual tree crowns.

The overall aim of this work is to develop a method to monitor subtle changes in canopy water relationships by operational remote sensing at the crown level for a tropical mountain forest. In addition, we identify potential sensitive tree crowns as early warning indicators for a change in ecosystem water regulation. The developed method combines state-of-the-art optical remote sensing data and recent field meteorology techniques (scintillometer). The area-wide ET at the crown level is assessed by considering the radiometric and spectral variability, the realistic meteorological input, and the effects of local climate variability. Finally, the applicability of the area-wide ET at the crown level is tested by its capacity to track climate variations over one year based on potential indicator trees.

2. Materials and methods

This study's approach combined area-averaged measurements of evapotranspiration (ET_{Sci}) with a surface layer scintillometer (SLS) to calibrate a potential evapotranspiration (ET_{PM}) that was adjusted by satellite reflectance data, thus obtaining the actual area-wide evapotranspiration (ET_{sat}). First, the SLS measurements were processed to consider biomass energy storage as a solution for the surface energy balance above the forest. The Penman-Monteith model was used to calculate the potential evapotranspiration (ET_{PM}), which requires parameters for the surface and atmospheric resistances. A particular case is provided by precipitation events when transpiration is suppressed while the surface resistance increases until the canopy-intercepted water is released in the atmosphere. Thus, a second processing step was considered to identify canopy evaporation, i.e., data that are directly influenced by precipitation events. Then, the area-wide product (ET_{sat}) was calculated based on the calibration coefficient and monthly averages of meteorological data (e.g., temperature and humidity). The calibration of the ET_{sat} was demonstrated for each period (humid and less-humid) by using the daily course of flux measurements on the two closest days to the corresponding day of the year of the satellite overpass. Afterwards, the proposed calibration was analyzed along one year of measurements by considering sub-daily precipitation interference on ET_{sci} measurements. Finally, the area-wide product ET_{sat} for humid and less-humid periods was applied in an object-oriented analysis by using individual tree crowns. The response of each individual to a change to a drier atmosphere helped us to identify sensitive crowns or potential indicator individuals in the mountain forest.

2.1. Study site

The study area (Fig. 1) is located in the *Reserva Biológica San Francisco* (RBSF) in South Ecuador. The RBSF is located in the *San Francisco* River Valley, which breaches the main eastern Andean cordillera in the ecozone of the humid tropics and has elevations between 1600 and 3140 m a.s.l. While the south-facing slopes of the valley are extensively deforested and now covered by pasture land, the north-facing slopes are covered by a pristine tropical mountain forest. The forest types in the RBSF are spatially distributed according to the topography and altitudinal gradient. Altitudes from 1900 to 2100 m a.s.l. are covered by evergreen lower mountain forest with considerably different species between valleys or lower slopes and upper slopes or ridges. The research station *San Francisco* (ECSF) is located at S 3° 58′ 25″ W 79° 4′ 31″ at 1850 m a.s.l., with an average temperature of 15.5 °C and annual precipitation of 2050 mm. Diverging evapotranspiration observations indicate annual evapotranspiration between 540 and 1580 mm at the ECSF (Beck et al., 2008). Higher values were obtained by measuring the inflow and outflow of three micro-catchments (954 and 1580 mm), while sap flux and gas exchange measurements showed annual evapotranspiration between 561 and 654 mm at the forest-stand level (Motzer et al., 2005). In a subsequent review, annual transpiration between 919 and 1281 mm was reported for the study site (Bruijnzeel et al., 2011).

2.2. Field measurements

Two towers (30 and 36 m high) were erected in the forest to the west and east to measure the flux above the forest canopy. The western tower was located at 1975 m a.s.l., 36 m above ground, and 90 m (220° SW) from the eastern tower. The SLS-40 transmitter (Scintec AG, Germany) was set up in the western tower and the SLS-40 receiver in the eastern tower, both ~13 m above the forest canopy. The SLS is an optical instrument that uses the covariance in a dual-beam laser (wavelength = 670 nm) to estimate the dissipation rates of the measurements. The dissipation rates are used alongside the Monin-Obukhov similarity theory (MOST) to calculate atmospheric turbulence, heat and momentum flux (Nakaya et al., 2006; Odhiambo and Savage, 2009). The calculation of the latent heat, which is converted to evapotranspiration, is based on the energy balance equation and requires additional meteorological data.

An automatic weather station was installed in the eastern tower to provide additional energy balance terms (net radiation and soil heat flux) alongside the air temperature, air pressure, and relative humidity. Net radiation sensors (8111; Schenk GmbH, Austria; and CNR01; Kipp & Zonen, Netherlands) were installed at 20 m above ground, 5 m above the canopy. The air temperature and relative humidity were measured with a shield protected thermometer and hygrometer (HC2S3; Campbell Sci. Inc., USA) at 20 m above ground. At the same level, the air pressure was measured with a barometric pressure sensor (61302V; RM Young, USA), the precipitation was measured with a tipping bucket rain gauge (52203; RM Young, USA), and the wind direction was measured with a wind vane (W200P; Vector Instruments, Ltd., UK). Additionally, the air temperature was measured at 25 m above ground. The soil heat flux was measured by two soil heat plates (HFP01; Campbell Sci., USA) that were installed 5 cm below the soil surface. Data from a second weather station 150 m from the eastern tower was available to analyze the soil moisture and temperature (Rollenbeck and Peters, 2009). These data were stored with two data loggers (CR1000; Campbell S-ci. Inc., USA), which used a 10-min interval.

The observation towers operated for one year from March 2014 to March 2015. Previously, SLS measurements were conducted during a week in November 2013 on a pasture site at 1960 m a.s.l. at the opposite

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