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Evapotranspiration of subtropical forests and tree plantations: A comparative analysis at different temporal and spatial scales

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ABSTRACT

The area of tree plantations in the humid subtropical region of Northern Argentina has recently increased five folds. However, the impact of this land use change on evapotranspiration (ET), one of the main components of the hydrologic cycle, has not been evaluated. We studied the ET at tree and ecosystem levels for native forests and three tree plantations (*Pinus taeda*, *Araucaria angustifolia* and *Eucalyptus grandis*). Water consumption of individual trees was estimated using sap flow measurements. Ecosystem ET was characterized using both remote sensing derived data products (ET_{MODIS}) for 2000–2011 and scaling up from tree sap flow measurements to stand level. Canopy conductance (g_c) was estimated using both sap flow measurements and ET_{MODIS} data. At individual level, transpiration was positively related to the size of the tree, and the relationship was well described by an exponential function when all species (both native and cultivated trees) were included in the analysis. The average annual leaf area index was similar between native forest and tree plantations. The ET estimates obtained from scaling up sap flow measurements and from ET_{MODIS} were relatively similar in most cases and differed by 4–34%, depending on the ecosystem. The tree plantations, regardless of density or age, did not show higher ET_{MODIS} than native forests. The ET ranged from 1161 to 1389 mm per year across native forests and tree plantations according to remote sensing, representing 58–69% of the annual precipitation. Furthermore, the good agreement between ET estimates, with the exception of *E. grandis*, obtained using sap flow and remote sensing provide a good basis for predicting the effects of land conversion from native forest to most non-native tree plantations on regional ET. Monthly ET_{MODIS} increased with increasing monthly air saturation deficit (ASD) up to 0.8 kPa, value at which ET_{MODIS} did not increase further probably due to stomatal control and low values of g_c. Different negative exponential relationships between g_c and ASD were obtained when g_c was calculated by scaling up daily tree sap flow to ecosystem level. Canopy conductance (estimated by remote sensing) declined in a similar negative exponential fashion with increasing ASD, and no differences were observed across ecosystem types. The result of increasing the time step, from daily to monthly, and the spatial scale from individual tree to stand level, had the consequence to lower, even to eliminate differences in annual ET and g_c among ecosystems in their responses to climate drivers. This suggests that the nature of ET regulation at individual and ecosystem levels could be different, which should be taken into account when predicting the effects of changes in land use on regional hydrology.

Abbreviations: ASD, air saturation deficit; DBH, diameter at breast height; ET, evapotranspiration; ET_{MODIS}, evapotranspiration estimated from remote sensing with MODIS; ET_{upflow}, evapotranspiration at stand level, scaled up from field sap flow measurements; g_c, canopy conductance; GR, global radiation; MODIS, moderate resolution imaging spectroradiometer; SF, total diurnal sap flow; *T*, transpiration at stand level from field sap flow measurements.

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1. Introduction

One of the major processes regulating water exchange between terrestrial ecosystems and the atmosphere, particularly in forests, is evapotranspiration (ET), which has two different components: evaporation and transpiration. Evaporation in dense forests refers to the exchange of water from the liquid to the gaseous phase mostly from the canopy, while transpiration indicates the process of water vaporization from leaves of trees. Both processes are driven by the available energy and the drying potential of the surrounding air, but transpiration also depends on the capacity of plants to transport water from the roots and internal water storages to the leaves as well as the stomatal control of water losses (Bucci et al., 2008; Giambelluca et al., 2009).

Information on the effects of tree plantations on regional hydrological cycle processes is extremely important in assessing the impact of land use changes and in developing strategies related to sustainable use of water resources. Some information is available about the hydrological impacts of converting grasslands or shrublands to tree plantations (e.g., Jobbágy et al., 2006). In humid regions where forests are the dominant vegetation type, such as in Northeastern (NE) Argentina, the impact of tree plantations on hydrological processes, particularly evapotranspiration, has not been assessed.

These moist subtropical forests maintain high photosynthetic rates during most time of the year because many tree species are evergreen and the winter period during which the deciduous canopy species drop their leaves is short and with infrequent subzero air temperatures (Gatti et al., 2008; Tan et al., 2012; Cristiano et al., 2014). Changes in land use, particularly the replacement of native forests by tree plantations may have an impact not only on the water balance but also on the carbon balance at a regional level. Tree plantations are expanding at a rate of 5000 km^2 per year in South America (Jobbágy and Jackson, 2004; Jobbágy et al., 2006). In NE Argentina, the area dedicated to tree plantations has recently increased five folds (Izquierdo et al., 2008). A paradigm that has not been assessed for humid forest ecosystems is that tree plantations have high productivity with great annual evapotranspiration (Jackson et al., 2005). However, this trade-off between carbon sequestration and water utilization may not be valid for humid subtropical forests (Zhang et al., 2013; Cristiano et al., 2014).

The use of information provided by remote sensing has emerged as a useful tool in studying spatial-temporal dynamics of ecosystem processes. For example, some models allow the estimation of ET from satellite data. The most widely used ET model is the MOD16A2 product from the MODIS-Terra sensor (Mu et al., 2011). This product has been validated using 46 sites with eddy-covariance towers which are mostly located in North America while only two sites are in tropical rain forests close to the equator in Brazil. Currently there is no validation of this model for subtropical Argentinean forests neither using eddy covariance methods nor using sap flow measurements from individual trees. The current study investigates physiological mechanisms regulating transpirational water losses at different scales for native subtropical forests and high yield tree plantations in Northeast (NE) Argentina. The objectives of this study were (1) to understand mechanisms controlling the ET at tree and ecosystem levels including environmental factors such as evaporative demand and incoming solar radiation, and the interaction between canopy structure and the physical environment, described by canopy conductance (g_c), and (2) to determine whether ET and g_c from high yield tree plantations of *Eucalyptus grandis* W. Hill ex Maiden, *Pinus taeda* L. and *Araucaria angustifolia* (Bert) O. Kuntze were comparable to native subtropical forests in the same region. In this regard it was assessed whether the results of scaling up sap flow measurements to ecosystem level ET were consistent with ET estimated from remote sensing. Research on tree and ecosystem level determinants of evaporative fluxes should improve our understanding of how subtropical trees and tree plantations regulate water fluxes. This information will also help to predict the impact of land use changes on ET at a regional scale.

2. Materials and methods

2.1. Study area

Field measurements of stand structure and transpiration were made in tree plantations of *P. taeda*, *E. grandis* and *A. angustifolia*, and in a native subtropical forest stand in the Atlantic Forest within the Iguazú National Park, Misiones Province, NE Argentina (26°25′ S, 54°37′ W). Mean annual rainfall in the area is about 2000 mm and is evenly distributed throughout the year. Mean annual temperature is 21 °C, and frost seldom occurs in winter, thus, temperatures are favorable for growth during most of the year. Relative air humidity is high throughout the year with mean monthly values ranging from 73 to 85%, from 1961 to 2014. Average monthly wind speed at 10 m ranges from 5.3 to 7.8 km h^{-1} for the same time period. The soils, which are derived from basaltic rocks containing high concentration of Fe, Al and Si, correspond to the 9a type (Ligier et al., 1990) and include Alfisols, Molisols and Inceptisols (Soil Survey Staff, 1992).

2.2. Sap flow

Sap flow was measured in two trees for each of 10 dominant woody species with different leaf phenology in native forests and one palm and two lianas which contribute to 72% of the entire canopy and sub-canopy woody species. Sap flow was measured also in five trees in *E. grandis* and in six trees in *P. taeda* and *A. angustifolia* tree plantations, which were 12, 6, and 28 years old, respectively, at the time of the study. The species selected in the native forest, were *Parapiptadenia rigida* (Bentham) Brenan, *Cedrela fissilis* Vell., *Balfourodendron riedelianum* (Engl.) Engl., *Cabralea canjerana* (Vell.) Mart., *Chrysophyllum gonocarpum* (Mart. & Eichler) Engl., *Ocotea diospyrifolia* (Meisn.) Mez., *Lonchocarpus muehlbergianus* Hassl., *Cordia trichotoma* (Vell.) Arráb. ex Steud., *Holocalyx balansae* (P. Micheli), *Ceiba speciosa* (A. St. -Hil. Juss & Cambessds) Ravenna, *Euterpe edulis* Mart., *Pisonia aculeata* L. and *Amphilophium* Kunth sp. Thirty percent of the trees are deciduous and leaf drop occurs during the cold season (Cristiano et al., 2014). Understory plants were not included in the sap flow measurements across all systems. Sap flow measurements were obtained throughout 2012 and 2013, during the spring–summer and autumn–winter seasons, in order to have a good representation of annual variations in diurnal sap flow patterns (142 days in ten native forest species, 44 days in *P. taeda*, 46 days in *A. angustifolia* and 56 days in *E. grandis*). The heat dissipation method (Granier, 1985, 1987) was used for sap flow measurements. A pair of hypodermic needles 20-mm long and 2-mm in diameter, which contain a copper–constantan thermocouple inside a glass capillary tube and a heating element of constantan coiled around the tube, were inserted into the sapwood at 1.5 m from the ground in the main stem in each tree. The probes were installed in the same azimuthal position for all trees. Measurements in the outer 20 mm of sapwood may overestimate sap flow in few tree species because flow rates may decrease with sapwood depth in large trees. The upper (downstream) probe was continuously heated at a constant power by the Joule effect, while the unheated upstream probe served as a temperature reference. Temperature differences between the upstream and downstream probes were recorded every 10 s and 10-min averages were recorded using dataloggers (CR 10X, Campbell Scientific, Logan, Utah, USA). Sap flux density was calculated from the temperature difference between