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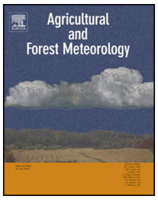

Modeling canopy conductance under contrasting seasonal conditions for a tropical savanna ecosystem of south central Mato Grosso, Brazil

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ABSTRACT

Temporal variations in land-atmosphere water vapor exchange are more pronounced in seasonal environments, especially grass-dominated savannas (known as *campo sujo Cerrado*) of the southern and eastern Amazon Basin. Recent work in *campo sujo* indicates that rates of canopy conductance (g_c) were directly and indirectly affected by a variety of meteorological variables, which limited our understanding of how seasonal variation in meteorology affected rates of g_c. Thus, our overall objective here is to determine how individual meteorological variables affect seasonal variations in g_c. Estimates of g_c were derived using the inverted Penman–Monteith equation from hourly eddy-covariance measurements of evapotranspiration made between March 2011 and December 2013. We employed the so-called Jarvis-type model to estimate g_c, which allows us to specify the functional role of each variable on g_c, to evaluate how variations in meteorology affect rates of Cerrado g_c. The model was parameterized using eddy covariance data from 2012 and tested with data collected in 2011 and 2013. Using orthogonal regression and the Willmott index of agreement, we found that the model estimates compared well to those derived from eddy covariance, especially in 2011. Sensitivity analyses revealed that g_c was sensitive to warming and drying, particularly during the dry season when drought stress from low soil moisture availability was already limiting g_c. Warming and drying in response to climate change is expected to increase dry season duration, and dry season intensification may already be occurring in central and southern Mato Grosso. Given the high degree of surface-atmosphere coupling for this ecosystem, and the fact that g_c is an important link between canopy-scale C and water cycling, our data suggest that dry season intensification may further limit CO_2 and H_2O vapor exchange during the dry season.

1. Introduction

The rate of water vapor (H_2O) exchange between the vegetated surface and the atmosphere is one of the most important energy exchange processes at the air–land interface (Kumagai et al., 2004). This is especially true for tropical ecosystems, which can return 45–65% of the precipitation to the atmosphere as evapotranspiration (ET) annually (Hutyra et al., 2005; Vourlitis et al., 2014). However, the ET tropical ecosystems has been shown to be sensitive to climatic variation over seasonal and interannual time scales (Malhi et al., 2002; Rodrigues et al., 2013; Vourlitis et al., 2014), and climate variation is predicted to increase with human-induced climate change because of intensification of the dry season (Cramer et al., 2005; Li et al., 2008; Phillips et al., 2009; Cox et al., 2013; Gatti et al., 2014).

Temporal variations in land-atmosphere water vapor exchange are more pronounced in seasonal environments (Machado et al., 2004; da Rocha et al., 2009; Costa et al., 2010; Rodrigues et al., 2014), especially the grass-dominated savannas of the southern and eastern borders of the Amazon Basin (Giambelluca et al., 2009; Rodrigues et al., 2014; Biudes et al., 2015). Savanna covers approximately 45% of the area in South America (Scholes and Archer, 1997), and Brazilian savanna (locally known as Cerrado) is the dominant vegetation in areas subjected to a prolonged dry season (Lascano, 1991; San José et al., 1998; Rodrigues et al., 2011, 2013, 2014). The extremely seasonal environment of Cerrado is characterized by a dry season that extends between 5 and 6 months, with nearly all of the rainfall (ca. 90%) distributed between the

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months of October and March (Bucci et al., 2008; Vourlitis and da Rocha, 2011). Evaporative demand is substantially higher during the dry season (Rodrigues et al., 2013, 2014; Biudes et al., 2015), and the combination of higher evaporative demand and low soil water availability makes the Cerrado a potentially stressful environment for woody species (Bucci et al., 2008; Rodrigues et al., 2014). This is especially true for short-rooted vegetation such as grasses and shrubs, which are important components of Cerrado (Meinzer et al., 1999; Giambelluca et al., 2009; Vourlitis and da Rocha, 2011; Rodrigues et al., 2014). As a result, rates of ET may decline by 40% in tree-shrub dominated Cerrado (*sensu stricto* or *denso*) to over 50% in grass-dominated (*campo*) forms of Cerrado during the dry season (Santos et al., 2003; Oliveira et al., 2005; da Rocha et al., 2009; Giambelluca et al., 2009; Rodrigues et al., 2014).

Plant control of ET occurs by variation in stomatal conductance (g_s; Wright et al., 1996; Harris et al., 2004; Costa et al., 2010), although variation in leaf area index (LAI) also affects rates of canopy-atmosphere water vapor exchange (Vourlitis et al., 2008; Giambelluca et al., 2009). However, “bottom-up” scaling g_s from the leaf to the canopy is difficult due to the fact that g_s varies according to species, leaf age, radiation exposure, internal CO_2 concentration, and/or nutrient content (Jarvis, 1976; Field, 1983; Leuning, 1990; Dalmagro et al., 2013). Thus, bottom-up scaling of g_s requires canopy-level estimates of leaf morphology and/or distribution, canopy structure (i.e., leaf area index), and vapor, heat, and radiative transfer (Jarvis and McNaughton, 1986; Baldocchi et al., 1991; Leuning et al., 1995; Li et al., 2008). An alternative approach is to use canopy-scale measurements to estimate canopy conductance (g_c); however, while g_c may be strongly affected by g_s it is also affected by evaporation and non-physiological terms such as the radiative and aerodynamic properties of the canopy (Jarvis and McNaughton, 1986; Baldocchi et al., 1991). In canopies that are highly coupled to the atmosphere, variations in g_c are more closely related to variations in g_s (Jarvis and McNaughton, 1986; Meinzer et al., 1993). Nevertheless, g_c represents an important link between canopy-scale carbon (C) and water cycling, and thus, is an important input to ecosystem C and water cycle models (Wang and Leuning, 1998; Harris et al., 2004; Kumagai et al., 2004).

Recent work in grass-dominated Cerrado indicates that both ET and g_c are limited by water availability during the dry season (Rodrigues et al., 2014), which is consistent with that reported for seasonal tropical forests (Vourlitis et al., 2008), humid tropical forests (Harris et al., 2004), and Cerrado woodlands (Giambelluca et al., 2009). However, using path analysis Rodrigues et al. (2014) found that rates of Cerrado g_c were directly and indirectly affected by a variety of meteorological variables, which limited our understanding of how seasonal variation in meteorology affected rates of g_c. Given the central role of g_c in C and water cycling, and the reliance of g_c in canopy models (Wang and Leuning, 1998; Harris et al., 2004; Kumagai et al., 2004), it is important to understand how meteorological variation affects g_c. Thus, our overall objective here is to determine how individual meteorological variables affect seasonal variations in Cerrado g_c. To fulfill our objective we employed the so-called Jarvis-type model to estimate g_c, which allows us to specify the functional role of each variable on g_c (Jarvis, 1976; Harris et al., 2004). This model has been used to study meteorological controls in a variety of other Amazonian ecosystems (Dolman et al., 1991; Wright et al., 1996; Harris et al., 2004; Von Randow et al., 2012), but to our knowledge this is the first time this type of model has been used for grass-dominated Cerrado. Here we evaluate how variations in meteorology affect rates of Cerrado g_c and qualitatively compare our results to those described for other Amazonian ecosystems.

2. Materials and methods

2.1. Site description

The study was conducted at the Fazenda Miranda in the Cuiaba Basin, 15 km SSE of Cuiaba, Mato Grosso, Brazil (Fig. 1). The vegetation is grass-dominated with scatter trees and shrubs, which is locally known as *campo sujo* or “dirty field” Cerrado (Rodrigues et al., 2013, 2014). Vegetation consists predominately of native and introduced grasses and the tree species *Curatella americana* L. and *Diospyros hispida* A. DC. The Koppen climate classification is Aw, tropical semi-humid, with dry winters and wet summers. The long-term (30 year) average mean monthly air temperature ranges from a minimum of 18 °C in June–July to a maximum of 29 °C in October, and the average rainfall is 1420 mm with a dry season that extends from May to September (Vourlitis and da Rocha, 2011). The research area is on flat terrain at an elevation of 157 m above sea level. The regional soil type is locally known as a Solo Concrecionário Distrófico, which is a rocky, nutrient poor, red-yellow latosol (Radambrasil, 1982). These soils have high porosity, low water holding capacity, and drain rapidly (within 3–5 days) following rainfall (Rodrigues et al., 2013, 2014).

2.2. Micrometeorological measurements

Micrometeorological and eddy covariance measurements were conducted between March 2011 and December 2013. A 20 m tall micrometeorological tower enabled the collection of data on air temperature (T_a), relative humidity (RH), wind speed (u), precipitation (P), soil temperature (T_s), heat flux (G), and moisture (θ_w), net (R_n) and solar radiation (R_s), and latent (L_e) and sensible heat flux (H). T_a and RH were measured 10 m above the ground level using thermohygrometer (HMP45AC, Vaisala Inc., Woburn, MA, USA). Wind speed was measured 10 m above the ground level using anemometer (03101 R.M. Young Company), and G was measured using heat flux plates (HFP01-L20, Hukseflux Thermal Sensors BV, Delft, The Netherlands) installed 1.0 cm below the soil surface ($n = 2$), with one placed in the sandy and the other placed in a laterite soil types that are representative of the tower footprint. θ_w was measured in the two soil types described above using time-domain reflectometry (TDR) probes ($n = 2$) installed 20 cm below the soil surface CS616-L50 (Campbell Scientific, Inc., Logan, UT, USA). Values of G and θ_w obtained from each soil type were averaged to obtain an estimate for the tower footprint, which is appropriate given that each soil type is equally represented in the footprint and both soils have similar vegetative cover and water holding characteristics. R_n and R_s were measured 5 m aboveground using a net radiometer (NR-LITE-L25, Kipp & Zonen, Delft, The Netherlands) and a pyranometer (LI200X, LI-COR Biosciences, Inc., Lincoln, NE, USA), respectively. Precipitation was measured using a tipping-bucket rainfall gauge (TR-525 M; Texas Electronics, Inc., Dallas, TX, USA). The sensors were connected to a datalogger (CR1000, Campbell Scientific, Inc., Logan, UT, USA) that scanned each sensor every 30 s and stored average and/or total (P) quantities every 30 min.

Latent (L_e) and sensible heat flux (H) were quantified using eddy covariance, and measurement details have been described in detail by Rodrigues et al. (2014). Briefly, eddy covariance sensors were mounted at a height of 10 m above ground level, or 8–8.5 m above the vegetation. Wind direction was typically out of the NNW and NNE, and analysis of the upwind fetch estimated using the Schuepp et al. (1990) model indicated that about 90% of the flux originated within 1 km upwind of the tower (Arruda, 2014).

The eddy covariance system consisted of a 3-dimensional sonic anemometer-thermometer (CSAT-3, Campbell Scientific, Inc., Logan, UT, USA) to measure the mean and fluctuating quantities of wind speed and temperature and an open-path infrared gas