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The influence of sugarcane crop development on rainfall interception losses

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ABSTRACT

The expansion of sugarcane plantations in Brazil has raised concerns regarding its hydrological impacts. One of these impacts is related to rainfall interception, which can be expected to vary in response to substantial changes in canopy structure throughout the cropping cycle. We collected field measurements to determine interception losses and interpreted the observations using an adapted Gash model during different stages of a sugarcane ratoon cropping cycle. Cumulative gross rainfall (P_G), throughfall (*TF*) and stemflow (*SF*) were measured biweekly, along with vegetation structure measurements of leaf area index (*LAI*) and plant height. For the first 300 days after the first harvest, the cumulative P_G of 1095 mm was partitioned into 635 mm *TF* (58%) and 263 mm *SF* (24%). The inferred interception loss (I_L) was 263 mm (24%). There was a gradual and clear increase in I_L from 3% to 46% while partitioning between *TF* and *SF* also changed during ratoon regrowth. After model parameter optimisation, observed I_L was simulated satisfactorily. Model estimates suggested that evaporation from the saturated canopy is the main I_L pathway, followed by evaporation after storms. Plant architecture, *LAI* and meteorological conditions during the cropping cycle appeared the main factors determining I_L.

1. Introduction

The expansion of sugarcane plantations in Brazil has raised concerns regarding its hydrological impacts (Loarie et al., 2011; Pongratz et al., 2006). One of these impacts is related to rainfall interception, which may be expected to vary in response to the substantial changes in canopy structure throughout the cropping cycle. Rainfall interception is the fraction of rain that falls onto vegetation but never reaches the ground, instead evaporating from the wet canopy. Canopy interception loss (I_L) is commonly derived as the residual between event gross rainfall (P_G) measured above the canopy or in a nearby clearing and net rainfall, calculated as the sum of separately measured throughfall (*TF*) and stemflow (*SF*) below the canopy (Helvey and Patric, 1965). Such measurements have been made mainly in natural or planted forests (e.g. Dykes, 1997; Deguchi et al., 2006; Chen and Li, 2016) and relatively few studies have investigated crops. For sugarcane, some papers have studied *TF* (Silva et al., 2016) but not *SF*, which leaves large uncertainty regarding interception loss. The absence of *SF* measurements may be due to the difficulties involved in *SF* measurement on plants with tillers such as sugarcane (e.g., Friesen et al., 2013).

Measurements of P_G, *TF*, and *SF* provide estimates of I_L, but models are required to interpret the effect of variations in canopy characteristics and meteorological conditions (Linhoss and Siegert, 2016). Conversely, interception models require detailed data on canopy cover and storage capacity, partitioning between *TF* and *SF*, rainfall characteristics, and wet canopy evaporation rates (Rutter, 1975; Gash, 1979; Deguchi et al., 2006). The original Gash model (Gash, 1979) was based on the Rutter (1975) model, but required less data, and has been shown to be useful for vegetation with a closed canopy. The revised Gash model (Gash et al., 1995) is more robust and provides more accurate estimates of I_L for sparse vegetation (Valente et al., 1997; Carlyle-Moses and Price, 1999) and has been used with considerable success for tropical rainforests (Dykes, 1997) and agroforestry systems (Jackson, 2000).

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Van Dijk and Bruijnzeel (2001b) used an adapted version of the Gash model and reported good agreement for a mixed cropping system after accounting for the relationship between vegetation leaf area index (*LAI*) and canopy capacity (S_L) or evaporation rate from the saturated canopy. Moreover, Van Dijk and Bruijnzeel (2001a) proposed adjustments in the relationship between the canopy cover fraction (c) and *LAI* based on the Beer-Lambert equation and by using a method that derives the free throughfall coefficient (Gash, 1979). These vegetation parameters would be expected to change during the cropping cycle and consequently affect I_L. Rapid vegetation changes occur in non-perennial crops such as sugarcane (Silva et al., 2016).

Sugarcane is usually harvested between 12 and 24 months after planting and allowed to regrow from stubble in the following years (known as ratoon crop). The entire crop cycle usually takes five to six years, during which the sugarcane is harvested annually. Over this period, as the sugarcane is harvested and regrows, there are large changes in canopy cover. These dynamics may be expected to have important implications for hydrological processes such as interception and overland flow and related to this, gradually declining crop yields (Cabral et al., 2012) and ecohydrological impacts (Silva et al., 2016).

In this context, the objectives of this study were: (1) to assess the influence of the rapid sugarcane canopy changes during the growth phases on rainfall interception losses; (2) to apply the adapted Gash model for agricultural crops proposed by Van Dijk and Bruijnzeel (2001a,b) in order to simulate and interpret the main factors determining interception loss over the course of the cropping cycle.

2. Study site and materials

2.1. Study area

The measurements were conducted within a small catchment of approximately 17 ha, covered by sugarcane and riparian forest (2 2°36′46.98″S, 47°39′57.888″W), located in the municipality of Piracicaba, São Paulo State, Southeast region of Brazil. The mean elevation of the catchment is 510 m and it has an average slope of 10% (Fig. 1a). Soils in the study area are classified as Ultisols. The climate of the region is subtropical (Cwa in the Köppen system) with a distinct dry season from April to September. Meteorological variables were available from 30 years of observations from the nearest automated meteorological station, at the "Luiz de Queiroz" Agricultural School of the University of São Paulo, sited about 11 km from the study site (22°42′12.2″S, 47°37′26.7″W).

At the station, mean annual rainfall is 1330 mm, with a mean annual relative humidity of 75% and mean annual temperature of 22 °C. The rainy season is generally from October to March with a mean monthly temperature around 25 °C and relative humidity around 80%. The dry season has a monthly average temperature of 20 °C with average relative humidity of around 70%. Long-term monthly mean wind speed is 2.2 m s^{-1}, and around 60% of the time winds are from the ocean (SSE). Pan evaporation is 4.8 mm day^{-1} or 1740 mm per year.

The studied sugarcane was planted in 2011, covering about 8 ha of the catchment and harvested in July 2012. The measurements reported here covered the first re-growth (i.e., first ratoon), from July 2012 to May 2013. The planting arrangement was 0.7 m between rows and 1.5 m plant spacing on rows, resulting in planting density of 9500 plants per ha, that is, an average 1.05 m^2 per ratoon. The cultivar planted was 'RB 96-6928', bred for hardiness, high productivity, high tillering rate and early maturation.

The sugarcane re-growth cycle can be divided into four phases (Ellis and Lankford, 1990): i) establishment (hereafter "S_I") which starts with germination or emergence and lasts until 30 to 50 days after planting or harvest (DAH), ii) tillering (hereafter "S_{II}") which lasts from 50 to 100 days within the respective phase, iii) stems elongation (hereafter "S_{III}") which lasts 80–140 days, and iv) ripening (hereafter "S_{IV}") which remains from the end of S_{III} until plant senescence (lasts about 130–190 days).

2.2. Canopy water budget measurements

Three trough-type collectors made of PVC pipe were installed to measure P_G in an open area approximately 800 m away from the sugarcane plantation (Fig. 1a). The rainfall receiving area of each collector was 0.185 m^2 (length 1.85 m, width 0.10 m and depth 0.15 m). The collectors were installed at 0.5 m above ground with 5% inclination. Collectors were connected via flexible tubes to plastic canisters of 20 L. In addition, two tipping bucket rain gauges (Rain Wise, Inc.) with 0.254 mm increment were installed to record 10-min rainfall intensity. We considered rain separated by four or more hours as separate rainfall events, otherwise, the events were merged (cf. Sentelhas et al., 1998). We calculated mean rainfall rate ($\overline{R}$) for all 10-min P_G intervals greater than 0.5 mm h^{-1} which, according to Gash (1979) are the events that saturate the canopy.

To measure *TF* below sugarcane, eight identical troughs were installed at the experimental site crossing rows at 90° angles. The troughs were placed with an average distance of 10 m apart (Fig. 1b,c). Seven troughs were connected to a collection vessel (Fig. 1b), and one was connected to a tipping bucket rain gauge (Fig. 1d).

SF was measured by funnels attached to sugarcane tiller stems like a collar and sealed with an epoxy resin (Fig. 1f). Collectors were fitted around stems at 0.5 m height, and each of the funnels was connected to a 2.5 L plastic bottle (Fig. 1e). The *SF* collectors were installed on all tillers of six plants, with an average five collectors per plant. *SF* was calculated by dividing the measured *SF* by the area occupied by each plant (1.05 m^2). Overflow of some *SF* bottles occurred for two rainfall events during the S_{II} phase. In those cases, corrections were made using the relationship between P_G and *SF* obtained from the other events.

The P_G, *TF* and *SF* were recorded on a biweekly basis, but *TF* and *SF* data could be obtained only from 40 DAH onwards: before that, the plants were less than 0.5 m high and the stems unable to support the *SF* collectors. I_L was calculated as the residual term in the canopy water budget, i.e. $I_L = P_G - (TF + SF)$ (Helvey and Patric, 1965).

2.3. Crop measurements

Plant height (h) and *LAI* were measured bi-weekly over the course of the whole sugarcane regrowth cycle. The h measurements were performed on six stems by measuring the height from the ground to the top of the tallest fully expanded leaf. The *LAI* was estimated using a Plant Canopy Analyzer (LAI-2000, LI-COR Inc., Lincoln, NE) that estimates leaf area based on canopy light transmission measured through a hemispherical lens. *LAI* measurements were made along and between rows above each of the *TF* collectors.

We used correlation analysis to verify relationships between vegetation *LAI* and h on the one hand, and the canopy water budget terms (P_G, *TF*, *SF* and I_L) for each growth phase on the other. As distributions were often not Gaussian, Spearman's rank order correlation (r_s) values were calculated to analyse relationships. All analyses were performed using the software STATISTICA v.9 (StatSoft, Inc., 2009) adopting a significance level of $p < 0.05$.