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Measurement and modelling of transpiration of a rain-fed citrus orchard under subhumid tropical conditions

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ABSTRACT

Granier type sap flow gauges were used to estimate canopy transpiration from a 7-year-old sweet orange (*Citrus sinensis* L. Osbeck) orchard in Ghana, West Africa. The aim of the study was to use sap flow based transpiration estimates in modelling the stomatal control of water transport under rain-fed and subhumid tropical conditions. Canopy conductance (g_c) of the sweet orange was calculated by inverting the Penman–Monteith equation. Both multiple linear regression and a Jarvis-type model, based on a set of environmental control functions, have been used to simulate half-hourly citrus canopy conductance. Both methods could adequately predict bulk stomatal conductance of the orchard and were suitable for use in the Penman–Monteith equation to estimate transpiration rates. In both models, the vapour pressure deficit was the dominant regulator of canopy transpiration as it explained about 80% of the variations in canopy conductance. A simple envelop function of canopy conductance as a function of the solar radiation and vapour pressure deficit was equally suitable for g_c prediction. However, the Jarvis formulation provided the best estimation of conductance compared to other models. Validation with separate data sets confirmed the good performance of these models to investigate the response of citrus to changing environmental conditions.

1. Introduction

World production of citrus, one of the most important (sub-)tropical economic horticultural crops of the world (Vu and Yelenosky, 1987), has increased rapidly in recent times (FAO, 2004; Rana et al., 2005). Similarly, citrus production in West Africa has increased by a factor greater than three since 1961, while the relative increase in cultivated area is about 2.5 in the last four decades (FAO, 2004). Increased orchard cultivation is expected to impact local and regional hydrological cycles through changes in surface albedo, leaf area, aerodynamic roughness, root depth, and stomatal behaviour (Wright et al., 1992; Giambelluca et al., 2003). The influence of land cover change may also lead to regional changes in atmospheric circulation (Giambelluca et al., 2003) with potential feedback effects of evaporation on rainfall and stream flow (Beljaars et al., 1996; Savenije, 1995, 1996; Zhang et al., 1999). According to Gong and Eltahir (1996), this local feedback mechanism contributes about 27% of precipitation of West Africa. However, the effects of increasing orchard cultivation on climate and hydrology are less known in this region.

Water is becoming increasingly a scarce resource in the West African sub-region (van de Giesen et al., 2001), therefore it is necessary to determine water use and requirements as

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well as assessing the effects of increasing orchard cultivation on the hydrological cycle. Sap flow techniques provide a simple, relatively inexpensive but robust means of continuous measurement of whole plant sap flow and help to measure transpiration from different species or a single component of mixed vegetation (Granier et al., 1996). Furthermore, measured sap flows have successfully been used to derive canopy conductance by inversion of the Penman–Monteith equation (Granier and Loustau, 1994; Cienciala et al., 2000; Lu et al., 2003; Oguntunde and van de Giesen, 2005). The canopy conductance (g_c) estimated in this way is helpful to understand the bulk behaviour of stomata in regulating canopy transpiration with respect to changing environmental conditions.

A screenhouse measurement has demonstrated that the leaf stomata conductance of sweet orange decreased significantly when exposed to drier air (Habermann et al., 2003), while Ortuno et al. (2004) reported a linear increase in sap flow with increasing vapour pressure deficit (D_ε) below 1.75 kPa in potted lemon trees. Changes in atmospheric vapour pressure may affect guard cells functionality, ultimately affecting the stomatal conductance (Zeiger, 1998). However, in the absence of water stress and high vapour pressure gradients, stomata of 'Valencia' orange tend to open with increasing temperature (Vu and Yelenosky, 1987). This seemingly good correlation with atmospheric conditions provided the basis for exploring ways of modelling orange water use with available mechanistic models.

One of the most important representation of stomatal controls, and hence prediction of transpiration from land cover in land-surface and numerical weather models, is based on the analytical model of Jarvis (1976), which was further developed by Stewart (1988) and Wright et al. (1995) among others. Therefore, the aim of this study is to use sap flow based transpiration measurements to parameterise simple models of canopy conductance suitable for inclusion in physically based models for predicting citrus transpiration. To reach this objective, estimated canopy conductance has been modelled with: (1) a multiple linear regression analysis with vapour pressure deficit (D_ε), air temperature (T) and solar radiation (S_R), and (2) a Jarvis-type model, in which a theoretical maximum canopy conductance is attenuated by a set of climatic response functions.

2. Study site and measurements

2.1. Site description

The study site is located in a 7-year-old citrus orchard in the *Kotokosu* watershed 15 km east of Ejura, Ghana. This experimental site (latitude 07°20′N, longitude 01°16′W, 210 m above sea level), a 2.3 ha citrus orchard of sweet orange (*Citrus sinensis* L. Osbeck) is within the pilot site of the Glowa Volta project, a research project designed to study "sustainable water use under changing land use, rainfall reliability, and water demands in the Volta basin" (www.glowa-volta.de). Tree spacing is 6 m × 6 m giving a density of 278 trees ha^{-1} with a mean tree height of 4.60 ± 0.70 m in 15 randomly selected trees. The leaf area index was measured as $4.64 \pm 0.95\ m^2\ m^{-2}$ using a canopy analysis system (*LAI-2000*, LiCor Ltd., Lincoln, NE). The climate is tropical monsoon characterized with distinct wet (April–October) and dry (November–March) seasons. Total annual rainfall in 2002 was about 1400 mm but the 20 years (1973–1992) average is 1264 mm with an annual mean air temperature of 26.6 °C. The daily pattern of rainfall and detailed climatic characteristics of the study watershed were presented in Oguntunde and van de Giesen (2005). The soil texture within the orchard is generally sandy clay loam.

2.2. Soil moisture and meteorological measurements

Soil moisture (θ) was regularly measured in 20 access tubes located under different covers across the watershed in 2002. Two of those access tubes were installed in the citrus orchard. A 1-m profile probe type PR1 (Delta-T Devices, Cambridge, England) was used for on the spot monitoring of soil water content. Four sensors were located at 10 cm depth intervals down to 40 cm, one was placed at 60 cm, and the last one at 100 cm depth. Meteorological variables, such as incoming solar radiation (SP-LITE pyranometer, Kipp & Zonen, Delft), net radiation (NR-LITE pyranometer, Kipp & Zonen, Delft), air temperature (50Y Temperature probe, Vaisala, Finland), relative humidity (50Y Relative humidity, Vaisala, Finland), wind speed and direction (A100R Anemometer, vector instrument, UK), were sampled at 10-s intervals and recorded as 10-min averages with an automatic weather station installed about 200 m away from the orchard.

2.3. Sap flow measurements

Sap flow was measured within a 50 m × 50 m plot, located in the center of the orchard to avoid possible edge effects, using the temperature difference method of Granier (1985, 1987). Two cylindrical probes (single measurement set), about 2 mm in diameter, were implanted in the sapwood of the tree trunks with previously installed aluminium tubes, separated vertically by 10 cm. The probes were installed on the north side of the tree, to minimise direct heating from sunshine, and then shielded with aluminium foil sealed with silicon grease to shield the probes from rainfall. The downstream probe was continuously heated with a constant power source, while the unheated upstream probe served as a temperature reference. The dissipation of heat from the upstream heated needle increases with increasing sap flow rate. During conditions of zero sap flow, such as nighttime, the temperature difference between the lower and the upper probes represents the steady state temperature difference caused by the dissipation of heat into non-transporting sapwood. A copper–constantan thermocouple measures the temperature difference between the heated upper needle and unheated lower reference needle. Whole-tree sap flux density has been computed through an empirical relationship validated and confirmed for many species (Granier, 1987; Braun and Schmid, 1999; Clearwater et al., 1999) as:

$$f = 0.0119\left(\frac{\Delta T_{max} - \Delta T}{\Delta T}\right)^{1.231} \quad (1)$$

where f ($g\ cm^{-2}\ s^{-1}$) is the average sap flow density, ΔT the temperature difference between the two probes and ΔT_{max} is