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Effects of planting density on the productivity and water use of tea (*Camellia sinensis* L.) clones
I. Measurement of water use in young tea using sap flow meters with a stem heat balance method

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ABSTRACT

Sap flow meters based on the stem heat balance method were used to measure the mass flow rates or water use in young potted tea (*Camellia sinensis* L.) plants of clones AHP S15/10 and BBK35. The meters were constructed on site and installed onto the stem or branch sections of field growing plants in an experiment originally designed to study the effects of plant population density and drought on the productivity and water use of young tea clones. The objective of the study was to use the SHB method as a first attempt to use sap flow meters for determining the water use of young tea growing in the field under well watered conditions in Tanzania. The results are reported and recommendation made for further work on using the technique.

1. Introduction

Since early in the 1990s, the tea industry in Tanzania continues to expand with substantial new planted areas especially in the Southern Highlands where tea plantations are predominantly irrigated during the long dry seasons. However, despite the extensive tea field expansions there is yet little information on plant population density and the effect on crop productivity and water use of young tea. High density planting can increase initial yields of young tea, encouraging early establishment of full ground cover and minimizing water losses due to surface evaporation and run-off. Although sap flow meters have been used to measure the water use of many crop plant species adoption of this technology in tea is very limited.

There are significant developments of techniques to measure directly sap flow in plants in order to quantify with precision the total amount of water transpired (Swanson, 1994). Briefly, there are two methods for sap flow measurements: the *heat pulse velocity* (HPV) based on the determination of sap velocity within a stem section (Huber, 1932; Dugas, 1990) which is invasive and may be destructive to the plant, and the *stem heat balance* (SHB) which estimates mass flow rates (Cermak et al., 1973; Sakuratani, 1984; Baker and van Bavel, 1987; Steinberg et al., 1989; Ishida et al., 1991; Batho et al., 1994; Boersma and Weibel, 1995). In a detailed review, Swanson (1994) reported that in recent years, techniques have been developed to measure the sap flow rate in a number of woody plant species including herbaceous plants (Sakuratani, 1984) and poplar (*Populus* spp.) clones (Souch, 1996), providing

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accurate quantification of the amount of water transpired. The main advantage of the SHB technique is that sap flow meters are non-destructive to the plants and have lower costs than other methods, including weighing lysimeters (Cermak et al., 1973, 1984; Sakuratani, 1981; Swanson, 1994).

The SHB method uses a small heater wrapped around the plant stem or branch section to provide a heat input into the section. Heat storage in the section may also be significant on trees with stem diameters greater than 25 mm, but this is negligibly small at smaller diameters (Batho, 1993; Batho et al., 1994; Grime et al., 1995). Thus if a known amount of heat is supplied into a stem section and a constant amount of sap (water) flows through the section during the process of transpiration, the temperature of the sapwood will reach a steady value which is inversely proportional to the water flow (Cermak et al., 1984; Swanson, 1994; Sakuratani, 1984). Therefore, under ideal conditions the amount of heat energy carried upwards out of the stem section (by conduction) by the mass flow of water will be equal to the amount of heat energy input to the section (Cermak et al., 1984; Batho et al., 1994). The objective of the current study was to use the SHB method described in detail by Weibel and Devos (1994), Batho et al. (1994) and Kigalu et al. (1995) to measure sap flow or transpiration rates in young tea plants in the field.

2. Materials and methods

2.1. Description of the site, climate and soils

The field trials reported here were conducted at Ngwazi Tea Research Station, NTRS (latitude 8°32′S, longitude 35°10′E, altitude: 1840 m a.s.l.) in the Mufindi District in Southern Tanzania. A full description of the climate, the weather and soils of the site is provided by Stephens and Carr (1991a,b), Burgess (1992), Burgess and Carr (1996), Kigalu (1997). Briefly, the climate of the area can be divided into three main seasons based on rainfall and temperature. More than 95% of the annual rainfall, ranging from 800 to 1100 mm occurs between the end of November and May. The corresponding monthly mean air temperature is 16–19 °C. The dry season can be divided into two: cool (13–16 °C) from June to August and warm (16–19 °C) from September to November.

The experimental area is on weathered soils classified as a Xanthic ferralsol (Baillie and Burton, 1993; FAO-UNESCO, 1988) with a kaolinitic sandy clay down to 0.15 m depth and friable clay below. The mean soil pH was 5.4 and 5.8 at 0.15 and 0.70 m depths, respectively, which is suitable for growing tea (pH 4.9–5.6). The volumetric water content of the soil at a water potential of −10 kPa were low for clay soils and more typical sandy loam, corresponding to field capacity (FC; −10 kPa), increased with depth from 24.7% in the top 0.15 m to 32.5% at 1.80 m where the silt and clay content was higher. The available water content held between field capacity (FC; −10 kPa) and permanent wilting point (PWP; −1500 kPa) ranged from 110 to 122 mm m^{-1} 1 in the top 2 m of soil to 93 mm m^{-1} at 2.70 m.

Regarding management of the tea bushes in the main field experiment before the field sap flow trials, fertiliser was applied in February and July 1995 on a per unit area basis at the rate of 100 kg N ha^{-1} as N:P_2O_5:K_2O in the ratio of 2:1:2. Also, in 1995 foliar zinc oxide (ZnO) was also uniformly applied at the rate of 4.5 kg ZnO ha^{-1} in three equal splits to correct for zinc deficiency. The experimental field was kept weed free by regular hand weeding and herbicide application.

At NTRS, overhead sprinkler irrigation of young tea may start in mid May to the end of November/December in bad years when rains stop early and start late. Irrigation scheduling and calculation of the potential soil water deficit (SWD, mm) are based on the soil water balance Eq. (1) described in detail at the site (Stephens and Carr, 1989; Burgess, 1992):

$$\mathrm{SWD_i} = \mathrm{SWD_{i-1}} - R_i - I_i + D_i + \mathrm{ET_i} \tag{1}$$

where SWD_{i-1} is the soil deficit on the previous ((i − 1)th) day, R_i the rainfall, I_i the irrigation applied, D_i the drainage and $\mathrm{ET_i}$ is the crop evapotranspiration all recorded on the ith day and measured in mm. The value of I_i on each date of irrigation was recorded in 56 catch cans which were spaced symmetrically across the experiment. Any irrigation or rainfall received when the soil was still at field capacity (i.e., SWD = 0) was assumed to drain instantly through the soil profile. Movement of surface water (run-off) between plots or treatments was assumed negligible as it was prevented by micro-catchments dug between the rows of tea bushes, and by the accumulated mulch and tea leaf liter. The value of $\mathrm{ET_i}$ was calculated from the daily evaporation pan measurement (E_{pan}, mm) multiplied by a crop factor K_c. The value of E_{pan} measured at NTRS gives a good estimate of the water loss from a mature stand of tea with or close to complete ground cover, implying negligible evaporation from the soil surface (Stephens and Carr, 1991a,b; Burgess, 1992). It was assumed that losses due to transpiration were directly proportional to the ground cover by the canopy, and K_c was assumed to be equal to 1.0 on the day of irrigation due to soil evaporation losses (Dagg, 1970; Ritchie, 1972). The soil water deficit (SWD; mm), incident solar radiation (S; MJ m^{-2} d^{-1}) and wind speed (u; m s^{-1}) were calculated daily from measurements recorded at a nearby NTRS meteorological weather station.

2.2. Features of the sap flow meters

This study used the SHB technique described in detail by Weibel and Devos (1994) and Batho et al. (1994) for the first time in tea in Tanzania. Briefly, the sap flow meters were constructed on site based on the SHM method following the procedures described by Batho et al. (1994) as briefly illustrated in Fig. 1, representing a schematic diagram of a sap flow meter attached to a stem or branch section with symbols briefly described as follows.

The sap flow rate (F; g s^{-1}) was calculated from the energy balance across the sap flow meter (Eq. (2)) which states that:

$$F = \frac{[P_{\mathrm{in}} - Q_{\mathrm{cd}} - Q_{\mathrm{r}} + Q_{\mathrm{s}}]}{(C_{\mathrm{s}} \times dT_{\mathrm{sap}})} \tag{2}$$

where using the symbols illustrated in Fig. 1: $Q_f = [P_{\mathrm{in}} - Q_{\mathrm{cd}} - Q_{\mathrm{r}} + Q_{\mathrm{s}}]$ is the amount of heat (W) transported in the moving sap at differential temperature dT_{sap} given by $dT_{\mathrm{sap}} = [dT_a + dT_b]/2$ (°C), where dT_a and dT_b are temperature differentials of the sap up and down stream measured by thermocouples a and b, respectively. P_{in} is the heater power