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Calibration of compensation heat pulse velocity technique for measuring transpiration of selected indigenous trees using weighing lysimeters

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ABSTRACT

The compensation heat pulse velocity (CHPV) is one of the most widely used methods to measure sap flow in woody plants. However, the accuracy of this method has not been fully explored especially for indigenous tree species of South Africa. The aim of this study was to evaluate the accuracy of the CHPV method in quantifying tree transpiration for selected tree species. Three indigenous trees sampled in a monolith form; black karee (*Sersia lancea*), buffalo thorn (*Ziziphus mucronata*) and wild olive (*Olea africana*) grown on weighing lysimeters (1 m × 1 m × 1.3 m) were installed with CHPV probes to measure sap flow on the stem half hourly, simultaneously with lysimeter measurements of transpiration. The surfaces of the lysimeters were covered with a 10 cm layer of Styrofoam, overlain by a 2 cm layer of gravel to minimize evaporation to a negligible level. Both the lysimeter and CHPV measurements were divided into two sets. The first set was used to develop tree specific calibration equations as well as an equation combining the three species used, here called a combination equation. The second set of data was used for validating the equations. Transpiration rates ranged from negligible at night to daily peaks of 3.5, 1.7 and 1.4 $L\,h^{-1}$ for buffalo thorn, black karee and wild olive, respectively. Good agreement indices between CHPV and lysimeters were obtained when using both the tree specific equations and combination equation across species (D = 0.778–1.000, RMSE = 0.001–0.017 $L\,h^{-1}$, MAE < 0.001 $L\,h^{-1}$ and MBE = −0.0007 to 0.0008 $L\,h^{-1}$). It was concluded that the CHPV method can accurately measure tree water use, and therefore can be useful for water resources management in forested areas.

1. Introduction

There are various ways of quantifying transpiration of field crops, but, for trees, sap flow measurement remains the most prominent. An array of automated thermodynamic techniques which use heat as a tracer of sap flow, have for several decades been employed to quantify water fluxes in the soil – plant – atmosphere continuum at the tree scale. Amongst the thermal based methods of sap flow measurement, the most common are the compensation heat pulse velocity (CHPV) (Huber and Schmidt, 1937; Marshall, 1958; Swanson, 1962; Swanson and Whitfield, 1981; Fernández et al., 2001; Green et al., 2003) and thermal heat dissipation (THD) (Granier, 1987; Lu et al., 2004) methods. These methods are user friendly and cause minimal damage to the tree stems (Granier, 1987; Green et al., 2003). The CHPV method also has an advantage of using less energy as it works on pulses of heat as opposed to the continuous heating principle of the THD (Fernández et al., 2006; Nourtier et al., 2011). The CHPV method has also been employed to measure transpiration of local and exotic commercial forest species of South Africa such as *Eucalyptus species* (Morris et al., 2004; Wildy et al., 2004) and *Jatropha curcas* (Gush, 2008). The accuracy of the CHPV method in measuring sap flow in indigenous trees of South Africa has unfortunately not been explored.

Lysimetry is considered as one of the standard methods to quantify plant water use (Johnson et al., 2005; Clawson et al., 2009), especially if their load cells are correctly calibrated (Misra et al., 2011) and can account for various components of the soil water balance while keeping other components under control (Dlamini et al., 2016). Even though lysimeters can accurately measure plant water use and can be applied in a number of studies such as soil nutrients, evaporation and drainage analysis, it has its own drawbacks such as high cost and limited replication. The indigenous trees in South Africa contribute significantly to the economy of the country in the form of goods and services (Gush et al., 2015). However, knowledge on the transpiration of most of these indigenous trees is limited (Dye et al., 2008). The objective of the present study was to evaluate the accuracy of CHPV method in measuring transpiration of selected indigenous tree species of South Africa.

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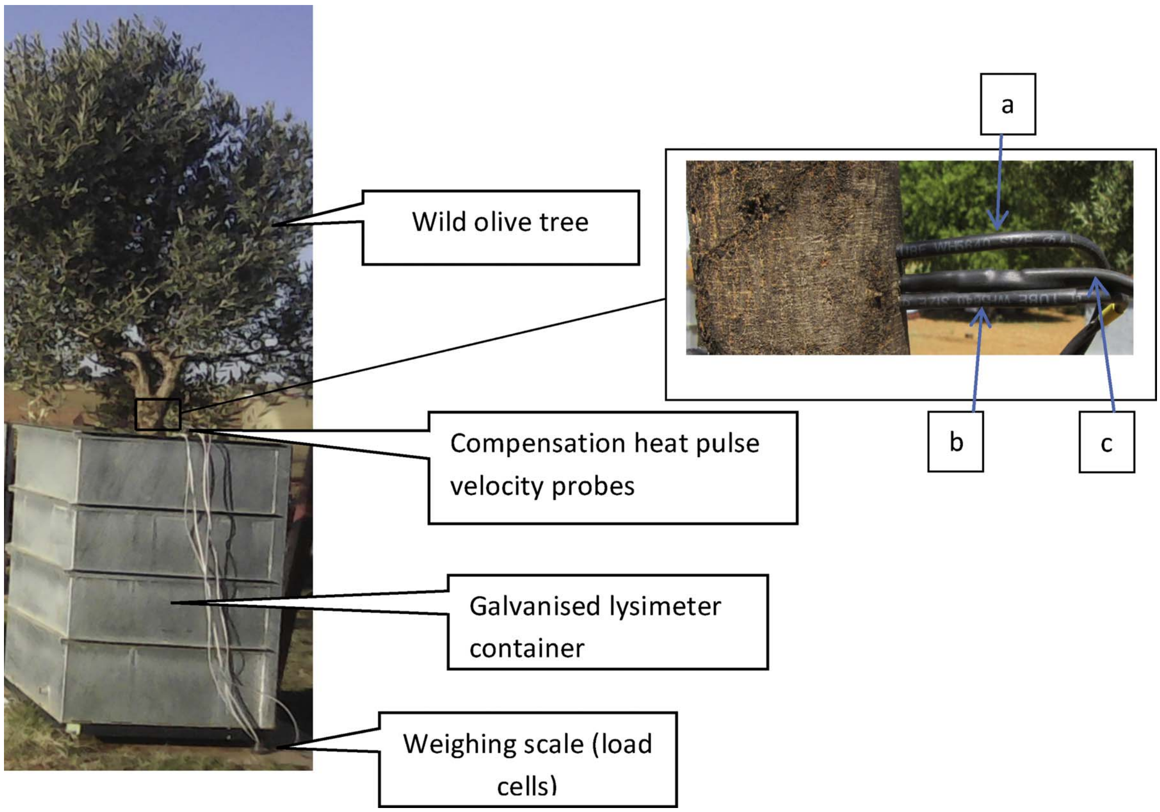

Fig. 1. An illustration of the experimental setup showing a wild olive tree installed with compensation heat pulse velocity sap flow probes, growing in a galvanized lysimeter container. Insert: a = downstream probe, b = upstream probe and c = heater probe.

2. Materials and methods

2.1. Study site description

The study was conducted at Kenilworth Experiment Farm (latitude: −29.02°, longitude: 26.15° and altitude: 1354 m) in the Department of Soil, Crop and Climate Sciences at the University of the Free State, in Bloemfontein, South Africa. This experiment was implemented over a period of 107 days during the summer season, from 9th December 2016 to 25th March 2017. The study area, with a mean annual precipitation of 528 mm mostly falling between October and April and average reference evapotranspiration (ETo) of 1 604 mm is classified as warm semi-arid (Thornthwaite, 1948; UNESCO, 1979; Peel et al., 2007). The mean annual minimum and maximum air temperatures are 11.0 °C and 25.5 °C, respectively.

2.2. Trees and lysimeter facility

An illustration of the equipment setup during the experiment is shown in Fig. 1. Three indigenous trees of dominant species within the study area; black karee (*Sersia lancea*), buffalo thorn (*Ziziphus mucronata*) and wild olive (*Olea africana*) were transplanted from within a radius of 3 km away from the study area into lysimeters (January, 2015) with their natural soil monoliths. On average, the trees were 4 m (2.5 m–5 m) in height and stem diameter between 90 and 120 mm. The ages of the trees were estimated to be within the range of 7–10 years. The dimensions of lysimeters were 1 m × 1 m and 1.3 m in depth. The lysimeter containers with their contents (soil and trees) were placed on top of Loadtech LT 1300 type of load cells supplied the Loadtech Load Cells (Pty) Ltd, South Africa. The load cells were placed on top of flat concrete slabs to ensure they remain level during the experiment. The soil surface on top of the monoliths was covered by a 10 cm layer of Styrofoam and then overlain by a 2 cm layer of gravel to minimize evaporation to negligible levels.

2.3. Compensation heat pulse velocity theory

In the CHPV method, two temperature sensors are inserted at unequal distances, downstream and upstream of a radially inserted heater in the stem. The upstream probe is placed closer to the heater (5 mm) and increase temperature faster (through conduction) than the downstream probe (placed 10 mm away) whose temperature change is influenced by transfer of energy by conduction through the wood and convection through the flowing sap whenever a heat pulse is released by the heater. The time taken by the two sensors to record equal temperature rise is related to the movement of sap flow and hence the plant water uptake (Swanson and Whitfield, 1981; Green et al., 2003). The heat pulse velocity (V_h) in cm h^{-1}, is calculated from the time (t) taken to record equal temperatures by the sensors at distances (X_u), upstream and (X_d) downstream as:

$$V_h = \frac{X_u + X_d}{2t} \tag{1}$$

V_h is basically indirectly proportional to t. This implies that if the sap movement is high, the convection of the heat pulse through the moving sap will be enhanced and then the recorded t will be minimal. Early studies revealed that the movement of the sap is a few folds more than the movement of heat in terms of sap flow density through the sapwood because the heat is also dependent on conduction through the stationary, interstitial tissue between the xylem vessels or tracheids. Marshall (1958) established a relationship between V_h and the sap flux (Q) and expressed it as:

$$Q = au = (\frac{\rho_{sm} c_{sm}}{\rho_s c_s}) V_h \tag{2}$$

where a is the fraction of the cross sectional area of the conducting