Validation of heat dissipation and heat pulse sap flow methods in *Eucalyptus grandis* Hill ex Maiden

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Background and focus

Ecological and physiological research aiming to understanding the complex relationships between plant ecosystems and their environment, rely on the proper determination of plant-level processes, such as sap flow within the conducting tissues; used to determine total water use at the plant level

Two of the most commonly used categories of sap flow methods are the heat dissipation method (HDM) and the heat pulse methods (HPM), each category with different methods with varying degrees of complexity and applicability

The HDM developed by Granier, 1985 is known to perform well when sap flux density (cm^3 cm^{-2} h^{-1}) rates are high, but significantly overestimates low sap flux rates. Conversely, the Heat Ratio Method (HRM), a HPM, developed by Burgess et al, 2001, performs well at low sap flux rates, but overestimates high sap flux rates

Another major difference, and limiting factor between these two methods is power consumption: HDM use constant current, and require large amounts of power, HPM on the other hand, can function for weeks at the time with a single 12 V 12Ah rechargeable battery

Despite the development of sap flow techniques, currently, no low-power method is able to properly estimate both high and low sap flux rates and today, such method is considered the holy grail in sap flow research. However, a modification to the algorithm used by the HRM, referred to as the maximum heat ratio (MHR, S. Burgess *pers. comm.*), has shown promising initial results in controlled laboratory set ups

Goals and methodology

Our goals for this study were: a) to assess the effects of reducing the power applied to HDM sensors on data quality, b) to compare MHR and HRM, and determine the precision of MHR under high sap flux rates and c) develop calibration equations for both HDM and HPM (MHR only) for *E. grandis*

This study was conducted at the Concordia Research Station of the National Institute of Agricultural Technology (INTA), in Concordia, Entre Rios, Argentina on May of 2015

Ten, one-year-old *Eucalyptus grandis* trees, and two, 40 cm long stems (used as zero flow controls) of the same species were harvested from an experimental plantation at INTA. Their diameters at breast height (DBH) ranged from 3.9 to 6.3 cm, which covered the DBH range observed in nearby one-year old *E. grandis* plantations

Sap flux density was estimated every 15 minutes with HDM and HPM sensors installed on each tree, and simultaneous gravimetric water use was monitored from 6AM to 9PM using a modified tree-cut method (Figure 1), to generate calibrated equations

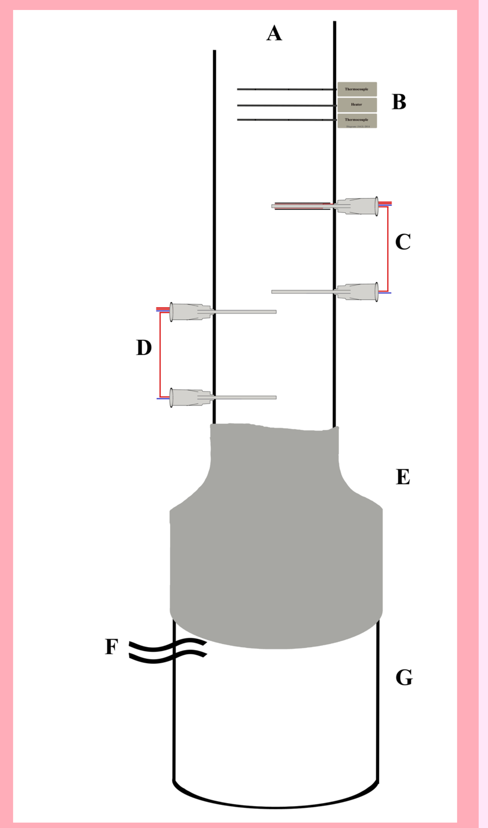


Figure 1. Diagram of the modified tree-cut experiment. A = the stem, B = HPM, C = HDM, D = NTG sensor, E = tire tube, F = tubing connected to 20 L bucket and G = FVR

Results

Heat dissipation

Changes in the current applied to HDM sensors, did not have a negative effect on sap flux estimates. However, proper determination of the maximum temperature (mV) for each adjustment period was essential

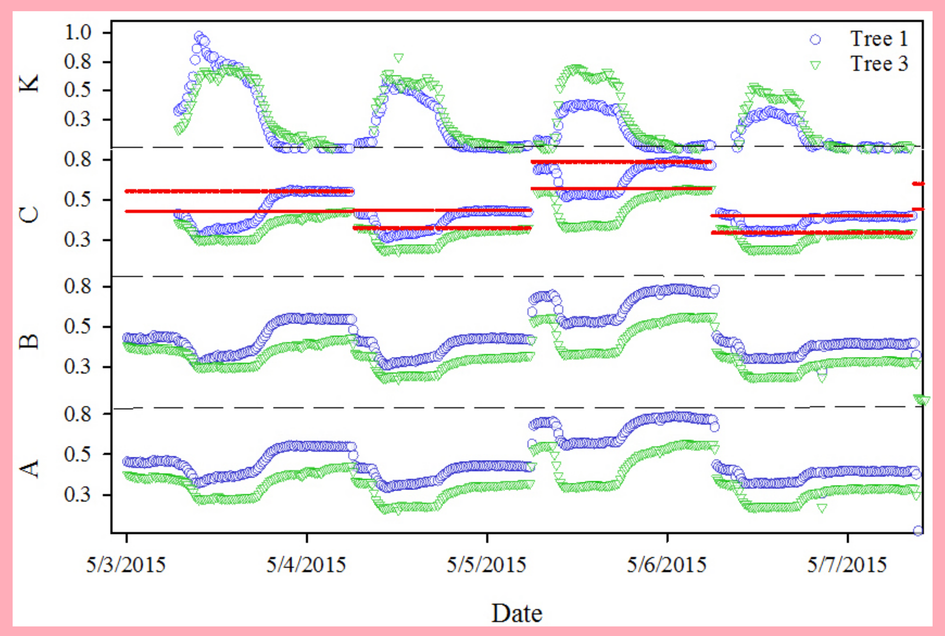


Figure 2. Main steps of the algorithm used to estimate sap flux density for the HDM sensors. Only data from trees 1 and 3 are shown. A is the raw data, or the T values collected from HDM sensors; B is the data adjusted following Clearwater et al. 1999; C is the data after equilibration periods were deleted, and where DiffTmax was identified for each adjustment period; and K is the flow index, prior to the estimation of sap flux density.

In general, sap flux estimates of HDM had less variability between measurements taken on the same tree, compared to HPM estimates. However, daily estimates of water use using HDM were ~50% lower, compared to HPM

For both methods, calibrated equations with high R^2 between predicted and observed values did not necessarily result in accurate estimates of total water use per day

Heat pulse

The alternative MHR method, significantly increased the measuring range of the HRM

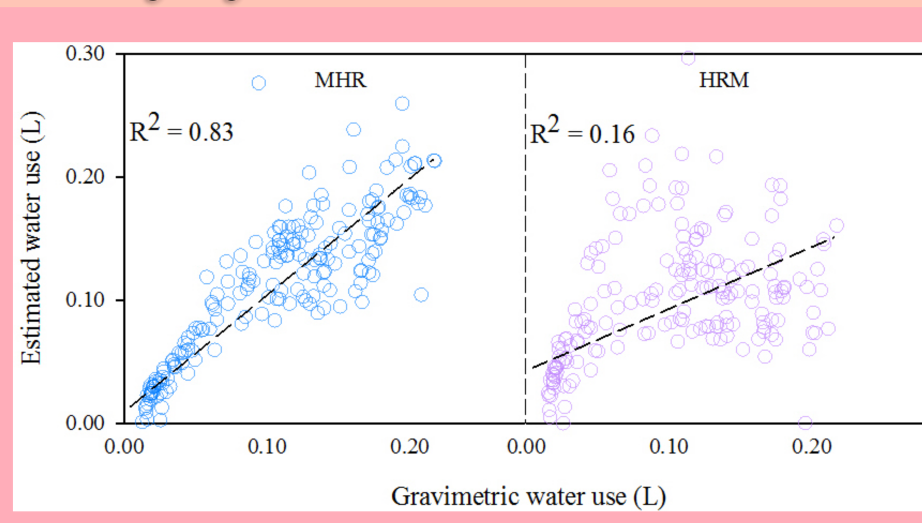


Figure 2. Regression between the gravimetric water use, and water use estimates using both MHR and HRM

Compared with HRM, MHR performed satisfactorily under conditions of both high and low sap flux densities. Sap flux densities higher than 90 cm^3 cm^{-2} h^{-1} were satisfactorily measured with MHR

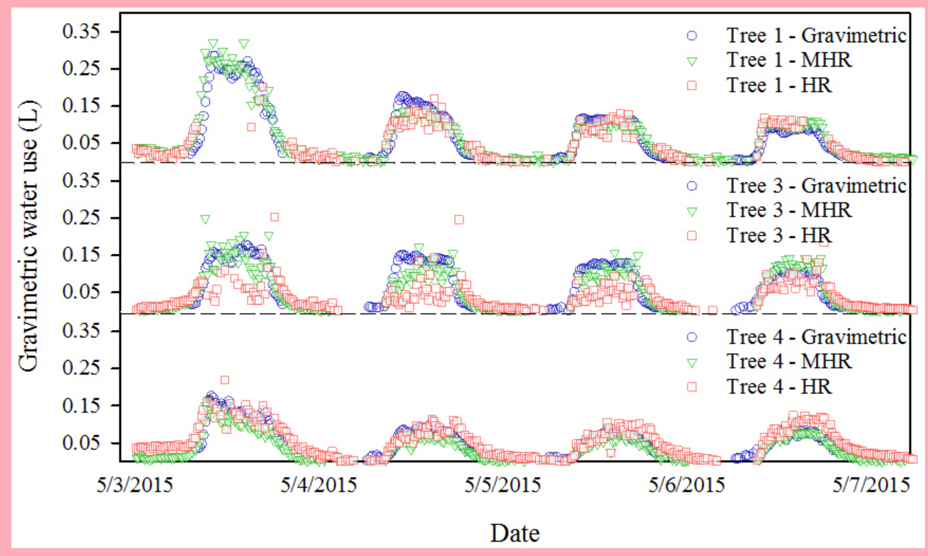


Figure 3. Comparison of sap flow estimates from HRM and MHR, with gravimetric water use measurements.

Under sap flux densities of ~50 (cm^3 cm^{-2} h^{-1}), the estimates for both methods were highly correlated (R^2=0.92)

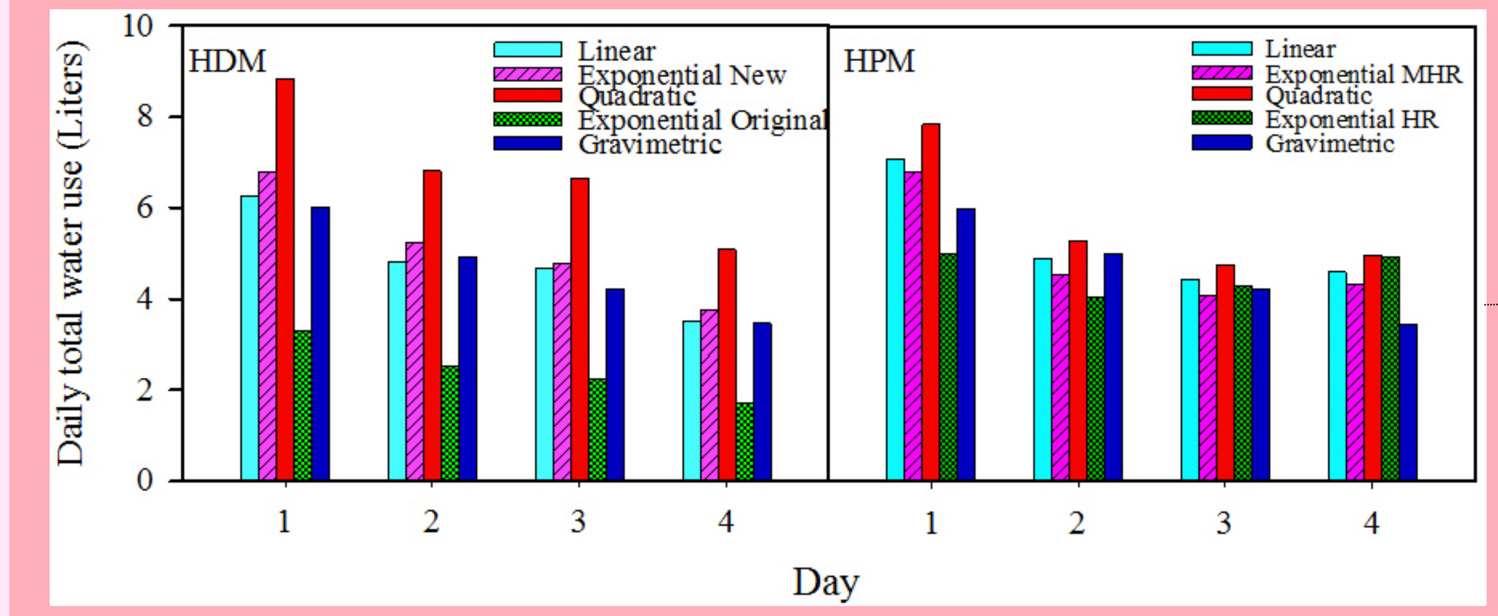


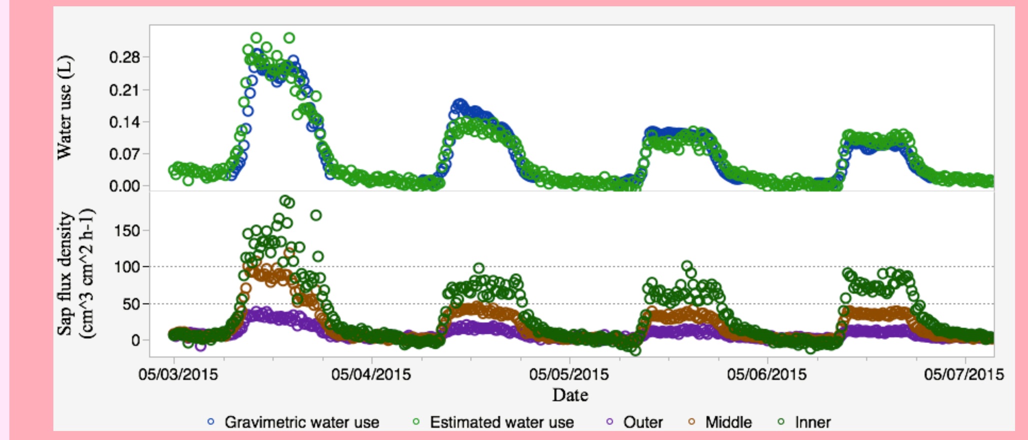
Figure 3. Total water use estimates for each calibrated equation using HDM and HPM sensors

We observed higher variability of predicted values among calibrated equations of HDM, than HPM

For HDM and HPM, an linear equation provided the most accurate estimates of daily water use

Future work

Due to the nature of our experiment, we were not able to control for sap flux densities within specific sections of the sapwood, and as a result our calibration focused on sap flow (L h^{-1}) estimates



Estimated vs Observed

Estimated sap flux densities (cm^3 cm^{-2} h^{-1})

Our results indicate that MHR, was able to read sap flux densities, higher than 100 cm^3 cm^{-2} h^{-1}, specially in the outer parts of the sapwood. A comparison of observed vs estimated water use values using these high sap flux estimates, provides an initial validation for the method

Future studies should focus on: validating, (under controlled conditions and for various wood types), the range of sap flux densities that MHR is capable of measuring, as well as generating wound correction factors for this alternative method

Conclusions

A modification of the tree-cut method allowed us to increase the number of possible replicates and perform high-precision measurements of plant water uptake. With additional equipment, our set up also has the potential to be used in plant physiological studies on tree hydraulics, which often use small branches due to the technical challenges of regulating water flow in stems

Our results indicate that using the original parameters, HDM sensors underestimated flux density and sap flow by nearly 50%. However, after calibration, our estimate of daily water use had less than 3% error using a simple linear regression between flux coefficient (K) and flux density. Using calibrated parameters and the exponential equation commonly used in HDM sensors, our estimates of total water use were within 10% of observed totals. For both methods, our results indicate that a high R^2 between estimated and observed values does not result in accurate estimates of total water use per day

Changes in the current applied to the heaters of HDM sensors significantly changed the patters of the raw data; however, as long as the maximum temperature (mV) was properly determined for each period when the current was modified, estimates of K (and flux density prior to calibration) were not affected

For HPM, using the maximum observed temperature after the release of the heat pulse (MHR), instead of the average from 60-100 s according to the original algorithm, allowed us to increase the measuring range of this method. While we did not control for flux density within the stems, our results provide an initial validation for the new algorithm. Further research and experiments under controlled conditions on different species and wood anatomies are needed to validate the applicability of this method under different environmental conditions.

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