https://doi.org/10.5194/hess-2019-257
Preprint. Discussion started: 18 June 2019

Hydrology and Earth System Sciences
Open Access
Discussions

Technical note on long-term probe misalignment and proposed quality control using the heat pulse method for transpiration estimations

Elisabeth K. Larsen[1,3], Jose Luis Palau[1], Jose Antonio Valiente[1], Esteban Chirino[2] and Juan Bellot[3,4].

[1]Mediterranean Centre for Environmental Studies (Foundation CEAM), Charles R. Darwin 14, Parque Tecnològico, 46980 Paterna, Valencia, Spain
[2]Faculty of Agricultural Sciences, Lay University Eloy Alfaro of Manabí, Ave. Circunvalación, Vía San Mateo, Manta 130802, Ecuador
[3]Department of Ecology, University of Alicante, Apdo. 99, E-03080 Alicante, Spain
[4]IMEM Ramón Margalef, Department of Ecology, Faculty of Sciences, University of Alicante, 03080 Alicante, Spain

Correspondence to: Elisabeth K. Larsen (eli@ceam.es)

Abstract

Whole-plant transpiration is a crucial component in the hydrological cycle and a key parameter in many disciplines like agriculture, forestry and ecology. Sap flow measurements are one of the most widely used methods to estimate whole-plant transpiration in woody species due to its wide application range and its ready automation for continuous data readings. Several different methods have been developed and adjusted to different climatic conditions and wood properties. However, the scientific literature also identifies several sources of error in the method that needs to be accounted for; misalignment of the probes, wound to the xylem, thermal diffusivity and stem water content. This study aims to integrate probe misalignment as a function of time to improve readings during long-term measurements (> 3 months). We conclude that even when geometrical misalignments errors are small, the introduced corrections can imply an important shift in sap flow estimations. Additionally, we propose a new set of statistical record to be recorded during the measurement period to use as a quality control of the heat ratio readings obtained from the sensors. By using standard deviation and slope as quality indicators we concluded that no general time limit can be decided for all sensors but should rather be determined from individual performance over time.

1. Introduction

Plant transpiration is a key process in the hydrological cycle and in forest ecosystems it is often the largest component of total evapotranspiration (Jasechko et al., 2013). Accurate estimations of transpiration are still difficult to obtain, and field assessments of transpiration estimations are therefore crucial in hydrological planning as well as in forestry, ecophysiological research and climate forecasting. Sap flow measurement is one of the most widely used techniques to estimate whole plant transpiration in woody species because it is a readily automated for continuous readings and is not limited to single leaf measurements (Forster, 2017). Although some sap will go to stem and leaf storage, it is estimated that 99% is lost through transpiration, and sap flow measurements can therefore be used to directly estimate transpiration values

https://doi.org/10.5194/hess-2019-257
Preprint. Discussion started: 18 June 2019

Hydrology and Earth System Sciences Discussions

(Forster, 2017). In addition, sap flow sensors estimate plant transpiration rates regardless of the orographic complexity and atmospheric conditions of stability or stratification, which can hinder the direct measurement of transpiration flows in forest environments.

There are a range of different approaches to sap flow measurements, and methods vary between heat dissipation (HD), steam heat balance (SHB), trunk segment heat balance (THB) and heat pulse velocity (HPV). However, they are all based on tracing heat within the xylem (Burgess et al., 2001; Davis et al., 2012; Forster, 2017). Marshall (1958) developed a theoretical method to determine sap flow from the thermal diffusion and dissipation theory of heat pulses in heterogeneous material. His theory relies on calculating the heat ratios measured in two parallel thermocouples aligned vertically and symmetrically with respect to a line heater along the direction of the xylem. Burgess et al. (2001) developed an improved HPV technique, termed the heat ratio method (HRM), based on the Marshall (1958) methodology, which is sensitive to the direction of sap flow and is capable of measuring low and reverse rates (Burgess et al., 2001), which is not possible using energy balance methods like eddy-covariance and which often is the case for nightly values (Burgess et al., 2001; Novick et al., 2009). Burgess et al. (2001) developed two steps of corrections for sap flow calculations by considering probe misalignment and wounding (caused by the implementation of the sensors). By accounting for these sources of error and additionally estimating the stem moisture content and radial variability, the heat ratio method (HRM) has been evaluated the heat pulse velocity method (HPV) with highest accuracy, although with a tendency of underestimating transpiration values (Forster, 2017).

Previous studies have suggested additional solutions for probe misalignment (Ren et al., 2017), or for determining thermal diffusivity (Vandegehuchte and Steppe, 2012), and correcting for heterogeneous heat capacity in wood (Becker and Edwards, 1999). However, we suggest attention should be given to check the accuracy of the heat pulse ratio itself, in which the rest of the methodology is built on. In addition, we found it necessary to develop a dynamic probe misalignment correction method. One way to account for changes over time has been to reinstall sensors throughout the study period (Moore et al. 2010), however there is little information to be found on the exact interval of which this needs to happen (Vandegehuchte and Steppe, 2013), and for continuous measurements this will interrupt the dataset. The adjustment proposed here, built on the calculations of Burgess et al. (2001), is necessary when monitoring transpiration continuously for more than 3 months because wood properties, the heterogeneity of the xylem and plant tissue growth might further misplace the sensor after its implementation (Barrett et al., 1995). Burgess et al. (2001) corrected for linear probe misalignment *in situ*. This correction must be effectuated during zero flow. Actual probe placement is therefore suggested to be calculated one time, usually at the end of the experiment when the root system can be severed to enforce zero flow (Burgess et al., 2001). However, this solution is not suitable for long term measurements, as the misplacement will change over time (Ren et al., 2017), or when intrusive methods are not an option. Thus, the objective of this research is firstly, to develop a statistical filtration method to ensure the quality and consistency of the measurements over time, and, secondly, to implement a modified version of the probe misalignment calculation for sap flow series longer than 3 months.

https://doi.org/10.5194/hess-2019-257
Preprint. Discussion started: 18 June 2019

This methodological paper is structured in two parts: the first one, dealing with the statistical analysis of long-term time series of heat pulse ratios to ensure the quality of data and their stability over time; the second part, proposing an adaptation of the method developed by Burgess et al. (2001) to contemplate a dynamic probe misalignment correction for the heat ratio method (HRM). The aim is to obtain a more precise calculation of transpiration by parameterising the probe misalignment as a function of time to correct for the effect of tree growth.

2. Materials and method

2.1 Field site

This study was carried out in the Turia river basin, Eastern Spain (39º57'45" N 1º8'31" W), in a Mediterranean climate. Average annual rainfall is 475 mm, average annual maximum and minimum temperature is 15.5 ºC and 4.4 ºC respectively. Sap flow sensors were installed in four pine trees (*Pinus halepensis* Mill.) according to the heat ratio method (HRM, Burgess et al., 2001). Three needles, one heater and two thermocouples (0.13 cm x 4 cm), were drilled into the uphill side of each tree trunk. Since *P. halepensis* has a higher sap velocity average near the cambium with the velocity steady declining nearer to the heartwood (Cohen et al., 2008), sensors were installed at 20 mm depth below the cambium for average sap velocity rates, as estimated by Manrique-Alba (2017). A metal plate was used as guide to assure a 0.6 cm spacing between the drilling holes. *P. halepensis* selected had a mean diameter of 24.5 cm at breast height (150cm). Continuous measurements were obtained from April 2017 to December 2018.

2.2 Construction of the sensors

The thermocouples were made after Davis et al. (2012), with a type E junction of chromium and constantan. The E type has a higher accuracy, stronger signal and more stability than the type K (Davis et al., 2012). The wires of the thermocouples were soldered together at temperatures not surpassing 200°C and placed 2 cm inside a glass tube (0.1 cm x 4 cm) and into a needle (0.13 cm x 4 cm). The heater was made of a constantan wire of 20 cm coiled around a 7 cm long aluminium wire before placed inside a needle of 4 cm. The wire-ends were then soldered on to an electrical cable. Another resistance of 10 ohms were soldered onto to the cable to get a total resistance of 20 ohms. The heater was connected to a 12 V battery and delivered 7.0 W of power. All three sensors were connected to a CR800 datalogger (Campbell Scientific Inc., USA).

2.3 Quality control of heat pulse ratios

Marshal (1958) parameterised the heat pulse velocity (*V*) in the HRM as a function of time following a heat pulse, and the instantaneous ratio of the increase of temperature (from the temperature prior to the release of the thermal pulse) at the downstream and upstream, v_1 and v_2 respectively, from a line heater:

$$V = \frac{4Kt \ln\left(\frac{v_1}{v_2}\right) - (x_2^2 + y_2^2) + (x_1^2 + y_1^2)}{2t(x_1 - x_2)} \qquad [1]$$

where *K* is the thermal diffusivity, *t* is time from the release of thermal pulse, (x_1, y_1) and (x_2, y_2) are the relative positions of the thermocouples to the line heater (considering x-axis along the xylem and y-axis the perpendicular direction both to the xylem and to the heater line), and v_1,v_2 represents the temperature increases following the heat release, in the downstream and upstream thermocouple respectively.

If probes are installed symmetrically above and below the heater line, $x = x_1 = -x_2$ and $y_1 = -y_2$, the equation 1 simplifies into a function not dependent on time:

$$V = \phi \ln\left(\frac{v_1}{v_2}\right) \quad [2]$$

$$\phi = \frac{K}{x}$$

where $\boldsymbol{\phi}$ is, a priori, a constant only depending on the placement of the probes and on the thermal diffusivity of both the xylem and the material used in sensors.

The "perfect symmetry" assumption renders that HPR remains constant with time if sap flow velocity (*V*), thermal diffusivity (*K*) and probe positions (in both, x and y directions) have negligible variations during the time following each heat pulse (Marshall, 1958). However, Burgess et al. (2001) describe how empirical results initially differ from the ideal approach described by equation 2, although they converge asymptotically at least 60 seconds after the heat pulse release and, for at least, 40 seconds more (until 100 seconds after the heat pulse release). A visual inspection of heat pulse velocities (*V* in equations 1 and 2) do not necessarily give enough information to decide if measured values are a good representation of the sap velocity or not. On these premises, we have built a methodology utilising a quality check of systematic sap flow measurements by means of a statistical analysis performed on the instantaneous values acquired between 60 and 100 seconds. Hereafter we will denote the averaged instantaneous heat pulse ratio between 60 and 100 seconds as HPR. Threshold values were established for the relative standard deviation (RSD) and the slope of the time evolution of instantaneous heat pulse ratios.

2.3.1 Logging specifications

The proposed analysis to ensure the reliability of long time series of sap flow measurements require the storage of statistics that are not usually recorded (as it is considered unnecessary). The datalogger to be used must have a minimum performance of the storage capacity (memory), the processing speed of the algorithm implemented (especially in the routines related to the statistical calculations to be performed). In this study a CR800 (Campbell Scientific, USA) was used. A flow chart of sampling and data log (Fig. S1) was specifically designed, programmed and implemented in the datalogger to enable the calculus that are presented in the next sections of this paper.

The RSD is statistically defined as the standard deviation divided by the mean. Therefore, we selected RSD (%) and Slope (s^{-1}) of the instantaneous ratio versus time calculated for each of the periods from 60 to 100 seconds and used for the quality control (Fig.1A and B). All HPR with relative standard deviation > 5%

https://doi.org/10.5194/hess-2019-257
Preprint. Discussion started: 18 June 2019

Hydrology and Earth System Sciences
Open Access
Discussions

and a |slope – median (slope)| < 0.003 s^{-1} were removed. The 5 % threshold was chosen to ensure that 95 % of the dataset was considered in the data processing. The slope median was taken from all slope values obtained during the measurement period. The magnitude of this slope threshold was chosen from modelled output of instantaneous ratios performed by Burgess et al. (2001), were low heat pulse velocities (5 cm h^{-1}) are shown to display a slope of 0.001. The specific threshold of 0.003 was decided upon inspection of the measurements and can be modified according to the sensor.

2.4 Correction for long-term probe misplacement

Under the assumption of "perfect symmetry", in periods when V = 0 cm h^{-1}, the ratio of the increase of temperature at the downstream and upstream from a line heater would be equal to one ($v_1 = v_2$ in equation 2). However, this is not always the case with field measurements due to misalignment of the probe or heterogeneous wood properties (Fig. 1A). Burgess et al. (2001) showed how probe placement can be estimated *in situ* with the HRM. He proposed a methodology for probe misalignment which builds on the assumption that errors arising from inaccurate probe spacing can be treated one-dimensionally. His approach assumed that the total effect of probe misalignment (in both axis directions), observed in the ratio of the increase of temperature, can be parameterised calculating an "effective" probe misalignment in only one direction (x direction, parallel to the xylem). Thus, without the assumption of "perfect symmetry", in periods when V = 0 cm h^{-1} equation 1 takes a more simplified form:

$$4Kt\ln\left(\frac{v_1}{v_2}\right) = (x_2^2 + y_2^2) - (x_1^2 + y_1^2) \qquad [3]$$

Which becomes equation (4) if $y_1 = -y_2$

$$4Kt\ln\left(\frac{v_1}{v_2}\right) = x_2^2 - x_1^2 \qquad [4]$$

As it is unknown if the misalignment is in x_1 or in x_2, the calculation is repeated twice, assuming first that x_1 is correct when calculating actual x_2 placement and vice versa. Two different heat pulse velocities, V_1 and V_2, are then derived (using equation 1 but with the assumption $y_1 = -y_2$) for both misalignments x_1 and x_2 obtained; and the final V provided as their average.

Zero sap flow conditions can either be imposed artificially by severing the root or stem (Burgess et al., 2001), or assumed when atmospheric vapour pressure deficit (VPD) is close to zero, the soil is saturated, usually after substantial precipitation, and values taken at predawn to avoid any biophysical driving force (Forster 2017). Saturated soil is a necessary criterion due to the possibility of reverse flow at night-time. If not considered, low HPR values representing reverse flows can be interpreted as zero flow. The latter approach allows the parameterisation of misalignment as a function of time (equation 5), if several calculations of x_1 and x_2 (equation 4) are performed. By applying equation 4 at varies times throughout the measurement period, it is possible to calculate a linear regression using the estimation of Burgess et al. (2001) for misalignment for each of the thermocouples:

https://doi.org/10.5194/hess-2019-257
Preprint. Discussion started: 18 June 2019

Hydrology and Earth System Sciences
Open Access
Discussions

$$x_i = m_i\, d + n_i \quad ; \quad i = 1, 2 \qquad [5]$$

where x_i are the relative positions of the thermocouples to the line heater in cm, d is the time along the measuring campaign in days, m_i is the slope of the regression for thermocouple i, and n_i is the interception coefficient.

By introducing equation 5 in equation 1 and allowing the simplification assuming $y_1 = -y_2$, two equations of the corrected heat pulse velocities are obtained as a function of the time in the measuring campaign (equation 6).

$$V_1 = \frac{4Kt \ln\left(\frac{v_1}{v_2}\right) + (m_1\, d + n_1)^2 \; - 0.6^2}{2t(m_1 d + n_1 + 0.6)} \qquad [6]$$

$$V_2 = \frac{4Kt \ln\left(\frac{v_1}{v_2}\right) + \; 0.6^2 - (m_2\, d + n_2)^2}{2t(0.6 - m_2 d - n_2)}$$

In accordance to what Burgess et al. (2001) proposes, our approach averages the two estimates obtained from equation 6 to obtain a corrected heat pulse velocity.

3 Results

3.1 Heat pulse ratios

The HPR obtained during the measurement period displays a clear positive shift away from the theoretical ideal where the HPR would equal one at zero flow (Fig. 1A). This gives an indication of the necessity of corrections, that being due to wound inflicted by the probe, misalignment, misestimation of thermal diffusivity-or stem water content. However, the HPR data by itself does not give an indication of the quality of each measurement, nor if it deteriorates over time. Therefore, the quality of the measurements was indicated by calculating the RSD and slope for each HPR (Fig. 1B and 1C). All HPR with RSD higher than 5% were eliminated. The data points eliminated corresponded to a 1 % of the total dataset. Because the method is built on the theoretical assertion that the temperature in each of the thermocouples is steady with time, specifically between 60 and 100 seconds after the release of a heat pulse, the slope of the HPR should be close to zero. All HPR with |slope – median (slope)| < 0.003 s^{-1} were eliminated, which corresponded to a 12 % of the original dataset (Fig. 1C).

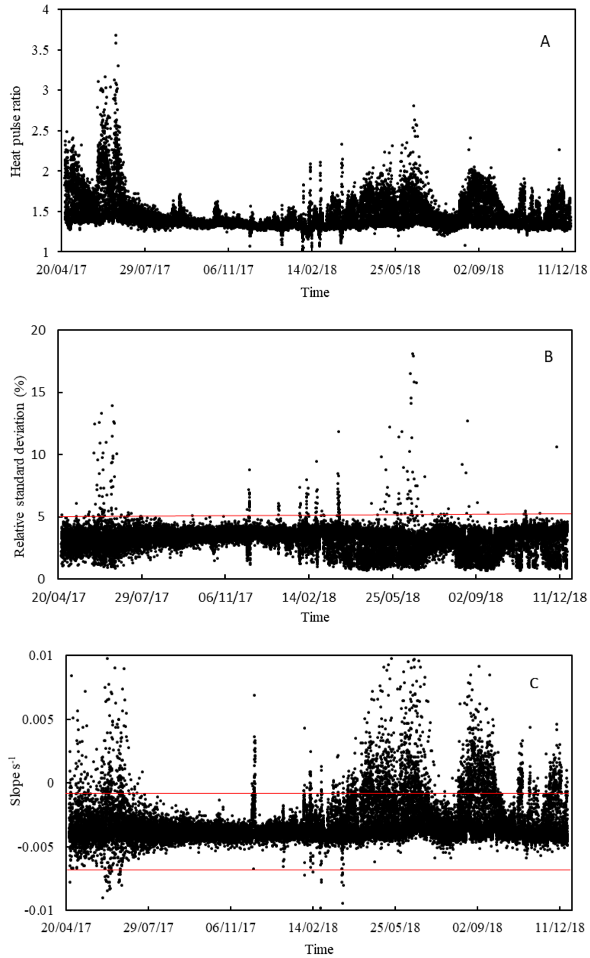


Figure 1. (A) Heat pulse ratios (HPR) throughout the measurement period in 30-minute intervals in tree number 1. Each HPR is an average of 41 instantaneous ratios corresponding to the temperature difference in two thermocouples at 0.6 cm up and down stream from a heater probe. (B) Relative standard deviation (%) for each HPR in tree number 1 for the whole measurement period. Red line indicates threshold used for the quality control were all HPR relative standard deviation > 5% were removed from the data analysis. (C) Slope (s^{-1}) for each HPR in tree number 1 for the whole measurement period. Red line indicates threshold used for the quality control for this particular sensor. HPR with |slope – median (slope)| < 0.003 s^{-1} were removed from the data analysis.

3.2 Heat pulse velocities

A linear regression was obtained from misalignment calculations for each sensor performed during zero-flow conditions. Because of the dry climate, only five events fulfilled these criteria (field capacity, low VPD, predawn), during the measurement period of 20 months. The outputs indicate a clear shift of placement in each of the sensors over time, here denoted as x_1 and x_2 in the case of tree number 1, with a greater shift in x_2 than x_1 (Fig. 2). On average, the eight sensors (two per tree) showed a shift of 0.04 cm in placement after twenty months of measurement. The equation obtained from the linear regression was then implemented in equation 6, and corrections to the heat pulse velocity data was done using an average

https://doi.org/10.5194/hess-2019-257
Preprint. Discussion started: 18 June 2019

Hydrology and Earth System Sciences Open Access EGU
Discussions

of V_1 *and* V_2 (Fig. 3,4). Outputs were compared with one-time misalignment correction calculated in the beginning of the measurement period to demonstrate the evolution of the probe misalignment. The one-time correction demonstrated a steady decline in accuracy over time (Fig. 3, 4). The difference between the two correction methods showed significance after three months of employment (Fig. 3).

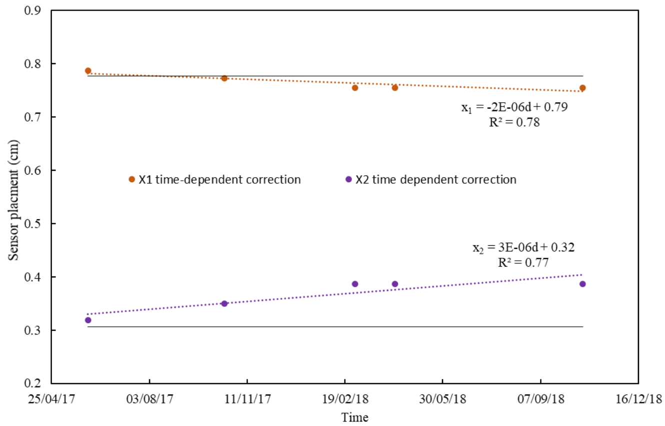


Figure 2. Sensor misalignment positions calculated once (solid lines) compared to probe misplacement over time in (solid circles with dotted lines). Each point represents the probe misalignment position calculated during its respective zero flow event.

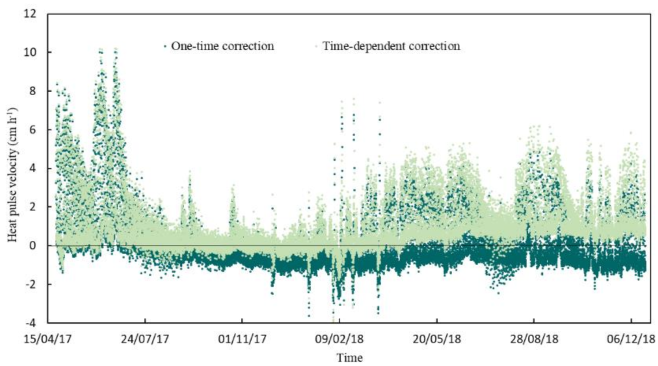
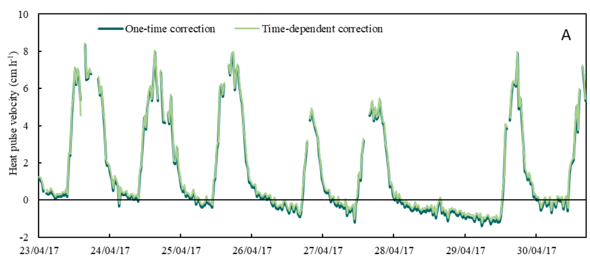


Figure 3. Heat pulse velocities for tree number 1 throughout the measurement period. Dark green represents velocities with only one-time misalignment correction applied at the beginning of the campaign. Light green represents velocities with time- dependent probe misalignment corrections. Each circle represents a measurements every 30 minutes.



https://doi.org/10.5194/hess-2019-257
Preprint. Discussion started: 18 June 2019

Hydrology and Earth System Sciences
Discussions

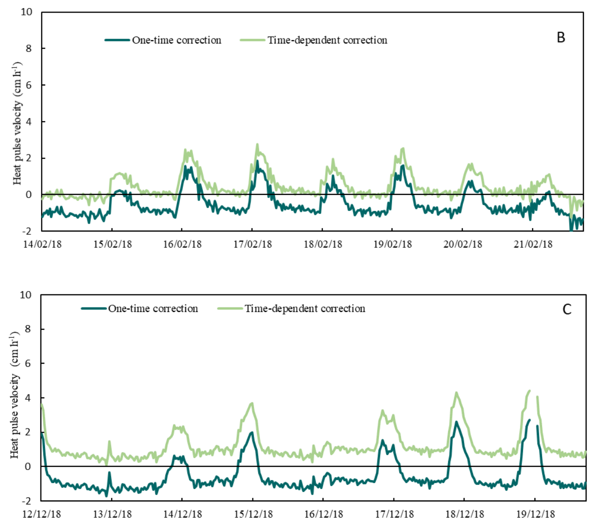


Figure 4. Heat pulse velocities during one week of measurements in the beginning (A), halfway (B) and at the end (C) of the measurement period. Dark green lines represent velocities with probe misalignment corrected for once at the beginning of the experiment. Light green lines represent velocities with the time- dependent probe misalignment corrections.

3.3 Sap velocities

Heat pulse velocities (both corrections) were converted into sap velocities according to Burgess et al. (2001). Our data demonstrated that by not correcting for changes in probe misalignment under continuous measurement for more than 3 months, the errors corresponded to an averaged difference of 0.29 cm h^{-1} in sap velocity per quartile for the four trees. At the end of the 20-months period, this corresponded to an averaged difference of 0.53 cm h^{-1} (Table 1, Fig. 5) In terms of transpiration values, this corresponded to a mean difference of 0.7 L tree $^{-1}$ day^{-1} (sapwood area = 170 cm^2), which would correspond to a difference of 542 L ha $^{-1}$ day $^{-1}$ (775 tree ha $^{-1}$) assuming 8 hours of daylight. It is relevant to note our conversion did not consider the differences in stem moisture content, which can also affect the output values (Vandegehuchte and Steppe, 2013). The outputs obtained should be considered as relative differences as the one-time correction was applied in the beginning of the experiment.

Table 1. Seasonal averages of sap velocity for 4 different trees. All sap velocities are expressed in cm h^{-1}. Sap velocities corrected for with time-dependent misalignment calculations are compared with sap velocities corrected for once in the beginning of the measurement period. Averages were taken from daily values. Abbreviations Sp, Su, Fa, and Wi indicates Spring, Summer, Fall and Winter respectively, each with the corresponding year.

Pine number	Correction method	Sp-17	Su-17	Fa-17	Wi-17/18	Sp-18	Su-18	Fa-18
1	One-time correction	0.98	0.23	-0.31	-0.37	0.12	0.05	-0.16
	Time-dependent correction	1.08	0.44	0.04	0.10	0.64	0.70	0.67
2	One-time correction	1.33	0.49	-0.28	-0.25	0.06	0.04	-0.05
	Time-dependent correction	1.40	0.66	-0.02	0.09	0.36	0.42	0.45
	One-time correction	0.82	0.73	-0.02	-0.24	0.57	0.75	0.53

https://doi.org/10.5194/hess-2019-257
Preprint. Discussion started: 18 June 2019

Hydrology and Earth System Sciences
Discussions

3	Time-dependent correction	0.84	0.79	0.09	-0.09	0.76	0.99	0.80
4	One-time correction	0.79	0.55	0.09	-0.05	0.29	0.18	0.05
	Time-dependent correction	0.82	0.66	0.29	0.23	0.61	0.56	0.55

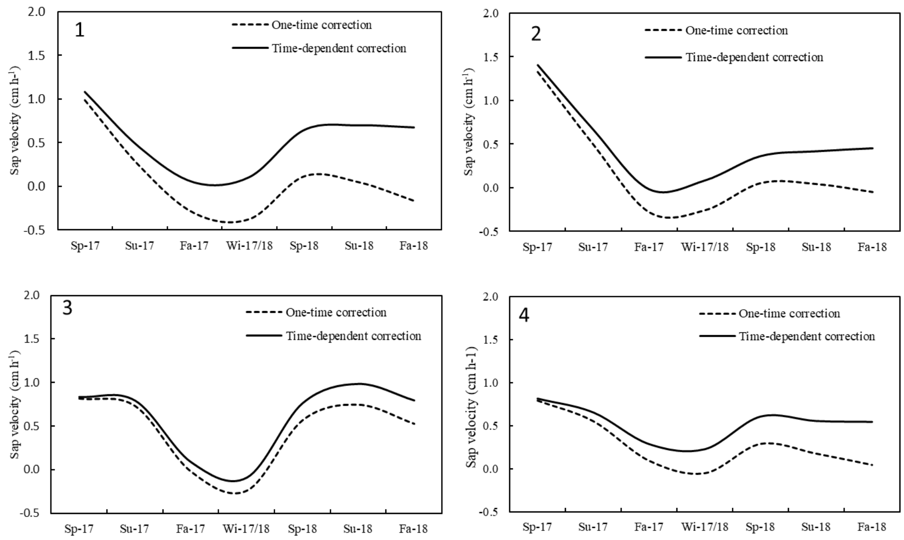


Figure 5. Seasonal averages of sap velocities (cm h^{-1}) calculated using the two misalignment corrections throughout the 20-month measurement period. Dotted lines represent probe misalignment corrected for once. Solid lines represent sap velocity corrected for with the time-dependent probe misalignment method. Abbreviations Sp, Su, Fa and Wi indicates Spring, Summer, Fall and Winter respectively, each with the corresponding year. 1, 2, 3, 4 corresponds to different trees.

4 Discussion

4.1 Filtration of heat pulse ratios

Because the HPR is an average of instantaneous ratios it is difficult to ensure its accuracy only by visual inspection of the averaged output, and without further statistical information. We suggest RSD and slope to filter out random ratios, and to ensure the quality of the data. A clear tendency was seen of higher RSD and slope values during periods of higher flow rates when compared to the HPR data (Fig. 1A, 1B and 1C), indicating more noise and less trustworthy data during higher flow rates. The HRM is known for being limited at higher rates (> 45 cm h^{-1}, Forster, 2017), but our dataset showed no sap velocity values higher than 6 cm h^{-1}, and therefore was not initially considered as a limitation.

During twenty months of field measurements the thermocouples showed no visible sign of deterioration with time. However, it is still important to note that this does not consider the possible diminishing amplitude of the ratios over time, which can also lead to underestimations of actual flow (Barett et al.,

https://doi.org/10.5194/hess-2019-257
Preprint. Discussion started: 18 June 2019

Hydrology and Earth System Sciences Discussions

1995; Green et al., 2003; Forster, 2017). Therefore, this should be observed separately, comparing sap flow ratios using data obtained under similar climatic conditions (Moore et al., 2010).

4.2 Long term variation in probe placement

When applying the HRM for longer than a few weeks it is relevant to quantify how ϕ in equation (2) and the misalignment term in equation (4) evolve during the measuring period. The predicted variation of x_1 and x_2 is due to the growth of the tree and, on the other hand, periodical variations of K due to annual and seasonal variations of the physiological properties of the tree (Green et al., 2003; Vandegehuchte and Steppe, 2012; Ren et al., 2017). In the HRM the probe misalignment calculations can be corrected using the methodology proposed here, considering that as an average, each sensor displayed a 0.04 cm displacement within the tree after twenty months of measurements. The correction would also be more rigorous with more assumed zero flow events which would be easier to obtain in humid environments.

By going back to the original assumption of "perfect symmetry" we investigated the original premises the method is built on. Even though Burgess et al. (2001) elaborated a correction method for sensor misalignment we saw that changes in sensor misplacement was detectable after each season. Therefore, multiple corrections should be carried out throughout the measurement period. The proposed modified method coincides with the one-time correction method (Burgess et al., 2001) for short time periods (< 3 months) but differs progressively over time. We found that this shift in placement is significant already after 3 months, and therefore dynamically misplacement calculations should be carried out or sensors should be reinstalled at this frequency.

5 Conclusion

Continuous measurements for 20 months in *Pinus halepensis* under semi-arid Mediterranean conditions confirmed the theory of steady temperature difference between the sensors with time (60- 100 s) for 87 % of the obtained values (every 30 min over 20 months), when using 5 % relative standard deviation and |slope – median (slope)| < 0.003 s^{-1} as quality filter. High quality long-term measurements can be obtained with sap flow sensors if proper data filtering is carried out and the time-dependent misalignment technique applied. Long-term measurements can therefore be performed without reinstallation of the sensors to obtain a continuous dataset, if the species allows for the sensor to be removed again after long-term implementation. In conclusion, the HRM method can be used in long-term studies if probe misplacement is corrected for at varies stages throughout the measurement period when exceeding 3 months of sampling.

Author contributions

JLP and EC conceptualized the study. EKL made the sensors with the supervision of JB. EKL implemented the sensors and had the responsibility of the data processing and field site. JLP, EKL and JAV all worked on the data analysis. JAV wrote the script for the datalogger and had the technical responsibility. EKL and JLP prepared the manuscript with inputs from all the co-authors. JLP and JAV designed the flow chart to be programmed in any data logger system.

The authors declare that they have no conflict of interest

Acknowledgements

The CEAM Foundation is supported by the Generalitat Valenciana (Spain). This study is partially funded by the Spanish Ministry of Science, Innovation and Universities and the European Regional Development Fund CGL2015-67466-R (MICINN/FEDER) through the research project "VERSUS", and by the Conselleria de Cultura (Generalitat Valenciana, SPAIN) through the research project "DESESTRES"–PROMETEOII/2014/038. We thank the municipality of Aras de los Olmos for permitting field experiments on a public managed forest site. We thank J. Puértolas and H. Moutahir for their feedback and encouragement on the manuscript.

References

Barrett, D.J.; Hatton, T.J.; Ash, J.E.; Ball, M.C.: Evaluation of the heat pulse velocity technique for measurement of sap flow in rainforest and eucalypt forest species of south-eastern Australia. Plant Cell Environment, 18, 463–469. https://doi.org/10.1111/j.1365-3040.1995.tb00381.x, 1995

Becker, P., Edwards, W. R. N.: Corrected heat capacity of wood for sap flow calculations. Tree Physiology, 19, 767–768. doi:10.1093/treephys/ 19.11.767, 1999

Burgess, S. S. O., Adams M, Turner NC, Beverly CR, Ong CK, Khan AAH, Bleby TM,: An improved heat pulse method to measure low and reverse rates of sap flow in woody plants. Tree Physiology, 21, 589–598. doi:10.1093/treephys/21.9.589, 2001

Cohen, Y., Cohen, S., Cantuarias-aviles, T., Schiller, G.: Variations in the radial gradient of sap velocity in trunks of forest and fruit trees. Plant and soil, 305, 49-59. DOI:10.1007/s11104-007-9351-0, 2008

Davis, T.W., Kuo, C. M., Liang, X., Yu, P. S.,: Sap Flow Sensors: Construction, Quality Control and Comparison. Sensors, 12, 954-971; doi: 10.3390/s120100954, 2012

Forster, M. A., How reliable are heat pulse velocity methods for estimating tree transpiration? Forests 8(9), 350: doi:10.3390/f8090350, 2017

Green, S.; Clothier, B.; Jardine, B. Theory and practical application of heat pulse to measure sap flow. Agron. J. 95, 1371-1379. doi:10.2134/agronj2003.1371, 2003

Jasechko, S., Sharp, Z. D., Gibson J. J., Birks S.J., Yi, Y., Fawcett, P. J.: Terrestrial water fluxes dominated by transpiration. Nature, 496, 347-350. Doi: https://doi.org/10.1038/nature11983, 2013

Manrique-Alba, A.: Ecohydrological relationships in pine forests in water-scarce environments. Ph.D. thesis, University of Alicante, Spain, 165 pp., 2017.

Marshall, D. C.: Measurement of sap flow in conifers by heat transport. Plant Physiology, 33, 385–396. doi:10.1104/pp.33.6.385, 1958

https://doi.org/10.5194/hess-2019-257
Preprint. Discussion started: 18 June 2019

Moore, G. W., Bond, B. J., Jones, J. A., Meinzer, F. C.: Thermal-dissipation sap flow sensors may not yield consistent sap-flux estimates over multiple years. Trees – Structure and Function, 24, 165–174. doi:10.1007/s00468-009-0390-4, 2010

Novick, K.A., Oren, R., Stoy, P. C., Siquiera M. B. S., Katul, G. G. Nocturnal evapotranspiration in Eddy-covariance records from three co-located ecosystems in the Southeastern U.S.: Implications for annual fluxes. Agricultural and Forest Meteorology, 149, 1491-1504. doi:10.1016/j.agrformet.2009.04.005, 2009

Ren, R.; Liu, G.; Wen, M.; Horton, R.; Li, B.; Si, B. The effects of probe misalignment on sap flux density measurements and in situ probe spacing correction methods. Agric. For. Meteorol. 232, 176–185. https://doi.org/10.1016/j.agrformet.2016.08.009, 2017

Vandegehuchte, M.W., Steppe, K.: Sapflow+: A four-needle heat-pulse sap flow sensor enabling nonempirical sap flux density and water content measurements. New Phytologist, 196, 306–317. https://doi.org/10.1111/j.1469-8137.2012.04237.x, 2012

Vandegehuchte, M. W., Steppe, K.: Sap-flux density measurement methods: working principles and applicability. Functional Plant Biology, 40, 213-223. http://dx.doi.org/10.1071/FP12233_CO, 2013