Testing of a custom, portable drill press to minimize probe misalignment in sap flow sensors

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Key Words

- Sap Flow
- Heat Pulse
- Portable Drill Press
- Probe Misalignment

Abstract

The accurate estimation of plant transpiration is critical to the fields of hydrology, plant physiology, and ecology. Among the various methods of measuring transpiration in the field, the sap flow methods based on head pulses offers a cost-effective and energy efficient option to directly measure the plant-level movement of water through the hydraulically active tissue. While authors have identified several possible sources of error in these measurements, one of the most common sources is misalignment of the sap flow probes due to user error. Though the effects of probe misalignment are well documented, no device or technique has been universally adopted to ensure the proper installation of sap flow probes. In this paper we compare the magnitude of misalignment errors among a 5 mm thick drilling template, a 10 mm thick drilling template, and a custom designed, field-portable drill press. The different techniques were evaluated in the laboratory using a 7.5 cm wood block and in the field, comparing differences in measured sap flow. Based on analysis of holes drilled in the wood block, we found that the portable drill press was most effective in assuring that drill holes remained parallel, even at 7.5 cm depth. In field installations, nearly 50% of holes drilled with a 5 mm template needed to be redrilled while none needed to be when drilled with the drill press. Widespread use of a portable drill press when implementing the heat pulse method would minimize alignment uncertainty and allow a clearer understanding of other sources of uncertainty due to variability in tree species, age, or external drivers or transpiration.

Introduction

Accurate estimation of plant transpiration is of vital importance to the hydrologic, agricultural, ecological, and climate sciences. Transpiration can represent between 60-80% of the water returned to the atmosphere, depending on the ecosystem (Jasechko et al., 2013). While there are a variety of techniques used to quantify transpiration or partition total evapotranspiration, sap flow measurements are one of the most cost-effective options for measuring tree-level fluxes. The different sap flow methods fall broadly into two categories, 1) heat dissipation, including thermal dissipation (TD; Granier, 1985) and transient thermal dissipation (TTD; Do & Rocheteau, 2002) and 2) heat-pulse sap-flux methods, including the compensation heat pulse (CHP; Swanson & Whitfield, 1981), Tmax (Cohen et al., 1981), heat ratio (HR; Burgess et al., 2001), and dual method approach (Forster, 2019).

Of these, the TD method continues to be the most widely implemented due to its general ease of use and accessibility, despite noted systematic biases (Flo et al., 2019). While not sensitive to sensor installation, the empirical equation used to derive sap flux density has been identified as a source of uncertainty. Originally considered to be universal across all wood types, the calibration parameters of the TD method have been shown to be species specific and require rigorous calibration to obtain accurate results (Bush et al., 2010; Fuchs et al., 2017; Steppe et al., 2010). This uncertainly, species-specific calibration, and a general underestimation of sap flow, has led some researchers to recommend the heat-pulse methods, particularly when absolute flow estimations are required (Flo et al., 2019; Vandegehuchte & Steppe, 2013).

Unlike the TD method, there is little fundamental uncertainty by species via the family of heat pulse (HP) methods as long as thermal diffusivity and physiological parameters, such as moisture content and sap wood density, are known (Flo et al., 2019; Vandegehuchte & Steppe,

2012). However, the most common source of uncertainty may be caused by error in probe placement (Cohen et al., 1981; Forster, 2017; Figure 1) given that HP methods typically require the drilling of three near-perfectly aligned and spaced holes for probes. While probe misalignment can be minimized by implementing a proper drill guide, use of these tools is not ubiquitous, or their use is not always detailed in the methods section.

Probe placement error can be characterized in three ways (Figure 1): vertical misalignment, lateral misalignment, and angular misalignment. Vertical and lateral misalignments are characterized by any offset along the y or x axis, respectively, at the outer surface of the tree. While most common when drilling "free hand", these misalignments can occur due to improperly constructed or worn drill guides, though they can be easily detected in the field with a ruler or level. Angular misalignment is characterized by an installation in which the drill hole does not remain perpendicular to the tree surface as it is drilled into the tree. This misalignment can be more difficult to detect, and can be caused by user error (i.e., drill was not held level during installation) or narrow drill guides which allow the bit to deviate in the sapwood.

There has been relatively little work to quantify error in sap flow measurements due to misalignment when compared to the frequent use of the sap flow methods. In a laboratory experiment using a container filled with glass beads attached to a peristaltic pump, angular misalignment of 4˚resulted in errors as high as 8%, 13%, 45% for the HR, Tmax, and CHP methods, respectively (Ren et al., 2017). While Ren et al. (2017) proposed corrections for angular misalignment for the common heat pulse methods, it was noted that these corrections resulted in systematic underestimation of sap flow. In a greenhouse experiment conducted in potted *Eucalyptus marginata* situated on weighing lysimeters, Bleby et al. (2004) found vertical

misalignment of only 2 mm resulted in a 100% error in sap velocity estimates, the largest source of error identified in a comprehensive review of biases. However, *in situ* calibrations have been developed to rectify this type of misalignment (Liu et al., 2013) as long as the vertical misalignment is within a suitable threshold.

Despite this limited work on quantifying the effects of misalignment error, there has been widespread recognition of the need to develop techniques to identify, minimize, or rectify misalignment errors. The over-length method inserts long blank probes into freshly drilled holes to try to detect the presence of angular misalignment; probe spacings could then be recalculated using trigonometry (Dye et al., 1991; Hatton et al., 1995). Inverse mathematical methods have been applied to use measured heat pulses to calculate the distance between probes when sap flux is zero (such as during rainy nighttime conditions) and thermal diffusivity is known. Previously assumed distances are replaced with new calculated value as an *in situ* correction (Burgess et al., 2001; Forster, 2019). The saturation method, an assessment of predicted sap flow at assumed zero flow conditions, has been used to shift, or offset the error due to misalignment, of entire time series of data as long as the raw heat pulse velocity is within a suitable threshold, typically -5 to 5 cm hr^{-1} (Hogg & Hurdle, 1997; *Implexx Manuals and Guides | Implexx Sense*, 2019; Looker et al., 2016; M. Zeppel et al., 2010). Using the same technique as the saturation method, the cut stem method artificially induced zero flow conditions by severing the sap stream (Roddy & Dawson, 2013). While this method has been considered more accurate than the saturation method, it required destructive harvesting of the plant.

The most common technique to properly align sap flux probes has been to use a drilling template or guide (Forster, 2017; Ren et al., 2017; Vandegehuchte & Steppe, 2013).

In the few cases where published literature describes templates, they are typically constructed of steel and no more than 10 mm in depth (Bleby et al., 2004; Burgess et al., 2001), although templates as thick as 20 mm have been used (Dye et al., 1991; McJannet & Fitch, 2004). While these guides can be useful in minimizing lateral and vertical misalignment, they can be less effective in minimizing angular misalignment. Because there are minimal options currently available to prevent angular misalignment, we developed a portable drill press operated by a handheld cordless drill designed to accurately align probes of all lengths in mature trees.

This drill press was designed with the intention of improving errors due to misalignment, as well as ease of use. This device needed to be relatively light weight and allow the drill bit to move up and down independent of the frame secured to the tree. The initial prototype included a prefabricated portable drill guide (portable drill guide #4525, Rockler), however the tolerance on the bearings and drill carriage proved insufficient for accurate drilling. We therefore opted to craft a custom-built drill carriage on precision linear bearings and rods attached directly to a movable mount on the frame of the press.

Despite a broad recognition of the need to avoid misalignment, there has been no systematic assessment of the ability of different templates and guides to minimize alignment error. In this paper, we consider differences in hole alignment error when using guides of different design. This includes templates of different thickness as well as the custom-designed, portable drill press that can be mounted to a tree. Included are details of the design and fabrication of the custom drill press. A standardization of methods for aligning and installing probes for the heat pulse method can enhance repeatability and reduce experimental uncertainty in heat pulse measurements, better allowing the identification of true controls on sap flow such as tree species, tree location, and climate drivers.

Methods

An initial section describes the construction of the drill press as well as the templates. Following this is an overview of the two portions of the experimental assessment: 1. comparison of hole alignment when drilled through a wooden block and 2. comparison of sap flow measurements when drilled into actual trees.

Drill Press Construction

The drill press was comprised of three main components: 1) the frame, 2) the drill carriage mount, and 3) the drill carriage (Figure 2).

The frame of the drill press was constructed of four pieces of lightweight 40-4040C T-slotted aluminum rails. The two lengthwise pieces were cut to 40.64 cm, while the widthwise pieced were cut to 7.62 cm, giving the drill press a total width of 12.7 cm. The rails were connected using 45 series 2 hole- 39mm slotted inside corner brackets. The carriage mount was attached to the frame using two double flanged linear bearings that slid along the lengthwise T-slotted aluminum rails. The inner edges of the two flanged bearings were screwed to a 8.9 x 8.9 cm piece of Delrin plastic to ensure unison motion along lengthwise aluminum rails. The 8.9 x 8.9 cm Delrin plastic was hollowed out creating a 6.4 x 6.4 cm window for the drill chuck and bit when the carriage was lowered during drilling.

The movement of the drill carriage mount was controlled by Velmex UniSlide screw drive model, mounted on the lower widthwise aluminum rail and connected to the 8.9 x 8.9 cm piece of Delrin plastic. The screw drive allowed the drill carriage mount approximately 3 cm of precision motion along the lengthwise slotted aluminum rails. Two 31.75 cm long, 0.95 cm

diameter, one-end-threaded linear bearing shafts, each attached to a ¼”-20 tread camera mount located in the center of the flanged bearings, held the drill carriage.

The drill carriage was constructed using a 15.2 x 3.2 cm piece of Delrin plastic. On either end of the drill carriage matching the position of the linear bearing shafts, two precision 0.95 cm diameter, 3.8 cm, linear ball bushing bearings were machined into the Delrin plastic. The linear bearings and shaft provide a smooth, controlled in-and-out action for the drill carriage mount. In the center of the drill carriage, four 1.3 cm diameter, 0.79 cm long radial ball bushing bearings were stacked atop each other to create a snug fit to hold the 41BA 1/2-20 Jacobs drill chuck. The drill press was operated using a 20 V handheld cordless drill, and was secured to the trees using ratchet straps (Figure 3). The drill bit was aligned at each probe position by twisting the knob of the Velmex UniSlide screw drive. Beneath the drill carriage, an optional 10 mm drilling template could be aligned with the drill bit and attached to the lengthwise lightweight 40-4040C T-slotted aluminum rails. Installations via the portable drill press were drilled with a 14 cm, No. 54 bit, with approximately 3 cm of the bit inserted into the drill chuck.

Both the 5 mm and 10 mm drill templates were constructed out of plate steel, with the guide holes spaced 5 mm apart from each other. A small level guide was attached to the side of each drill template to ascertain vertical alignment. Four holes, one in each corner of the templates, allowed for the ability to secure the template to the tree with short nails or screws. Installations via the templates were drilled with a 11 cm, No. 54 bit, with approximately 3 cm of the bit inserted into the drill chuck.

Method Comparison of Hole Alignment in a Wood Block

Drilling accuracy was compared between the constructed drill press with the optional template (DT), without the optional template (D), a 5 mm deep drilling template (T5), and a 10

186 mm deep drilling template (T10) at both 3.75 cm and 7.5 cm drilling depth. The 3.75 cm depth
187 was selected to represent the standard drilling depth for most commercial sensors (i.e. TDP-30
188 from Dynamax), while the 7.5 cm depth was selected to highlight potential errors in deep
189 sapwood studies such as Ford et al., (2004). Using each drill guide device, six drilling attempts
190 were made in a 7.5 cm block of pine wood. The wood block was strapped to a tree to simulate
191 field conditions while not requiring destructive measures to analyze the positioning of the drilled
192 holes. Following the drilling, the wood block was cut in half along the depth of the block to
193 analyze the positioning of the holes in a standard deployment (3.75 cm), as well as the full 7.5
194 cm depth of the board. The front, middle and back of the wood block was imaged with a
195 mounted and leveled DSLR camera (Nikon D5600). A reference hole was drilled through the
196 depth of the wood block using a machine shop drill press to establish a uniform coordinate
197 system between photos. The x and y coordinates of the holes were measured using ImageJ
198 (Image J, NIH, USA, http://rsbweb.nih.gov/ij/).

199 The vertical and lateral alignment of the drill attempts were assessed via the distance
200 from the ideal positioning of -5, 0, and 5 mm for the upstream, heater, and downstream probes,
201 respectively, on the front of the wood block. In order to establish a uniform reference for each
202 drill attempt, the heater probe was assumed to be perfectly aligned (i.e., 0,0 on an x,y coordinate
203 system) in each drill attempt, and only the up- and downstream probes were measured for
204 vertical and lateral misalignment. The mean and standard deviation of the misalignments were
205 measured for each drill guide type (i.e., drill press with the optional drilling template [DT],
206 without [D], 10 mm template [T10], and 5 mm template [T5]).

207 The angular misalignment for each drill attempt was assessed in the vertical and lateral
208 directions. The angle of misalignment was calculated by the arctangent of the depth of the board

209 (i.e., 7.5 cm) and the vertical or lateral distance between the entry and exit wounds. The mean
210 drilling angle, as well as the standard deviation, were assessed to gauge both the precision and
211 accuracy of each drill guide type.
212
213 *Method Comparison of Hole Alignment in Field-Instrument Trees*
214 One *Tsuaga canadensis* (HEM-3) and two *Acer saccharum* (MAP-8 and MAP-13) were
215 instrumented in summer 2022 with a pair of custom sap flux sensors (Beslity et al., 2022), one
216 installed using the custom drill press (D), the second using a drilling template (T5), with the two
217 sensors installed at a 90˚angle on the north and east face of the tree. The tree selected for this
218 study were part of a larger ongoing study in Hammond Hill State Forest, Dryden, NY. Each
219 sensor probe was 50 mm in length and contained four independent temperature sensors located at
220 5, 15, 25, and 35 mm. The sensor probes were spaced 5 mm apart from the heater probe in the
221 up- and downstream positions. The sensors collected measurements at 30-minute intervals,
222 skipping the hours of 2100-0100 and 0300-0500 to conserve battery life. All sensors were
223 operational from 6/10/2022 through 7/20/2022.
224 We applied the dual method approach of heat pulse sensing (DMA), a combination of the
225 heat ratio method and Tmax method (Forster, 2019). The standard heat ratio utilizes two sensor
226 probes installed up and downstream of the heater probe. This method was adjusted to calculate
227 differences in the vertical positioning of probes and duration of the applied heat pulse
228 (Kluitenberg et al., 2007):

229 $$V_{h,HRM} = \frac{2D\left(ln\left(\frac{\Delta T_d}{\Delta T_u}\right)\right)}{x_d + x_u} + \frac{x_d - x_u}{2\left(t - \left(\frac{t_o}{2}\right)\right)} \quad \text{Eq. 1}$$

where $V_{h,HRM}$ is the heat pulse velocity (cm s^{-1}), D is thermal diffusivity (cm^2 s^{-1}), ΔT_u and ΔT_d are the changes in temperature upstream and downstream following the heat pulse (K) averaged between 60 and 100 seconds (Burgess et al., 2001), t_o is the heat pulse duration, and x_d and x_u are the distances between the heater probe and the down- and upstream sensor probes, respectively. The thermal diffusivity for each instrumented tree was calculated via the improved methods detailed by Vandegehuchte & Steppe (2012). Sap wood samples were collected using a 5 mm increment borer. The sap wood was immediately placed in airtight bags and stored in a cooler until processed in the laboratory.

The Tmax method utilizes a single downstream sensor probe with the equation:

$$V_{h,Tmax} = \sqrt{\frac{4D}{t_o} ln\left(1 - \frac{t_o}{t_m}\right) + \frac{x_d^2}{t_m(t_m - t_o)}} \quad \text{Eq. 2}$$

where $V_{h,Tmax}$ is the heat velocity (cm s^{-1}), x is the distance between the heater and downstream sensor probe, and t_m is the elapsed time (s) for the downstream sensor to reach the maximum temperature of the heat pulse (Cohen et al., 1981, Kluitenberg & Ham, 2004).

The Tmax equation can be rearranged to back-calculate for the distance x between the probes:

$$x = \sqrt{\frac{D4t'_m\, ln\left(\frac{t'_m}{t'_m - t_o}\right)(t'_m - t_o)}{t_o}} \quad \text{Eq. 3}$$

This does require that D is known and presumes that sap flow velocity is nearly zero, a condition that is presumed to occur on rainy nights when the vapor pressure deficit is low. This back-calculation of x allows for non-destructive, in situ comparisons of alignment between the template and drill press in the field.

Additionally, the saturation method (Hogg & Hurdle, 1997) and over-length (Hatton et al., 1995) methods were used to assess suitability of field installations of sensors. In the saturation method, raw heat pulse velocity measurements ($V_{h,HRM}$) measured via the HR method were used to assess the viability of each installment at each thermistor depth by assessing if $V_{h,HRM}$ exceeds a given threshold. Academic literature detailing the saturation method advises using best judgment but rarely gives an explicit threshold for assessing viability. Here, we make use of guidance provided for widely used commercial heat pulse probes from Implexx Sense that indicates a threshold of -5 and 5 cm hr^{-1} (*Implexx Manuals and Guides | Implexx Sense*, 2019). If $V_{h,HRM}$ at any depth falls outside this pre-determined threshold during a nighttime precipitation event a reinstallation was considered necessary. In the over-length method, oversized dummy probe were inserted into the drill holes to gauge to lateral alignment of the probes. The distance to the hundredth mm between the probes was measured at the entry (0 mm), middle (25 mm), and end points (50 mm) of the dummy probes using digital calipers (IP54 - 6-Inch Digital Caliper, Baileigh Industrial), and the change in distance between the probes was used to assess the installations. The mean change in distance between the two drill guide types was assessed using a Student's t-test.

Results

The drill guides were initially assessed based on lateral, vertical, and angular misalignment in the 7.5 cm thick block. Figure 4 illustrates the position of the exit holes from the wood block for the three different types of drill guides. Qualitatively, it is evident that most exit holes are not perfectly aligned with the entrance holes. However, the actual source of misalignment needs to be determined based on different methods of analyzing hole position.

Lateral and vertical alignment were assessed based on absolute position of the holes at entry for the upstream, heater and downstream probes. Suitability of the position of the holes is characterized by the absolute mean and standard deviation. The mean represents aggregate error, while the standard deviation represents the scatter about mean misalingment. While there was no statistical difference between drilling guides (Table 1) in terms of absolute vertical and lateral misalignment as based on standard deviation, T10 did provide a slightly more precise placement of holes than the drill press and T5 in the vertical plane, due to the fixed position of the guide holes in the templates. The need to use the UniSlide screw drive in the drill rig to move the bit to the proper position increased the standard deviation of the hole alignment along the vertical axis (Table 1). When a 10 mm drilling template was attached to the portable drill press, the absolute mean misalignment and standard deviation were further reduced.

Angular misalignment was assessed by considering the angle between the actual entry hole (not the ideal entry hole) and the corresponding exit hole. The drill press with and without the attached template outperfomed both T10 and T5 when assessing the angle of misallignment (Table 2). The main measure of interest for assessing angular misalignment is the standard deviation of the angle; mean angle represents systematic error but standard deviation represents the reliability of the drill guide type to install parallel, if equally misaligned, holes. In both the vertical and lateral direction, the standard deviation was smallest via the drill press with the attached template, 0.46˚and 0.24˚, respectively, which represented a more consistent alignment of probes and ensuring the measurement points along the temperature sensors would be more equally spaced across different radial depths. The mean angle of misalignment for the drill press was 0.37˚and -0.49˚in the vertical and lateral directions, resepectively, compared to 1.07˚and 0.21˚for the drill press alone, and -0.36˚ and -0.93˚ for T10.

297 In the field, the alignment of drilled holes was estimated using heat pulse data in
298 conjunction with Eqn. 3, as well as the over-length method. Using time differences in heat pulse
299 arrival at different thermistors, Eqn. 3 estimates the distance between the heating probe and
300 sensing probes. Based on this method, the drill press resulted in more parallel holes compared to
301 T5 as measured by the difference in the mean distance between drilled holes (p-value = 0.06),
302 consistent with the experiments made using the wood block. Measured via the inverse
303 mathematical method, the mean absolute change in vertical position from the 5 mm thermistor to
304 the 35 mm thermistor was 0.5 mm for the drill press but over 1.0 mm for the 5 mm template
305 (Figure 5). Using the overlength method, the mean absoluste change across the entire length of
306 the probe (50 mm) was 1.5 mm for the drill press and 3.3 mm for the 5 mm template (Figure 5).
307 As with the inverse mathematical method, the drill press resulted in more parallel holed
308 compared to T5 when compared with the overlength method (p-value = 0.11).
309 When comparing the field data between D and T5, the drill press consistently delivered
310 measurements within the acceptable range based on guidance given for the saturation method
311 (Hogg & Hurdle, 1997; *Implexx Manuals and Guides | Implexx Sense*, 2019). Across all four
312 depths of the three field-instrumented trees installed via the drill press, the raw heat pulse
313 velocity ($V_{h,HRM}$) measured during a night time precipitation event via the drill press fell within
314 the 5 and 5 cm hr^{-1} threshold, representing a successful installation. Measurements from probes
315 installed via T5 failed to fall within the threshold at 5 of the 12 of the tree-depth combinations.
316 Measurements via T5 at 25 and 35 mm in Hem-3 were unable to be resolved using Eq. 1 due to
317 extreme misalignment. Figure 6 graphically shows the difference in alignment between the
318 template and drill press installed in the same tree as based on the saturation method. In this

example, the installation via T5 was deemed successful at 5 mm, with $V_{h,HRM}$ not exceed ±5 cm hr^{-1}, though not at 15 mm, as the misalignement of the probes had increased with depth.

Discussion

As indicated in the introduction, the minimization of misalignment in the installation of sap flux probes has been identified as a major challenge in ensuring accuracy of measurements, though one that can potentially be rectified with proper techniques. To gain some insight into the frequency to which researchers typically employ techniques to avoid misalignment errors, we reviewed a subset of papers published since 2000 that involved HP sap flow measurements. While the use of drilling templates has been repeatedly recommended in meta-analyses of potential sources of error in sap flow studies (Flo et al., 2019; Forster, 2017; Vandegehuchte & Steppe, 2013), their use has not been ubiquitous or consistently documented. Using the search terms “heat pulse”, “sap flow”, “transpiration”, and “water use”, as well as these review papers, 36 published articles using a heat pulse method since 2000 were identified. Of these, only 17 mentioned the use of a drilling guide (Ballester et al., 2011, 2013; Bleby et al., 2004; Burgess et al., 2001; Clulow et al., 2013; Deng et al., 2021; Doronila & Forster, 2015; Dragoni et al., 2009; Fernández et al., 2006; Forster, 2020; Fuchs et al., 2017; Intrigliolo et al., 2009; Madurapperuma et al., 2009; McJannet & Fitch, 2004; Pearsall et al., 2014; Pfautsch et al., 2011; Wullschleger & King, 2000), only five described the drilling guide in any detail (Bleby et al., 2004; Burgess et al., 2001; Deng et al., 2021; Madurapperuma et al., 2009; McJannet & Fitch, 2004), and just one provided information on the depth of the guide (McJannet & Fitch, 2004). Just over half of the published articles in this review did not use, or did not mention the use of, a drill guide (Alarcon et al., 2005; Ferrara & Flore, 2003; Forster, 2012; Gutiérrez-Soto, 2012; Hernandez-Santana et

al., 2015; Looker et al., 2016; Molina et al., 2016; Perez-Priego et al., 2017; Prendergast et al., 2007; Raulier et al., 2002; Skelton et al., 2013; Tfwala et al., 2018; Van de Wal et al., 2015; Xu et al., 2011; Yunusa et al., 2000; M. Zeppel et al., 2010; M. J. B. Zeppel et al., 2011; Zhao et al., 2018). Thus, despite the recognition of probe alignment as vital to accurate sap flow measurements, there still remains a lack of standardization in techniques to minimize misalignment.

Analyses in this paper strongly suggest that not all drill guide designs are equivalent and that certain designs should become the standard while others should be discontinued. In particular, there was a substantial difference between the 5 mm drilling template and the 10 mm drilling template in the controlled wood experiment. Intuitively, the successful drill rate declined with depth; no holes drilled via T5 were within ±0.5 mm of the ideal position at 7.5 cm. The use of a drilling template less than 10 mm in depth would consistently lead to probe misalignment greater than 0.5 mm and error in raw heat pulse velocity measurements that would necessitate a redrill under the saturation, inverse mathematical solution, or over-length methods. When a drilling template is used in HP experiments, it should be of at least 10 mm depth and tested before deployment. Additional methods, such as the overlength and inverse mathematical methods should be used to determine more exact probe spacings, and it can be noted that these two methods found relatively similar results when applied at the same installation.

Furthermore, while all drill guide types alleviated lateral and vertical misalignment, the drill press outperformed both templates in minimizing angular misalignment. Based on our review of the literature, this is the first instance of a suggestion for a technique for minimizing angular misalignment, aside from post-hoc corrections. Besides improving accuracy of the measurement of sap flow, use of the drill press can also reduce costs and the time required to

start collecting data. Without the drill rig, we would normally need to wait for periods with nighttime precipitation events to assess via Eqn. 3 and the saturation method whether probes were suitably aligned. When they were not properly aligned, the probes would need to be redrilled, requiring additional time in the field, increasing the potential for damaging sensors, and decreasing the sampling period available during the growing season.

The portable drill press detailed in this study provided a solution to probe misalignment and would allow for a focus on alternative sources of error, including nocturnal xylem flow (M. Zeppel et al., 2010), radial and circumferential variability (Berdanier et al., 2016), and seasonal variation in thermal diffusivity (Vandegehuchte & Steppe, 2012), when using the HP family of sap flow methods. Aside from the improved performance compared to more traditional drilling guides, this press offers the ability to switch between heat pulse methods by adjusting the spacing of the probes without the need for multiple templates, though results were further improved when the optional template was attached to the drill press. Use of the press without the attachable template would provide researchers with a reliable flexibility to select the heat pulse method best suited to their experiment. Moving forward, we would suggest sap flow researchers use a drill press of similar design to the one detailed in this paper.

Data and Materials Availability

The data and materials used to test and design the portable drill press will be made available in a free to access public data repository.

Conflict of Interest

None declared.

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Authors' Contributions

JB and SS jointly designed the portable drill press. JB tested the device, with guidance from SS. JB prepared the manuscript, with guidance and edits from SS.

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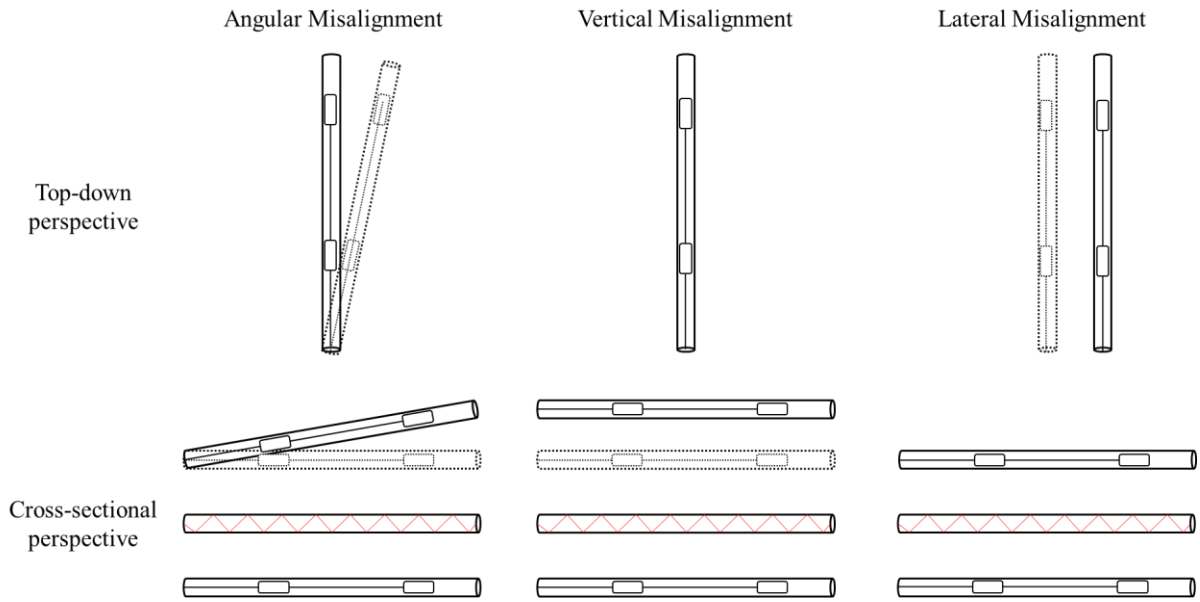
List of Tables and Figures



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632 **Figure 1:** Three types of probe misalignment portrayed from the top-down and cross-sectional
633 perspectives. Angular probe misalignment can occur in the lateral and vertical direction.
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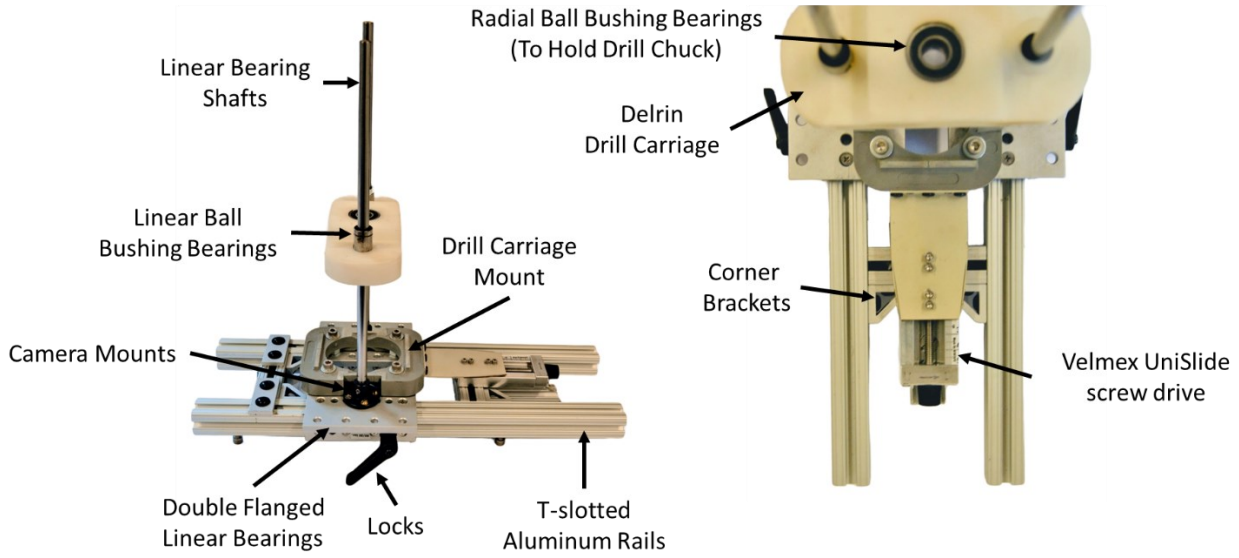


Figure 2: Annotated images of the portable drill press detailing the parts used in construction.

Figure 3: Image of the drill press mounted on a mature tree in the field using a ratchet strap.

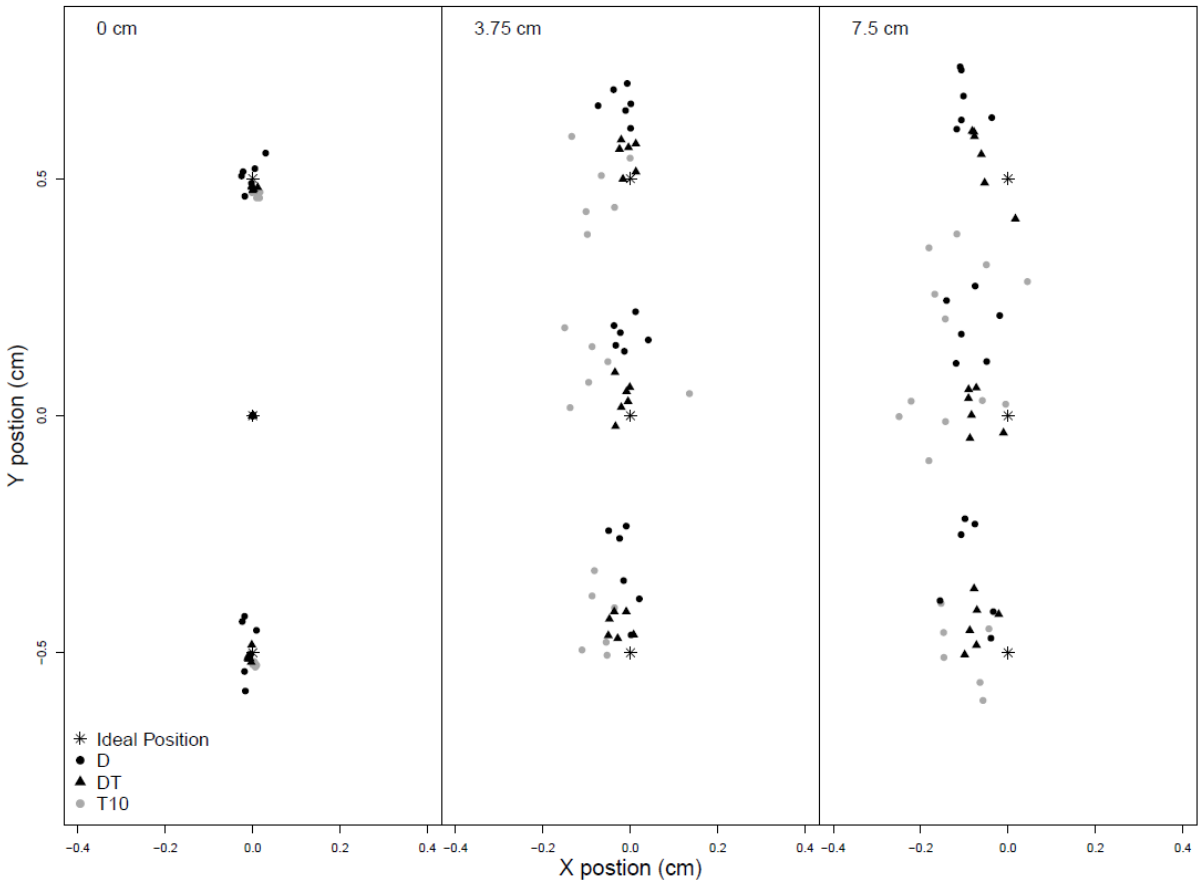


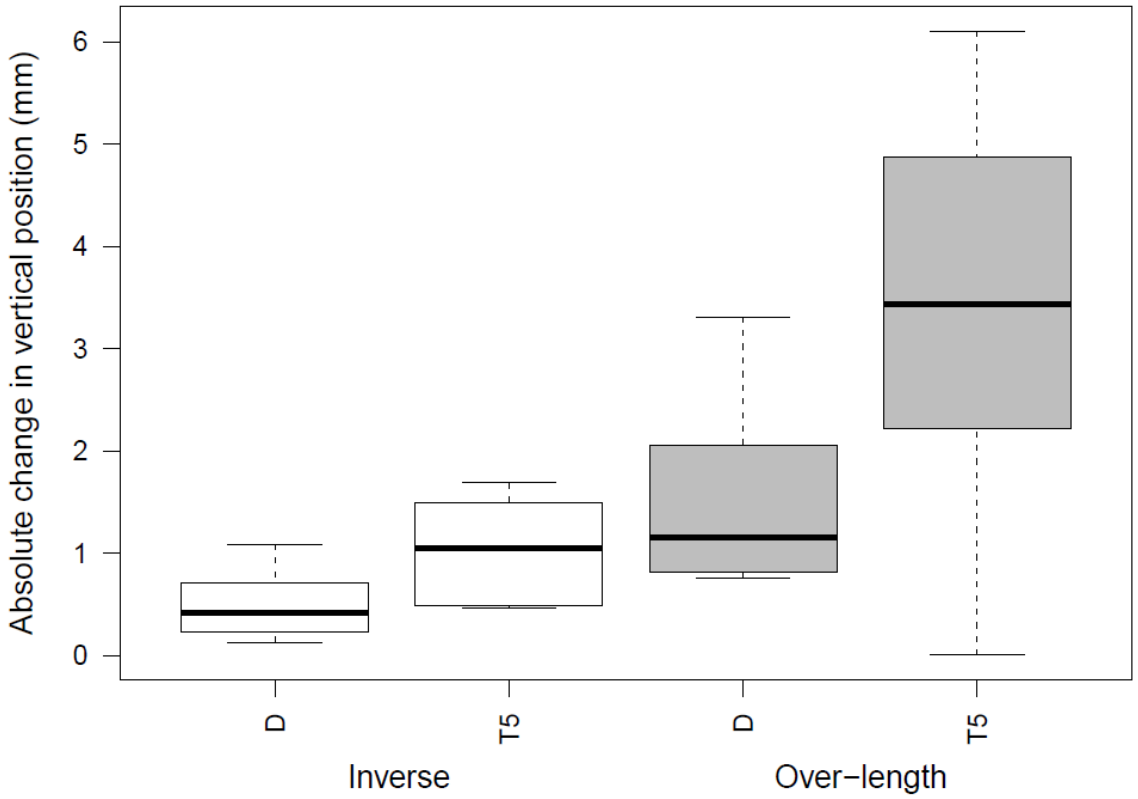
Figure 4: Position of each exit wound in wood block relative to the ideal position of -5, 0, 5 mm for the upstream, heater and downstream probe, respectively, at 0 (i.e., entry; left), 3.75 cm (middle) and 7.5 cm (right). Generally, the drill press (black) was more accurate along the lateral direction than the 10 mm deep drilling template (light grey), and both were more accurate than the 5 mm deep drilling template.

Table 1: Mean and standard deviation (in parentheses) of absolute misalignment in the vertical and lateral directions at entry for each drill guide.

Drill Guide Type	Lateral Misalignment (mm)	Vertical Misalignment (mm)
DT	0.03 (0.04)	0.11 (0.08)
D	0.10 (0.10)	0.25 (0.27)
T10	0.05 (0.05)	0.19 (0.15)
T5	0.09 (0.16)	0.29 (0.30)

Table 2: Mean, standard deviation (in parenthesis), and mean absolute error of the vertical and lateral angular misalignment.

Drill Guide Type	Mean vertical angle (˚)	Vertical MAE (˚)	Mean lateral angle (˚)	Lateral MAE (˚)
DT	0.37 (0.46)	0.49	-0.49 (0.24)	0.51
D	1.07 (0.48)	1.07	0.21 (0.40)	0.35
T10	-0.36 (0.82)	0.68	-0.93 (0.59)	0.96
T5	5.44 (1.88)	5.43	3.47 (3.02)	3.9



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732 **Figure 5:** Absolute change in vertical position of the up- and downstream probes across all
733 instrumented trees between the drill press (D) and the drilling template (T5) determined via the
734 inverse mathematical (white) and over-length (grey) methods. The inverse mathematical method
735 assesses the change in position from the shallowest thermistor (5 mm) to the deepest (35 mm)
736 while the over-length method acounts for change in position across the entire length of the probe
737 (50 mm).
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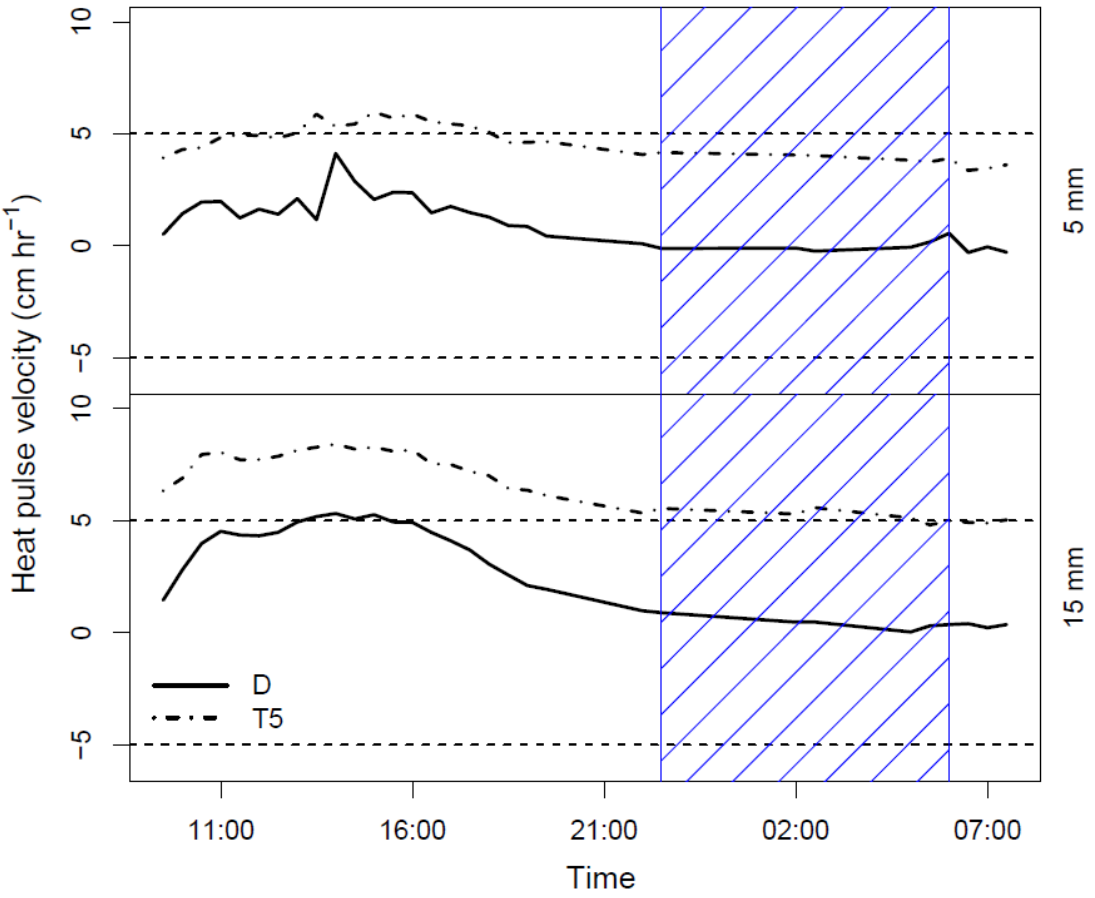

Figure 6: Example of heat pulse velocity measurements ($V_{h,HRM}$) via the drill press (D; solid line) and the 5 mm drilling template (T5; dashed and dotted line) during a nighttime precipitation event (blue hashing), for two radial depths in Hem-3. Each Installations where $V_{h,HRM}$ fell outside the -5 to 5 cm hr^{-1} threshold (dashed line) during the nighttime precipitation event (bottom) were identified as overly misaligned and requiring of a redrill. Installations that fell within this threshold (top) were identified as aligned or suitable for post-hoc corrections, such as the saturation method.