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ESTIMATION OF SAP FLOW RATE IN *Hopea odorata* AND *Khaya ivorensis*

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INTRODUCTION

The amount of water used by plants has been the subject of worldwide research since a long time ago, driven by the need for water resource, managers and planners to understand the effect of forest cover on water supplies (Bosch & Hewlett 1982, McCulloch & Robinson 1993, Marryanna et al. 2016). There are two ways trees use or lose water; first by the root water uptake from soil, and second from the interception of water by the surfaces of leaves, branches and trunks during rainfall (Nisbet 2005). Sap that contains water, sugars and minerals, is simply referred to as a fluid transported from the root towards leaves through xylem and phloem cells of plants (Marryanna et al. 2016). The xylem sap consists of watery solution, mineral elements and nutrients, whereas phloem sap consists of sugars, hormones and mineral elements dissolved in water. Tree growth is directly impacted by the sap flow rate. Trees can absorb more water and nutrients when the sap flow rate is high, which promotes increased photosynthesis and growth. In contrast, trees may struggle to get adequate water and nutrients and may not develop as well when the sap flow rate is low.

In Malaysia, studies of sap flow rate have been conducted on several forest plantation species, such as *Acacia mangium* Wild. (Fabaceae) and *Tectona grandis* L.f. (Lamiaceae) (Marryanna et al. 2016, Marryanna et al. 2017). However, such studies are still lacking in introduced and potential species for forest plantation. These include *Khaya ivorensis* A. Chev. (Meliaceae), one of the species selected for forest plantation (MTIB 2023) and *Hopea odorata* Roxb. (Dipterocarpaceae), a potentially important tropical plantation hardwood tree. Both species are found to be especially suitable for planting in degraded sites of logged-over lowland rain forests (Wan Razali & Ang 1991).

Khaya ivorensis or locally known as African mahogany is one of the fastest-growing trees, introduced to Malaysia in 1950s (Ahmad Zuhaidi et al. 2006), and has been promoted as a plantation tree in Malaysia. It is a tall forest tree with a buttressed trunk that adapts well to the local climatic conditions (Jeyanny et al. 2009). It grows to about 40–50 m high. This species produces new crown leaves between September and November and flowers from July to December, with bunches of small and white flowers at the end of branches. It was found that this species responded positively to irrigation. However, in water-stressed areas, the growth of this species is restricted because it interferes with its metabolism, indicating moderate tolerance (Albuquerque et al. 2013).

Hopea odorata or locally known as ‘merawan siput jantan’ is a medium to large-sized tree with a large crown and grows up to 45 m high. This species is a late successional tree species that requires shade and high soil moisture content for its natural regeneration (Bunyavejchewin et al. 2003). This riparian plant grows in deep, rich soils, usually along the bank of a stream. Because of its potential, *H. odorata* is one of the species planted in Bukit Hari at the Forest Research Institute Malaysia (FRIM). The 0.3-hectare plantation has been established on *renggam* soil series (Nordahlia et al. 2013).

The sap flow study in *H. odorata* and *K. ivorensis* was conducted by monitoring the sap flow rates involving trees of various diameter sizes in order to comprehend the relationship between sap flow pattern and diameter size.

MATERIAL & METHODS

Three diameter classes of *Hopea odorata* and *Khaya ivorensis* were selected for this study. The sap flow measurement was conducted at Field 48, Bukit Hari, FRIM (Figure 1), using the sap flow meter (SFM)

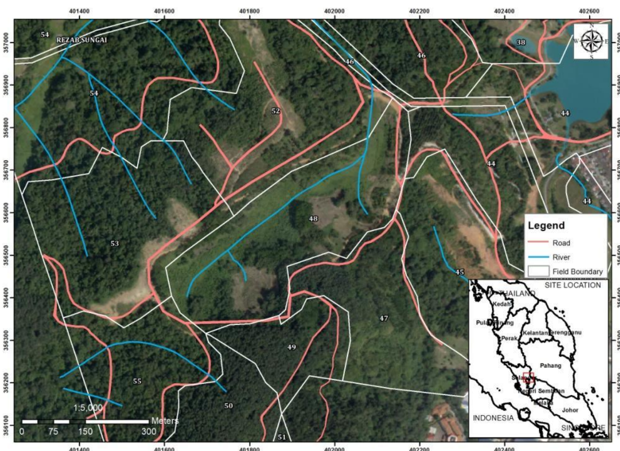

Figure 1 Location of monitoring plot at Field 48, Bukit Hari, Forest Research Institute Malaysia (FRIM)

Figure 2 The sensors inserted to the tree consist of downstream, heater, and upstream needles

with a heat ratio method (HRM). The SFM consists of a set of three measurement needles and a data logger with software for instrument configuration and data downloading. The colour code differentiates each needle based on the specific use: blue for measurement and red for the heater. The length of each needle is 35 mm long, integrally connected to a 16-bit microprocessor. The SFM is powered with internal Lithium polymer batteries that are used to operate the measurement. In addition, 12 V external battery supplies were required for the measurement of two weeks duration, at 30-minute intervals. The SFM employs the HRM, which entails precisely spacing the downstream and upstream needles to detect the heat differential over time. The heater needle is to be placed in the sapwood region to provide heat pulse.

Before the measurement, the apparatus and equipment for establishing the SFM sensor were prepared. This equipment includes the SFM sensor, drill, drill guide and methyl orange. Tiny holes were prepared for sensor insertion. A drill needle guide was used to ensure that the holes were prepared diametrically or straight. The sensors were inserted into the tree, a downstream needle at the top position, followed by a heater (red needle) at the middle and an upstream needle at the bottom position (Figure 2). It is important to ensure the correct orientation in order to get the sap flow data.

Wood samples were collected using a borer applied with Methyl Orange for 15 minutes. The lengths of the bark and sapwood were then measured on site (Figure 3). The wood samples were then brought to the laboratory to measure the fresh and dried weights. The results from SFM were corrected with this information to determine the values of sap flow in the Sap flow tool lite software. Sap flow methods hold important advantages over other techniques (Smith & Allen 1996). This method has been used to quantify water use by arable crops (Soegaard & Boegh 1995, Senock et al. 1996). Sap flow techniques, according to Smith and Allen (1996), are appropriate for applications requiring routine measurement of plant water usage that is predominantly driven by evaporative demand (Thomas et al. 2012). The quantity of water that leaves the plant by transpiration is determined by a number of parameters, including soil water content, root density, root distribution, transpiration rate, and plant species.

Figure 3 Measurement of the lengths of the bark and sapwood

We divided the trees according to their diameters. Trees classified as small have a diameter of 15–20 cm, medium trees have a diameter of 20–25 cm, and large trees have a diameter of 30–40 cm. The *Hopea odorata* in this study had the diameters of 16, 23, and 33 cm, whereas *Khaya ivorensis* were of 18, 24, and 37 cm diameter. The wood properties detail for the two species is tabulated in Table 1. The sap flow was measured 24 hours for each diameter class. The data sample was taken as a daily flow rate and the total data sample was estimated as monthly flow rate. Due to uncertainty during the measurement period, HRM recorded only 13 days of complete sap flow data.

Table 1 Wood properties for the selected trees of *Hopea odorata* and *Khaya ivorensis*

	Hopea odorata			*Khaya ivorensis*		
Stem diameter (cm)	16	23	33	18	27	37
Xylem radius (cm)	7.95	11.20	16.35	8.19	11.30	17.59
Sapwood depth (cm)	7.6	10.8	15.8	1.3	1.8	1.2
Fresh sapwood weight (g)	1.845	2.486	3.106	0.279	0.405	0.125
Fresh sapwood volume (cm^3)	1.492	2.121	3.103	0.26	0.353	0.236

RESULTS & DISCUSSION

Climatic conditions for the measurement period

The average daily rainfall during the measurement was 11 mm, with the highest rainfall recorded on the second, followed by the fourth day, at 50 and 44 mm per day, respectively (Figure 4). The number of rainy days throughout the measurement duration was 13 days. The area was relatively humid, with an average relative humidity (RH) of 88% (±3.95), ranging from 80 to 95%. The vapour pressure deficit (VPD) averaged at 0.39 (± 0.15) kPa and the solar radiation averaged at 162% (±22). The VPD is an index for dryness, and it increases with the decrease in rainfall amount. The state of the surrounding environment will have an impact on the physiological characteristics of the tree processes, particularly the transfer of water from the soil and root into the atmosphere. Soil moisture is limited during a dry season, and trees must work harder to get water, leading to evapotranspiration decrease.

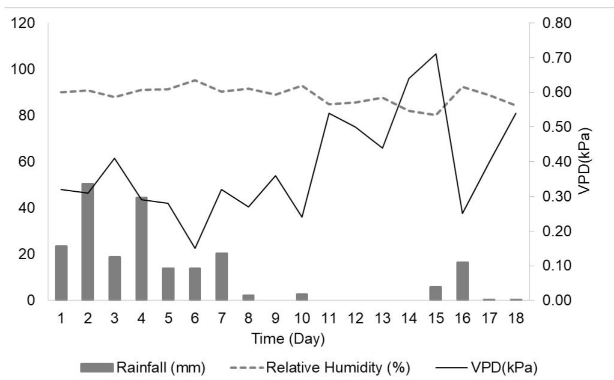

Figure 4 Climatic data for the measurement period; daily precipitation (mm), relative humidity (%) and vapour pressure deficit (kPa) at Bukit Hari during the measurement campaign.

Water-stressed plants and low soil moisture cause forests to lose their cooling effect and contribute to increased local temperatures. When VPD levels are high, the rate of evapotranspiration rises. As a result, more water is lost from the soil and plants, resulting in a decrease in soil moisture over time. When exposed to high VPD levels, plants might suffer unfavourable consequences. This is because stomatal conductance (*gs*) decreases exponentially as VPD increases.

Daily sap flow rate

The average daily sap flow rate of *Hopea odorata* dan *Khaya ivorensis* is depicted in Figures 5 and 6. The daily sap flow fluctuation for the observed species showed the opposite trend in the large diameter; whereby the 33 cm *H. odorata* has the highest sap flow rate but the 37 cm *K. ivorensis* showed the lowest sap flow rate. According to the early results, larger diameters in *H. odorata* tend to have higher sap flow. However, in *K. ivorensis*, the sap flow readings did not increase with the increment in diameter size. The medium tree exhibited slightly higher sap flow than the small and large tree, but with higher fluctuations. The daily sap flow rate pattern in *H. odorata* increases with tree diameter, however, this was not the case in *K. ivorensis*.

Transpiration and water consumption in the plant are measured by its sap flow. Our findings show that *H. odorata* uses more water compared to *K. ivorensis*, for all the diameter classes. The daily average sap flow rate of *H. odorata* was 21.90 (±4.59) L/day (small tree), 23.05 (±7.94) L/day (medium tree) and 46.20 (±7.84) L/day (large tree), whereas *K. ivorensis* has the daily average sap flow rate at 17.52 (±4.66) L/day (small tree), 19.83 (±5.90) L/day (medium tree) and 6.93 (±1.66) L/day (large tree). Because water is drawn out of internal storage compartments as transpiration begins each day, there are delays between changes in transpiration and sap flow at the base of the tree (Meinzer et al. 2004). Thus, it is believed that the variation in sap flow in large trees was influenced by the transpiration activity of the tree. This was in line with several studies conducted in different types of forests, which have discovered that the majority of the water lost from the canopy may be transpired by a few number of big trees (Čermak et al. 2004, Berry et al. 2017).

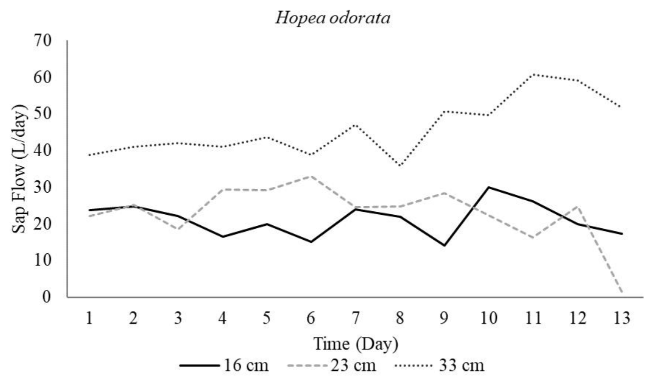

Figure 5 The pattern of daily sap flow rate (L/day) for the three *Hopea odorata* planted at Bukit Hari, of different diameter sizes

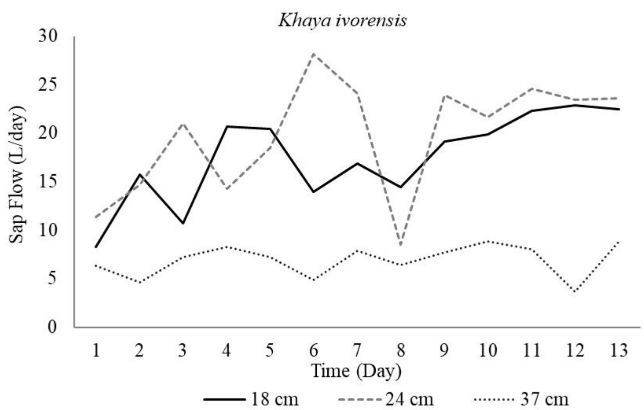

Figure 6 The pattern of daily sap flow rate (L/day) for the three *Khaya ivorensis* planted at Bukit Hari, of different diameter sizes

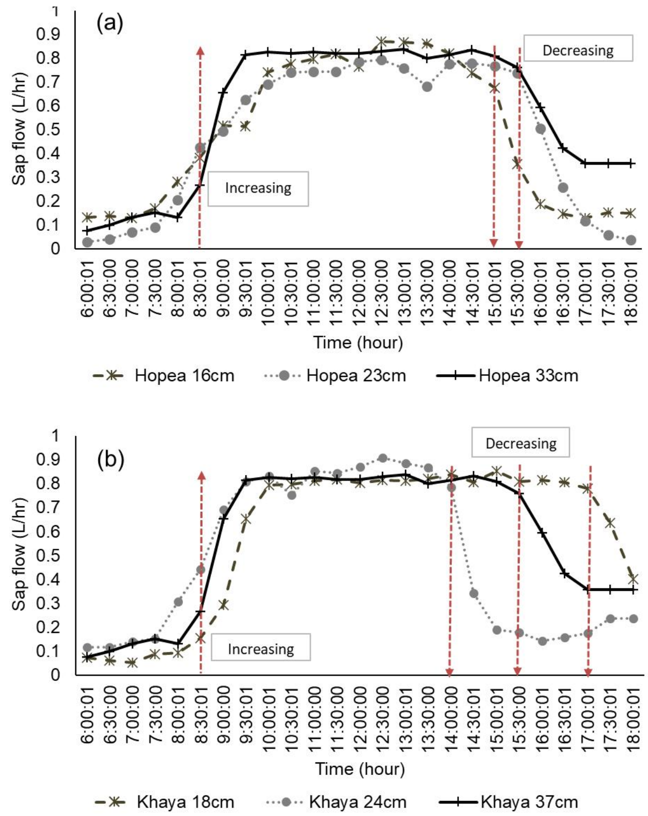

Figure 7 Daytime sap flow (L/hour) for (a) *Hopea odorata* and (b) *Khaya ivorensis*

Daytime sap flow pattern for *Hopea odorata* and *Khaya ivorensis*

The decreasing trend of sap flow time across all diameter classes is relatively more consistent in *H. odorata* compared to *K. ivorensis* (Figure 7), whereby the latter exhibited longer sap flow activity in the small tree, suggesting late stomata closure. From the data collected, both the sap flow in *H. odorata* and *K. ivorensis* for all diameter classes began to rise at 08:30 a.m. This pattern is associated with the leaf stomata opening in both species. Stomata opened to perform photosynthesis and transpiration, leading to water loss from the tree.

In *H. odorata*, the sap flow began to decrease at 15:00 p.m. for the small tree, followed by the medium and large trees half an hour later. In *K. ivorensis*, we noticed a distinct pattern in the sap flow-decreasing time for each tree varied. Among the three trees, the medium tree decreased in sap flow first at 14:00 p.m., followed by the big tree and subsequently the small tree. These results suggest that in *K. ivorensis,* trees of different diameter sizes have different productivity rates, with the small tree taking a longer time to perform its physiological processes compared to the matured trees (big and large trees).

Total sap flow of *Hopea odorata* and *Khaya ivorensis*

Unlike *H. odorata*, with the large tree showing the highest total sap flow mass among the three trees, in *K. ivorensis*, it was the medium tree that exhibited the highest total sap flow volume during the observation period. In comparison to the highest total sap flow volume of 600.64 L observed in the large *H. odorata*, about half the amount was estimated in the medium *K. ivorensis*, i.e. 257.79 L (Figure 8 and Table 2), for the observation period. The difference is even higher when comparing both large trees (600.64 L vs 90.14 L).

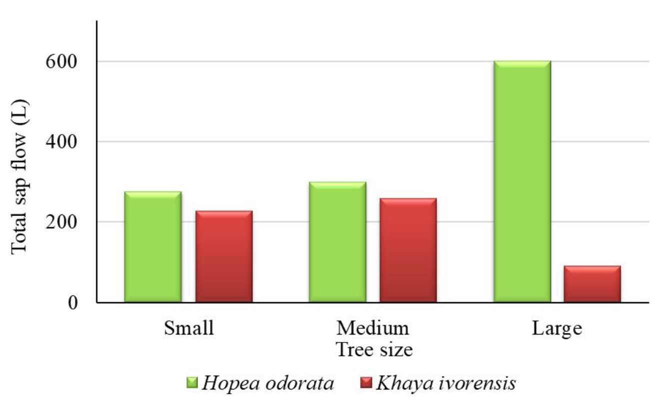

Figure 8 Comparison of the total sap flow for the different tree size classes of *Hopea odorata* and *Khaya ivorensis*

Table 2 Total sap flow of *Hopea odorata* and *Khaya ivorensis*

	Hopea odorata			*Khaya ivorensis*		
Diameter size	16 cm	23 cm	33 cm	18 cm	24 cm	37 cm
Total (L)	275.41	299.59	600.64	227.82	257.79	90.14
Mean (L/day)	21.19(±4.59)	23.05(±7.94)	46.20(±7.84)	17.52(±4.66)	19.83(±5.90)	6.93(±1.66)
Max (L/day)	29.90	33.07	60.82	22.85	28.15	8.89
Min (L/day)	14.16	1.39	35.76	8.30	8.55	3.67

The total sap flow volume in *H. odorata* was almost seven times higher compared to *K. ivorensis*, for the large tree. The difference in the sapwood depth between these two species was remarkably huge, which could be the primary factor affecting the volume of sap transport. Sapwood depth was much shallow in *K. ivorensis* compared to *H. odorata* (Table 1). Sapwood is the outer, living layer of the secondary wood of a tree, which engages in transporting water and minerals to the tree crown. Another reason could be because *H. odorata* is a late-successional tree species, which requires shade and high soil moisture content for its natural regeneration.

The variation of sap flow rate in different diameter sizes of *H. odorata* and *K. ivorensis* could be due to several reasons. Firstly, the stem diameter and xylem size of a tree affect the hydraulic conductivity and resistance of the xylem thus affecting its water needs (Marryanna et al. 2017, Sevanto et al. 2008). Large-diameter trees have a greater surface area and more leaves, which means they require more water and nutrients. Therefore, they tend to have higher sap flow rates than small-diameter trees. However, it does not apply in *K. ivorensis*. Secondly, the sap flow rate varies depending on the tree species, age, growth stage, and management practices (Poyatos et al. 2016). Berry et al. (2017) explored how the sap flow rate of a tropical montane forest ecosystem is influenced by the tree diameter distribution and sap flow parameters. They found that sap flow-based estimates of transpiration may be particularly sensitive to large trees due to nonlinear relationships between tree-level water use and tree diameter at breast height. They also found that variation in how sapwood depth is determined in the largest trees can alter estimates up to 26% of transpiration, while variation in how sap velocity is determined can vary results by up to 132%.

From our study, the difference in sapwood depth is one of the main factors. Different tree species have different characteristics such as leaf area, stomatal conductance, depth of roots, and water use efficiency, which can influence the rate of water uptake and transport. For example, coniferous trees have lower sap flow rates than broad-leaved trees due to their smaller leaf area and lower stomatal conductance. Furthermore, changes in environmental conditions such as temperature, humidity, and drought stress can also affect the sap flow rate in different ways, depending on the species. For instance, some species can maintain high sap flow rates under drought stress while others may significantly reduce sap flow. However, there is still much to learn about the relationship between tree species and sap flow rate.

CONCLUSION

Sap flow is the movement of water and nutrients in the xylem of a tree. It is important to trees as it ensures that they receive the necessary water and nutrients needed for growth and survival.

Sap flow rate can vary according to the diameter size and species of a tree, as trees of different species and sizes have different water needs and physiological characteristics. In this study, the diameter size influenced the pattern of sap flow rate in *H. odorata* and *K. ivorensis.* Short-term sap flow rate observed in *H. odorata* and *K. ivorensis* revealed that the water use of the small and medium tree sizes differed slightly, but there were significant variances when compared with the large trees. In *H. odorata*, the large tree had the highest mean daily sap flow, followed by the small and medium trees. In contrast, *Khaya ivorensis* has the highest mean daily sap flow rate in the medium tree, followed by the small tree, while with the lowest observed in the large tree.

In conclusion, the sap flow rate varies according to diameter size and species due to the differences in physiological characteristics and water requirements for growth and survival in different tree species and sizes. The flow of sap is crucial in controlling the water balance of a tree. For instance, when there is a drought, the tree may preserve water by slowing the flow of sap. By doing this, the tree is kept from drying out or dying. On the other hand, as the tree absorbs more water during times of heavy rain or irrigation, the sap flow rate may rise. Overall, knowing sap flow in trees is critical for enhancing growth and guaranteeing survival, particularly in the face of climate change. These differences may affect the suitability of planting these two species for different purposes, such as timber production, landscaping, or carbon sequestration. It would be ideal to gather more data about the hydrological and physiological functions of trees in future studies. Besides, in order to give a fuller image of the species traits that are closely associated with resistance against any change in local climatic patterns, the emphasis should be placed not only on a variety of sizes and species but also on distinct landscapes.

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In this study, the sap flow rate of two tropical timber species, *Hopea odorata* and *Khaya ivorensis*, was estimated. The sap flow pattern of *H. odorata* and *K. ivorensis* at the Forest Research Institute Malaysia (FRIM) campus was assessed, involving trees of three different diameter sizes, respectively. The diameters of the *H. odorata* trees chosen for this study were 16 cm (small), 23 cm (medium), and 33 cm (large), whereas the *K. ivorensis* trees under examination had diameters of 18 cm (small), 24 cm (medium), and 37 cm (large). The sap flow rate of these trees was measured using a sap flow metre (SFM) with a heat ratio method (HRM). It was found that the average daily sap flow rate was higher in the large *H. odorata* (46.20 L/day), compared to small (21.19 L/day) and medium (23.05 L/day). As for *K. ivorensis*, the daily sap flow rate was higher for the medium tree (19.83 L/day) compared to the small (17.52 L/day) and large (6.93 L/day). Our findings show that the sap flow rate pattern in *H. odorata* and *K. ivorensis* differ by diameter size. In other words, diameter size contributes to the varied water use in *H. odorata* and *K. ivorensis*.

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