

IMAGE-SCANNING APPROACH IN MONITORING OIL PALM ROOT PRODUCTION ON PEAT

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ABSTRACT

Understanding root mortality and production is critical for creating a uniform strategy for root growth estimations and modelling. Several approaches have been devised to assess root development and behaviour of oil palms in peat soil. There are two types of existing techniques: Traditional (destructive) methods and non-destructive approaches. However, due to the complexity of soil characteristics and circumstances, there is no precise method to date for assessing different root morphological features, particularly in tropical peat soil. The root dynamics performance of oil palms in peat soil was measured using a non-destructive, in situ scanning approach in this study. This study discusses the possibility of utilising image-scanning technology for investigating rhizosphere activities such as root development and turnover, root morphology and below-ground interactions.

Keywords: non-destructive, oil palm, peat soil, root dynamics.

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INTRODUCTION

Oil palm cultivation has proven to be a critical factor in Sarawak's economy, with a significant impact on Malaysia's palm oil industry. The State of Sarawak is noted for its leading role as an exporter of palm oil, resulting in a substantial increase in revenue for the region and stimulating economic expansion, primarily in rural areas where numerous smallholders are involved in oil palm cultivation (Koh et al., 2017). According to Jaafar (2020), by 2018, 657,273 ha of Sarawak's peatland had been converted to oil palm plantations, making up to 34% of the state's total oil palm area. Peatlands are complicated areas with very high content of organic matter, waterlogged conditions and dense vegetation such as ferns creating hurdles for both oil palm cultivation and scientists studying roots (Page et al., 2011).

The study of oil palm root architecture allows for a better understanding of the hydrological properties of oil palm roots, particularly those that are cultivated on drought-prone soil types and it allows for the development of a view on early drought detection of oil palm to optimise production and ensure oil palm sustainability. Exploring root morphology will ensure the longevity of the oil palm industry and protect the environment and sustainable cultivation practices. Study on root production and mortality can serve as a guiding framework for implementing sustainable practices that preserve soil health, biodiversity and water resources.

Throughout history, researchers have largely concentrated on the above-ground aspects of the oil palm, including productivity, fruit quality and disease resistance, due to their direct effect on the economy. The limited attention given to root-related factors has contributed to a lack of comprehension of the critical role pledged by oil palm roots in relation to plantation productivity (Jamaludin et al., 2019). Although oil palm production depends heavily on the health and vigour of its root system, most studies have concentrated on destructive methods including excavation and trenching, which involve laborious

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work but produce meagre data output (Corley & Tinker, 2015). Research involving oil palm roots planted on peat is less observable and more challenging to study (Dannoura et al., 2008) because it has been hindered by the limitations of the peat soil's complexity. The lack of dependable techniques for analysing roots has restrained scientific study in oil palm estates (Baraloto et al., 2010).

Comprehending the complexity of oil palm root systems is paramount in maximising farming techniques, as these systems are central to the uptake of water and nutrients from the soil, which is indispensable for the plant's expansion and maturation. Proper nutrient intake, including nitrogen, phosphorus and potassium, fundamentally impacts fresh fruit bunch (FFB) production, stressing the importance of a well-developed and effective root system in fostering oil palm health and output (Arifin et al., 2020). Investigating the underlying root structures of oil palms planted on peat is vital in perfecting cultivation methods, guaranteeing eco-friendly output and exploring better ways to grow oil palms while safeguarding the environment (Razak et al., 2018).

Recently, novel investigation techniques have allowed researchers to examine oil palm roots on peat without causing harm to the vegetation, microbes and soil properties. Non-destructive approaches, which were developed by Dannoura et al. (2008), allow researchers to study the delicate root system, growth tendencies and nutrient assimilation procedures without disrupting the natural process. Thus, the objective of this study is to employ a non-destructive technique to monitor oil palm root establishment in peatlands.

MATERIALS AND METHODS

Study Site

The study site was located at Sebungan Estate (03°09'00" N, 113°21'00" E) situated approximately 70 km from Bintulu within the Lavang-Sabauh Zone which is managed and belongs to Sarawak Oil Palm Berhad (SOPB). *Figure 1* indicates the position of Sebungan Estate, indicating the location of the exact research site.

Originating from a mixed-species swamp forest, the area was transformed into an oil palm estate in 2006. The impressive Sebungan Estate, totaling 9,614 ha, was meticulously planned with strategic placement of sand drainage ditches at every 28 m, leading to a larger ditch running through the block's centre.

The oil palm estate was established in 2007 and is in its first cycle of productivity (Cook et al., 2018; Manning et al., 2019; McCalmont et al., 2021; Sim et al., 2019). The majority of the plantation is covered with Teraja series tropical peat, comprising very deep organic soil approximately 4 m thick, with severely degraded sapric (42.2%) and mostly hemic subsurface tie (42.6%) (Lewis et al., 2020; Param Agricultural Soil Survey, 2013). According to the reports by Param Agricultural Soil Survey (2013) and Sim et al. (2019), the water table is generally positioned between a depth of 30-40 cm.

There is a total of 160 palms planted ha⁻¹, with each palm spaced 8 m apart in rows. Standard management strategies are employed to manage the estate, including the use of urea as nitrogen input at a rate of 158 kg ha⁻¹ in two split

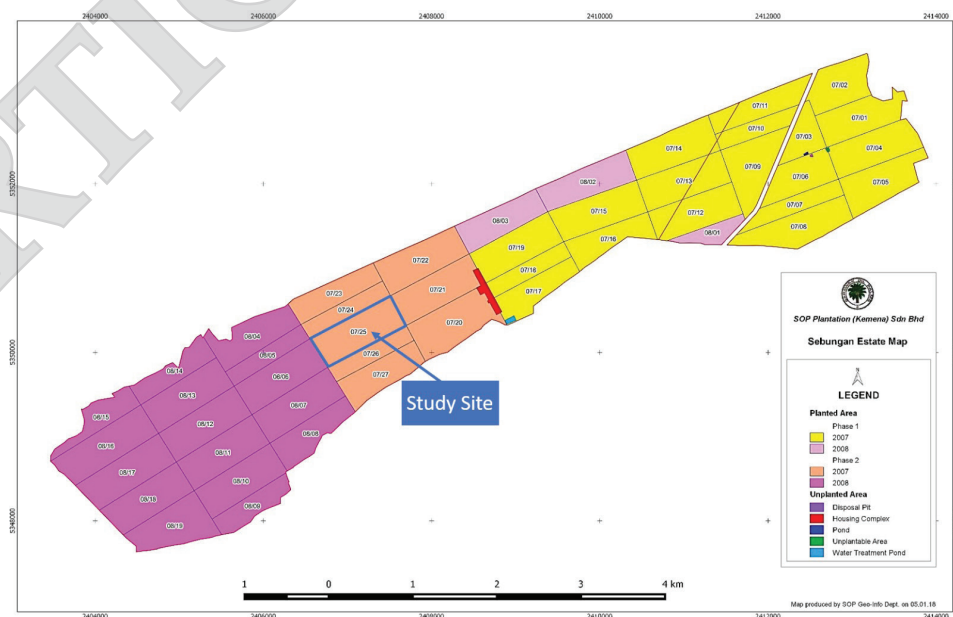


Figure 1. Location of the study site (07/25) at Sebungan Estate where the palms were planted in 2007.

applications. The average bulk density of the upper 1 m of peat in the Sebungan estate was found to be 0.2 g m^{-3} (Cook et al., 2018). Compaction is achieved by manoeuvring caterpillar-tracked machines over the peat surface to provide enhanced anchoring stability for the palms (Sarawak Oil Palm Berhad, 2006). The semi-mature palms create a partially closed canopy setting, with approximately 70% closed canopy and some shade for the peat surface due to the age of the plantation.

Climate

In this region, the average temperature hovers around 26°C , and the mean annual precipitation amounts to 3,200 mm. Evaporation averages $111\text{--}133 \text{ mm month}^{-1}$, with the highest levels occurring during the dry season, typically in the mid-year months (Sarawak Oil Palm Berhad, 2006). During the dry season, monthly rainfall often exceeds $100\text{--}150 \text{ mm}$. Droughts can transpire from June through August if evaporation surpasses rainfall, although these periods typically last no more than two months. Rainfall data were collected from the rainfall stations in Sebauh and Lavang, while evaporation data were obtained from the Bintulu Airport Station (Sarawak Oil Palm Berhad, 2006). Precipitation is more substantial during the Northwest Monsoon season (October-January) than in the Southwest Monsoon season (May-August). The daily relative humidity (RH) fluctuates between 60% and 95%, causing the area to be generally hot, humid and wet throughout the year (Sarawak Oil Palm Berhad, 2006).

Geology and Topography

The plantation features a relatively level terrain, comprising slopes ranging from 0%–4%, as well as undulating areas with slopes between 4% and 12%, all of which are composed of peat soil (Param Agricultural Soil Survey, 2013). The peat formation is estimated to have occurred during the quaternary era, encompassing approximately 83% of the total area, with 70% classified as deep peat (Sarawak Oil Palm Berhad, 2006). The estate is situated on peat domes that were created by the Batang Kemena, Sungai Sebungan and Sungai Pandan rivers. As the peat extends away from the rivers, it adopts a dome-shaped morphology, with the highest point recorded at the centre of the dome, reaching 7.5 m in height (Cook et al., 2018; Sarawak Oil Palm Berhad, 2006).

The Scanner Setup

The non-destructive scanning method was utilised to assess root development in oil palms

planted on tropical peat, with the technique adapted from (Dannoura et al., 2008, Kume et al., 2018; Nakahata et al., 2017). For this study, three clear acrylic boxes with size $30 \text{ cm (L)} \times 50 \text{ cm (H)}$ were custom-made to accommodate the scanner, referred to as the “scanner box.” These boxes were strategically placed near the palm base (PB), harvesting path (HP) and under the stacking fronds (FP) of 13-year-old oil palms (Figure 2).

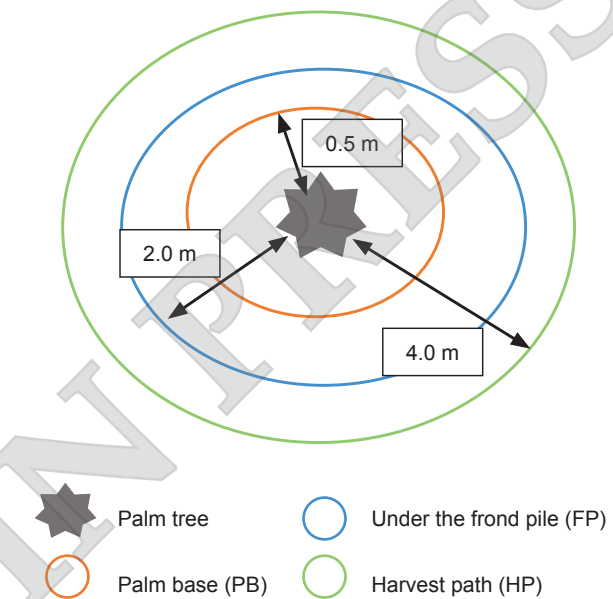


Figure 2. The diagram of three concentric zones surrounding the palm, each designated by a precise distance from the palm trunk.

The soil was carefully dug using a spade and trowel to accommodate the scanner box, which was then inserted vertically 25 cm below ground level. The area surrounding the boxes was backfilled with soil, and a PVC pipe cut in half lengthwise (C-shape) was employed to cover the scanner box. Figure 3 illustrates the on-site installation of a scanner box. In this study, the installation took place in May 2020. Ideally, installation should be conducted during the dry season to avoid excessive rainfall, which may jeopardise the interface between the screen and the soil, particularly in peat. During the installation process, roots were not forcibly pulled to differentiate them from the walls; instead, they were gently cut as close to the boundary as possible using a knife or scissors. One side of the scanner box was labelled with ‘A’ as the side intended for root image collection so that the scanned roots do not get mixed up during the scanning process. The scanner boxes were left undisturbed for three months to allow for root recovery from installation-related disturbances and to facilitate acclimatisation.



Figure 3. The scanner box installation. The soil was dug and the scanner box was inserted vertically. A half-open PVC pipe was then placed to cover the scanner box. 'A' side is facing the palm and 'B' side is away from the palm.

Scanner Outline

A flatbed colour Charged Coupled Device (Epson Perfection V39) with dimensions (9.9" (W) x 14.4" (D) x 1.5" (H)) was connected to a laptop to capture images of the roots, as shown in Figure 4. The root images were captured at monthly intervals, saved in TIFF format at 1,080 resolutions. During the data collection, the scanner boxes were kept dry without excessive water trapped inside.

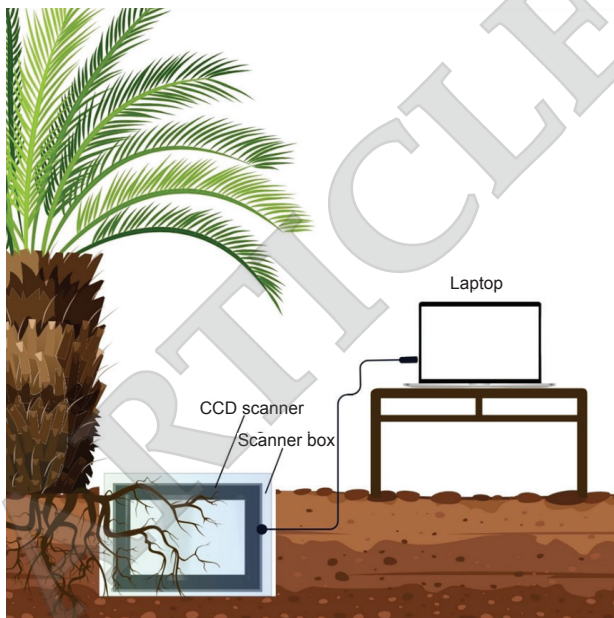


Figure 4. Schematic representation of the root image scanning process using a Charged Coupled Device scanner.

Root Image Acquisition

The software used for image analysis in this study included the GNU Image Manipulation Program (GIMP) and ImageJ, following the

procedure described by Kume et al. (2018). Figure 5 illustrates the sequential steps involved in processing images to monitor the root development of a palm over time, from August 2020 to November 2021. The acquired root images were manually marked and classified into distinct categories based on their diameter: Primary roots (>6.0 mm), secondary roots (>2.0 mm) and tertiary roots (>1.0 mm), as per the classification by Tinker (1976) and Corley and Tinker (2015). Dead roots were identified by their dark brown or black colour while growing and active roots appeared bright. By overlaying images taken at different time points, the root development, including new root growth or dying roots, could be identified (Figure 5). In cases where the images were too dark, GIMP was employed to adjust the image resolution. Once the root tracing was complete, ImageJ was utilised to calculate the total roots by determining the difference between the living and dead roots, following the protocol (Nakano et al., 2013).

Figure 6 clearly illustrates that the palm roots were effectively detected using this method. The images enabled the differentiation between living, dead, new roots and root elongation. Additionally, the method facilitated the measurement of root diameter and length. Moreover, this approach allowed for the monitoring of root trends over time with minimal disturbance compared to conventional methods like soil coring. As seen in the study, a new root appeared after three months (November 2020).

RESULTS AND DISCUSSION

The root system plays a vital role in the health, development and productivity of oil palms and can be classified into three main categories, each with

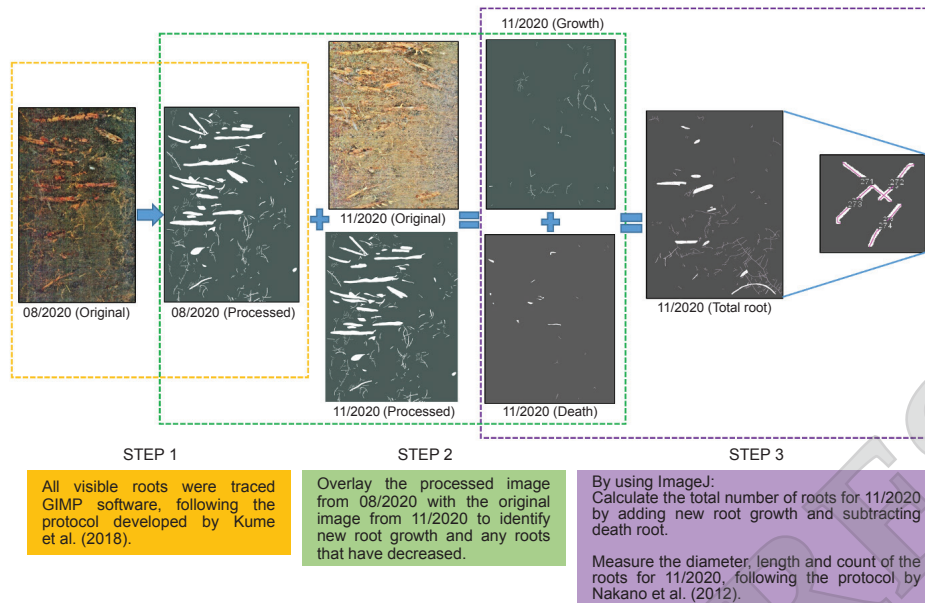


Figure 5. Illustration of a set of root images obtained from a mature palm; the images illustrate the development and turnover of the roots and how the root images were processed by manually drawing the root using GNU Image Manipulation Program (GIMP) software and calculating the root with Image J.

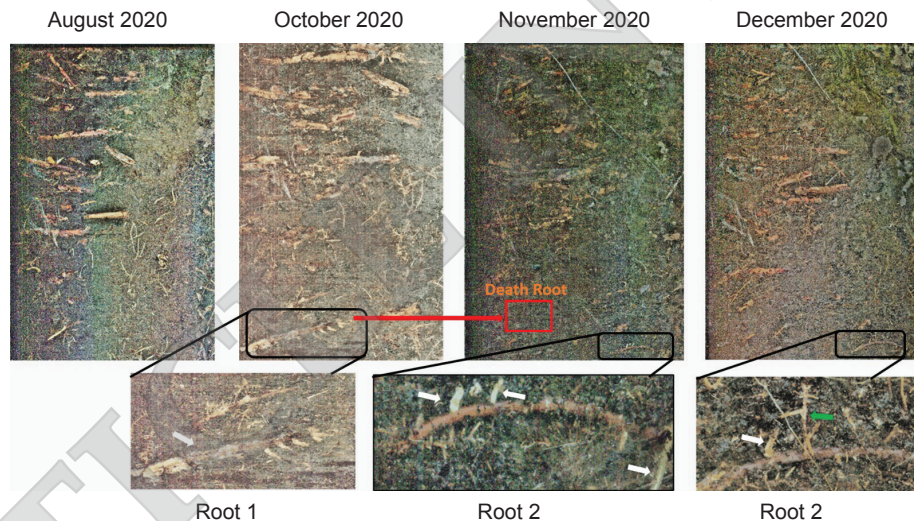


Figure 6. The development and turnover of the roots of a mature palm. The white arrow represents a new root and green for root elongation, whereas the red represents the dead root. As we can see here, a new root emerged in October 2020 (Root 1) but in November 2020, Root 1 was missing (dead root) from the captured images and a new root grew (Root 2). Then, in December 2020, Root 2 grew longer.

distinct functions. Root studies offer insights into plant responses to soil conditions and agricultural practices, supporting healthy growth and long-term yield. Understanding root distribution, particularly of fine roots, under different management strategies may improve plantation practices (Figure 7).

The primary root originates from the palm trunk base and provides anchorage and structural support, helping the palm resist wind damage. With a diameter of 6–10 mm, it penetrates deeply and extends horizontally (Corley et al., 1976; Corley & Tinker, 2003, 2015).

The secondary roots, arising from the primary root, are key for water and nutrient uptake. They spread horizontally within the top 60 cm of soil, with diameters of 2–4 mm, forming a widespread network that enhances resource acquisition (Corley et al., 1976; Corley & Tinker, 2003, 2015).

The tertiary and quaternary roots are the finest, branching from secondary roots. Tertiary roots (0.7–1.2 mm) and quaternary roots (0.1–0.3 mm) are primarily responsible for fine nutrient absorption, ensuring efficient access to soil resources (Corley et al., 1976; Corley & Tinker, 2003, 2015).

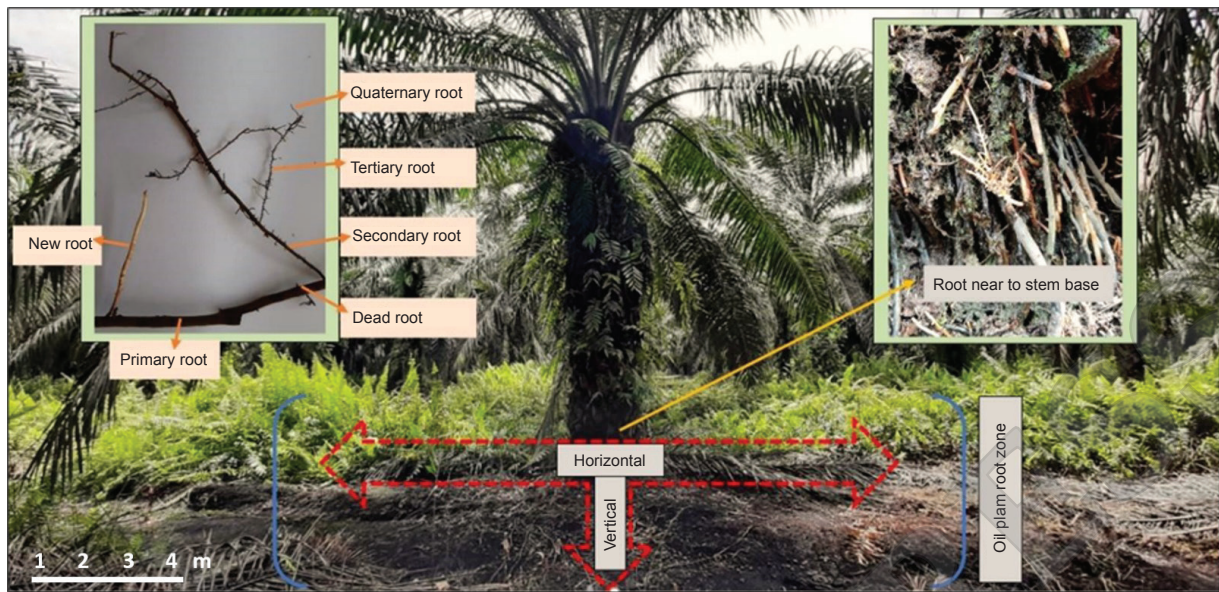


Figure 7. The oil palm root distribution in the field. The image on the left shows the root image from primary to quaternary, as well as the structure of dead and new roots. On the right is a close-up image of roots growing near the stem base.

During the study period, the palm vegetative measurement was recorded and overall, the palm is healthy, with the diameter at breast height (DBH) increasing from ~44.4 to 50.0 cm and the palm height increased from ~145 to 250 cm between 2020 and 2021. Aside from that, we observed palm frond growth, and we discovered that as the root grows, the number of palm fronds also increases. In this case, an increase from 24 in 2020 to 34 fronds in 2021.

The root activities of the mature oil palm were monitored from August 2020 to November 2021. All the existing root images were counted using ImageJ software. During the first stage, the cumulative root production detected throughout the study period can be summarised in Table 1 where PB was shown to have the highest total root growth detection at 14,508 root yr⁻¹, followed by HP with 9,567 root yr⁻¹ and FP at 4,558 root yr⁻¹.

TABLE 1. THE CUMULATIVE ROOT PRODUCTION OF OIL PALM PLANTED ON PEAT IN DIFFERENT MANAGEMENT ZONES

Area	Total root
Palm base (PB)	14,508
Harvesting path (HP)	9,567
Frond pile (FP)	4,558

This data covers the total roots recorded from August 2020 to November 2021. It does not represent the total root yr⁻¹. Tomlinson (2006) highlights that palms develop dense root networks near their base, crucial for anchorage, nutrient uptake and

respiration, enabling them to thrive in diverse environments. The decomposition of organic matter such as amino acids released to the surrounding soil will nourish soil microorganisms and enhance nutrient availability, thus creating a nutrient-rich environment that fosters root proliferation near the palm (Santos-Medellín et al., 2017).

The physical presence of the palm contributes significantly to the abundance of roots near the PB area. Study conducted by Wahid et al. (2019) supports the idea that the palm trunk functions as an anchor, providing support and stability for the growing roots and the dense network of roots surrounding the palm trunk creates a favourable atmospheric condition that protects against extreme temperatures and moisture fluctuations, promoting root growth and expansion near the palm trunk.

According to Omar et al. (2021), another contributing factor to the increased abundance of palm roots near PB is the higher availability of nutrients. As the palm matures, nutrient-rich organic matter and decomposed fronds, accumulate around the base. This organic matter serves as a natural fertiliser, enhancing nutrient availability and promoting root growth near PB.

The abundance of oil palm roots near PB is also influenced by the adaptation root system of the palm. Oil palm roots have evolved into shallow, fibrous structures that are well-suited for efficient nutrient and water absorption and this adaptation allows the roots to effectively utilise the resources available near the base of the palm, leading to enhanced root growth in this management area (Pulingam et al., 2022).

In contrast, root production is generally lower under the FP area due to the negative impact of decomposition residue. Santos-Medellín et al. (2017) explained that the decomposition of leaf litter like stacking fronds during the harvest process releases carbon dioxide and other by-products, which adversely affect soil conditions. These changes lead to increased acidity and reduced nutrient availability, ultimately inhibiting root growth and lowering overall palm root productivity in this area.

Similarly, root production along the HP is also affected by soil compaction resulting from the movement of heavy machinery or human activities during palm fruit harvesting or fertilisation (Yahya et al., 2015). Jamaludin et al. (2019) also emphasised that soil compaction reduces soil aeration and increases soil density, creating obstacles for root growth and penetration. Consequently, root production is typically lower along HP when compared to the area near the palm base.

The root is divided into two categories: (a) New/young root in Figure 8 and (b) root death in Figure 9. The presence of roots was captured using a Charged Coupled Device scanner three months after installation. We found that PB has a higher cumulative new root production compared to HP and FP. In the early stages of root observation, in August 2020 for PB and HP and October 2020 for FP in Figure 8, the root detection was <math> < 500 </math> root month⁻¹. However, as the palm grew, new roots emerged, with the cumulative root detected reaching around 13,577 root yr⁻¹ at PB, 9,123 root yr⁻¹ for HP and 4,227 root yr⁻¹ for FP in November 2021.

Root mortality refers to the death of roots upon reach in a certain lifespan. The type of soil, diseases, pests and extreme conditions like drought or flood can lead to root mortality. Plus, as the palm gets older, roots might get weaker and disappear as new roots grow (Kushairi & Kee, 2019).

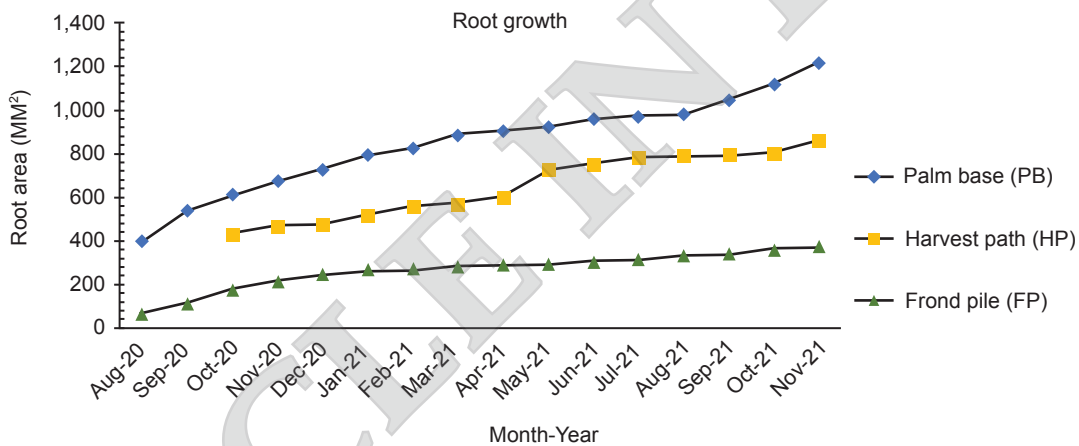


Figure 8. Monthly root growth. The PB zone has the highest and most variable root growth, HP is intermediate, while FP is more stable and consistent.

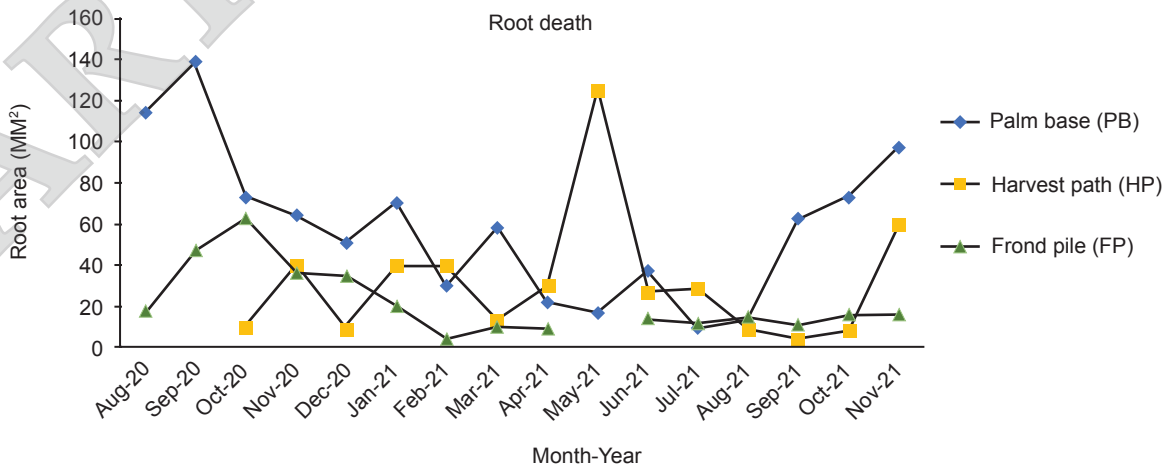


Figure 9. Trend of root death throughout a monthly monitoring interval in PB, HP and FP areas.

Our image found that root mortality tends to be higher in PB (Figure 9) area as compared to the other management zones. PB has an excessive cumulative mortality rate of around 931 root yr^{-1} as compared to HP (444 root yr^{-1}) and FP (331 root yr^{-1}).

Soil structure near the palm trunk is denser due to root density. Our field observations indicate that the mound technique, which involves planting oil palm seedlings on raised soil to prevent waterlogging and improve growth, may lead to increased root mortality (Corley & Tinker, 2015). Improper implementation could lead to soil compaction that restricts the water, air and nutrient movement. This was supported by Hashim et al. (2019), where healthy root requires good soil aeration to promote nutrient uptake and respiration. As roots need oxygen, compacted soil would block oxygen flow leading to a hypoxic situation in the roots. In the long run, this situation impairs root function causing root-enhanced mortality.

Another factor contributing to root mortality in the PB area is the accumulation of decomposed organic matter from fronds, leaf litter, fruit and empty fruit bunch (EFB). When excessive natural materials undergo decomposition, they release several by-products that can lead to nutrient imbalance, soil acidity and toxicity resulting in root mortality (Mando et al., 2018). The root in the PB area is also most exposed to pathogens and diseases such as *Ganoderma boninense* because the fungus usually attacks the palm base or trunk, hence the name basal stem rot (BSR), which leads to root decay and weakened palm (Turnbull et al., 2016).

The large values observed for HP in May 2021 are concerning and may require further investigation. One possible explanation could be the impact of heavy machinery used during harvesting, fertilisation, or pesticide application activities. These machines can compact the soil, disturb root systems, or alter soil conditions, potentially leading to unusual fluctuations in root growth or mortality (Abdul Rahim et al., 2021; Horn & Fleige, 2003).

This study provides baseline data using a newly introduced scanner method to monitor fine root production in oil palm on peat. As the method is still being tested for feasibility, only one measurement was taken at each location. We acknowledge that repeated measurements are important to capture changes over time and to allow for statistical comparison between sites. This is a limitation of the current study, and future work will include repeated measurements to improve data reliability and support wider application of the method.

CONCLUSION

The image-scanning technique has proven to be a highly effective tool for studying root production. It offers a simple, cost-effective and quick way to directly observe and analyse root dynamics. Since it is non-destructive, this method has significantly improved our understanding of root systems, making it easier to study root behaviour compared to traditional destructive methods. While the technique requires careful scanner installation for continuous measurements and sufficient memory for frequent image capture, it provides a larger observation area (A4 paper size) than minirhizotron or rhizotron tubes. This scanning method allows researchers to monitor many previously unknown aspects of root dynamics, such as root growth, elongation and mortality. The findings highlight the potential of this technique for gaining a clearer understanding of oil palm root development. However, it's important to note that these are just preliminary results. Further study will be needed to confirm these findings and enhance the applicability of the image-scanning method, especially in peat soil conditions.

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