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Effects of Root Pruning on Organic Carbon Stock Levels in Oil Palm Plantation

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ABSTRACT

Palm oil (*Elaeis guineensis* Jacq.) is a crop that can transfer carbon dioxide into carbon storage within the soil. Root pruning also plays a role in enhancing carbon stocks in the plant. This research aims to evaluate the effects of root pruning on oil palm carbon reserves and their association with nutrient absorption. The study was conducted over six months using four-year-old oil palm plants. A nested experimental design with two factors was employed. The first factor, serving as the main plot, involved three root cutting depths (0, 10, and 20 cm), while the second factor consisted of four root cutting intensities (0%, 25%, 50%, and 75%). The findings indicated that root pruning increased the plant's carbon stock, though it remained lower compared to the control. The highest CO_2 emission was recorded in the afternoon, specifically in the 20 cm root cutting treatment at 75% intensity, measuring 4.3 $\mu mol \cdot m^{-2} \cdot sec^{-1}$. The greatest carbon reserve, 16.98 $tons \cdot C \cdot ha^{-1} \cdot year^{-1}$, was observed at a 20 cm depth and 75% intensity, with a positive correlation.

Keywords: emissions, CO_2 emissions, CG-measurement CO_2, CH_4, root respiration.

INTRODUCTION

Following the juvenile phase, the oil palm root system undergoes changes in both growth and structure. Morphologically, there are eight distinct types of roots in oil palms, classified based on their developmental patterns and levels of specialization. These include primary roots, vertical and horizontal roots, secondary horizontal roots, secondary vertical roots that grow either upward or downward, and surface and deep roots. Additionally, tertiary and quaternary roots are present. These root types constitute the structural and functional components of the oil palm's root system, known as 'root system units'. This root diversity allows for the identification of morphogenetic gradients, which mirror the development of the oil palm root system (Jourdan and Rey, 1997).

The process of carbon movement from photosynthesis to plant roots and ultimately to the soil is a complex and vital cycle in ecosystems. It begins with photosynthesis in the leaves, where carbon dioxide from the air is converted into glucose using solar energy. This glucose is then translocated through the phloem to all parts of the plant, including the roots. Most of this carbohydrate is used for plant growth and metabolism, but about 20–40% is excreted by the roots into the soil as exudates. These root exudates provide a food source for soil microorganisms, creating an important symbiotic relationship in the rhizosphere. When plant roots die, the carbon stored in them begins to be decomposed by soil microorganisms. This decomposition process produces simpler carbon compounds, some of which can be stabilized in the soil through aggregate formation or binding with minerals, storing carbon for long periods. However, some carbon is also released back into the atmosphere as CO_2 through microbial respiration and plant roots. This cycle is a crucial component of the soil-plant-atmosphere carbon dynamics, the understanding and management of which is critical in the context of sustainable agriculture and climate change mitigation efforts (Yang et al., 2023). Consequently, any changes to the root system will inevitably impact soil carbon availability.

Pruning the roots of oil palm plants can impact the availability of carbon stocks in the soil, as roots are a significant source of organic carbon. Cutting the roots reduces the amount of organic carbon they generate, which can affect the carbon stock levels, especially in the soil layers where the roots are present. According to Rüegg et al. (2019), increased root growth in oil palm plants has been shown to enhance soil carbon sequestration and bolster soil carbon reserves, even when organic residue input is low. Additionally, some studies indicate that variations in the mineralization of organic carbon stocks due to different agricultural practices have a minimal effect on the soil's capacity to maintain stable carbon reserves.

Root pruning can increase levels of nitrogen, phosphorus, potassium, and total organic carbon, and also stimulate higher organic carbon activity within the rhizosphere. Moderate root pruning enhances the carbon and nitrogen content in microbial biomass, boosts basal respiration, and reduces metabolic quotients in rhizosphere soils by 8.9%, 5.0%, and 11.4%, respectively. It also significantly promotes growth in trunk diameter, tree height, and overall volume. Additionally, root pruning can elevate the production of plant exudates, resulting in a 25.82% increase in organic acids, a 1.63% rise in amino acids, and an 18.25% boost in sugar levels. These exudates are utilized by microorganisms (Jing et al., 2018). Increased exudate production fosters microbial growth, which accelerates organic matter decomposition. Root pruning stimulates microbial activity, influencing interactions between microbes and plant roots and ultimately affecting soil carbon levels (Jing et al., 2017).

Pruning roots at a depth of 5 cm increased root fresh weight and volume in sugarcane by 21–59% and 41–127%, respectively, compared to pruning at depths of 0 and 10 cm. Root pruning at a depth of 5 cm also boosted sugarcane yields by 43% and 28% compared to depths of 0 and 10 cm, respectively, by optimizing ratoon management and improving ratoon crop cycles (Yang et al., 2021). This research aims to assess the carbon stock values in oil palm plants and observe the changes in CO_2 emissions following root pruning.

MATERIALS AND METHODS

Research procedures

The study was conducted in Teluk Merbau Village, Dayun District, Siak Sriindrapura-Riau Regency, from December 2022 to October 2023. Analysis of soil content was conducted at the Soil Science Laboratory within the Department of Soil Science and Land Resources, Faculty of Agriculture, Bogor Agricultural University.

The primary research subjects were 5-year-old oil palm plants of the PPKS variety. The research utilized several tools, including ruler, hoes, ground drills (hand augers), digital scales, an Haga Altimeter, CG-measurement devices for CO_2 and CH_4, and GPS.

The study employed a nested design with two factors. The primary factor was the depth of root cutting, which had three levels (0, 10, and 20 cm). The secondary factor was the intensity of root cutting, with four levels (0, 25, 50, and 75%). Each combination of treatments was replicated four times, resulting in 28 experimental units. Each unit contained 5 plants, making a total of 140 plants.

The cutting treatment is applied to randomly selected trees with consistent plant conditions. Root cutting is performed 1.5 meters from the plant stem, with variations in depth and intensity as specified by the treatment. Carbon analysis was conducted on 5-year-old oil palm plants, with observations at 0, 3, and 9 months after the treatment.

Experimental observations included measuring the levels of N, P, and K in plants and analyzing carbon reserves. Carbon reserve analysis was performed using a modified Li-cast tool. For nutrient content testing, three distinct methods were employed: the Titrimetry method for N content, spectrophotometry for P content, and atomic absorption spectrophotometry (AAS) for K content.

Data were analyzed using ANOVA at level $\alpha = 5\%$. If the treatment had a significant effect, the analysis was continued with Duncan's Multiple Range Test (DMRT) at a 95% confidence level (α = 5%) using the SAS V.04 software.

RESULTS AND DISCUSSION

NPK content of soil

Soil nutrient content was analyzed prior to the study. Table 1 indicates that the soil had an acidic pH ranging from 5.5 to 6.5, with high levels of soil N, P, and K (Kundu et al., 2023). Changes in nutrient content were observed post-treatment. As shown in Table 2, the analysis revealed significant differences in soil nutrient levels across various treatments. The treatment with a root cutting depth of 10 cm and a 50% intensity resulted in the highest nitrogen content (0.30), while a depth of 20 cm generally showed lower nitrogen levels. This suggests that reducing the number of plant roots may enhance nitrogen availability in the soil. Additionally, the highest phosphorus content was found in treatments with lower cutting intensity, particularly at a root cutting depth of 10 cm. This implies that the impact of root cutting can vary with depth and intensity. Similarly, the highest potassium content was observed in treatments with a 10 cm root cutting depth and 50% intensity, indicating that root reduction might lead to more efficient nutrient redistribution in the soil.

Consistent with the research by Dawson et al. (2016), a reduced root system can result in lower phosphorus and nitrogen absorption, making these nutrients more prone to leaching. This supports the observation that root cutting influences nutrient availability in the soil, as evidenced by higher phosphorus and nitrogen levels in treatments with lower cutting intensity. Additionally, this aligns with the concept of root exudation proposed by Tian et al. (2019). Root exudation can transform unavailable nitrogen forms into ones that plants can use, thereby increasing nitrogen availability in the soil. This principle may also apply to phosphorus, as a reduction in root cutting intensity might enable roots to more effectively release exudates that enhance phosphorus availability in the soil.

Carbon reserves

Table 3 displays the results of the soil carbon stock analysis for oil palm plants subjected to root cutting treatments and their variations. Both at the start of the experiment (0 months) and after 6 months of root cutting, there was an increase in plant carbon stocks. Additionally, potential biomass also showed an increase following the root cutting. Comparing with the

Table 1. Soil nutrient content before observation

Observation	pH H_2O	N (%)	P (ppm)	K (me/100 g)
Depth 10 cm intensity 25%	5.5	0.15	42.48	0.21
Depth 10 cm intensity 50%	5.7	0.15	71.89	0.86
Depth 10 cm intensity 75%	6.4	0.16	72.34	0.70
Depth 20 cm intensity 25%	6.5	0.10	34.75	0.88
Depth 20 cm intensity 50%	6.5	0.12	51.89	0.12
Depth 20 cm intensity 75%	6.1	0.12	60.56	0.04

Note: Samples taken based on Dayun research locations.

Table 2. Soil NPK analysis after treatment

Treatment	N (%)	P (ppm)	K (me/100g)
Control	0.19 b	45.00 a	0.18 b
Depth of 10 cm with 25% intensity	0.18 b	51.04 a	0.16 b
Depth of 10 cm with 50% intensity	0.30 a	20.76 c	0.23 a
Depth of 10 cm with 75% intensity	0.22 c	10.35 d	0.22 a
Depth of 20 cm with 25% intensity	0.10 c	46.71 a	0.17 b
Depth of 20 cm with 50% intensity	0.15 b	27.68 c	0.17 b
Depth of 20 cm with 75% intensity	0.25 b	38.93 b	0.21 a

Note: Numbers in the column that share the same lowercase letter do not differ significantly according to the 5% Duncan test.

Table 3. Analysis of carbon stocks in ton per hectare conversion

Treatment	Pot biomass		Carbon stock		Carbon stock/year	
	(ton)		(ton C/ha)		(tons C/ha/year)	
	Month					
	0	6	0	6	0	6
Control	2.83	3.04	1.33	1.43	15.96	17.12
Depth 10 cm intensity 25%	2.62	2.57	1.23	1.21	14.75	14.49
Depth 10 cm 50% intensity	2.56	2.86	1.20	1.35	14.42	16.15
Depth 10 cm intensity 75%	2.90	2.68	1.36	1.26	16.37	15.12
Depth 20 cm intensity 25%	2.96	2.98	1.39	1.40	16.69	16.81
Depth 20 cm intensity 50%	2.92	2.99	1.37	1.40	16.47	16.84
Depth 20 cm intensity 75%	2.87	3.01	1.35	1.41	16.20	16.96

Note: The numbers in the column that are followed by the same letter did not differ significantly at the 5% level according to the Duncan test.

0-month data, the treatment with a root cutting depth of 20 cm and an intensity of 75% showed the most significant overall increase in soil carbon stocks. The depth of root cutting impacts soil organic carbon because plant roots contribute to soil organic carbon through decaying roots, tissues, and decomposed organic matter (Jing et al., 2017). Root cutting can stimulate new root growth, which facilitates the rapid turnover of soil organic carbon through stabilization and destabilization processes (Dijkstra et al., 2020).

CO_2 emission value

Table 4 indicates that while the carbon assimilation of oil palm is lower compared to tropical forests, its oxygen production is higher. This study included an analysis of CO_2 emissions following root cutting. The results, presented in Figure 1a, show CO_2 emission levels (μmol·m^{-2}·sec^{-1}) in oil palm subjected to various root cutting treatments across four measurement periods: Month 0, Month 3, Month 6, and Month 9. Each graph displays CO_2 emission data collected at three different times of the day: morning 09.00 AM, noon 13.00 PM, and afternoon 17.00 PM.

Detailed observations reveal that CO_2 emissions rise with time, whether in the morning, noon, or evening. During the 3-month period, CO_2 emissions were relatively low across all treatments, but a noticeable increase was observed at a 20 cm depth with a 75% intensity. By the 6-month period, CO_2 emissions showed a more significant rise, particularly at a 20 cm depth with 50% and 75% intensities. The highest CO_2 emissions occurred at the 9-month mark, with the peak observed at a 20 cm depth and 50% intensity, especially in the afternoon, reaching nearly 4.3 μmol m^{-2}·sec^{-1}. The temperature remained relatively stable, varying between 29.1 °C and 33.3 °C. During the 3-month period, the average temperature ranged from 31.0 °C to 33.0 °C, while in the 6-month and 9-month periods, it increased slightly but stayed within the range of 30.4 °C to 33.3 °C.

Increased CO_2 emissions are closely linked to the oxidation of organic matter in the soil, which is influenced by soil moisture and temperature (Smith et al., 2018). Deeper planting depths (20 cm) generally lead to greater organic matter accumulation, and higher planting intensities (75%) enhance plant respiration and microbial activity, resulting in higher CO_2 emissions (Lal, 2004).

Table 4. Sequestration of more carbon (C) than tropical forests

Indicator	Tropical forests	Oil palm plantations
Gross assimilation (tons CO_2/ha/year)	163.5	161.0
Total respiration (tons CO_2/ha/year)	121.1	96.5
Net assimilation (tons CO_2/ha/year)	42.4	64.5
Oxygen production (O_2)/ha/year)	7.09	18.70

Note: Hensen (1999).

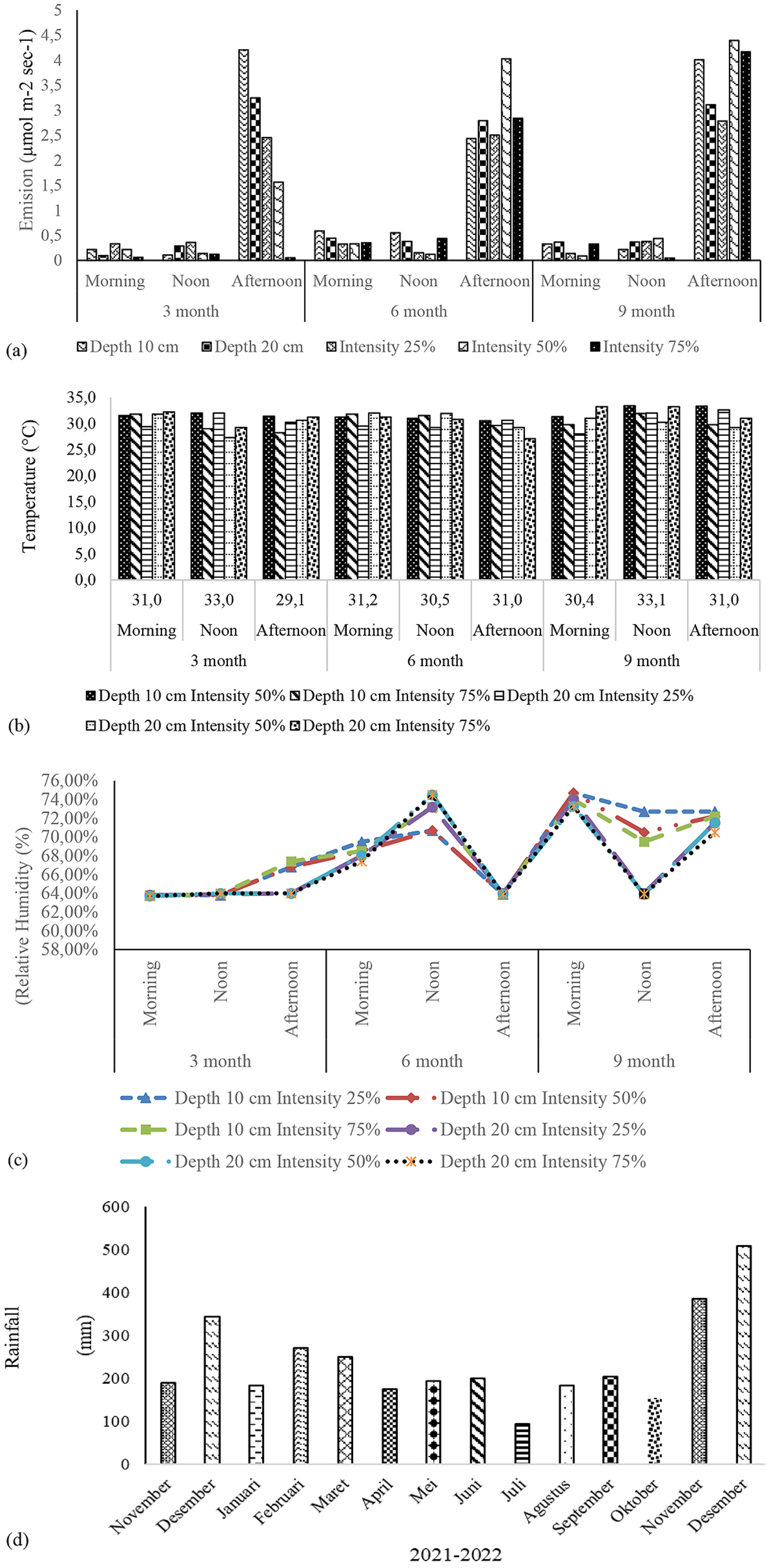

Figure 1. Graph of CO_2 emission values and temperature, humidity at various root cutting conditions: (a) CO_2 emissions; (b) temperature; (c) humidity, and (d) rainfall

Research indicates that higher soil temperatures accelerate microbial activity and organic matter decomposition, thereby increasing CO_2 emissions (Davidson and Janssens, 2006). However, temperature data shows that environmental temperatures are relatively stable, suggesting that the rise in CO_2 emissions is more affected by planting depth and intensity than by temperature fluctuations. Previous studies have noted that oil palm is highly adaptable to environmental changes, including physical disturbances like root cutting (Turner et al., 2011; Lamade and Bouillet, 2005).

Daily fluctuations in temperature and relative humidity significantly impact soil respiration rates and CO_2 emissions in oil palm ecosystems (Novita, 2016). The relatively stable temperature conditions imply that variations in emissions are more affected by soil physical properties and biological activity rather than daily temperature changes. Future research could focus on optimizing planting depth and intensity to minimize CO_2 emissions, while also considering additional factors such as soil moisture and crop type (Janssens et al., 2010).

The daily humidity in this study (Figure 1) showed the lowest value in the afternoon, this low humidity value was also in line with the increase in flux CO_2 every afternoon in all treatments, Humidity had an effect on photosynthesis and plant respiration. Root cutting at a depth of 10 cm also shows a high CO_2 flux value, this is also influenced by lower moisture values in surface areas compared to root cutting at a depth of 20 cm, areas with more open land cover or shallower soil areas generally have lower humidity so that CO_2 flux values tend to be higher (Vergara et al., 2019). Optimal humidity will affect carbon growth and fixation. Increased soil moisture will decrease the respiration rate of plants (Man et al., 2021).

The analysis results show that root cutting practices in oil palm substantially influence CO_2 emissions. Therefore, it can be concluded that root cutting methods impact respiration rates and carbon emissions in oil palm plantations. Additional research may be required to better understand the mechanisms behind oil palm adaptation and the intricate interactions between physical and environmental factors affecting CO_2 emissions.

Correlation of carbon reserves, CO_2 emissions, nutrient status with production

Carbon stocks in oil palm crop production have a negative correlation with fruit bunch weights, as shown in Table 5, with very small values of -0.09 at 3 months and -0.01 at 9 months. In contrast, the relationship between carbon stocks and NDVI is positive; as NDVI increases, carbon stocks also rise, with the highest increase observed in the 3rd month, reaching a value of 0.29. A positive correlation was also found between carbon stocks and the nutrients N and K at both the 3rd and 9th months. However, the correlation with phosphorus was negative in the 3rd month. Additionally, the correlation with carbon dioxide flux in the 3rd month was also negative.

The carbon reserves at the 3rd and 9th months exhibit a negative correlation with low values, indicating that the impact of this relationship may be minimal. In general, higher carbon content in plants enhances their role in carbon sequestration. For effective sequestration, the carbon present above ground must exceed that in the soil (Canadell et al., 2002).

Table 5. Correlation of carbon stocks with nutrients, production and carbon dioxide emissions

Carbon stocks correlated with fruit bunch weight, NDVI and CO_2 emissions						
Treatment	Btd3	Btd9	NDVI0	NDVI3	NDVI9	FCO2
CS0			0,22	0,28	0,15	-0,16
CS3	-0,09	-0,03	0,23	0,29	0,15	-0,16
CS9	-0,12	-0,01	0,20	0,27	0,15	-0,17

Carbon reserves correlate with nutrients NPK										
Treatment	N0	N3	N9	P0	P3	P9	K0	K3	K9	FCO2
CS0	-0,11	0,09	0,17	0,04	-0,04	0,15	-0,07	0,13	0,02	-0,16
CS3	-0,11	0,09	0,17	0,04	-0,03	0,15	-0,07	0,13	0,02	-0,16
CS9	-0,09	0,08	0,16	0,04	-0,06	0,14	-0,07	0,12	0,01	-0,17

Note: CS: carbon reserve; BTD: fruit bunches weight; FCO_2: flux carbon dioxide

These data show the correlation between carbon stocks (CS) and various parameters of oil palm farming. Generally, the observed correlations tend to be weak, with values ranging from -0.17 to 0.29. Carbon stocks have a weak positive correlation with NDVI, which may indicate a relationship between carbon storage and vegetation health. There is a weak negative correlation between carbon stocks and CO_2 emissions, indicating a potential reduction in emissions as carbon storage increases. The relationship between carbon stocks and soil nutrients (N, P, K) varies and is generally weak, indicating the complexity of these interactions. The correlation with fruit bunch weight also varies depending on the measurement time. Although some trends are visible, the weak correlations indicate that the relationship between carbon stocks and other parameters is influenced by factors not captured in these data, requiring further research for a more comprehensive understanding.

The NDVI value at the 3rd month is higher compared to the values at the 0th and 9th months. Various factors can influence NDVI values, including plant photosynthetic activity, biomass, moisture levels in both plants and soil, and plant stress, which affects vegetation conditions. Differences in carbon absorption by plants can also be influenced by the plant's age, such as stem diameter, which increases with plant growth and thus enhances carbon storage. However, environmental factors like soil fertility and rainfall also impact carbon absorption levels (Pratama et al., 2016).

The relationship between carbon stocks and nutrients N, P, and K shows a positive correlation with N and K, but a negative correlation with P. According to Rusdiana and Lubis (2012), carbon stocks correlate positively with N and K, while there is no significant relationship with P in the soil. Nitrogen (N) is crucial for plant growth as it contributes to chlorophyll formation, which is essential for photosynthesis and enhances carbon absorption. Potassium (K) is actively involved in various biochemical and physiological processes in plants, affecting growth, yield, and resistance to stress. Although K is less critical for carbon absorption compared to N, its presence is important for regulating stomatal movement through cell turgor pressure (Munawar, 2011).

Carbon emissions refer to the amount of carbon transferred between Earth's carbon reservoirs, including oceans, atmosphere, soil, and living organisms, typically measured in gigatons of carbon per year (GtC/year) (Schimel et al., 2024). In this study, the correlation between carbon reserves and carbon emissions is negative. This indicates that higher carbon emissions can deplete carbon stocks in the oil palm ecosystem.

CONCLUSIONS

This study concluded that root cutting treatments on oil palm plants significantly affect soil nutrient availability and organic carbon reserves. The analysis showed significant variations in nitrogen, phosphorus, and potassium levels across different treatments. Root cutting at a depth of 10 cm with an intensity of 50% exhibited the highest nitrogen content, indicating that reducing root density may improve nitrogen availability in the soil. Treatments involving deeper root cutting depths generally resulted in higher phosphorus and potassium levels, indicating more efficient nutrient redistribution in the soil. Additionally, carbon stocks in soil biomass ranged from 16.84 to 16.96 tons C/ha/year, showing varied responses to root cutting treatments. The treatment with a 20 cm depth and 75% intensity exhibited the best growth performance and optimum carbon stocks at 3 months. However, this treatment also resulted in the highest CO_2 emissions, particularly in the afternoon after 6 months, with emissions being more influenced by soil physical properties and biological activity rather than by relatively stable daily temperature fluctuations.

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