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Evaluating Carbon Stocks in Tropical Primary Forests and Oil Palm Plantations Across Three Tropical Regions

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Abstract. Tropical rainforests are presently being cleared to large parts by humans. What is mostly characterized primarily by the transition of primary, old-growth forests into industrial oil palm plantations? This global shift severely disrupts carbon dynamics. Nevertheless, raising critical questions about its long-term impact on ecosystem carbon sequestration capacity. This study uses a meta-analytical approach and a standardized SOC vertical distribution model to evaluate and contrast total carbon stocks across aboveground biomass and variable soil depth profiles (0-30 cm and 0-70 cm) across three distinct tropical regions.The results show on a localized context, agronomic measures can sometimes result in a facade of recover on SOC on some localized field in a mid to later cycle, but also oil palm always suffer from a high carbon debt while comparing to pristine ecosystem. Overall primary forests remain in overwhelming structural superiority in terms of biomass and maintenance of deep-soil carbon for sustained periods. This should prompt establishment of site-specific conservation and circular management measures to reverse ecosystem degradation on a localized scale along with prevention of future destruction of remaining primary carbon sink.

Keywords: Oil palm plantations, carbon stocks, soil organic carbon

1. Introduction

Forests are crucial in controlling the climate. More precisely they can store carbon which helps counter the effects of the anthropogenic greenhouse-effect. They are known as 'lungs of the Earth' due to their importance. According to the C2ES article [1], Forests in the U.S. remove 2.6 billion tons (2.6 gigatons) of CO_2 annually. Considering the fact that EPA reports that carbon dioxide accounts for roughly 79% of U.S. greenhouse gas emissions by mankind, any mass extinction of forests will be disastrous for the climate. Despite storing carbon, forests do not simply remove it from the atmosphere; they simply store it, releasing it into the atmosphere only when it is not disturbed (destroyed, as during a forest fire). It takes decades for an afforestation to clear carbons, so it is a slow process; Young vegetation emits carbon dioxide and ethylene as part of routine physiological activity, so newly planted forests require time before becoming effective net carbon sinks. EPA figures [2] indicate over 66%-80% global warming was caused by carbon dioxide which is one of the greenhouse gases most abundant on the globe . Other kinds of anthropogenic activity -

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burning fossil fuels- Global fossil fuel emissions reached 10.0 GtC in 2023., revealed Global Carbon Budget [3].

With an expanding global population, the use of land previously covered by natural forests changed to agricultural land exponentially over the tropical zones, where palm oil is considered an important cash crop with its products making up 40% of demand for vegetable oils around the world as recorded by The United States Department of Agriculture (USDA) Productions Supply and Distribution (PSD) Database [4]. Supportive government policies, perfect weather conditions and high economic returns meant that oil palm plantations grew exponentially. Unsurprisingly given was stated in the previous section the areas of global oil palm cultivation saw an approximate 3.7 times increase between 1982 and 2019 to about 19.6 million hectares [5]; The expansion and remaining suitable areas of global oil palm plantations" by Zhao et al.

Currently, the vast majority of these commercial operations utilize mono-cropping—an intensive agricultural management practice where a single, specific crop species is cultivated repeatedly across the same plot without crop rotation. While mono-cropping maximizes operational efficiency, facilitates large-scale mechanization, and optimizes short-term production yields. Mono-croping simultaneously encourages severe environmental degradation. Specifically, it exhibits heavy agrochemical dependencies(fertilizer), regional biodiversity reduction, soil nutrient depletion, and, most critically- the main reason for the importance of this study-massive terrestrial carbon loss. With the combination of these critical ecological concerns. The primary objective of this article is to comprehensively review the quantitative differences in carbon stocks between managed oil palm plantations and undisturbed old-growth forests, focusing specifically on subterranean soil organic carbon and aboveground carbon.

2. Quantitative modeling and carbon fraction scaling

2.1. Soil organic carbon vertical distribution model

To systematically evaluate the drivers and consequences of oil palm expansion on carbon stocks, this section utilizes the SOC vertical distribution function [6] to standardize the soil depths reported across the collected literature. This framework categorizes the collected data into two categories. First, the shallow layer 0-30 cm depth group. Second, the deep layer 0-70 cm depth group. This model standardises tropical regions to the same depth (of sample collection), enabling direct comparison. To investigate 0-30 cm and 0-70cm depths of vertical distribution of soil organic carbon content, Jobbágy and Jackson (2000)'s modelling approach was employed where $Y = 1 - \beta^d$ to estimate the proportion of carbon at any given depth d, where β is an ecosystem-specific value for the particular ecosystem under study that describe the distribution with depth, Y is the proportion of total carbon. By applying the beta value, the study produced a persuasive comparison of SOC in oil palm plantation relative to tropical old-growth forest that will yield conclusive results.

2.2. Carbon fraction of dry matter

In the study, the above ground biomass is converted into above ground carbon using the carbon fraction of dry matter based on IPCC [7]. A carbon fraction of 0.47 is used which is calculated as $AGC=AGB\times0.47$. Using this value a carbon fraction is used which takes into account the different elemental compositions for different woody plant material and thereby consistency in values across the studying site is achieved.

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3. Cross-regional synthesis of aboveground biomass and vertically stratified soil organic carbon (SOC) stocks across primary forests and oil palm conversion chronosequences

3.1. Subterranean carbon stratification in the shallow profile (0-30 cm)

First of all, forest soil health & underground carbon sequestration as an indicator (i.e. highest detected concentration at most shallow 0-30cm layer), this is the abundance in most biochemical-in activity-bacterial nitrogen fixation & continuous inputs of plantation organic litter & animal wastes (the above prove the importance of quantifying topsoil & SOC) by measuring up microbial vitality as well as stores of carbon. To evaluate it on a macro scale, it incorporated empirical data of Brazil, Malaysia and Indonesia in the context of a standard as well as control- converted global tropical forest [8-11]. Secondly, as the past raw data typically reported the carbon stocks of a wider range starting from 0 to 100cm; it utilized SOC of asymptotic vertical distribution functional to mathematically standardize (0-30cm). This ensures direct, cross-regional comparability. As indicated by the 0–30 cm SOC data table below, global tropical forest carbon stocks serve as a baseline, ranging from 67–80 tC/ha, with peaks in Indonesia reaching 80–90 tC/ha, followed by 53.7 tC/ha in Brazil and 49 tC/ha in Malaysia with post-conversion to monoculture plantation, the soil organic carbon dropped significantly across south east asian. Falling to 50-60 tC/ha in Indonesia and 37 tC/ha in Malaysia. This widespread decline indicates a serious top soil organic carbon loss. Interestingly, there is something unexpected while the study is comparing the Brazil data to the control. As shown from the 0-30 cm SOC data from Brazil below. Despite the similar decreasing trend for 23 year old plantations previously, 34.5 tC/ha. The older plantation demonstrated an unexpected high SOC value, 66.6 tC/ha (Table 1).

Table 1. Subterranean carbon stratification in the shallow profile SOC 0-30cm [7-10]

location	Control group (old-growth forest) tC/ha	The treatment (Oil Palm) tC/ha
Brazil	53.5	34.7(23years old)/66.6(34 years old)
Malaysia	49	37 (average, 29-49 years old)
Indonesia	80-90	50-60
Global (universal control)	67-80	N/A

3.2. Macro-profile (0-70cm) subsoil dynamics and deep sequestration capacity

In order to make the comparison more comprehensive. This study also compared and contrasted the SOC In 0-70cm. SOC in 0-70cm are generally accepted as the soil depth where soil has the most abundant long-term SOC in a broader macroscopic scale. This deep zone reflects the Environmental History of a soil, Soil Mineralogy, and Hydrology and Redox. To systematically evaluate these dynamics on a macro scale, the study remains all the variables same as the previous 0-30cm. Note that this study takes advantage of the asymptotic SOC vertical distributions function again to mathematically quarantine and unify the SOC data to 0-70cm for the data from some regions and the control [6]. Native forest controls at this depth baseline at 127 tC/ha in Indonesia, 96 tC/ha in Malaysia, and 79 tC/ha in Brazil [8-10]. And an average global value of 117 tC/ha [11]. After long

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term oil palm monoculture, Indonesian deep soil stocks decline drastically to 87 tC/ha, while Malaysian sites drop to an average of 57 tC/ha [9, 10]. This severe decrease that the study observed indicates a critical subsoil problem: the lack of variation in root depth and organic inputs from monocropping fails to refill and consolidate deeper soil layers over decades. However, as the study predicted, paralleling from the 0-30 cm data. Older plantations from Brazil exhibit an unpredicted high value in SOC, 120 tC/ha (Table 2) [8]. This unexpected exception can be explained for several reasons. First, the model's limitations. Although the model is highly reliable, the model might lack specificity to certain conditions such as plantation. Second, based on the original article explanations, "The soil C stocks were higher in frond piles (1.7 times in OP23 and 2.6 times in OP34) than in the avenues, due to inputs of soil organic matter by pruned fronds." [8]

Table 2. Macro-profile (0-70cm) subsoil dynamics and deep sequestration capacity [7-10]

Location	Forest-control (tC/ha)	Oil palm (tC/ha)
Brazil	79	62(23 years old)/ 120 (34 years old)
Malaysia	96	57 (average, 29-49 years old)
Indonesia	127	87
Global (universal control)	117	N/A

3.3. Biomass

To enhance the accuracy and to add more perspectives in order to make this study more convincing. The study evaluated aboveground carbon stocks as well as the subterranean profiles. Aboveground biomass represents an elementary above ground carbon pool. It serves as a critical determining factor in dictating the overall carbon sequestration capacity of tropical forest ecosystems. Quantifying this aboveground pool ensures a comprehensive accounting of total ecosystem carbon dynamics-mainly acts as a compensation for the unanticipated situation from the earlier Brazil data-preventing the underestimation of macro-level losses driven by land-use conversion. According to the biomass data compiled in Figure 1. Native forest controls at this level are 141 tC/ha in Indonesia, 153 tC/ha in Malaysia, and 123 tC/ha in Brazil [9, 12, 13]. When the land is cleared from these habitats for oil palm monoculture, the carbon stocks decline greatly to 36 tC/ha in mature Malaysian oil palm plantations , 43 tC/ha in Indonesia and 24 tC/ha in Brazil [9, 12, 13]. These results show that the change is statistically different by an order of magnitude. Thus, from the analysed data, it can be concluded that the monoculture oil palm plantations do cause damage to the amount of the carbon stocks overall. Although the fact still remains that under certain management the SOC will increase locally.

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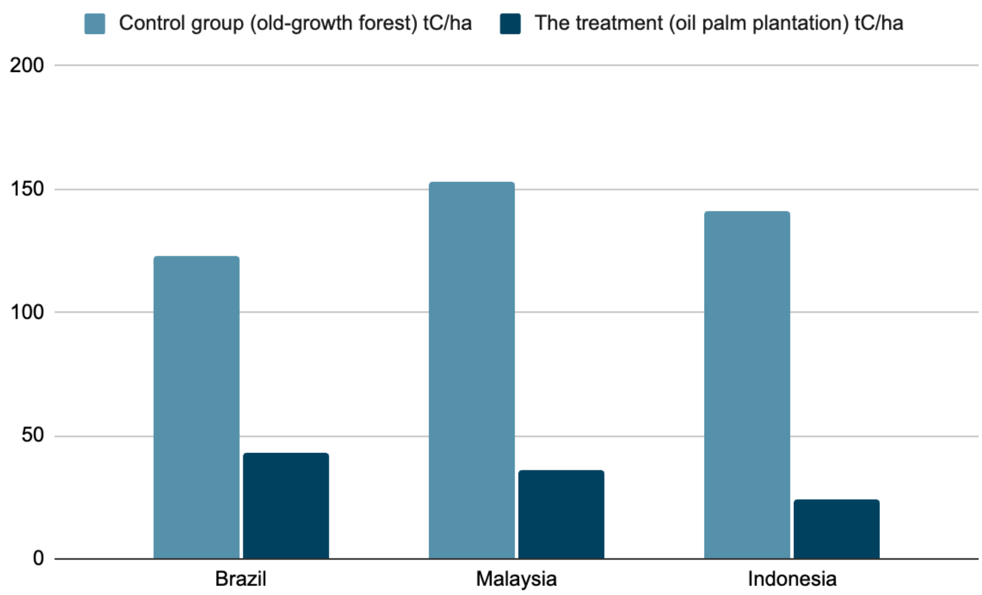

Figure 1. AGC(above ground carbon bar chart.) [9, 12, 13]

4. Discussion: mechanisms & anomaly interpretation

4.1. Mechanisms

The expansion of agricultural plantations contributes to multi-layered ecological degradation. This is largely caused by the structural characteristics of oil palm. When establishing commercial systems, it standardises monoculture. This includes little variation in root depth, a simplified canopy structure and the fact that decomposition and turnover rates are much faster. The changing environmental dynamics lead to loss of a lot of biodiversity. However, also a disruption in subterranean carbon processes can arise from the monoculture system. Because of the loss of complex layered forest inputs and destabilisation of topsoil it resulted in consistently lower levels of soil organic carbon (SOC), measured at multiple depths within the plantation systems, than those determined for the untouched primary forest control areas.

4.2. Exception for Brazil data

4.2.1. Factor 1: limitations of the predictive framework

The vertical distribution model employed within the meta-analysis establishes a statistically robust platform for the study. However, the model designed at macro-scale leads to overt local constraints. Its strength rests to a wide extent upon over 2,700 soil profiles originating from three global soil databases and covers biomes ranging from all types of forests to intensive agricultural systems. All things considered, this global synthesis results in an overgeneralization bias. The condensation of all regional differences into a single global structure means that the model does not have sufficiently flexible parameters to represent regional fine scale micro-level heterogeneity. As such, predictive error should increase as more localized and distinctively tropical conditions are encountered (specific soil types, localities on the scale of a farm or particular agricultural circumstances).

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Therefore instead of generalizing a global function, locally calibrated higher-resolution soil distribution function is more promising and required.

4.2.2. Factor 2: optimized agronomic management practices

The phenomenon of peculiar soil conditions being reported on plantation sites are likely linked closely with conservation based practices. The dead fronds or pruned parts may have been collected and piled along and next row in the field over a long period. In such a way the soil will not be left open with no much vegetation and it will have isolated pockets of high surface organic matter, with slow release of decomposing matter resulting in long-term nutrient cycling and sustained carbon through humus formation which enables to maintain active micro-bacterial activity in a cycle and reinforces the cycle in the long-term. As long as the residue pockets are not removed, it will restrict the further carbon losses found otherwise under monocropping. Therefore, it is not unreasonable for it to contribute to an increase in shallow SOC over cycles in cultivation, equally improving the top soil condition.

5. Conclusion

In Conclusion, Comparison and estimation of capacity of primary tropical forest and management oil palm plantation sequestration of carbon in three major regions-Malaysia, Brazil, Indonesia using the combination of evidence is made, which reveals that oil palm is generally a carbon neutral activity causing loss in above ground biomass while contributing to general Soil Organic Carbon downslide, but a major factor for causing severe loss where its value turns out to be several-fold below those observed in control plots and natural forest sites besides leading up to an adverse effect through depletion of top soil in Malaysia and Indonesia while surprisingly no effect and carbon recovery in case of old up in years Brazilian oil palm plantation. These values become helpful in developing policies at governments for sustainable agriculture, in the southeast where oil palm is still a dominant sector due to its economics besides being controversial because of its effect. Some questions of concern about depth and crop specific models need to be formulated. The question of depth still remains uncertain and it will be resolved once a depth distribution for a specific crop model is formulated; however, efforts need to move further to refine localized agronomic practices to bring decline in ecological impacts caused by tropical monoculture.

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