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Review

A Review of Southeast Asian Oil Palm and Its CO_2 Fluxes

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Abstract: Palm oil production is a key industry in tropical regions, driven by the demand for affordable vegetable oil. Palm oil production has been increasing by 9% every year, mostly due to expanding biofuel markets. However, the oil palm industry has been associated with key environmental issues, such as deforestation, peatland exploitation and biomass burning that release carbon dioxide (CO_2) into the atmosphere, leading to climate change. This review therefore aims to discuss the characteristics of oil palm plantations and their impacts, especially CO_2 emissions in the Southeast Asian region. The tropical climate and soil in Southeast Asian countries, such as Malaysia and Indonesia, are very suitable for growing oil palm trees. However, due to the scarcity of available plantation areas deforestation occurs, especially in peat swamp areas. Total carbon losses from both biomass and peat due to the conversion of tropical virgin peat swamp forest into oil palm plantations are estimated to be around 427.2 ± 90.7 t C ha^{-1} and 17.1 ± 3.6 t C ha^{-1} $year^{-1}$, respectively. Even though measured CO_2 fluxes have shown that overall, oil palm plantation CO_2 emissions are about one to two times higher than other major crops, the ability of oil palms to absorb CO_2 (a net of 64 tons of CO_2 per hectare each year) and produce around 18 tons of oxygen per hectare per year is one of the main advantages of this crop. Since the oil palm industry plays a crucial role in the socio-economic development of Southeast Asian countries, sustainable and environmentally friendly practices would provide economic benefits while minimizing environmental impacts. A comprehensive review of all existing oil plantation procedures is needed to ensure that this high yielding crop has highly competitive environmental benefits.

Keywords: palm oil; tropical area; carbon emission; CO_2; flux

1. Introduction

laeis guineensis, or oil palm, is a tree in the palm family (Arecaceae) that is cultivated as the most important source of oilseed today [1–3]. Oil palm trees are found only in the tropical forest ecosystem and grow in the range of 10° north and south of the equator. This tree species can grow in areas where the other tree species cannot grow well [4]. With average yields in major producing countries ranging between three and four mesocarps (palm) oil ha^{-1} $year^{-1}$, the oil palm is regarded as the most productive oil crop on the market [2]. Global palm oil production is increasing by around 9% per year and the oil is used in various kinds of products. Two of the biggest markets for palm oil are China and India [5–7].

Oil palm plantations have been associated with deforestation in many tropical regions [8–10] and affect the biodiversity of tropical forests [11]. Oil palm plantations support much fewer species than other tree crops [12,13]. In terms of global palm oil production, Indonesia and Malaysia are the largest producers, with the capacity to produce ≈43 million t $year^{-1}$, accounting for 87% of all palm oil. From 1990, Indonesia and Malaysia had a total oil palm harvested area of 6.5 million ha. However, between the years 1990 and 2010, more than 10% of the total deforestation in Indonesia and Malaysia was due to oil palm, even when assuming that only half of the oil palm expansion caused forest loss [14].

Other than deforestation, oil palm plantations have also been associated with carbon emissions and climate change [15,16]. Oil palm plantations have been associated with a 2.5 Gigaton Carbon (Gt C) loss in carbon stock in tropical peatlands since 1990 [17], and in many cases oil palm plantations have been linked to the loss of carbon stored within peatland areas [18–21]. Total carbon losses from biomass and peat of 427.2 ± 90.7 t C ha^{-1} and 17.1 ± 3.6 t C ha^{-1} $year^{-1}$, respectively, due to the conversion of natural tropical peat swamp forest to oil palm plantations, were recorded over the past 25 years. The amount of total carbon loss from peat is around 63% of the total carbon loss, demonstrating that it is essential that mitigation measures are developed to preserve tropical peat swamps from land conversion, which will, in turn, reduce the greenhouse gas load [22].

Since palm oil is important as a cheap source of vegetable oil, this study aims to discuss the characteristics of oil palm plantations and the surrounding environment. The associations of oil palm plantations with carbon dioxide (CO_2) fluxes are also presented, particularly those from the Southeast Asian region. A systematic review method based on relevant literature regarding oil palm plantations from various sources was used in this study. Peer-reviewed literature was identified and scrutinized for information, and data relating to oil palm plantations in tropical regions were summarized.

2. Oil Palm Characteristics and Its Environment

2.1. The Oil Palm Crop

The oil palm tree is a single-stemmed plant [7]. The woody stem carries a single terminal growing point, from which leaves appear at regular intervals in a double spiral [23]. According to Johnson [24], general oil palm leaves are branched into leaflets joined to a central leaf axis (the rachis) and often feature a feather. Palms bearing such foliage are often recognized simply as feather palms. An oil palm leaf can reach up to 5 m in length. Each leaf supports a single inflorescence, which can be either male or female [25]. Oil palms bear both functionally male and female flowers on the same tree in an alternating cycle to minimize the chances of self-pollination [26].

An oil palm tree begins to bear fruit 3–4 years after planting. The fruits are in bunches, encompassing the oily pericarp, shell and kernel, which contains 45–55% of edible oil [7,27,28]. The weight of each fruit bunch is approximately 15–30 kg and can reach up to 50 kg [29,30]. The harvested product is a fruit bunch comprising between 1500 and 2000 fruitlets [25]. The products of the fresh fruit bunch include crude palm oil, which is extracted from the orange-yellow mesocarp, while palm kernel oil is usually extracted from the white kernel [25,29].

2.2. Climate

Geographically, the oil palm flourishes best in lowland regions in the tropical rainforest [30,31]. The oil palm is planted in a wide range of latitudes on each continent, roughly 10° north and south of the equator. This distribution is due to how the global oceanic and atmospheric currents affect the climate, as well as the presence and relative position of large landmasses that can greatly alter the temperature and rainfall [32].

In general, the equatorial belt offers suitable cultivation environments for oil palm, because it provides a suitable amount of sunshine, high temperatures, and wet and humid conditions with a high rainfall rate [33,34]. Specifically, there are five important climatic conditions for oil palm cultivation as proposed by Goh [35] (Table 1). Ultimately, to achieve the best yield from oil palms, the oil palms need minimum climatic requirements, such as adequate sunshine and solar radiation of 16–17 MJ m^{-2} day^{-1}, annual rainfall of 2000–2500 mm, low vapor pressure deficit and temperatures of a mean maximum in the range of 29–33 °C and a mean minimum in the range 22–24 °C.

Table 1. Proposed classification of climatic properties in relation to the suitability for oil palm.

Climatic Element	Highly Suitable	Suitable	Moderately Suitable	Currently Unsuitable	Permanently Unsuitable
Annual rainfall (mm $year^{-1}$)	2000–2500	2500–3000 1700–2000	3000–4000 1400–1700	4000–5000 1100–1400	>5000 <1100
Duration of dry season (month)	0	1	2–4	5–6	>6
Mean annual temperature	26–29	29–32 23–26	32–34 20–23	34–36 17–20	>36 <20
Daily solar radiation (MJ m^{-2})	16–17	17–19 14–16	19–21 11–14	21–23 8–11	>23 <8
Wind (m s^{-1})	<10	10–15	15–25	25–40	>40

Source: Goh [36].

The oil palm industry plays a crucial role in the socio-economic development of Malaysia [36]. The oil palm yield critically depends on climatic factors [37,38]. Hence, local microclimate changes due to altering land-use, topography, soil properties, etc. and regional changes forced by large-scale global changes are expected to impose significant impacts on the palm oil industry in the coming decades. Therefore, assessing these impacts requires information at both the regional and local scales.

From a large-scale perspective, the El Niño-Southern Oscillation phenomenon (ENSO) is known to influence palm oil production months after its peak. Both warm and cold events negatively impact oil palm production. In the short term (a few months) the warm event, or El Niño, is associated with prolonged dry spells that may lead to bunch failure and floral abortion in oil palm trees [39]. In the longer term of 1–2 years, the production of oil palm is commonly disrupted due to sex differentiation. On the other hand, La Niña, which brings about more rainfall in the country, often disrupts harvesting and logistics management. In addition, La Niña also induces poor pollination and fruit-sets [40].

There is a lack of comprehensive studies on how climate change impacts oil palm production and yield and the underlying socioeconomics. Most studies have focused on a broader scale perspective and discussed the climate suitability instead of focusing on the yield, which is likely determined by the complex interplay between broad climatic factors and local-scale biotic and abiotic interactions. For instance, Paterson et al. [41], using the results from Global Climate Models (GMCs) and a niche model via a stepwise approach, argued that climate change is expected to reduce the area with suitable climates for oil palm plantations over the maritime continent. Studies linking oil palm to ENSO and its implications for short-term forecasts are numerous [42,43]. However, there is a lack of studies discussing the implications of ENSO variability in the future warmer climate and how this is linked to local environmental changes that may affect oil palm cultivation in the future. The hypothesis is that the warmer climate is expected to enlarge the variance of natural climate variability and bring about stronger El Niño and La Niña events [44]. This alteration is expected to impact the regional circulation over Southeast Asian regions, and this impact will be cascaded down to the local scale. The assessment

of climate change impacts at a specific plantation thus requires relevant information at both large and plantation scales.

2.3. Soil Classification and Characteristics

The tropical soils used for the cultivation of oil palms have been classified based on the United States Department of Agriculture (USDA) Soil Taxonomy system [45]. There are four types of common soils found: ultisols, oxisols, histosols and mollisols. The types of soil differ between regions in the equatorial tropics. For example, ultisols, oxisols and histosols are generally available in Southeast Asia. In Africa, the soil types oxisols, ultisols and mollisols are commonly found, while in America, oxisols and ultisols are the common soils [25].

Soil characteristics are crucial for oil palm cultivation because they are contributing factors to oil palm production levels [25]. There are two systems available that assess the suitability of soils for growing oil palm. The first system is by Olivin [46,47], who suggested a systematic method for assessing soils for oil palm. The system grades the soils based on soil texture, the quantity of gravel and stones, drainage, and chemical composition, i.e., pH, organic matter and exchangeable cations. In general, Olivin [46,47] defined a good soil as one with little gravel, a texture of soil that allows reasonable drainage, and soil that manages to retain plenty of exchangeable cations and contains a good amount of organic matter.

The second system is that of Paramananthan [48], which provides a detailed set of suitability criteria for the cultivation of oil palm. The system is intended for Southeast Asia, but would probably be relevant in all similar climates [49]. Several important characteristics have been determined by the system, and one is that land with a slope of more than 20° is considered unsuitable, because planting on steep slopes is prone to erosion and can cause problems, e.g., difficulty in harvesting and degradation of the average quality of the soil for the planted oil palm trees [50,51]. In addition, the system selects land that is neither insufficiently or excessively drained, nor prone to flooding. In terms of soil physical criteria, the soil structure needs to be stable and able to provide excellent stable drainage. Additionally, Paramananthan [52] identified and discussed the number of soil types that are generally unsuitable for palms and in which oil palm cannot thrive. They are soils in dry regions, highly weathered soils, soils on steep terrain, lateritic soils, acid sulphate soils, saline soils, sandy soils and organic soils.

3. The Oil Palm and Climate Change Factors

3.1. Deforestation

Forests play important roles in the global ecosystem, where they absorb CO_2 by photosynthesis, which is then released by autotrophic respiration [53]. Forest areas are also known to be carbon pools that trap carbon content in the soil and sub-surface for thousands of years. Any changes or modification to forest areas, as well as forest fires, contribute to carbon emissions. As reported by van Der Werf et al. [54], it has been estimated that between 1997 and 2009 there were carbon emissions of 2.0 Pg C year^{-1} with important contributions from Africa (52%), South America (5%), Equatorial Asia (10%), the boreal region (9%) and Australia (7%). Figure 1 shows the benchmark map of carbon stored in the earth's tropical forests for over 2.5 million ha of forest area and 75 countries, as reported by NASA [55].

Deforestation is usually defined as the loss of forest cover through the conversion of the land to another land-use [56,57]. Factors that contribute to carbon emissions from deforestation include the high profits that come with international trade, which in turn mean losses of unsustainable production are most noticeable at local levels [58–60]. Large amounts of forest areas have been cleared for food crops and also plantations [61]. Global policy changes and the increased demand for biofuels in the transport and energy sectors are also contributing factors [58]. Moreover, deforestation in Southeast Asia is also linked with the logging of tropical timber for economic development [62]. Estimations on deforestation rates were 17–127% for oil palm, 44–129% for timber and 3.1–11.1% for logging in

Indonesia [63]. It is been estimated that an area of 3.5×10^6 ha was burned in east Kalimantan between 1982–1983, which then happened again in 1994 [64]. A study by Yong [65] found that there was a 0.54% deforestation rate in Malaysia with an annual average tree cover loss of 2%. Major drivers of deforestation in Malaysia are commercial loggers, commercial oil palm and other tree planters, infrastructure developers and governmental agencies that are reducing areas of forest land [65].

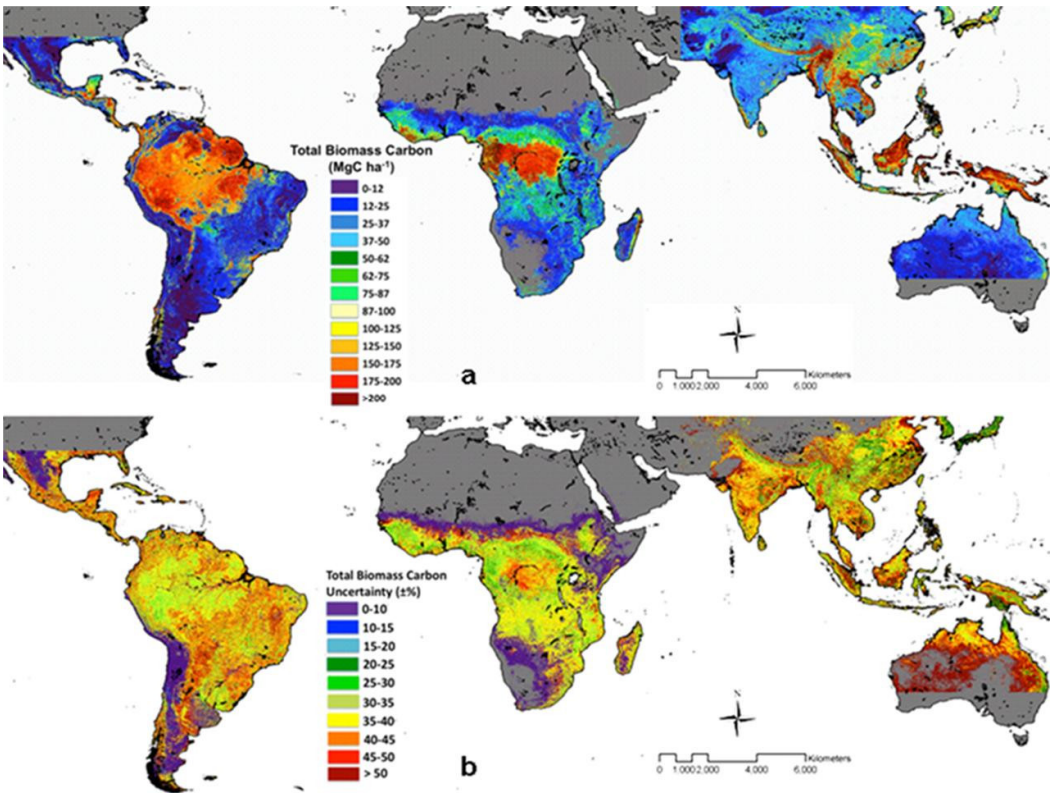

Figure 1. Map of (**a**) total biomass carbon; (**b**) total biomass carbon uncertainty. Source: NASA [55].

Deforestation can also have economic and health impacts, and impacts on the environment, flora and fauna of an area. As reported by Wolf [62], deforestation can significantly affect soil erosion, flooding and climate change; it can cause agricultural losses, and wildlife and indigenous peoples are also impacted. A study by Chua, Chua and Wang [64] also revealed that the 1997–1998 deforestation and forest fires in Southeast Asia led to the Nipah virus outbreak, and the deforestation was then exacerbated by drought driven by the ENSO event. Another environmental impact was suggested to be the daily temperature in terms of reduced daytime temperatures and increases in boundary layer clouds. This also had the consequence of rising albedo, transpiration and latent heat loss [66]. Deforestation was suggested to influence the regional climate, elevate local temperatures, cause a decline in precipitation and limit soil moisture, thus increasing climate variability and causing drought [67]. The role of a state or country in preserving forests can support environmental sustainability. The Sabah state government, through the Sabah Structure Plan 2033, has committed to preserving the permanent forest reserve based on the priority conservation area. The state of Sabah also retains forest areas as the largest land-use areas in 2033 with 66.71% of the total area of Sabah (Town and Regional Planning Department of Sabah, Kota Kinabalu, Sabah, 2016). The Sabah Structure Plan 2033 is a legal document that focuses on the prioritization of the conservation of forests [68].

3.2. Peatland Areas

Peatland plays a significant role as a carbon pool and is an important component of the carbon soil–atmospheric exchange process [69]. In Southeast Asia only, forested peatland stores at least

42,000 million metric tons (Mt) of soil carbon [70]. According to Yoshino et al. [71], the total area of peat swamps in Southeast Asia was estimated to be 25 million ha, with 43.1% in Papua, Indonesia, 22.5% in Sumatera, 22% in Kalimantan, and other areas in Peninsular Malaysia, Thailand and Malaysian Borneo. When peatland areas are developed for agriculture, the peat soil in these swamp forests tends to decay and release huge stores of carbon into the atmosphere [69,72].

The natural ecosystem of peatland is usually wet, where un-drained peat consists of 10% plant matter and 90% water, making these areas waterlogged where ponding of rainwater on peat surfaces occurs [70,73]. However, due to economic pressures, peatland areas are being deforested, drained and often burned for agricultural purposes, such as oil palm and pulpwood plantations [70]. Drained peatlands, such as in Sumatra and Kalimantan, are susceptible to fires where drought has intensified the flammability of the peat, and fires are widely used to clear the land, degrade re-growing vegetation and maintain the land for growing crops [72]. Fires in peatland areas are not easy to extinguish and often burn for a long period. Moreover, anthropogenic activity with the use of fires by people to clear and convert the land to agricultural areas, particularly for oil palm plantations, contributes to uncontrolled burning, which in turn damages large areas of peatland [74]. It is estimated that the peat swamp forest in Sumatra has declined by about 4% over the last two decades due to timber activities, plantations and fires [67,75].

There are five flux components of peatland, including net CO_2 uptake by vegetation, CO_2 emissions from disturbed peatland, CO_2 emissions and other emissions from fires, exports of dissolved and particulate organic carbon and emissions of methane [70]. A study by Othman and Latif [76] found that 1 hour of peat combustion releases 13.850–20.610 μg m^{-3} of CO, and concluded that peat soil fires produce various amounts of air pollutants and significantly affect atmospheric chemical reactions.

3.3. Biomass Burning

Biomass burning, particularly of agricultural waste, is a major source of aerosol [77]. Certain areas in the world face severe haze episodes due to biomass burning of wheat straw, peatland soil, agricultural waste and forest areas. Biomass burning has also been performed with the aid of fire for land clearing. As reported by Yokelson et al. [78] and Langmann et al. [79], biomass composition plays a significant role in the combustion process, where during the first phase of burning the biomass fuel undergoes thermal degradation and water and volatiles are released. The second phase is pyrolysis, which includes cracking of the carbon chain fuel molecules. Then, several complex mixtures are released and formed during the distillation and pyrolysis process that forms flaming combustion. Shouldering combustion then occurs when the oxygen supply is limited and exothermic reactions take place, which are gas–solid reactions between oxygen and carbon, which then produce high levels of CO_2. Moreover, intense biomass burning episodes, for example in the year 2015, can also be enhanced by dry weather related to the occurrence of strong El Niño conditions [80].

Biomass burning is related to smoke haze and this recurring environmental problem in Southeast Asia affects regional air quality [81,82]. Biomass burning is also a top contributor to particulate pollution in Southeast Asia. Almost every year, fires from biomass burning in Sumatra and Borneo during the dry season, particularly between September to October, contributed to PM_{10} concentrations above 150 μg m^{-3} at multiple locations in the southern region of Southeast Asia [81]. Another impact of the burning of garden and agricultural residue, especially in suburban areas, is an additional source of anhydro sugars and other organic compounds to aerosol [83].

Emissions from biomass burning have been estimated, particularly targeting carbon emissions. Among the key parameters in estimating fire emissions and biomass burning are the burned area, the fuel load, the combustion factor and the emission factor [84,85]. Estimated Greenhouse Gases (GHGs) and carbon emissions from fires, particularly including non-forest, Acacia species, forest and peat soil fires in Central Sumatra in the year 2013 were calculated by Gaveau et al. [67], where 172 ± 59 Tg CO_2-eq of GHGs were released during the period of 18–24 June. These fire emissions were 26% of the average annual carbon emissions from tropical Asia between 2003 and 2008. A study by Shi et al. [86] on

carbon emissions from biomass burning in Southeast Asia for the period 2001–2010 used different types of satellite data. The study found that more than 60,000 km^2 $year^{-1}$ was burned in areas predominantly concentrated in Myanmar, northern Thailand, eastern Cambodia and northern Laos, while the Biosphere Model Integrating Eco-physiological and Mechanistic Approaches using Satellite (BEAMS/MCD45A-Peat) data analysis determined that 210.7 Tg C was released from 2001 to 2010 with the largest contributor being Indonesia. Emission inventories of non-agricultural open fires from 2000 to 2009 in Asia was performed by Song et al. [85], who determined that annual emissions for CO_2 and CO were 83 and 6.1 Tg $year^{-1}$, respectively. They also suggested that burning emissions originated from forest areas because of the large biomass density.

4. Oil Palm and Gas Emissions

GHGs from oil palm areas are expected to influence climate change and air quality. Previous studies have shown that common biogenic GHGs can be both emitted naturally and absorbed by oil palm trees. In terms of GHG absorption, CO_2 is always the focus in relation to land-use changes relating to oil palm areas. According to Henson [87], a hectare of oil palm trees can absorb a net amount of 64 tons of CO_2 each year and produces around 18 tons of oxygen, which is higher than a forest's net absorption (42.4 t ha^{-1} $year^{-1}$).

Recently, a study by Nadzir et al. [88] revealed that the emissions of isoprene (C_5H_8), CO_2, and surface ozone (O_3) from oil palm plantation areas in the state of Pahang, Peninsular Malaysia, were significantly high due to meteorological factors such as temperature. The study observed high mixing ratios of isoprene during the day and low mixing ratios at night, which is consistent with many previous studies [89–92]. The maximum daytime peak values observed were ~25 ppb, while the lowest values were measured during the night with mixing ratios of ~0.5 ppb for isoprene. Surface O_3 was observed to have the same pattern where high mixing ratios were measured during the daytime (~60 ppb). CO_2, on the other hand, showed a diurnal pattern with high mixing ratios during the night compared to the daytime.

In addition to climate change issues, air quality problems can also be linked to oil palm land-use changes. Biogenic GHGs, also known as BVOCs (Biogenic Volatile Organic Compounds), such as isoprene (C_5H_8), can be released from oil palm trees. BVOCs contribute to about 90% of all VOCs in the atmosphere [93]. Isoprene and other BVOCs are linked to the production of surface O_3 in the presence of nitrogen oxide (NO_x) [94], which contributes to climate change and poor air quality. Surface O_3 is a widespread air quality problem if present in high concentrations with present-day levels of NO_x as well as biogenic and anthropogenic VOC emissions [95,96]. NO_x can be emitted from industrial and city areas near oil palm plantations depending on the prevailing wind. According to Nadzir et al. [97], the three major NO_x sources responsible for increased NO_x over oil palm plantation areas are all linked to agro-industrial activities, such as vehicle exhaust, palm oil plant combustion, and substantial soil nitrogen fertilization for plantations.

4.1. Emissions of CO_2

Oil palm plantations and related activities have been associated with climate change, where CO_2 is the main key driver. The main pathways where oil palm-related CO_2 is released into the atmosphere are through deforestation, peatland exploitation and biomass burning, as well as the oil palm plantations themselves [98]. This section, however, will only focus on CO_2 emissions from oil palm plantations on peat soil and related aspects as there is growing concern regarding the magnitude of CO_2 losses from one of the earth's natural carbon storage areas [99,100]. Better constraints on oil palm CO_2 have been addressed through common field CO_2 emission measurements on plantation soil (peat), while there is limited information on emissions from the drain, trunk, and leaf of the oil palm tree. Indonesia and Malaysia have been the main target areas of CO_2 emissions measurements, as they aim to dedicate millions of metric tons of palm oil to meet global demand in producing biofuels [101].

Oil palm plantations on peat soil in Indonesia have been estimated to have CO_2 emissions ranging between 12 and 95 t C ha^{-1} year^{-1} (Table 2). While most of the measurements were located in Sumatra, Indonesia, the highest CO_2 emission was recorded in Jambi and Riau (95 t C ha^{-1} year^{-1}) [102]. The lowest CO_2 emissions, however, were also recorded in Jambi (10 t C ha^{-1} year^{-1}) [103], which could imply high spatial variability of emissions from peat soil. In Malaysia, CO_2 emissions were estimated between 7 and 79 t C ha^{-1} year^{-1} (Table 2). The highest Malaysian peat soil CO_2 emissions were recorded in Selangor at 79 and 65 t C ha^{-1} year^{-1} in the years 2000 and 2006, respectively [104]. The lowest CO_2 emission was recorded in Sarawak (7 t C ha^{-1} year^{-1}), which also has the largest area of oil palm plantation on peat soil in Malaysia [105]. Comparisons between Indonesia and Malaysia's CO_2 emissions show that both countries, as main palm oil producers globally, have a comparable magnitude of emissions, which could be due to similar peat soils as well as oil palm tree characteristics.

Table 2. Peat soil CO_2 emissions from previously reported studies.

Country	Area	Year	Emissions (t C ha^{-1} year^{-1})	Reference
Indonesia	Jambi and Riau	2007–2010	95	Hooijer et al. [102]
	Jambi	2010–2011	13	Marwanto and Agus [106]
	Jambi	2011–2012	10	Dariah et al. [103]
	Riau	2011–2012	18	Husnain et al. [107]
	Riau	2016–2017	12	Marwanto et al. [108]
Malaysia	Selangor	2000	79	Matysek et al. [104]
	Sarawak	2002–2003	17	Melling et al. [109]
	Sarawak	2002–2003	41	Melling et al. [110]
	Sarawak	2003	7	Matysek et al. [104]
	Selangor	2006	65	Matysek et al. [104]

Extensive measurements on oil palm CO_2 emissions, such as from the root, trunk, drain and also above the canopy are essential to better understand the role of oil palm on global scale carbon emissions (Table 3). Oil palm root CO_2 emissions were estimated at 19 t C ha^{-1} year^{-1} in Aceh Barat, Indonesia [111], while a separate study in Sarawak, Malaysia showed the average trunk, drain and soil CO_2 emission was 24 t C ha^{-1} year^{-1} [112]. Comparisons between the two studies on CO_2 emissions suggest the oil palm tree root could release a huge portion of the high CO_2 emissions. On the contrary, a large area of oil palm plantation in Sabah, Malaysia recorded an average CO_2 uptake of 82 t C ha^{-1} year^{-1} above the oil palm canopy, higher than an intact forest (32 t C ha^{-1} year^{-1}) [113]. The high rates of carbon uptake of oil palm mean it is theoretically possible to achieve carbon neutrality for biofuels, in the long term replacing fossil fuels [114,115]. Based on the above argument, the overall emission and absorption of oil palm plantations with factors that influence these exchanges in tropical regions are presented in Figure 2.

Table 3. Oil palm plantations related CO_2 emissions.

Country	Area	Year	Emissions (t C ha^{-1} year^{-1})	Reference
Indonesia	Aceh Barat	2008	19 (Root)	Agus et al. [111]
Malaysia	Sabah	2008	82 (Above canopy-uptake)	Fowler et al. [113]
	Sarawak	2015–2017	24 (Trunk, drain, soil)	Manning et al. [112]

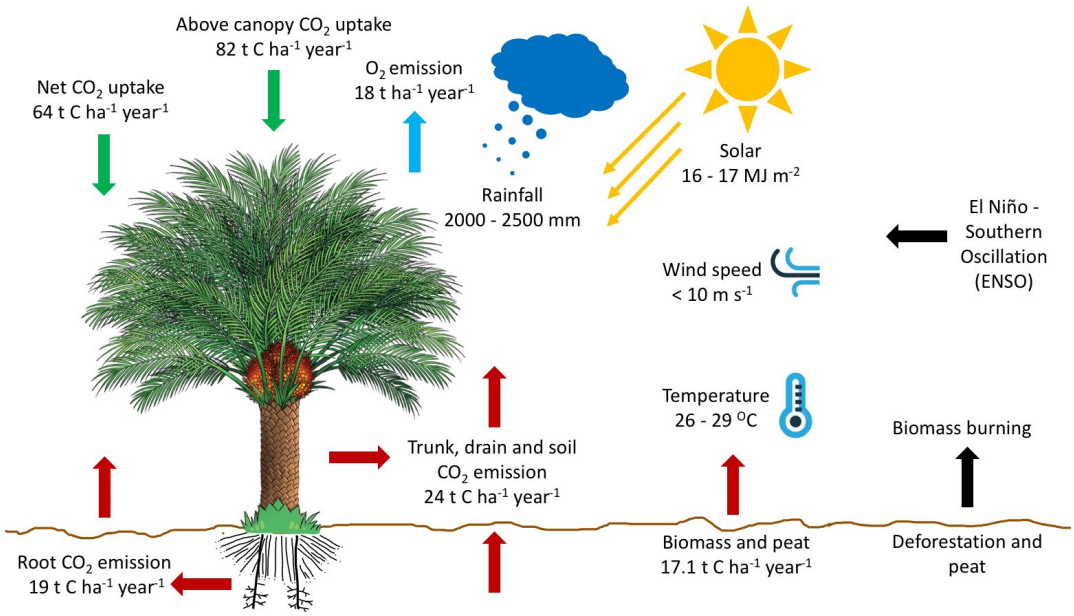

Figure 2. Emission and absorption of oil palm plantations with factors that influence these exchanges in tropical regions.

4.2. Comparison Studies on Oil Palm CO_2 with Other Crops

In this section, the focus on CO_2 flux has not been expanded upon in detail for other crops besides oil palm. The challenge in comparing emissions between different crops lies in the fact that not only do the soil types, rainfall and temperatures vary, but agricultural practices such as tillage, liming of soil and addition of nitrogen fertilizer can also influence CO_2 emissions [116–121]. In some cases, plantations such as rubber plantations have been shown to have a lower CO_2 flux compared to a natural forest [122]. Any useful comparison of emissions between different crops will require careful consideration of both the natural properties of the soil and agricultural practices in specific regions.

Table 4 shows some of the CO_2 emissions from different crops as well as intact forest. The CO_2 fluxes in these studies show that, overall, oil palm plantation CO_2 emissions are about one to two magnitudes higher compared to other crops, such as barley, corn and rubber. Corn appears to have the lowest emissions at 0.4 t C ha^{-1} year^{-1}. Based on these values alone, it would seem that CO_2 flux is highest in oil palm plantations. However, as mentioned in the earlier paragraph, various factors can affect the flux in the soil, as even oil palm flux has a range between 7 and 95 t C ha^{-1} year^{-1}, as shown in emissions studies in Malaysia and Indonesia (Table 2). The intact forest CO_2 flux recorded by Zhao et al. [122] is higher than that of oil palm recorded in a study by Matysek et al. [104]. Additionally, crop yields per hectare should be an important consideration, as total flux may be offset for crops with high yields, such oil palm, which has a potential yield that generally exceeds 8 t oil ha^{-1} year^{-1} [25].

Table 4. CO_2 emissions from different crops.

Plant	Type	Time Measured (Location)	Emissions (t C ha^{-1} year^{-1})	Reference
Barley	Soil	November 1998 to October 2000, over non-irrigated barley (Central Spain)	0.63	Sánchez et al. [123]
Corn	Soil	Based on agricultural inputs detailed by Frye and Blevins (1997) and Ismail et al. (1994), Blevins et al. (1983). (Kentucky, USA)	0.4	West and Marland [119]
Rubber Intact Forest	Soil	January and March 2016 (China)	5.7 9.5	Zhao et al. [122]

5. Conclusions

Overwhelming global demand for affordable vegetable oil has driven the fast expansion of oil palm plantations, especially in the Southeast Asian region. This expansion has led to many disastrous environmental issues, such as the destruction of natural carbon storage. The utilization of peatland and deforestation for oil palm plantations has been identified as the main challenge to controlling natural carbon emissions to the atmosphere. Previous estimation studies show that oil palm carbon and CO_2 emissions are a magnitude higher compared to other crops (e.g., barley, corn, rubber). Natural climate variability, such as El Niño and La Niña events, is expected to influence oil palm plantations at both large and small scales, and the change in this variability under warmer climates is expected to influence the palm oil yield. The ability of oil palms to absorb CO_2 (a net of 64 tons of CO_2 per hectare each year) and produce around 18 tons of oxygen is an advantage of this type of plantation.

To further reduce oil palm-related natural carbon emissions, a number of key processes can be implemented. For instance, curbing biomass burning, reducing the exploitation of peatland or swamp areas for plantation and replacing fossil fuels with biofuels to power plantation and production activities can achieve sustainable oil palm. The sustainability of plantation expansions can be achieved through a comprehensive review of all existing plantations to ensure that they align with existing sustainability criteria.

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