

Review

Carbon Sequestration by Tropical Trees and Crops: A Case Study of Oil Palm

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Abstract: Carbon sequestration by photosynthetic organisms is the principal mechanism for the absorption of atmospheric CO₂. Since the 1950s, however, the global carbon cycle has been distorted as increased anthropogenic CO₂ emissions have greatly outstripped rates of carbon sequestration, with a 50% increase in atmospheric CO₂ levels in less than a century, leading to perturbation of global climate systems and threatening food production and social stability. In order to address the current imbalance in CO₂ flux, it is important to both reduce net emissions and promote sequestration. To address the latter issue, we need to better understand the roles of systems, such as natural forests, coastal wetlands, and tropical croplands, in carbon sequestration and devise strategies to facilitate net CO₂ uptake. Carbon sequestration by tropical trees and crops already removes in excess of 1000 million tonnes of atmospheric CO₂ annually but is threatened by anthropogenic activities such as deforestation and the drainage of carbon-rich peatland. Improvements in carbon sequestration can be achieved by policies such as growing tropical crops as part of agroforestry systems, enforcing limitations on deforestation and the use of peatland, and auditing the carbon impact of major cropping systems in order to focus on those crops that deliver both high yields and carbon efficiency. As an initial step in this process, a detailed case study is presented on the tropical tree crop, the African oil palm, *Elaeis guineensis*. This analysis includes a comparison of the carbon sequestration potential of oil palm with that of tropical forests and other oil crops, the biomass sequestration potential of oil palm and current and future strategies aimed at achieving net-zero carbon targets for oil palm and related crops.



Citation: Murphy, D.J. Carbon Sequestration by Tropical Trees and Crops: A Case Study of Oil Palm. *Agriculture* **2024**, *14*, 1133. <https://doi.org/10.3390/agriculture14071133>

Academic Editor: Peng Zhang

Received: 30 May 2024

Revised: 2 July 2024

Accepted: 8 July 2024

Published: 12 July 2024



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Keywords: biomass; carbon sequestration; forests; oil palm; peatland; tropical crops

1. Introduction

Biological carbon sequestration by photosynthetic organisms is the dominant mechanism for the absorption of atmospheric CO₂ and has been responsible for modulating global CO₂ levels for billions of years [1,2]. Today, the global carbon cycle has been significantly distorted, as rates of carbon sequestration are no longer able to keep up with CO₂ emissions. The vast majority of these CO₂ emissions are released via anthropogenic processes, such as heating, cement production, transport, numerous industrial processes, arable and pastoral agriculture, and the deliberate burning of vegetation [3–6]. Over the past century, and particularly after 1950 CE, these anthropogenic activities have resulted in a massive increase in the emissions of two potent greenhouse gases (GHGs), namely CO₂ and methane (CH₄) [7–9].

Shortly after 1950 the rate of anthropogenic CO₂ emissions entered a new phase of an ever-accelerating increase from 311 ppm in 1950 to 339 ppm in 1980 and 412 ppm in 2020 to 427 ppm in 2024 [10]. In contrast, rates of carbon sequestration have either declined or remained more or less constant, meaning that the tonnage of global carbon emissions is now vastly in excess of the amount of carbon sequestration. According to the latest Global Carbon Budget data, total CO₂ emissions in 2023 were about 41,000 Mt, while biological carbon sequestration was only about 24,000 Mt [10]. The negative balance

between anthropogenically related GHG emissions and carbon sequestration by plants has led to a more than 50% increase in atmospheric CO₂ levels in the past century. This is contributing to increasing global temperatures and related climatic changes that are adversely affecting human societies and ecosystems around the world.

An important strategy to tackle this so-called ‘climate emergency’ is to decrease emissions of CO₂ and CH₄, for example, by ‘de-carbonising’ many transport and industrial processes. However, another important strategy is to increase carbon sequestration, and this will be vital to the eventual removal of excess atmospheric CO₂ in order to restore pre-industrial levels and hence reduce the risks of further climate change. Numerous non-biological carbon capture/storage processes are currently being researched, but none of these come close to the potential of biological carbon sequestration, which has been acting successfully on a global scale for billions of years. The most effective natural carbon sink is the perennial vegetation in tropical forests and agroforestry systems [11]. In this article, the contribution of tropical vegetation to biological carbon sequestration and its potential to at least partially restore a balance to the global carbon cycle will be examined, with a particular focus on the perennial tree crop, the African oil palm, *Elaeis guineensis*.

2. Carbon Sequestration by Tropical Vegetation

Biological carbon sequestration occurs due to photosynthetic CO₂ fixation, of which 56% is carried out by land plants and 44% by aquatic organisms [12]. As shown in Figure 1, a large proportion of terrestrial photosynthesis occurs in tropical forests, which are highly productive due to the year-round hot and moist conditions that favour rapid growth [13–16]. The world has a total forest cover of 4060 Mha, of which 1800 Mha (or 45%) is tropical forest [17]. It is estimated that intact tropical forests globally sequester an average 0.5 tonnes of carbon per hectare/yr and that, collectively, they annually store 1000 million tonnes (Mt) [18], although other estimates are higher, possibly exceeding 2000 to 4000 Mt/yr [13]. Tropical forests store captured carbon in the form of foliage and woody biomass, as well as in organic litter that is shed to the ground. About half of the dry weight of tree biomass is made up of carbon [19]. In a study of a tropical forest in Amazonia, it was found that fixed carbon was initially stored mainly as above-ground biomass (such as leaves) for about 16 years. After which, much of this carbon was retained in the form of below-ground biomass (such as roots and mycorrhizae) in the rhizosphere for a further 13 years [13].

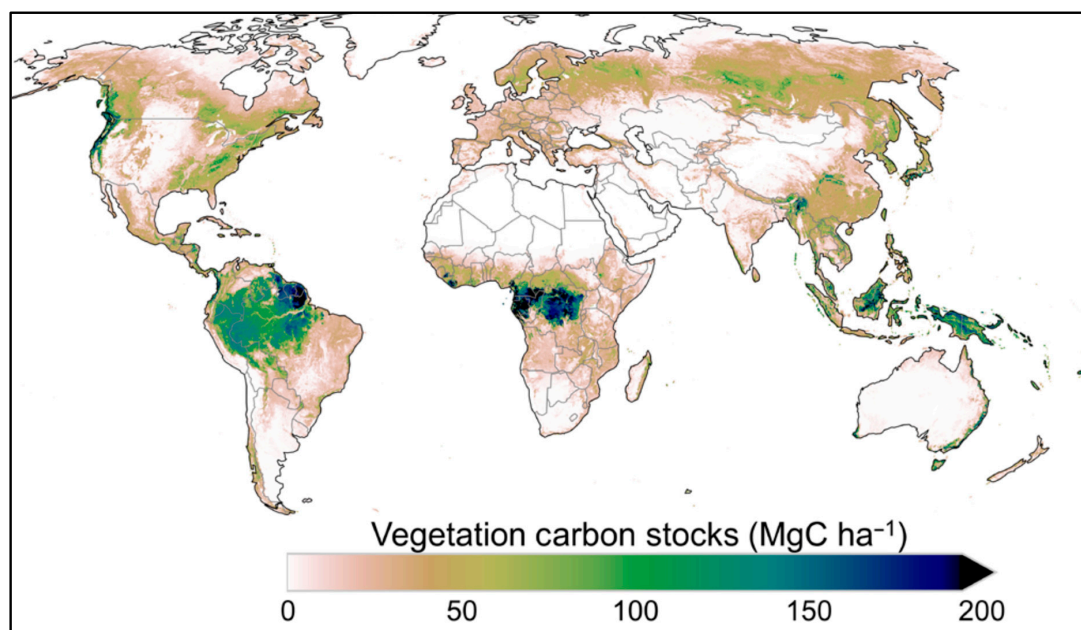


Figure 1. The major vegetative carbon stocks are located in three tropical regions: the Congo and Amazon River basins and the Indo–Malay Archipelago. Graphic from [20].

There is some evidence that increased levels of atmospheric CO₂ coupled with higher temperatures could increase photosynthetic rates and hence carbon sequestration; although, most of the currently available data come from non-tropical regions [21]. Increases in photosynthetic rates in tropical forests due to higher levels of atmospheric CO₂ will probably peak when the latter reach 800 to 1000 ppm, which according to many climatic models could occur by the end of the 21st century. The magnitude of this ‘carbon fertilisation’ effect is still disputed, and the resulting additional carbon sequestration may not be sufficient to offset more than a small fraction of current CO₂ emissions [22], as evidenced by responses in [23,24]. Other studies, for example in South America, show that some or all of the benefits of this increased photosynthesis might be cancelled out due to higher rates of respiration due to the more rapid decomposition of shed vegetation as temperatures rise [25–27]. A further complication in the tropics is that, in these normally wet biomes, photosynthetic rates can be acutely sensitive to moisture availability. Hence, during drier periods (which appear to be increasing in frequency in some regions), some forests could even become net sources of atmospheric CO₂ [28].

For many decades the overall, global rates of carbon sequestration by tropical forests have been in steady decline as they become degraded, destroyed, or replaced as a result of ongoing human activities. For example, during the period from 2002 to 2022, the annual loss of primary tropical forest land in Brazil averaged between three and four Mha/yr (million hectares/year) [29]. In many cases, especially in Brazil, tropical forests and productive cerrado biomes have been replaced by soybeans, a crop which, as we will see below, sequesters very little net carbon, as nearly all of its biomass is harvested annually and re-emitted as atmospheric CO₂. This means that much of the carbon sequestration potential of the original tropical forest is lost following land use conversion (LUC—sometimes also referred to as land use change) to short-lived annual crops of this nature. Interestingly, over the same period of 2002 to 2022, losses of primary tropical forest in Indonesia and Malaysia were substantially reduced to about 0.25 Mha/yr. This was largely due to more stringent anti-deforestation policies including a moratorium on the conversion of tropical peatlands into commercial oil palm and forest plantations, plus economic factors such as a fall in palm oil prices [29–32].

Efforts are now underway to restore or otherwise ameliorate the damage done to tropical peatlands, for example, by minimising drainage that can lead to exposure of dry peat and the consequent loss of this immense source of sequestered carbon due to respiration or combustion [33–35]. Another factor in Indonesia and Malaysia is that most felled forests were replaced by oil palm plantations and other tree crops. Unlike soybean plants, which typically reach a height of about 60 cm, commercial oil palms grow as tall perennial trees that can reach over 10 metres in height and are able to store an annual 2.5 tonnes of carbon per hectare during their productive lifetime of about 20 to 25 years. This productivity is comparable to and can even exceed that of a primary tropical forest [36]. The potential role for oil palm crops in large scale carbon sequestration will be examined in more detail later, in Sections 5–7.

3. Carbon Sequestration by Tropical Crops

As shown in Figure 2, tropical cropland is an important potential source of carbon sequestration that globally occupies over 700 Mha [37]. Despite their ability to absorb CO₂ during photosynthesis; however, most croplands are also strong net CO₂ emitters during their growing cycles. Their CO₂ emissions are due to factors such as respiration, soil disturbance, use of energy-rich inputs such as fertilisers, land use conversion, etc. [13,38]. Indeed, on a global scale the annual CO₂ emission by all the world’s croplands are roughly comparable with all fossil fuel-derived emissions, at about 2000 to 3000 Mt/yr, which contrasts with the IPCC CO₂ removal target of 10,000 Mt/yr [39–42]. The major crop culprits as net CO₂ emitters are annual species, such as cereals and legumes, which occupy 90% of all global arable land. From 1999 to 2008, the four tropical crops with the fastest rate

of increased land conversion for cultivation, with combined increases totalling 4.4 Mha/yr, were the four major annual grain crops: soybean, maize, rice, and sorghum [37].

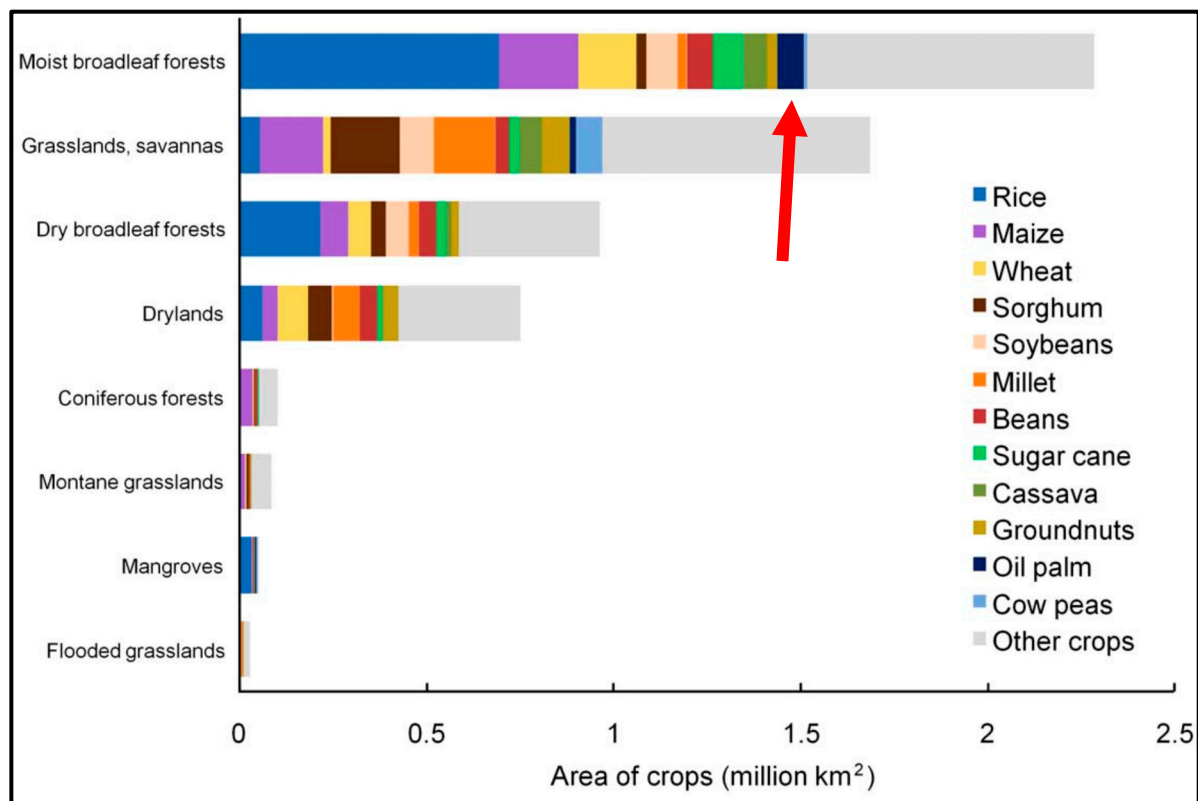


Figure 2. Area of the 12 major crops as a proportion of cropland in the principal tropical biomes. The relatively small area of oil palm crops (dark blue rectangle) is arrowed in red. Graphic from [37].

One of the most important tropical crops in terms of its increasing land use and carbon footprint is soybean. Globally, soybean production has increased tenfold between 1961 and 2021 to reach 372 Mt, of which one third is grown in the tropics [43]. About 77% of the soybean crop is used for livestock rearing (mainly chickens and pigs), and it is mainly the global demand for poultry products that has driven the expansion of soybean production in the Brazilian tropics. In recent decades, soybean yields per hectare in Brazil have doubled thanks to breeding advances leading to higher-yielding varieties. However, crop production has increased almost sevenfold, resulting in an accelerating rate of tropical land conversion. The role of new soybean cultivation in deforestation is much debated, but it is clearly a contributing factor, in tandem with land clearances for cattle pasture and small-scale farming, that contributes to increased forest loss in Brazil [44–47]. On the plus side, regarding carbon sequestration by soybean crops, a recent study in part of Mato Grosso State in Brazil reported that rates of assimilation were higher than CO₂ emissions caused by some of the anthropogenic activities during cultivation, albeit in the context of remediation measures such as no-till, in order to retain soil carbon [48,49].

One of the measures proposed to reduce future deforestation caused by soybeans and other tropical crops, including oil palm, as discussed below, is for downstream users and/or governments to impose moratoriums and/or voluntary restrictions [50]. However, if such measures are not carefully implemented, there is a danger that the crop is simply grown elsewhere, a phenomenon known as ‘leakage’ [51]. A notable example of government-backed moratoriums related to deforestation is that of the European Union (EU), which is the second largest (after China) importer of soybeans and hence complicit in their embedded or embodied tropical deforestation. In recent years, the EU has started to accept that imports like soybeans are, in effect, outsourcing the environmental impact of its own

food consumption and shifting it to growing countries, mostly in the tropics. By this logic, it is estimated that such outsourced tropical deforestation makes up one sixth of the carbon footprint of a European citizen's diet, although this figure is often allocated instead as a carbon debit for the producing countries [52,53]. As applied to the consumption of imported oil palm products, it is estimated that a typical European citizen has been responsible for the historical deforestation of 40 to 80 m² of tropical forest [52]. One caveat here is that there have been allegations that parties on all sides sometimes use moratoriums based on such data to restrict certain crop imports to protect local markets [54].

In contrast with annual crops, perennial crops such as fruit trees, oil palm, coconut, coffee, and cocoa plantations, tend to be effective net sequesters of CO₂. However, such crops only occupy 10% of global arable land, meaning that the vast majority of crops are relatively poor in terms of carbon sequestration potential. An often-overlooked category is the so-called production forests, which are primarily managed as a source of wood. Some of these were originally natural forests that have been logged over and subsequently replanted to serve as long-term cropping systems [55]. Such forests occupy an estimated 1150 Mha of mainly slow-growing trees, although future use of faster-growing commercial species could boost their overall carbon sequestration potential, at least in the short term [14]. For example, the average dry biomass (above + below ground) in a 5-year plantation of eucalyptus in Tamil Nadu, India is about 150 tonnes/ha [56]. Other high-yield tropical hardwood species include *Acacia mangium* and *Gmelina arborea* [57].

One strategy to promote more effective carbon sequestration is to grow tropical crops as part of agroforestry systems [11,58–60]. It was estimated that such agroforestry systems could sequester between 12,000 and 228,000 tonnes of carbon per year [11]. However, efforts to quantify the sequestration potential of agroforestry systems are notoriously difficult to achieve. Hence some quoted values of <1000 Mt of potentially sequestered carbon per year should be treated with caution [58,60]. In agroforestry systems, trees and ground crops are normally grown together, but it is far more common to grow tropical crops as monocultures. In terms of overall land use, the most widely grown tropical crops include rice and soybean, both of which can also be grown in warm, temperate regions. As with other ground crops, rice and soybean are annual species that only grow for part of a single year before being harvested. This limits their capacity to assimilate carbon because, unlike tree crops, no long-term standing biomass is produced in annual crops [61].

In comparison with grain crops, perennial crops in the tropics only occupy a relatively small proportion of total arable land, although this has been increasing in the case of a few crops, such as oil palm. Between 1990 and 2021 the global area of oil palm cultivation increased fivefold from 6 to 30 Mha [62]. While the latter is a substantial area, it is only 4.2% of global tropical cropland and 0.7% of global tropical forest land [17,62]. However, while in some regions as much as 84% (Kalimantan) and 63% (Papua) of new oil palm plantations between 1990 and 2010 came from forest or shrubland, in other regions the figures were much lower at 42% (Malaysia) and 29% (Sumatra) [63]. In a 2024 study, it was shown that the majority of direct conversion of tropical forests to oil palm in Indonesia, which is the major centre of cultivation, occurred before 2000 and decreased thereafter [32]. This finding is supported by other data showing that post-2010 oil palm plantation expansion has primarily originated from former plantations, such as rubber, cocoa, tea, or from scrubland [64–66].

More recently, zero-deforestation pledges coupled with new certification standards, have started to reduce the conversion of forest land and in some newer regions, such as Colombia, there is hardly any forest conversion [50,67–70]. Despite concerns about increasing forest loss, the overall quantity of CO₂ emissions due to global deforestation, caused by either shifting cultivation or permanent removal, has remained relatively constant at about 6000–8000 Mt/yr, with the figure for 2022 at about 7000 Mt [10]. In a recent study, oil palm-related emissions in two of the major growing regions in Indonesia had declined by 44–73% between 1990 and 2019 [32], as also noted previously as occurring during the period after 2010 [30]. Moreover, as shown in Figure 3, forest regrowth on a global scale

has resulted in increased sequestration of CO₂ from about 2900 to 4800 Mt over the period from 1961 to 2022 [10].

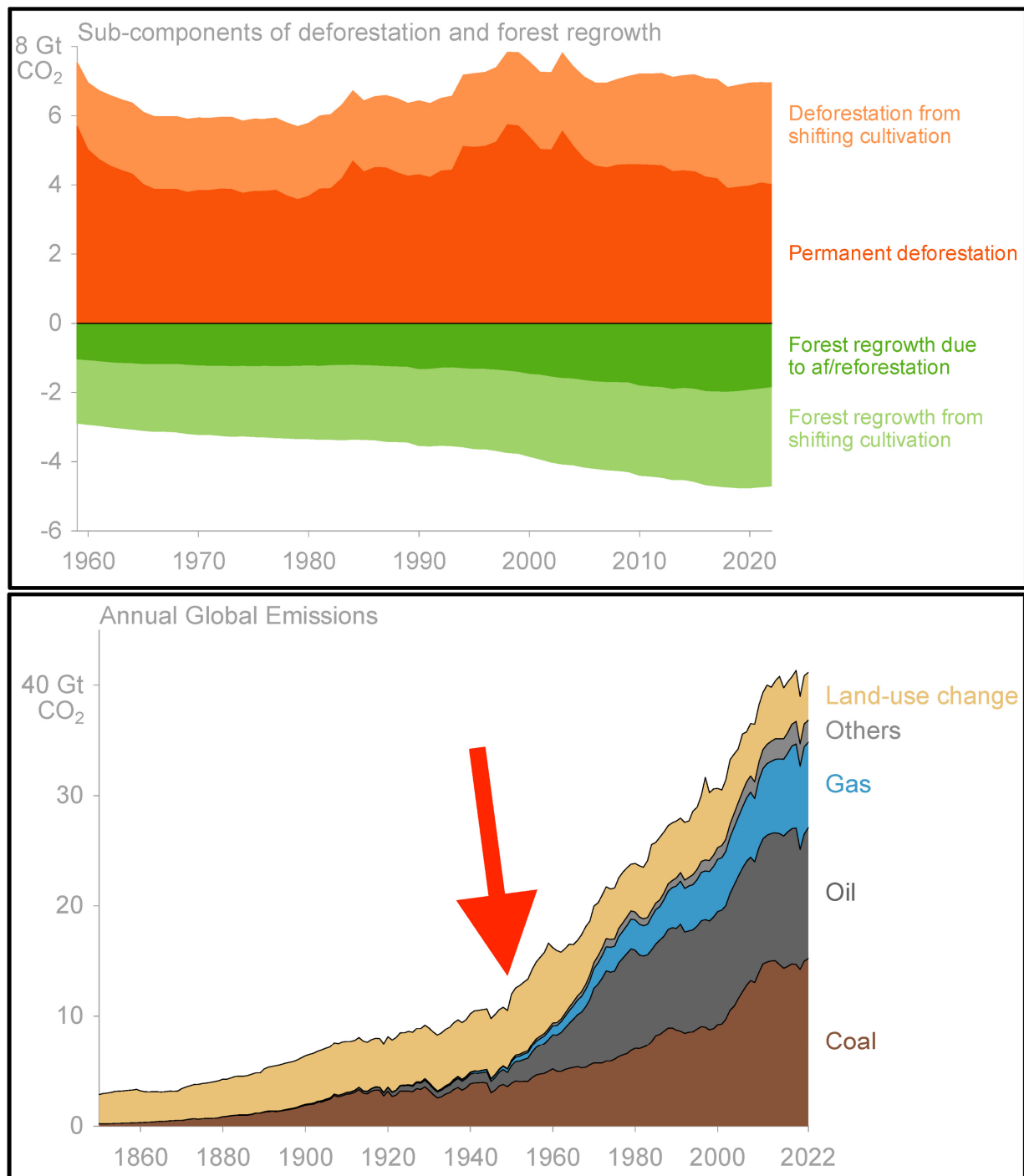


Figure 3. Upper panel: Global CO₂ emissions due to land use conversion (LUC) from deforestation and re- or af-forestation. Graphic from [10]. Lower panel: Global anthropogenic CO₂ emissions by source. LUC was the main CO₂ emissions source until the 1950 inflection point (red arrow) when fossil-derived CO₂ emissions took over. Graphic from [71].

In 2022, there was still a net deficit in the forest carbon balance, with net CO₂ emissions of about 2200 Mt in that year. However, this was significantly lower than the net CO₂ emission rates during the early 2000s, which were close to 4000 Mt/yr. These data suggest that the ongoing, relatively constant rate of deforestation is gradually being balanced by increased forest regrowth in both tropical and temperate regions. Whether this trend will continue into the future is a moot point due to several factors that might either favour or inhibit further loss of tropical forest land, and as well as the type of uses to which any cleared land is subjected [72]. In the short to medium term, the main pressures that encourage deforestation are economic. For example, forest clearance for pasture or soybean cultivation in Brazil has often been a gamble on increased future demand for meat or grain products that could level off, if consumers continue to switch away from meat. Another factor is that, after a few years, cleared forest land often becomes less productive as nutrients are depleted or the soil structure is otherwise unsuitable [73–75]. This has been found on some former deep peatlands in SE Asia and rainforests in Amazonia and results in much reduced yields of the new crops [76] and, in some cases, the abandonment of the converted land.

In response to these factors, it is now increasingly recognised that governments around the world have important roles in regulating the short-sighted deforestation of tropical biomes that serve as powerful carbon sinks [15,16]. However, the public sector in both individual countries and regional blocs (such as the EU) need to work with and be supported by other stakeholders, including business, smallholders, and NGOs. Important crop-related initiatives, such as deforestation, peatland moratoriums, and biofuel mandates should involve consensus agreements between producing countries and the countries where the crops and their derivatives are eventually consumed. For example, as mentioned above, the EU is engaged in discussions about moratoriums relating to soybean in South America, and, as mentioned below, the EU and other consuming blocs are engaged in discussions about moratoriums relating to oil palm in SE Asia [53,77]. In the remaining sections of this review, we will focus on a case study of a single tropical tree crop, namely oil palm, and consider its carbon sequestration capacity in the context of its carbon emissions and the climatic changes that are mainly related to imbalances in the global carbon cycle.

4. Oil Palm as a Tropical Tree Crop

The African oil palm, *Elaeis guineensis*, is used for this case study due to its economic importance, widespread cultivation across the tropics, predicted increased future demand, and reported high rates of net carbon sequestration [78–81]. Several studies have reported its high CO₂ assimilation rates that are comparable to those of tropical forests [33,61,63,79,82–89]. As discussed above, tropical biomes dominated by trees as their major vegetal components are capable of especially high rates of net carbon sequestration. Oil palm is grown across the three tropical continents in regions where the highest recorded rates of global photosynthetic productivity and net carbon sequestration are found [10]. Before looking into the carbon sequestration potential of oil palm, it is useful to consider whether these tall plants can be considered as bona fide trees, and whether oil palm plantations, each of which can cover tens of thousands of hectares, can be regarded as bona fide forest biomes. These issues, which have important policy implications, are explored, respectively, in Boxes 1 and 2.

Oil palm is unusual in being cultivated via two quite distinct business models, namely either on large commercial plantations, often run by multinational corporations and employing a paid labour force, or, alternatively, on small (<5 ha) family-run smallholdings [80]. In Indonesia, which is the major global centre of oil palm cultivation, 2.7 million smallholders manage 6.7 Mha or 41% of the total oil palm area in the country. On these smallholdings, vegetable plots and livestock often coexist with the oil palm trees, with some farmers also benefiting from additional understory cash crops, such as pineapple, banana, and tapioca, that are planted amongst the palm trees [90]. Arguably, such oil palm plantations (and those of other tropical tree crops) can be regarded as bona fide (but obviously anthropogenic

rather than ‘natural’) tropical forests. The potential of tree crops, such as oil palm, extends further to the production of foodstuffs, oleochemicals, pharmaceutical and health care products, liquid biofuels, lumber, and livestock feed [91]. With an oil yield of ~80 Mt, oil palm crops currently supply about 40% of global traded vegetable oil [92]. There is some uncertainty about the precise land use of oil palm crops, with estimates between 24 and 30 Mha given between 2022 and 2024. For example, both FAO and USDA reported a figure of about 30 Mha [92,93], while Solidaridad and Descals et al. reported significantly lower figures of about 24 Mha, respectively [70,94]. The vast majority of the crop (90% by area) is grown in SE Asia, with increasing amounts also grown in Latin America (3%) and West Africa (3%).

Box 1. Are oil palm plants wood-bearing trees?

The issue here is that a ‘tree’ is sometimes defined botanically as a ‘large woody perennial plant, usually with a single trunk enclosed by an outer cambium layer that grows annually to produce an outer layer of bark’. In contrast, the trunks of palm species and other monocots have no cambium but can still grow long stems that contain thicker parenchyma cells in between their scattered vascular bundles (e.g., coconut and pandanus). Other monocots have overlapping leaves with thick, lignified petioles wrapped around the stem that provide mechanical support (e.g., oil palm) [95,96].

All palm species are members of the large monophyletic family, Arecaceae, named after their nut-like fruits (Portuguese ‘*areca*’). Most palm species are tropical or subtropical, with growth habits including shrubs, vines, and tall arborescent (tree-like) plants. Several of the tree-like species, such as date, coconut, and oil palms, have been cultivated as food and fibre crops for many thousands of years. Many arborescent palm species can reach heights of 10–30 m in the case of oil and coconut palms, and the Quindio wax palm, which is the national tree of Colombia, can be over 60 m tall. Most people would regard such arborescent palms as obviously being trees, or at least tree-like.

Moreover, although palms do not make what is commonly known as softwood or hardwood, the palm trunk is nevertheless a fibrous and highly lignified but flexible structure that can often withstand hurricane-force winds. While palm wood lacks the strength and durability of hardwood, its greater flexibility endows it with many other uses as a structural material, as discussed in the main text. To summarise, oil palm plants satisfy a practical definition of being trees that have tall, lignified trunks that can be processed into many durable woody products. In their native habitats in West Africa, oil palms were probably mainly pioneer woodland species that colonised the edges of or clearings within densely forested areas in which they would eventually be shaded out by the taller vegetation [78].

The main commercial products of the crop are two types of oil harvested, respectively, from the mesocarp and kernel tissues of its plentiful fruits. Palm fruits are produced year-round in large bunches that can weigh up to 30 kg, with each bunch containing hundreds of fruits. Oil palm plantations start yielding useful amounts of fruit within about 3 to 5 years of planting and ideally have an economic life of 25–30 years before replanting is required due to falling yields and build-up of disease [79,80,97]. Palm oils have numerous uses in human nutrition and for various industrial applications, ranging from renewable liquid biofuels to cleaning products. Remarkably, an estimated 50% of all packaged supermarket products, from ready meals and cakes to toothpaste and infant food, contain palm oil ingredients [80,98]. As we will see below, other parts of the crop can be used as solid biomass for energy production, to manufacture various structural products, and even as high value medical therapeutics derived from palm mill by-products.

Box 2. Can oil palm plantations be regarded as (anthropogenic) forests?

The word forest is derived from a Latin term used for a wooded area. Forested landscapes have been exploited by humans across the world for millennia. For example, in England the Forest of Dean and New Forest are densely wooded regions used to supply natural resources, such as timber, ochre, charcoal, and saltpetre, since pre-Roman times. Recent findings also suggest that in pre-Colombian times, parts of the Amazon rainforest were inhabited by people who managed the woodland landscape in a mixed fashion reminiscent of modern agroforestry.

More recently, the FAO has defined a forest as “land spanning more than 0.5 ha with trees higher than five metres and a canopy cover of more than 10%, or trees able to reach these thresholds in situ” [50]. Puzzlingly, however, the FAO definition excludes treescapes that have any agricultural use, despite the fact that almost every forested region on Earth is actively utilised by people to some extent; although, the FAO definition has also been challenged [99]. The latter study makes the point that a more inclusive definition of a forest is required and that “*Such clarity is needed for zero deforestation commitments and the protection of natural ecosystems from conversion, even though the exact definition may depend on its purpose or target group, conservationists, foresters, or agroforesters may also have different views*” [99].

Oil palm plantations can be regarded as a satisfying at least some criteria of being forests, albeit human-planted arborescent monocultures that often additionally harbour significant amounts of understory vegetation and fauna [100]. In terms of harbouring a dominant tree species, there are numerous examples of ‘natural’ monodominant forests in both temperate and tropical biomes that contain large stands of a single species, such as members of the *Dipterocarpaceae* in Asia and *Gilbertiodendron dewevrei* in Africa [101,102]. There are also increasing numbers of oil palms and other tropical crops that are planted in multi-species assemblages as part of agroforestry enterprises, as seen in some carbon sequestration initiatives, as well as being common on smallholdings where livestock, such as cattle or poultry, are also present [11,58–60,81,103,104]. Therefore oil palm plantations have attributes seen in at least some ‘natural’ forests that consist mainly of a single dominant tree species and this needs to be taken into account by international bodies seeking to define complex terms like ‘forest’.

As with other major crops, oil palm cultivation fulfils a variety of social and economic purposes [80,81,91,105]. Globally, almost half of the oil palm crop by area is grown by over five million smallholder farmers and it is a key element in the social advancement and agricultural diversification in many rural communities across the tropics from Colombia and the Congo to Borneo and Thailand [81,106,107]. In contrast, in SE Asia, over half of the crop by area is grown on large commercial plantations by multinational agribusiness concerns whose supply chains are closely integrated with the wider global economy. As an export commodity, crude palm oil is typically transported by sea in huge tankers that supply millions of tonnes of oil annually to far-flung destinations, such as China, India, and Europe [80,108]. In terms of opportunities for improved carbon sequestration potential, there are numerous options for both smallholders and commercial growers, even within current production systems. Examples include reducing land use requirements by breeding for increased oil yields, more widespread replanting of superior genotypes, reducing inputs with high carbon footprints (such as fertilisers), eliminating carbon-emitting deforestation and the use of sensitive peatland habitats, and the more widespread adoption of methane-capture technologies in processing mills [38,50,72,90,109–115], as we will now explore.

5. Carbon Sequestration Potential of Oil Palm versus Tropical Forests

There have been numerous studies of the carbon sequestration capacity of oil palms under both experimental and field conditions, as summarised in the example shown in Figure 4. This Figure shows that above-canopy CO₂ uptake is 82 t C/ha/yr, but this is offset by O₂ emissions of 18 t O₂/ha/yr, hence, giving a net CO₂ uptake of 64 t C/ha/yr. Below-canopy CO₂ emissions include 19 t C/ha/yr from roots and 24 t C/ha/yr from trunk, drain, and soil totalling 43 t C/ha/yr [88]. In this case, the overall value for CO₂ uptake is 23 t C/ha/yr, although this can be substantially diminished if the crop is grown on peat soil, as discussed in Section 6.

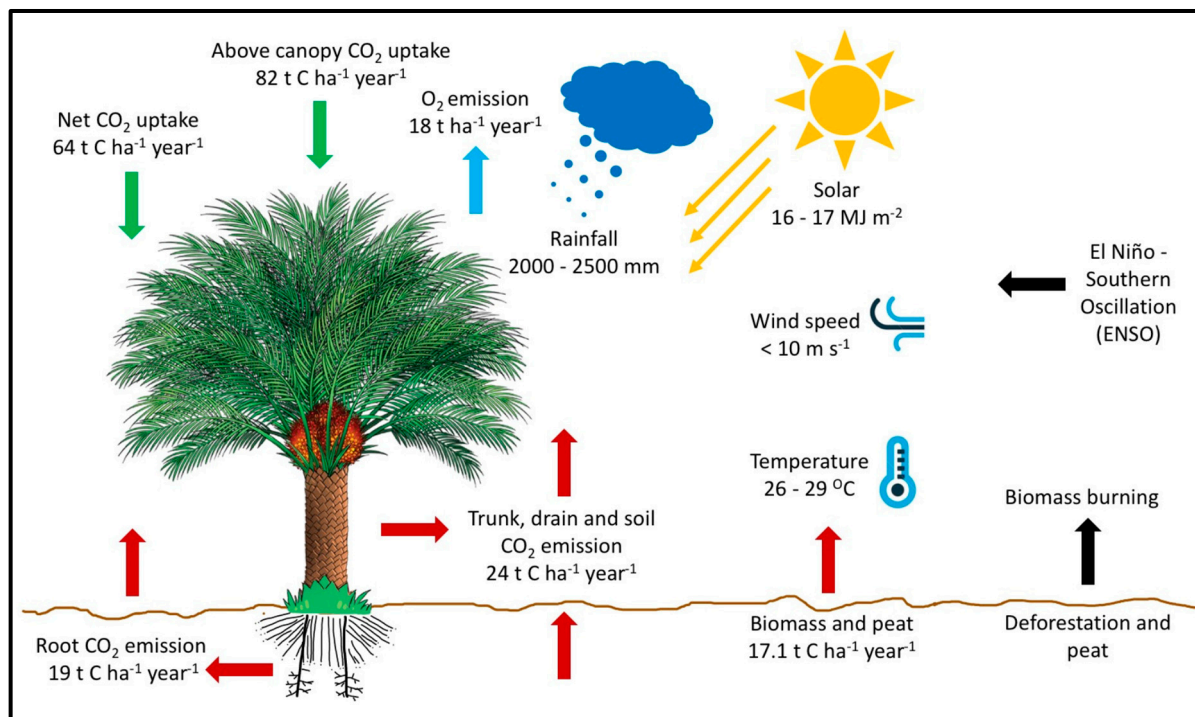


Figure 4. CO₂ emission and absorption in oil palm plantations with factors that influence these exchanges in tropical regions. Graphic from [88].

In terms of agronomical and economic utility of the crop, the major initial focus is on the rate of fruit production and, particularly, the accumulation of the mesocarp and kernel oils, which are the main commercial outputs of the crop. Here, it is evident that oil palm is a uniquely efficient crop that can sequester three to ten times more carbon as oil per hectare than any other oil crop [80]. The amount of carbon sequestered (in tonnes/ha/yr) into its oil by oil palm is also well over three times the amount of carbon sequestered into starch in the major cereal crops, such as rice and wheat. More recently, other parts of the oil palm crop have been studied in terms of their carbon sequestration capacity, for example as renewable biomass for energy or materials production.

In a series of papers, Henson et al. assessed CO₂ fluxes in oil palm plantations in SE Asia and Colombia and compared their net carbon sequestration capacities with those of neighbouring tropical forests [68,79,82,83,86,116,117]. Perhaps the most notable finding was that net carbon sequestration in a group of oil palm plantations was 64.5 tonnes CO₂/ha/year, which was significantly higher than the 42.4 tonnes CO₂/ha/year measured for nearby tropical forests [79]. This was similar to a previous report from Indonesia showing higher rates of CO₂ fixation and biomass production in oil palm plantations compared to a nearby tropical forest [36]. One source of variability in some reports is the age of the sampled plantations, which can vary considerably, with more mature plantations of 10+ years having significantly higher rates than younger plantations. In contrast, undisturbed rainforests typically have a mixture of tree ages where such differences are smoothed out. For example, other studies report carbon sequestration rates of 49 tonnes CO₂/ha/year in mature oil palm plantations but only 12 to 17 tonnes CO₂/ha/year in younger plantations [84,87,118]. In a study of plantations over their 25-year optimal lifetime, average annual rates of 63 tonnes CO₂/ha/year were reported, although actual rates would have varied considerably, for example between very young and mature plantations [61], while other studies in Malaysia and Indonesia, respectively, reported 2 to 60 and 36 to 40 tonnes CO₂/ha/year [119,120]. In the latter study, which took place over six years, the gross rate of carbon sequestration was 209 tonnes CO₂/ha/year, but this was offset by respiratory emissions of between 138 and 173 tonnes CO₂/ha/year.

In another study in Sabah, Borneo, the rate of CO₂ fixation in an oil palm plantation, measured as net primary productivity, was 1200 mg C/m²/hr, which was far higher than the nearby rainforest value of 700 mg C/m²/hr [121]. These values translate to about 105 tonnes CO₂/ha/year for the oil palm plantation versus 61 tonnes CO₂/ha/year for the rainforest. These figures are higher than the Henson et al. data [68,79,82,83,86,116,117], but both data sets are of the same order of magnitude, and both indicate 60–70% higher rates of carbon sequestration in oil palm plantations versus comparable tropical forests. Methane emissions from the Sabah oil palm plantation, which was on mineral soil, were 4.8 µg CH₄ m²/h, while the primary tropical forest was 2.8 µg CH₄ m²/h, both of which are relatively low values that reflect the modest rates of methane released from the soil, rather than from the canopy [121]. The superior CO₂ fixation rates of oil palm plantations over rainforests may be surprising to some, but there are several factors that might explain such results. It could be due to the difference in respiration rates between plantations and mature forests because the latter release more of their fixed CO₂.

As shown in Table 1, in oil palm plantations, the rate of photosynthesis is much greater than the rate of respiration [122,123]. In contrast, tropical forest biomes include much larger amounts of decaying organic matter and associated heterotrophic fauna that, together, cause higher rates of respiration, hence releasing, rather than sequestering, CO₂ [79]. Similarly, natural forests had 30% higher respiration rates than a neighbouring rubber plantation in southern China [124]. In general, long-lived mature tropical forests tend to be in a steady-state condition whereby the rate of photosynthesis and the rate of respiration are relatively in balance, whereas oil palm plantations are permanently akin to young forests (the former are replanted every 25–30 years), from which surplus sequestered carbon is regularly removed for a renewable, human-related function, for example as food, liquid biofuel, or solid biomass. After about 20+ years, the standing biomass in oil palm plantations stops increasing and, if the trees are not replaced, it declines substantially after 30 years [79,86,117]. Even though they are essentially young tree systems, oil palm plantations up to 25 years in age are still able to sequester vegetative biomass on the ground, which adds an additional 18% to that of the main tree biomass [79,86,125].

Table 1. Assimilation data for oil palm plantations versus tropical forests. Source [82].

Indicator	Tropical Forest	Oil Palm Plantation
Gross assimilation, ton CO ₂ /ha/yr	163.5	161.0
Total respiration, ton CO ₂ /ha/yr	121.1	96.5
Net assimilation, ton CO ₂ /ha/yr	42.4	64.5
Oxygen production ton O ₂ /ha/yr	7.09	18.7
Leaf area index	7.3	5.6
Photosynthetic efficiency, %	1.73	3.18
Radiation conversion efficiency, g/mj	0.86	1.68
Total area biomass, ton/ha	431	100.0
Incremental biomass, ton/ha/yr	5.8	8.3
Dry matter productivity, ton/ha/yr	25.7	36.5

6. Tropical Peatland Impacts on Carbon Sequestration

A major reservoir of long-term sequestered carbon is tropical peatland, where 30 to 45 million hectares sequester an estimated 70,000–90,000 Mt [126–133]. Indeed, in global terms, peatlands contain almost double the amount of biomass stored in all of the world's tropical rainforests [129,133,134]. There are several different types of tropical peatland ranging from shallow (sapric) to deep peat (sapric + hemic). Deep or very deep peat is the most problematic potential substrate in terms of its high carbon content and poor suitability for oil palm planting [76,88,135,136]. For example, the instability of peatland converted

to oil palm can lead to lodging of the trees, increased risk of fungal infection, and fluvial carbon loss to atmospheric CO₂ [132]. The complexity of peat soil composition means that carbon flux data can vary considerably between regions, and even within a single large plantation where several types of peat may be present. It also means that the auditing of carbon flux on former peatland can be imprecise, and this is reflected by the wide variations in published data. For example, plantations on peat soil in Indonesia have been estimated to have CO₂ emissions ranging from 12 to 95 t C/ha/year [137–139], while in Malaysia the emissions ranged from 7 to 79 t C/ha/year [33,88,140–142]. The vast majority of oil palm on former peatland is found in the two major producing countries, Indonesia and Malaysia, where pressures to grow more oil palm increased markedly after 2000, mainly due to elevated demand from importing regions such as the EU and China [131].

A major factor in the initial drive to import more palm oil into the EU in the early 2000s was a misguided policy to use palm biodiesel on a large scale as a renewable biofuel in order to balance adverse fossil fuel emissions [52,143]. The policy was initially supported by environmentalists, but it had the negative effect of stimulating land conversion of tropical forests and peatlands to satisfy the sudden increased demand from the EU [144]. From a very small area before 2000, peatland conversion to oil palm cultivation expanded to over 2 Mha by 2010 and doubled to over 4 Mha by 2020. Overall, from 2001 to 2020, the EU, as a whole, was directly responsible for the conversion of at least one Mha of forest and peatland to oil palm [145]. Between 1990 and 2015, exposed and drained peatlands converted to pulpwood and oil palm plantations in SE Asia have lost 2500 Mt of sequestered carbon due to oxidation [146]. The combined land footprint (i.e., annual oil palm plantation usage) of just four EU palm oil importing countries rose from 0.3 Mha in 2000 to almost 1.3 Mha in the late 2010s, followed by a decrease to 1 Mha by 2020 [52].

While a considerable amount of sequestered carbon is lost during the initial peatland drainage and conversion to oil palm cultivation, the remaining peat substrate continues to retain large quantities of stored carbon that is gradually released as CO₂ due to oxidation. This is partly driven by microbial organisms, principally bacteria and archaea, and represents an ongoing negative impact in terms of GHG releases and the loss of sequestered carbon from the system [133,147]. There are various strategies to mitigate this and other sources of carbon loss, often referred to as soil organic carbon sequestration in various peatland settings. These include the use of fertilisers, pesticides, nutrient cycling through manuring [33,69,148–150] and even land-swapping, which might be an attractive option for some smallholders [90,151]. Another recently reported option is to establish agroforestry schemes including species such as *Coffea liberica* and *Shorea balangeran* in threatened peatland ecosystems as a way of enhancing the carbon footprint and economic value while also limiting forest conversion [115].

7. Climate Change Impacts on Carbon Sequestration

Oil palm cultivation occurs on a relatively small scale compared to other biological processes that might contribute to or mitigate global climate change. For example, in 2014 the crop only occupied 24–30 Mha, or 2.8–3.5% of total tropical cropland, <1% of global cropland, and <1% of the land occupied by tropical forests and tree crops [93]. The land area occupied by oil palm is dwarfed by major grain crops such as soybean (126 Mha), rice (165 Mha), maize (194 Mha), wheat (160 Mha) and sorghum (338 Mha), with these five crops alone occupying 40 times more land than the entire global oil palm land footprint [98]. Hence the land use impacts of oil palm crops are relatively modest compared to these grain crops. Although there will be higher historic land conversion impacts in those cases where deforestation or peatland use were involved, these one-off impacts in terms of adverse GHG emissions and carbon flux will gradually be reduced and eventually fully amortised as oil palm plantations become established over a period of decades.

Nevertheless, it is still useful to audit oil palm cropping and processing systems in terms of their comparative status with regard to climate change. As noted above, most mature oil palm plantations have good rates of carbon sequestration relative to other

crops, and ongoing initiatives to limit or halt forest or peatland conversion should improve matters further. It will be desirable to avoid further expansion of tropical crop areas in general. However, the main culprits here are not oil palm, but rather the annual grain crops of soybean, maize, rice, and sorghum. In one decade, these four crops increased in area by >40 Mha of new tropical land, which is 10 Mha more than the entire area occupied by oil palm in 2024 [37]. In the case of oil palm, further land expansion can be minimised by increasing the already high oil yield of the crop by replanting with existing superior genotypes and by improving the management of existing plantations [80].

One future pressure for oil palm expansion will come from the global population rise from eight to ten billion by the 2080s. Palm oil is already part of the diet of an estimated three billion people and its consumption is also correlated with improved economic circumstances, for example in major importing nations such as China and India [114]. As matters stand, this could entail an expansion of oil palm cultivation in the region of 7–10 Mha, although the required area could be reduced substantially if higher yield crop varieties are deployed on a global basis [80]. A recent report highlighted significant decreases in oil palm-related GHG emissions in the Riau and North Sumatra regions of Indonesia over the period 1990 to 2019 [32]. The respective decreases in emission flux from 1.98 to 1.15 tonne $C_{eq.}$ ha⁻¹ yr⁻¹ in North Sumatra and 9.63–2.67 tonne $C_{eq.}$ ha⁻¹ yr⁻¹ in Riau were ascribed to decreased deforestation and burning plus an increased biomass increment that resulted from lower carbon stock area conversion to oil palm.

If, however, some oil palm expansion is required, the new plantations should ideally be in regions such as South America and West Africa, where deforestation or peatland conversion do not occur [90,151,152]. Such considerations do not only apply to oil palm, and it is estimated that fully adopted zero-deforestation policies for all crops could save as much as 96 Mha of tropical forests from conversion, of which 16 Mha would be saved directly or indirectly from conversion to oil palm [50]. Therefore, in the case of oil palm there is no compelling case for any future expansion of cultivation to contribute to negative carbon sequestration via deforestation or peatland conversion.

Future climate change is likely to affect many aspects of oil palm cultivation including its carbon sequestration potential [80]. Indirect effects could include reduced oil yields due to increased incidence of drought and disease [80,153–158]. However, other effects could include higher oil yields due to increased rates of photosynthesis that will be a consequence of higher average temperatures and levels of atmospheric CO₂ [159–162]. A recent study compared historical oil palm fruit yields in four countries from 1971–2000 with predicted yields from 2070–2099, as based on several simulations [162]. In all growing regions and with all models, there were significant increases in predicted crop yields, between 16% and 50% by the 2070–2099 timeframe. However, there are also uncertainties about the real-life impact of this ‘CO₂ fertilisation effect’. For example, whether CO₂-driven increased rates of photosynthesis would not be limited by other factors, such as nitrogen or water availability [163].

These findings suggest that climate change could simultaneously result in both increases and decreases in overall oil palm yields. It is also difficult to predict the magnitude and location of climate-related factors, such as rainfall and disease incidence, that may result in decreased yields and, hence, lower rates of carbon sequestration. However, there is already evidence of an increasing incidence of localised mini-droughts in some oil palm-growing regions where regular year-round rainfall was previously the norm [164–167]. If improved predictive models are forthcoming, it should be possible to mitigate the effects of more erratic rainfall patterns using strategies such as micro-irrigation, as is already in use in India and parts of South America [168–170]. Meanwhile, it will be important for the sector to be aware of these uncertainties and the potential volatility in supply chains that could ensue.

8. Land Use Conversion (LUC) Impacts on Carbon Sequestration

Land use conversion (LUC) refers to a long-term change by humans in the use of an area of land from one type to another. For example, a primary or secondary forest might be converted to cropland. Alternatively, cropland might be converted to grassland (or vice versa) or one type of cropland might be converted to completely different type of cropland, such as the conversion of rubber or rice plantations to oil palm. The planting of oil palm onto non-palm land as an LUC process can have very different impacts on carbon sequestration depending on the nature of the converted land. In particular, the conversion of non-forest land such as pasture or cropland could result in an increase in net carbon sequestration as the oil palm plantations mature. On the other hand, conversion of ‘natural’ forest or high-density rubber plantations could result in a decrease in net carbon sequestration [104]. In Colombia, oil palm plantations have typically been established on poor-quality pasture or cropland and even on former coca farms [69].

Several studies in Colombia have shown that oil palm plantations act as net carbon sinks due to their high rates of carbon sequestration [68,86]. The main emission sources, in decreasing order of magnitude were as follows: LUC (40.9% of total), mill methane production (21.4%), direct use of fossil fuel (18.5%), indirect use of fossil fuel (11.9%), and nitrous oxide production (7.3%). Total carbon emissions of 0.194 Mt/yr were exceeded by the carbon sequestration rate of 0.207 Mt/yr, giving a net positive balance of 13,000 tonnes/yr. As is normally the case with oil palm, the major emissions source in Colombia was LUC, but the magnitude of this component was significantly lower than in SE Asian plantations [117,171]. Later studies in 2012 and 2014 gave estimates of the carbon footprint of palm oil of between 6 and 8 tonnes CO₂ eq per tonne of processed and transported oil [172,173].

In SE Asia, oil palm LUC has been historically higher due to the conversion of tropical forest and peatland (see Figure 5)—two negative LUC components that do not apply in Colombia [68–70]. As noted above, the undesirability of deforestation and peatland conversion is now well recognised across the oil palm industry, with several moratoriums in place to minimise or eliminate such practices [32,53,72,77,106,114]. Providing these measures are rigorously implemented, LUC-based emissions will start to decline, which in turn will eventually enable oil palm crops globally to be classified as net carbon sinks, as is already the case in Colombia. Another important factor in LUC is the nature of the vegetation that is replaced by an oil palm plantation, which in many cases is not tropical forest. It has been proposed that vegetation with a carbon stock value of >40 tonnes C_{eq}/ha should not be replaced, which would include monocultural rubber plantations, rubber agroforests, and secondary or logged-over forests that respectively have carbon stock values in the range of 44, 177, and 65–219 tonnes C_{eq}/ha. In contrast, grasslands and shrublands with lower carbon stock values, respectively, of 3 and 34 tonnes C_{eq}/ha would not incur a carbon debt upon conversion to oil palm [174].

Recent studies of the potentially positive role of oil palm cultivation in carbon sequestration have sought to balance factors such as LUC-related GHG emissions with a more nuanced perspective that includes ongoing mitigation strategies as well as economic and social wellbeing targets, such as the UN Sustainable Development Goals [2,72,81,107,113,175,176]. Other innovative strategies include the planting of one or more additional crops between the young trees on new or replanted oil palm plantations. These extra crops can provide important ecosystem services in terms of additional carbon sequestration plus economic returns that are of particular value to smallholders [177–179]. Examples include installing a leguminous ground cover to provide forage for livestock, such as cattle, buffalo, and sheep [180].



Figure 5. Three key strategies to promote net carbon sequestration and reduce GHG emissions in oil palm cultivation. (**Top** panel): avoid deforestation. (**Middle** panel): avoid use of deep peatland. (**Lower** panel): install methane capture and biomass recovery in processing mills.

There are encouraging indications that oil palm-related deforestation in Indonesia declined from 2018 to 2020 thanks to zero-deforestation commitments and associated measures, as well as for economic reasons [30,32,181]. Despite this decline in land use, however, palm oil production actually increased due to improved yields on existing plantations. NGOs and others estimate that GHG emissions from land-use change in the palm oil sector could drop by 13% to 16% by 2030 [182,183]. The wider oil palm sector has also been something of a trailblazer in establishing several sets of voluntary sustainability standards (VSS), many of which specifically address carbon imbalances, for example, around LUC [184]. The VSS was initially established in response to unfavourable publicity around issues such as rainforest conversion and the fate of iconic species such as orangutan [185]. However, they have now grown into a (sometimes confusing) network of agreements that seek to encompass the entire oil palm value chain from plantation to end-user, where the former might be a smallholder of a two-hectare plot, while the latter is often a supermarket shopper in a faraway city [186].

In the case of rainforest conservation, it has been stated that VSSs have ‘the most demonstrated positive impact in preventing deforestation’ [186]. Among the principal international VSS are the Roundtable on Sustainable Palm Oil (RSPO, established 2004) and the International Sustainability and Carbon Certification (ISCC, established 2010). These bodies tended to focus on larger producers and users of palm oil and did not engage widely with smallholders [184]. This led the two main producing countries to establish their own mandatory certification schemes that target both plantation operators and smallholders, namely the Indonesian Sustainable Palm Oil (ISPO, established 2011) and the Malaysian Sustainable Palm Oil (MSPO, established 2013). The latter mandatory certification schemes directly address improvements in sustainability criteria for producers. In the future it is hoped that they can work with international VSS bodies to develop broad sector-wide certification standards in order to address issues such as decarbonisation and LUC-related GHG emissions [69,72]. As of 2023, it was reported that only 17% of globally traded palm oil was VSS-compliant with the two major importing countries, China and India, significantly lagging behind other major regions, such as Europe and the Americas [184]. On the plus side, the uptake by smallholders of more user-friendly VSS-certification schemes such as ISPO and MSPO has increased substantially. In the longer term, commitments to no deforestation, coupled with the steady amortisation of existing LUC penalties, should reduce the impact of land conversions over recent decades and go some way towards establishing a more level playing field for oil palm versus the annual oil crops.

9. Biomass Sequestration Potential of Oil Palm

Because it grows continuously year-round in the tropics, oil palm plants sequester a large amount of annual biomass in addition to the oil-bearing fruits that are the major commercial products. The major harvestable biomass components produced during active growth are the leaves and fruit bunches. In addition, the woody trunks become available when the trees are replaced at the end of their productive life of about 25–30 years. Oil palm trunks make up about 42% of total plant biomass and typically contain about 20% lignin plus 65–80% holocellulose (α -cellulose and hemicellulose) and starch. Other potentially usable biomass components include kernel shells, empty fruit bunches and mesocarp fibres. Many of these biomass components are left to rot in the ground, where they can usefully increase soil nutrient content, although they can also leach antimicrobials that are detrimental to the rhizosphere [187]. There is increasing interest in utilising the various forms of oil palm biomass for a range of purposes and this has the potential to create new business models and well as contribution to carbon sequestration [188–190].

9.1. Biomass for Fuel

The above-mentioned oil palm waste products, which are mainly solid but not necessarily in the form of readily combustible dry mass, total about 350 Mt in Malaysia alone and are estimated to reach 415 Mt by 2030 [187]. Extrapolated to the global oil palm sector, this

means that as much as 1500 Mt of underutilised crop biomass is being produced annually. One possibility is to process some of the palm waste for the generation of carbon-neutral bioenergy [191]. This already occurs in the case of the ~20 Mt of oil-derived palm biodiesel that is produced annually as methyl esters in refineries mostly located in SE Asia [192]. The use of biodiesel in local markets in SE Asia is likely to increase in the short term as the EU plans to implement a ban on the use of biodiesel from both palm and soybean oil that is currently scheduled to take effect in 2030 [193]. Meanwhile, in Indonesia, palm biodiesel for vehicles is now mandated as a 35% blend (B35) with fossil-derived diesel. In the future, this will possibly be increased to a 50% blend (B50), with similar schemes involving B20 blends being implemented in Malaysia and Thailand [194].

There have been numerous studies into the feasibility of using solid biomass from oil palm plants as a feedstock for power generation, with varying conclusions about its net cost, logistics, and contribution to the overall carbon balance of the crop [195–197]. A recent estimate states that oil palm biomass from Malaysian sources alone could potentially generate 5 GW of electricity at an efficiency of 40% [197]. This is close to the current installed capacity of 7.6 GW for all renewables, of which only 0.8 GW comes from solid biofuels [198]. According to its National Energy Plan of 2022, the Malaysian government is now seeking to increase renewables output to 18.4 GW by 2050 [198,199]. Meanwhile, at the level of a single modest-sized mill in Indonesia, the use of oil palm biomass for power generation was estimated to reduce annual carbon emissions by 9600 tonnes of CO₂ while generating about USD 50,000 worth of electricity [196].

In general, the large-scale use of crop biomass for energy generation has sometimes been controversial, especially when the biomass is transported vast distances from its source to end-user power plants that might be on another continent. A particularly egregious example that is ongoing is the felling of mature trees in North America for the production of wood pellets that are then shipped to former coal-fired power stations in Europe, where they supposedly act as a carbon-neutral fuel, a claim decisively at variance with most scientific evidence [200–205]. This practice recently became a cause célèbre in the UK as the operators of the government-subsidised (but privately owned) Drax power station in 2022 imported 8.2 Mt of wood pellets while benefiting from a USD 780 million state handout [206]. Somewhat belatedly, the UK government issued a report in early 2024 in which the current support for tree biomass was questioned, both in terms of its cost in public subsidy of over USD 8 billion since 2002 and its unproven sustainability criteria [207–210].

In the case of oil palm biomass, its use for the generation of carbon-neutral bioenergy is probably more robust, as long as it operates at processing mills where the biomass does not require lengthy transport and can be used to produce power to operate the mills and ancillary operations, including providing electricity to local communities. However, in the case of larger mills, their capacity to generate electricity from biomass might exceed the requirements of the local region. In such cases, the mills or other bioenergy generators should be connected to a regional or national grid to avoid wasting energy and associated carbon savings. This is a generic issue that also applies to related infrastructure such as wind or solar farms, and it has yet to be satisfactorily resolved in most parts of the world, including in much of Europe. Meanwhile, it is already the case that most oil palm mills are self-sufficient in their energy use thanks to the use of solid palm biomass for steam and energy generation. In contrast, oilseed-processing facilities overwhelmingly rely on external energy sources, most of which are derived from non-renewable fossil fuels.

A related method of energy generation from oil palm is to utilise methane that is captured from the effluent at mills (see Figure 5). This abundant liquid waste is produced during sterilisation and clarification processes and is generally termed palm oil mill effluent (POME). POME is a fluid byproduct of the processing of fruit bunches. It is enriched in organic compounds that are a source of methane emissions of the order of 0.55 tonnes of CO₂ equivalents per tonne of crude palm oil [211]. While such emissions are sources of this potent greenhouse gas, they can also be utilised to provide a useful energy source if suitable methane-capture technologies are installed at mills [212–214]. Although methane-capture

technologies from POME have been available for decades, their uptake by mills has been rather slow. For example, in Indonesia, which is the world's largest producer of palm oil, only around 6% of POME produced is treated using methane-capture technologies, while the rest is generally treated using a series of aerobic and anaerobic open lagoons [109,112]. The situation is better in Malaysia, the world's second-largest producer of palm oil, where about 28% of mills have deployed methane capture [111].

Although more facilities are currently in the pipeline [110], the majority of palm oil mills have yet to adopt methane-capture technologies. It is estimated that a combination of improved agricultural practices, methane capture, and biomass energy generation could reduce net emissions from 2.94 to 0.07 tonnes CO₂ eq/tonne CPO (crude palm oil) [89,215]. In addition to mill operations, it should be possible to link other parts of the oil palm value chain, including plantation operations, oil refineries, transportation and food processing systems, etc. to move towards carbon neutrality [216]. According to a recent mathematical modelling case study based on the value chain in Johore, Malaysia, it was estimated that GHG savings of 6.04 tonnes of CO₂ per hectare in plantations and 0.62 tonnes of CO₂ per tonne of fresh fruit bunches in mills were possible [72,190,217,218]. Surprisingly, in many plantations, much of the fuel used for on-farm machinery, such as tractors and power tools, still comes from fossil-derived diesel, despite the availability of renewable palm-derived biodiesel. The wider use of locally generated biodiesel, coupled with other green energy sources, such as solar and wind, has the potential to significantly reduce the global carbon footprint of oil palm cultivation [219].

Oil palm biomass can also be used to generate fermentable sugars that can be processed into ethanolic biofuels similar to the bioethanol obtained from crops such as maize and sugar cane [220]. Dried biomass fractions of oil palm, such as empty fruit bunches, mesocarp fibres, palm trunks, and decanter cake, are mostly made up of polysaccharides and smaller amounts of lignin [221]. In order to extract simple sugars, lignocellulosic components of the biomass are pre-treated to remove the lignin fraction, hence exposing the cellulose and hemicellulose polysaccharide contents for digestion into sugars by industrial cellulases [221]. As alternatives to enzymatic digestion, other strategies to extract sugars from oil palm biomass are being investigated, including solvent extraction [222] and microbial fermentation [223]. As of yet, none of these processes have been demonstrated to be economic on a large scale, but in the future, they could lead to alternative ways to generate value from some of the biomass fractions currently used in comparatively low-value applications, such as biochar production [224].

9.2. Biomass for Structural and Other Materials

One alternative to simply burning oil palm biomass is to use it for manufacturing useful products that have a longer life and thereby extend the overall carbon sequestration value of the crop compared to immediate combustion. An obvious target is the more lignified parts of the biomass, and several research projects are now underway to investigate palm trunks in particular [225]. Like most arborescent monocots, oil palm trunks mainly contain vascular bundles and parenchyma cells, in contrast to dicot hardwood and softwood trunks, which contain mostly fibres, tracheids, vessels parenchyma, and ray parenchyma cells. Palm trunks also have different chemical compositions [226,227]. For example, unlike most other monocots, oil palm trunks have elevated levels of syringyl (Lg-S) units in their lignin polymers, which are similar to woody dicots. Moreover, the lignocellulose content and monolignol composition of oil palm trunks vary according to genetic background, indicating that it might be possible to breed for varieties with optimal mechanical properties [228].

There are several ongoing projects aimed at exploring the potential of oil palm biomass for structural and other materials, including the PalmwoodNet initiative, sponsored since 2015 by the German public sector DEG (Deutsche Investitions und Entwicklungsgesellschaft GmbH) [229,230]. This project seeks to build on earlier studies and pilot projects showing high technical and economic potential for using oil palm trunks to create value-added

products. For example, oil palm timber has a uniform quality due to the lack of knots and growth-related defects, while its unique wood grain structure enhances the aesthetic value of the eventual end product. On the negative side, the trunks have a high moisture and starch/sugar content that facilitates fungal decay and therefore requires an efficient supply chain from the logging of the palms to processing, including a complex drying process. In other applications, the manufacture of high-performance palm wood panels has been investigated in Malaysia by the IOI Group [231,232].

In terms of quantity, the major uses for oil palm biomass are for energy generation or the manufacture of structural materials, but there is also a great deal of research into much smaller-scale applications that could have considerable value. In one high-profile example, phenolic compounds extracted from POME have been tested for efficacy as anti-cancer agents in animal models and human clinical trials [233–235]. In another case, leaf waste has been used to produce antibacterial solid soap bars [236], while additional biomass components, such as coenzyme Q10, phenols, sterols, polysterols, terpenes, and glycolipids, are being investigated for use in edible formulations, including as antioxidants or nutritional enhancers [237].

10. Oil Palm Carbon Sequestration in Comparison with Other Major Oil Crops

In terms of its land use of 24–30 Mha, oil palm only occupies a tiny proportion (about 3 to 3.5%) of total cropland in the tropics but, thanks to its impressive capacity to sequester carbon, it also produces about 40% of the world's supply of vegetable oil. Similar vegetable oils are produced by the three major annual crops, soybean, rapeseed and sunflower, that together occupy a far greater land area of 203 Mha (seven- to eightfold more than oil palm) to produce about 52% of the world's supply of vegetable oil. On a global basis, oil crops currently occupy 37% of agricultural land [238] and, after cereals, they are the second most important source of calories for human nutrition [80]. The carbon sequestration capacity of oil palm crops to produce vegetable oil is at least five-times more efficient in terms of land use than that of the three major annual crops. A comparison between the carbon sequestration capacity of oil palm and the major starch-producing cereal crops yields similar results. Hence, rice, maize, wheat and sorghum collectively occupy over 850 Mha [98,184] but sequester an average of well under one tonne of carbon/ha/yr in their harvested starch products whereas oil palm sequesters 3.1 tonnes of carbon/ha/yr in its harvested oil. Part of the reason for the impressive carbon sequestration capacity of oil palm can be seen visually in the contrasting landscapes of this forest crop with the much shorter foliage and reduced biomass in the four annual crops as shown in Figure 6.

In a detailed analysis of 20 oilseed producing countries, calculated emissions for transitions from natural vegetation to cropland on mineral soils under typical management regimes over a 20-year period ranged from -4.5 to 29.4 t CO₂-eq ha⁻¹ yr⁻¹ for oil palm and 1.2 to 47.5 t CO₂-eq ha⁻¹ yr⁻¹ for soybeans [172]. In a comparison of the four vegetable oil crops shown in Figure 6, it was concluded that optimal results in terms of carbon storage potential were most likely with high-productivity crops or, less frequently, by growing moderate-productivity crops on land that was previously of low native productivity [113]. The only cited example of the latter case was the cultivation of rapeseed on land that was previously temperate steppe, where the crop stored 11.75 tonnes of carbon/ha more than the native vegetation, albeit with the proviso that no-till and manure enhanced production was used for the crop.



Figure 6. Contrasting landscapes of a perennial oil palm plantation (A) *versus* four annual crops, soybean (B), rapeseed (C), sunflower (D) and wheat (E). The oil palm plantation typically sequesters 3.1 tonnes of carbon/ha/yr in its harvested oil product whereas the other four crops sequester less than 1 tonne of carbon/ha/yr in their harvested oil or starch products. In reality, most oilseed crops are grown on land that was cleared of native forest, grassland or other crops many decades or even centuries ago and it is logical that agreed cutoff dates for more recently grown crops such as oil palm should also be established. Several oil palm regulatory schemes such as MSPO and RSPO have established cutoff dates for deforestation such that oil palm grown after this date should not be susceptible to LUC.

Another issue is that the energy requirements for growing oilseed crops, most of which comes from fossil fuels, has been underestimated. For example, data from a recent meta-analysis suggest that the energy consumption of open-field agriculture in the EU, most of which comes from non-renewable sources, has been considerably underreported [31]. In particular, significant energy inputs such as fertiliser and pesticide production are not assigned to agriculture and might not appear on an LCA audit. The authors conclude that *“there is need for the development and application of detailed and standardized methodologies for energy use analysis of agricultural systems”* [31]. Despite their inherent limitations, several comparative (but incomplete) LCA studies of major oil crops have been published. Hence, a 2015 study found that the LCA performance of oil palm was comparable to, and sometimes superior to, temperate oil crops [239]. Other examples include studies on the comparative water-use efficiencies of major crops, which showed that palm oil had considerably higher efficiencies than other crop oils and was even more effective compared to animal-based fats [240–243].

The environmental performance parameters of five major vegetable oil production systems were also compared [244]. For GHGs, the three major temperate oilseed crops had lower levels than oil palm, whereas for land use efficiency, the situation was reversed, with the oilseed crops performing much worse. In contrast, sunflower and rapeseed scored better than oil palm and soybean in terms of water use efficiency. In another study, oil palm performed better for GHG emissions, where methane capture at mills was employed [245]. However, when LUC is incorporated into the LCA calculations, GHG emissions from oil palm crops are substantially increased, especially when grown on peat-rich soil, although some progress has been made in addressing the peat issue in recent years [246]. As noted above, the scope and methodologies used in many LCA studies tend to lack consistency, even within a region such as Europe [31]. This makes it difficult to use LCA data to compare different cropping systems worldwide and to come to reliable conclusions about their respective merits and demerits. This is important as such conclusions can affect major policy decisions, such as how to regulate trade in a particular crop like oil palm.

11. Conclusions and Outlook

Over the past century, the global carbon cycle has become distorted as carbon sequestration is no longer keeping up with increased anthropogenic CO₂ emissions. The resulting 50% increase in atmospheric CO₂ levels is perturbing global climate systems, threatening future food production and social stability. In order to promote CO₂ sequestration, it is important to focus on systems such as natural forests, coastal wetlands, and tropical croplands that have high rates of net CO₂ uptake. Measures to promote sequestration and reduce emissions include limitations on deforestation and the use of carbon-rich peatland, as well as auditing the carbon impact of major cropping systems in order to focus on those crops that deliver both high yields and carbon efficiency.

A case study of the tropical tree crop, the African oil palm, *Elaeis guineensis*, demonstrated that it had favourable carbon sequestration potential that, under some circumstances, was comparable with tropical forests and superior to other oil crops, especially if used in an agroforestry context via intercropping [247]. The crop also has relatively untapped biomass sequestration potential in the form of its currently underutilised by-products, such as fronds and trunks. An important negative factor in carbon audits that especially impacts oil palm is the high LUC penalties that have historically resulted from the conversion of high-carbon-stock land, such as tropical forests and peatland.

Over the past decade, however, the conversion of land to oil palm has significantly decreased for both economic and sustainability-related reasons. However, population pressures are likely to drive some expansion of the current global oil palm area. It is now increasingly recognised that any further oil palm expansion must occur in the context of net-zero carbon targets, and one way of achieving this is to only use existing agricultural land with low-carbon stocks, such as degraded pasture or poorly productive annual cropland [248]. Another strategy that has already proved successful in increasing carbon

sequestration without using additional cropland is the development of higher yielding crop genotypes [249]. In the case of oil palm, where fruit yields have been increased by as much as threefold, this could more than double the crop's sequestration capacity as the new varieties are planted over the next decade [80].

The formidable scale that confronts efforts to significantly increase carbon sequestration is demonstrated by the following recent statistics: Data from 2022 showed that terrestrial plants globally sequestered 3800 Mt CO₂ eq, but this was greatly exceeded by total emissions of 11,100 Mt CO₂ eq (10,000 Mt from fossil sources and 1200 Mt from LUC) [10]. These anthropogenic emissions are a major factor in ongoing climatic changes likely to undermine the Holocene climatic stability that underpins food production. In order to mitigate this situation, it will be necessary to restore the global carbon cycle by a combined strategy of drastically reducing emissions and increasing carbon sequestration. As part of this strategy, the IPCC has set an ambitious carbon sequestration target of 10,000 Mt/yr alongside measures to reduce emissions via decarbonisation. Among the most effective carbon sequestration agents are tropical forests and tree crops; hence, deforestation should be avoided and high-yield tropical food crops encouraged.

Funding: This research received no external funding.

Acknowledgments: The author acknowledges the valuable discussions and feedback with numerous colleagues during the genesis of this work.

Conflicts of Interest: The author has no conflicts of interest regarding this work.

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