© naturepl.com / Christophe Courteau / WWF; yusnizam / iStock

Measuring and Mitigating GHGs: **Palm Oil**

Authors: Seeta Salgia Patel, Aviva Intveld, Evan Seeyave, Emily Moberg, Virginia Barreiro

There are millions of farms globally, each using a unique set of practices to cultivate their products in the local climate and soil. Thus, for any commodity, there are many thousands of different production systems and many thousands of different sources of greenhouse gases (GHGs). The relative GHG emissions of producing the same product may differ drastically depending on how and where it is grown. To fully understand how to mitigate emissions and on which farms to focus mitigation efforts, we need a better grasp of the variations and gaps in data.

The authors do not think all the information to quantify the full range of GHG emissions from the palm oil value chain exists – at the very least, not in one place. This document is our attempt to collate currently available information. This is a working draft; debate, discussion, and comments are welcomed to advance the understanding of this topic. WWF will be producing similar pieces on other key food commodities to stimulate similar discussions. All comments should be justified with evidence and data and sent to Emily Moberg at GHGCommodities@wwfus.org.

This version was last updated September 19, 2022.

ABOUT PALM OIL

Oil palms originated in West Africa but were exported for cultivation in other equatorial countries. Over the past 50 years, this productive plant has helped meet the exponentially growing demand for vegetable oils. Most palm oil is used as a cooking oil, with a large proportion used for consumer products like soaps and cosmetics; a small global percentage (but a large portion of Europe's imports) is destined to be used as biofuels.

From 2012 to 2015 an average of 25 million hectares (ha) were harvested,[1] producing 376 million tonnes (t) of fresh-fruit bunches (FFB), or 72 million t crude palm oil (CPO). In the last five years, the global area of palm oil cultivation has increased by about 23% as part of a decades-long increase in overall production. The yield per hectare varies across regions, with Asia/Oceania being the most productive and Africa being the least.

Oil palms are trees that are optimally productive for about 25 years, after which they are typically replanted.

The emissions from palm oil come primarily from the change in land use and can, therefore, be incredibly spatially heterogeneous.

PALM OIL SUPPLY CHAINS

Palm oil is produced from FFB from oil palm trees, which are then milled and separated into mesocarp and kernel. Mesocarp is pressed and yields CPO; kernels are crushed and pressed, yielding crude palm kernel oil (CPKO) and palm kernel cake, among other products; empty fruit bunches and palm oil mill effluent (POME) are produced as by-products or waste. CPO and palm kernel oil (PKO) are then refined. A tonne of FFB produces roughly 0.2 t of CPO (although this could range from 0.16 to 0.26), 0.04 t of palm kernel cake, and 0.02 t of PKO. By both economic and mass allocation, CPO receives about 80% of the emissions associated with production through milling. The amount of POME produced is variable.

Palm oil supply chains often have some vertical integration across farming and mills, although mills usually source a portion of FFB from independent growers. Some smallholders work in partnership with larger companies and mills; the emissions from these growers are accounted for within the "scope 3" for the larger company or mill. Refineries and downstream packaging are typically owned and controlled by large corporations. Note that in many cases, the initial land-use change (LUC) (logging, etc.) is not directly associated with palm oil; rather, timber harvest occurs (and that capital may fund the plantation), and a plantation is later established. The emissions from that land clearing do, however, still count toward that palm oil's GHG footprint.

Table 1: Palm oil production characteristics

Yields of FFB and CPO for select countries, averaged the five most recent years.

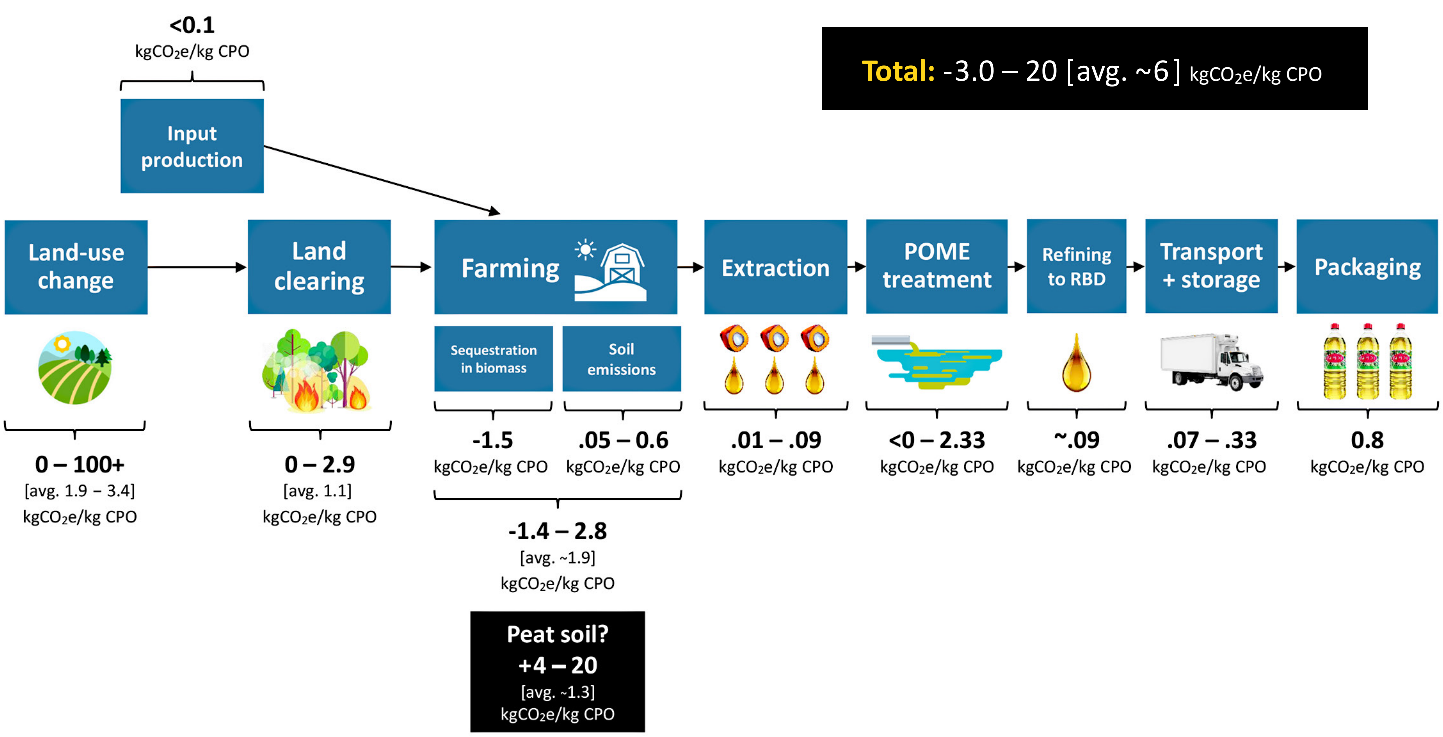
	FFB t/ha[2]	CPO t/ha[3]
Cameroon	14.2	2.34
Colombia	17.6	3.37
Indonesia	16.9	3.58
Malaysia	19.1	3.74
Nigeria	2.6	0.45
Papua New Guinea (PNG)	13.6	3.8

GHG EMISSIONS FROM PALM OIL SUPPLY CHAINS

Estimates of GHG emissions from palm oil range from about -0.3 to more than 20 kgCO_2e/kg CPO. Average emissions are likely about **6 kgCO_2e/kg CPO**, driven largely by significant LUC, peat soil emissions, and POME degradation, which are GHG-intensive.

Figure 1 shows the ranges and typical values for emissions in each stage of production: LUC, input production, land clearing, farming, oil palm extraction, POME treatment, transport and storage, refining to refined, bleached, and deodorized (RBD) oil and packaging. Note that later processing (e.g., refineries) is not included because of lack of data.

Figure 1: Range of GHG emissions from palm oil supply chains



The difference between the most and least intensive palm oil operations across geographies and production systems is driven by LUC and whether the palms are on mineral or peat soil, so emissions can be very different even within the same plantation.

The full range of impacts (in kgCO_2e/kg CPO) is shown here, with the typical range highlighted in darker orange.

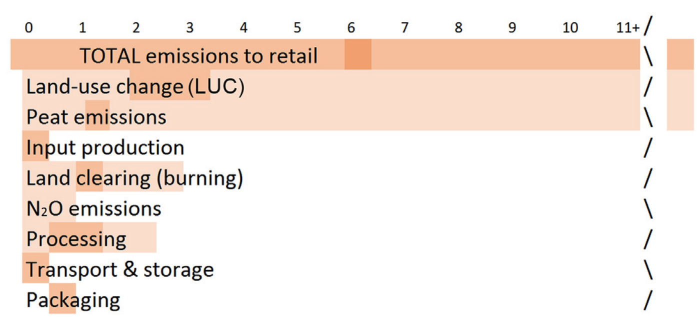
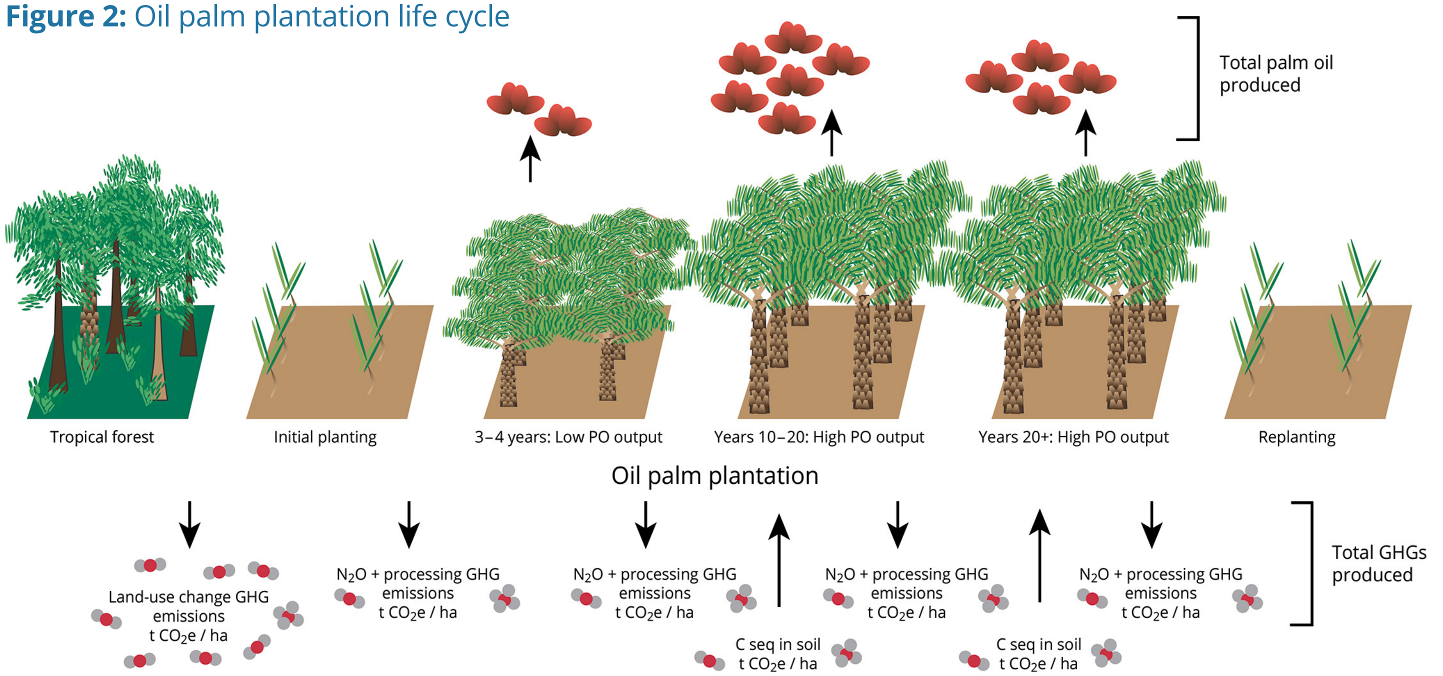


Figure 2: Oil palm plantation life cycle



LUC

The area of land cultivated for palm oil has increased, and much of that land was previously forest. The estimates of the GHG impacts from that LUC are much less settled.

LUC occurs when one land-use type is converted to another; when the original land-use type is cleared, the carbon that was stored in aboveground and belowground biomass is assumed to be (almost entirely) released into the atmosphere as CO_2. The carbon stored in the soil often also decreases through microbial decomposition. Because this carbon is typically lost within a decade of clearing (often much faster), we assign these emissions to the clearing event.

New biomass that grows will sequester carbon in these same categories but at a total amount much lower than a native forest, for example.

When we consider the total impacts of this LUC, we take the amount removed from the system by clearing, subtract the amount returned to the system by the oil palms, and then divide by the number of years (typically 25) of operation. If we want to measure the intensity, we instead divide by the total amount of palm oil produced during that 25-year period; higher yields reduce the intensity.

It should be noted that when reporting LUC, the value is sometimes reported as the net difference between the original land use and oil palm (e.g., peat swamp [207 tC/ha] minus oil palm [50 tC/ha] = net loss of 157 tC/ha), or sometimes just as the initial loss. Reported values also may include all or some subset of aboveground biomass, belowground biomass, necromass, and soil carbon. Table 2 provides some reasonable numbers for the carbon stored in these systems.

Table 2: LUC carbon fluxes

Land Use Change			
When land is cleared for palm oil, the carbon stored in plants both aboveground and belowground and in the soil is emitted into the atmosphere. The aboveground and belowground biomasses are expected to release their carbon relatively quickly; soil carbon may take longer to decay. Oil palm plantations will also grow new biomass and may sequester some carbon in the soil. The amounts of carbon for several land-covers are compared to oil palm below.			
Land-cover	**Aboveground C**	**Belowground C**	**Soil C**
Peat swamp[4]	182 (26)	25 (12)	?
Lowland forest[5]	147 (76)	24 (13)	120 (6)
Rainforest[6]	168 (6)	37	77 (6)*
Grassland[7]	6 (4)	8 (5)	?
Oil palm[8]	24 (8)	8 (2)	65 (7)*
Oil palm[9]	20–60		--
Palm GHG	50		--

Carbon in tC/ha, with standard deviation in (). *Indicates to 50 cm.

Between 2001 and 2015, 10.5 million hectares of land (about the area of Guatemala) were converted for palm oil; 6.1 million hectares were converted directly to oil palm farms and plantations, while the remaining had an intermediate land use.[10] Forests, especially those in the tropics, have a large amount of aboveground and belowground carbon stored. When these lands are cleared, the carbon stored in the soil is often decomposed, while the carbon stored in biomass is also released to the atmosphere (by decomposition or burning).

We have harmonized here several estimates of total deforestation or LUC attributable to palm oil or global estimates of palm oil GHGs to show how the magnitude of emissions from LUC varies widely:

- **World Resources Institute deforestation estimate:** 0.17 $GtCO_2e/yr$, or 2.3 $kgCO_2e/kg$ CPO (6.9 Mha non-primary forest and 3.6 Mha primary forest converted over 15 years; assuming difference in carbon content to oil palm of 30 tC/ha and 175 tC/ha, respectively)[11]
- **geoFootprint estimate:** 0.24 $GtCO_2e/yr$, or 3.4 $kgCO_2e/kg$ CPO (approximately 0.9 tCO_2e/t FFB, assuming 20% of FFB goes to CPO with 80% allocation)
- **Poore and Nemecek estimate:** 0.12 Gt/yr, or 1.7 $kgCO_2e/kg$ CPO (1.7 $kgCO_2e/kg$ CPO direct estimate from paper; assumes 36 tC/ha sequestered in palm oil plantations); estimate of LUC loss (not net) is 0.15 $GtCO_2e$, or 2.1 $kgCO_2e/kg$ CPO.
- **Roundtable on Sustainable Palm Oil (RSPO) estimate:** 0.042–0.067 $GtCO_2e/yr$, or 1.4–1.6 $kgCO_2e/kg$ CPO (2001–2010 GHG estimates; production numbers from the U.S. Department of Agriculture [USDA] for same time ranges)[12]

Given that LUC is still occurring, these values are likely to remain somewhat consistent for many years (amortization typically occurs over 20 years for GHG accounting or over the life span of the crop, which is approximately 25 years).


© joakimbkk / iStock

Looking forward, South America and Africa contain the largest amounts of forests vulnerable to conversion to oil palm, although there has been a trend of planting on degraded and pasture lands in South America.[13]

Huge amounts of land were cleared for oil palm plantations, much of it within the past 20 years, making the deforestation footprint very large across large areas of current palm oil plantations. The footprint for LUC can range from 0 to over 100 $kgCO_2e/kg$ CPO but averages between 2 and 4 $kgCO_2e/kg$.

© richcarey / iStock

Peat Soil Emissions

Peat forests have a large amount of biomass both aboveground and below ground but also a huge store of organic matter in the soils. Globally, peat soils store a total of over 550 Gt of carbon. When peat soils are drained, they directly emit CO_2, N_2O, and methane for at least 100 years. Globally, damaged peatlands emit about 1.9 $GtCO_2e/yr$.[14] GHG emissions from tropical peatlands converted for agriculture (of which oil palm plays a large role) are estimated at 0.4 $GtCO_2e/yr$.[15] Indonesia and Malaysia both have extensive oil palm planting on peat.

Recent work suggests that this conversion (conversion plus yearly emissions) is 90 $tCO_2e/ha/yr$ (range of 69.9–117.5).[16] Assuming average productivity, this translates to 36 $kgCO_2e/kg$ CPO for palm oil produced on peat. You typically will not see numbers this high for CPO because plantations are not typically all peatland, so this value is averaged out with CPO produced on mineral soils.

The RSPO palm calculator estimates these emissions at 55–91 tCO_2e/ha (roughly 11–18.2 $kgCO_2e/kg$ CPO) added in addition to the initial conversion, depending on the water drainage depth.[17] This is roughly in line with estimates from Carlson,[18] which suggest losses of 5.4 and 0.21 x WTD (in tC/ha/yr), where WTD is the water table depth in centimeters. Palm oil plantations often have ~50–70 centimeters drainage depth (58–73 $tCO_2e/ha/yr$).

Palm oil originating on peat soils may produce about 36 $kgCO_2e/kg$ CPO of additional emissions. Because peat soils are typically not an entire plantation, these emissions are typically averaged across an area, bringing the footprint lower. Global average emissions from peat are about 1.3 $kgCO_2e/kg$ CPO.

© Rhett Ayers Butler - Mongabay / iStock

Burning

Burning is often used to clear land, especially by smallholders who do not have access to mechanical clearing equipment. Emissions from burning range from 0 (when burning is not used) to 2.9 $kgCO_2e/kg$ CPO.[19] Burning activities may also spark larger wildfires, and when wildfires take place, drained peat from palm oil planting may accelerate the fires. How many of these wildfires are caused by palm oil plantations is unclear, but given the high burn rate of palm concessions in recent fires in Indonesia, palm oil fires may have contributed. The emissions from these wildfires can be a significant part of the global GHG emissions for a year.[20]

Emissions from burning oil palm trees to replant average 1.1 $kgCO_2e/kg$ CPO. This practice is more prevalent among smallholders.

© AFP / Getty

Nitrous Oxide (N_2O) and Methane Emissions

N_2O emissions originate from soils that have nitrogen (N) fertilizers added to them. These emissions are in proportion to the amount of N added. Because adding fertilizer can also boost yields, the amount of N_2O per unit of product depends on how much yield is boosted.

The Intergovernmental Panel on Climate Change recommends a default emissions factor of 12.8 $kgCO_2e/kg$ N, but the range for this emissions factor is large (low end 4.3; high 43). Without fertilizer, Indonesian yields per hectare are about 10 t FFB (~2 t CPO; this is like the yield in Cameroon [~2.4 tCPO/ha], which has low fertilizer use); every 10 kilograms of fertilizer add about 0.5 t CPO.[21] At current fertilization levels, many plantations could increase yields while improving emissions intensity.

Direct and indirect N emissions from fertilizer add between 0.05 and 0.6 $kgCO_2e/kg$ CPO. However, for many plantations, the increased yields from fertilization outweigh (on a per kilogram CPO basis) the increase in emissions from fertilizer application.

© James Morgan / WWF-International

POME Degradation

POME is an organic pollutant resulting from oil palm processing. When POME is left to degrade with no treatment, the emissions range between about 1 and 2 $kgCO_2e/kg$ CPO.[22] A better practice is to either use POME as fertilizer, flare the methane released, or generate electricity from the methane. Flaring methane reduces emissions to about 0.5 $kgCO_2e/kg$ CPO, while usage for electricity can in some cases generate excess (negative emissions) or reduce emissions to around 0.1 $kgCO_2e/kg$ CPO.[23]

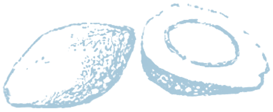
POME degradation causes 1–2 $kgCO_2e$/kg CPO emissions when untreated. Treatment can bring this number far lower, even negative, when methane is used for electricity generation.

© Tan Kian Yong / Dreamstime

Other Processes

There are various other on-farm and downstream processes that result in GHG emissions. Briefly, fertilizer production tends to be 0.07–0.1 $kgCO_2e$/kg CPO, and transport (to processing) less than 0.031 $kgCO_2e$/kg CPO. Diesel use on-farm is also typically very small.

Downstream refining, transport and storage (to retail), packaging, and retail emissions are not typically modeled. Poore and Nemecek estimate these values at 0.1–0.31 $kgCO_2e$/kg CPO for transport and storage, 0.81 $kgCO_2e$/kg CPO for packaging, and 0.041 $kgCO_2e$/kg CPO for retail.



OUTLIER EMISSIONS SOURCES

The variability in emissions per kilogram of palm oil highlights the large mitigation potential that exists across current practices. Here we highlight the "low hanging fruit," or practices that drive unusually high emissions intensity. These practices may be good targets for initial screening for improvement.

- **Prevent deforestation and development on peat:** The footprint from deforestation is large, and deforestation of rainforests continues for palm oil plantations. Peat forests are particularly carbon-dense and continue to emit additional GHGs long after conversion.
- **Manage water on or restore drained peat:** Drained peatlands continue to emit large quantities of GHGs. Water table management can reduce them.
- **Prevent burning:** Burning old trees for new planting contributes significantly to the GHG footprint but also risks fire spreading.
- **Treat POME at mills:** POME degradation releases significant amounts of methane. This methane can be used beneficially and has the benefit of being more concentrated (relative to oil palm plantations).

© ibnjaafar / iStock

PRODUCTION SYSTEMS

The largest differences in palm oil production from an operational standpoint are large commercial versus smallholder farms. The differences in practices across these groups can be stark; smallholders are more likely to use burning, lack water table management for peat, and have lower yields.

Beyond that, the previous land use and type of soil on which palm oil is grown largely determine GHG emissions.

Table 3: Production characteristics for key countries

	Production (1000 t CPO/yr)[25]	Export (%)[26]	Smallholder (land %)	Expansion (new OP 1000 ha/yr)[27]	Peatland (Mha/yr)	GHG intensity ($kgCO_2e/kg$ CPO)
Indonesia	40,600	68	40[28]	931	2.3[29]	7–10
Malaysia	19,519	87	33[30]	53	1.1[31]	3–7.5
Nigeria	1,129	2	61[32]	73	?	~6
Colombia	1,498	42	13[33]	34	0	~5
Cameroon	403	0	71[34]	5	0	3–6
PNG	630	100	40[35]	8	0[36]	?

REGIONS

Palm oil is produced in three main regions: Southeast Asia, West Africa, and Central America, although Southeast Asia dominates production. Yields (averaged from 2016–2021) are highest in Southeast Asia (3.6, 3.7, and 3.8 t CPO/ha for Indonesia, Malaysia, and PNG, respectively), followed by Latin America (Colombia ~3.3 t/ha). Yields in West Africa are lower (2.4 and 0.5 t/ha in Cameroon and Nigeria, respectively). The year-on-year variability is also much lower in Southeast Asia.[24] These differences are driven by a combination of local climate and input use.

Information on total production, percentage of palm oil exported, range of GHG intensity, percentage of oil palm land cultivated by smallholders (using the local definition of smallholders), rate of palm oil land expansion, and how much oil palm is currently on peat are listed in Table 3 (above).

These regions also have different histories of LUC for palm oil. The previous land-cover (e.g., intact forest, cropland) is critical for determining the GHG emissions from conversion; however, this data is not readily available in many areas. We have listed the rate of increase of palm oil cropland, some of which was caused by the conversion of natural habitats directly. Others may have been initially cleared for another purpose, but conversion still occurred within the last 20 years. Most data sources use a combination of satellite and cropland areas to infer deforestation and conversion rates.

Overall ranges were taken from Poore and Nemecek and checked against geoFootprint to ensure a representative number for farm-gate emissions was included.

© Tan Kian Yong / Dreamstime

MITIGATION

The steps for reducing GHG impacts from oil palm are well known and have a large mitigation potential; however, decades of experience working to avoid LUC have shown how difficult attaining these goals can be. Innovation in mitigation, particularly concerning POME management, is, however, ongoing.

Recognizing that the increasing demand for vegetable oils is an important agricultural priority and that shifts to other, lower-yielding vegetable oils could lead to even more deforestation and conversion, the following may be important for enabling the growth of palm oil production without deforestation and conversion.

Prevent further deforestation: Preventing further deforestation is the highest-impact action that can be taken for palm oil.

- **Prevent further development on peatlands:** When peatland is developed for agriculture, both the biomass there is lost and the organic matter

from the soils emits high levels of GHGs over time. Avoiding more peat conversion is critical.

- **Expand production onto degraded lands:** Restricting expansion of oil palm lands to degraded lands can minimize forest loss.

- **Increase yields for smallholders:** Smallholders typically have lower yields than larger plantations; increasing productivity can help livelihoods and increase supply. Supporting replanting for low yielding or poor-quality farms will also help improve yields and expand production for smallholders.

Managing peatland water levels: Peat emissions can be dramatically reduced by raising the water table in peatlands. Every 10 centimeters of water table increase can reduce emissions by 3 tC/ha/yr to a total mitigation potential of 15 tCO_2e/ha/yr (or about 4.8 $kgCO_2e$/kg CPO using our usual assumptions).[37] This is a conservative estimate, as it does not consider N_2O emissions or the effect of fewer peat fires.

Peatland solutions are critical; the mitigation potential for protecting and restoring global peatlands is similar to the entire sequestration potential for all agricultural soils.[38]

Retiring peatlands from production and rewetting: Restoration of peatlands provides both climate and biodiversity benefits. However, restoration typically involves both hydrological restoration and revegetation, which are expensive.[39]

Improving POME management: While the overall magnitude of GHG mitigation potential for POME management is lower than for the land-focused interventions, there are a variety of improvements in POME management that can significantly decrease emissions. These interventions are attractive also because they are more directly under the operational control of palm oil companies. Note that for the following interventions, many specific technologies exist, some of which can work in tandem.

The implementation of POME treatment involves high upfront costs for infrastructure (from 100k to more than 3 million USD; the exact magnitude depends on the scale).[40]

- **Compost:** Empty fruit bunches (EFB) are often used to replace fertilizers, which has a small GHG benefit. There are many methods to compost POME with EFB, which can reduce emissions by about 0.5 – 0.9 $kgCO_2e$/kg CPO.[41]

- **Biogas:** Methane capture and flaring prevent over 80% of emissions, while electricity generation avoids about 90%. Capital costs typically exceed 3 million USD.[42]

- **Novel treatments**: Other methods for treating POME are being developed. For example, a belt filter press to separate the organic matter reduces methane emissions by about 11%, which is much lower than biogas but may be more attractive when mills cannot sell energy back to the electrical grid.[43]

Despite the high emissions associated with palm oil, most of those emissions come from LUC. Oil palms are much more productive than other oil crops. If the global demand for the vegetable oils were met with a different oil, a much larger area of land than is currently used for oil palm would need to be cleared.

The mitigation potential table shows these interventions and rough estimates of mitigation potential, barriers, and costs. Note that costs are difficult to estimate because of differences in locations, scale, and life span of projects. Some data are thus missing.

Table 4: Mitigation potential summary

Mitigation Potential Table				
Intervention	**Target**	**Cost**	**Mitigation Potential**	**Barriers**
Prevent deforestation	Concession owners, governments	\$10–\$100/tCO_2e/yr	0.1 – 0.2 GtCO_2e/yr (based on current deforestation rates for OP)[44]	
Expand production on degraded lands	Buyers, governments			
Increase smallholder yields			0.14 GtCO_2e/yr[45] (All tropical plantation improvements)	
Peatland restoration	Governments, nongovernmental organizations	\$1.6k–\$2.8k/ha	0.5 GtCO_2e/yr (all tropical peatlands)[46]	High costs, technical expertise
Manage water levels in farmed peat	Farms		0.25 GtCO_2e/yr (All tropical croplands rewet to half) 0.4GtCO_2e/yr (All tropical croplands rewet to 10 cm)[47]	Costs, technical expertise
POME compost	Mills/farms		<0.04 GtCO_2e/yr (Upper limit assumes worst practices for all EFB/POME)	Capital expenditure, <4 years for capital payback[48]
POME biogas methane	Mills		<0.08 GtCO_2e/yr (Upper limit assumes worst practices for all POME)	Political support for fossil fuels/lack of market, >4 years for capital payback[49]
POME belt filter press	Mills far from electrical grid	30x less than biogas capture	<0.008 GtCO_2e/yr (Upper limit assumes worst practices for all POME)	Capital expenditure


© guenterguni / iStock


© slpu9945 / iStock


© jmsilva / iStock


© SuriyaDesatit / iStock

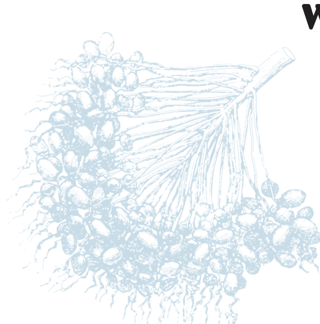
TOOLS AND DATA AVAILABILITY

The GHG footprint of palm oil is fairly well characterized in the literature. However, differences in emissions across smallholder versus commercial production and on peat soils are typically treated in aggregate. However, there are not many farm-focused tools focused on GHG emissions for oil palm; some tools have a generic "tree crop" category.

- **Palm GHG calculator:** The RSPO has a GHG calculator for palm oil production and milling. This is widely used in the industry.
- **Cool Farm Tool:** An online tool produced by the Cool Farm Alliance that allows farmers to specify fertilizer use and cultivation practices to calculate a GHG footprint. While oil palm is not a specific crop, tree crops, in general, can be modeled using this tool. The footprints are not regionally tailored, but the tool works globally.

Emily Moberg, Research Lead Specialist,
Markets Institute, World Wildlife Fund
Emily.Moberg@wwfus.org

WWF MARKETS INSTITUTE
Change at the speed of life



GORDON AND BETTY MOORE FOUNDATION

CITATIONS / FOOTNOTES

1 Food and Agriculture Organization (FAO), “FAOSTAT”; Foreign Agricultural Service Official USDA Estimates, “USDA Production, Supply and Distribution.”

2 FAO, “FAOSTAT,” 2020, http://www.fao.org/faostat/en/#data.

3 Foreign Agricultural Service Official USDA Estimates, “USDA Production, Supply and Distribution.”

4 Hergoualc’h, K., & Verchot, L. V. (2011). Stocks and fluxes of carbon associated with land use change in Southeast Asian tropical peatlands: A review. *Global Biogeochemical Cycles*, 25(2).

5 J Germer and J Sauerborn, “Estimation of the Impact of Oil Palm Plantation Establishment on Greenhouse Gas Balance,” *Environment, Development and Sustainability* 10, no. 6 (December 2008): 697–716.

6 Guillaume, T., Kotowska, M. M., Hertel, D., Knohl, A., Krashevska, V., Murtilaksono, K., ... & Kuzyakov, Y. (2018). Carbon costs and benefits of Indonesian rainforest conversion to plantations. *Nature Communications*, 9(1), 1–11.

7 J Germer and J Sauerborn, “Estimation of the Impact of Oil Palm Plantation Establishment on Greenhouse Gas Balance,” *Environment, Development and Sustainability* 10, no. 6 (December 2008): 697–716.

8 Id.

9 Lip Khoon Kho and Martin Rudbeck Jepsen, “Carbon Stock of Oil Palm Plantations and Tropical Forests in Malaysia: a Review,” *Singapore Journal of Tropical Geography* 36, no. 2 (2015): 249–66.

10 Elizabeth Dow Goldman et al., “Estimating the Role of Seven Commodities in Agriculture-Linked Deforestation: Oil Palm, Soy, Cattle, Wood Fiber, Cocoa, Coffee, and Rubber,” 2020.

11 Goldman et al. “Estimating the Role of Seven Commodities in Agriculture-Linked Deforestation: Oil Palm, Soy, Cattle, Wood Fiber, Cocoa, Coffee, and Rubber” (2020) https://doi.org/10.46830/writn.na.00001.

12 Fahmuddin Agus et al., “Historical CO2 Emissions from Land Use and Land Use Change from the Oil Palm Industry in Indonesia, Malaysia and Papua New Guinea,” Roundtable on Sustainable Palm Oil, Kuala Lumpur, 2013.

13 Varsha Vijay et al., “The Impacts of Oil Palm on Recent Deforestation and Biodiversity Loss,” PLOS ONE 11, no. 7 (July 27, 2016): e0159668, https://doi.org/10.1371/journal.pone.0159668.

14 Leifeld, J., Menichetti, L. The underappreciated potential of peatlands in global climate change mitigation strategies. *Nat Commun* 9, 1071 (2018).

15 Evans, C. D., Peacock, M., Baird, A. J. et al. Overriding water table control on managed peatland greenhouse gas emissions. *Nature* 593, 548–552 (2021).

16 Cooper et al., “Greenhouse Gas Emissions Resulting from Conversion of Peat Swamp Forest to Oil Palm Plantation.”

17 Fargione et al., “Land Clearing and the Biofuel Carbon Debt” and the documentation for the RSPO Palm GHG Calculator.

18 Carlson, Goodman, and May-Tobin, “Modeling Relationships between Water Table Depth and Peat Soil Carbon Loss in Southeast Asian Plantations.”

19 Poore and Nemecek, “Reducing Food’s Environmental Impacts through Producers and Consumers.”

20 Tacconi, “Preventing Fires and Haze in Southeast Asia.” Nature Climate Change 6, (2016) 640–643.

21 Meine van Noordwijk, Ni’matul Khasanah, and Sonya Dewi, “Can Intensification Reduce Emission Intensity of Biofuel through Optimized Fertilizer Use? Theory and the Case of Oil Palm in Indonesia,” GCB Bioenergy 9, no. 5 (2017): 940–52.

22 Kanokwan Saswattecha et al., “Assessing the Environmental Impact of Palm Oil Produced in Thailand,” Journal of Cleaner Production 100 (2015): 150–69; Heinz Stichnothe and Frank Schuchardt, “Life Cycle Assessment of Two Palm Oil Production Systems,” Biomass and Bioenergy 35, no. 9 (2011): 3976–84.

CITATIONS / FOOTNOTES (continued)

23 Laurence D C Chase and Ian E Henson, "A Detailed Greenhouse Gas Budget for Palm Oil Production," International Journal of Agricultural Sustainability 8, no. 3 (2010): 199–214, https://search.proquest.com/scholarly-journals/detailed-greenhouse-gas-budget-palm-oil/docview/859122443/se-2?accountid=14522.

24 Foreign Agricultural Service Official USDA Estimates, "USDA Production, Supply and Distribution," 2021, https://apps.fas.usda.gov/psdonline/app/index.html#/app/compositeViz. Note that throughout this document, "t" and "tonnes" refer to metric tons.

25 USDA Production, Supply, and Distribution data for 2016–2021.

26 USDA Production, Supply, and Distribution data for 2016–2021.

27 Data from FAOSTAT. Difference from 2014–2019, divided per year (most recent years available).

28 Emily Chow, "Indonesia Focuses on Palm Oil Smallholders to Raise Output," Reuters, November 2, 2017, https://www.reuters.com/article/palmoil-outlook-smallholders/indonesia-focuses-on-palm-oil-smallholders-to-raise-output-idINL4N1N831N?edition-redirect=in.

29 Hannah V Cooper et al., "Greenhouse Gas Emissions Resulting from Conversion of Peat Swamp Forest to Oil Palm Plantation," Nature Communications 11, no. 1 (2020): 407, https://doi.org/10.1038/s41467-020-14298-w.

30 Hannah V Cooper et al., "Greenhouse Gas Emissions Resulting from Conversion of Peat Swamp Forest to Oil Palm Plantation," Nature Communications 11, no. 1 (2020): 407, https://doi.org/10.1038/s41467-020-14298-w.

31 Cooper et al., "Greenhouse Gas Emissions Resulting from Conversion of Peat Swamp Forest to Oil Palm Plantation."

32 R. H. V. Corley and P. B. Tinker, "The Origin and Development of the Oil Palm Industry," The Oil Palm, Wiley Online Books, November 25, 2015, https://doi.org/https://doi.org/10.1002/9781118953297.ch1.

33 Potter, L. Colombia's oil palm development in times of war and "peace": Myths, enablers and the disparate realities of land control. *Journal of Rural Studies* 78, 491–502 (2020).

34 Corley & Tinker.

35 Id.

36 Gunarso Petrus et al., "Oil Palm and Land Use Change in Indonesia, Malaysia and Papua New Guinea," Reports from the Technical Panels of the 2nd Greenhouse Gas. Working Group of the Roundtable on Sustainable Palm Oil (RSPO), 2013.

37 Evans, C. D., Peacock, M., Baird, A. J. et al. Overriding water table control on managed peatland greenhouse gas emissions. *Nature* 593, 548–552 (2021).

38 Leifeld, J., Menichetti, L. The underappreciated potential of peatlands in global climate change mitigation strategies. *Nat Commun* 9, 1071 (2018).

39 Amanda Hansson, Paul Dargusch; An Estimate of the Financial Cost of Peatland Restoration in Indonesia. *Case Studies in the Environment* December 31, 2018; 2 (1): 1–8.

40 Yeoh, B. G. (2005). A technical and economic analysis of heat and power generation from biomethanation of palm oil mill effluent. *International Energy Journal*, 6. and Muhammad Ansori Nasution, Dhani S. Wibawa, Tofael Ahamed, Ryozo Noguchi, Comparative environmental impact evaluation of palm oil mill effluent treatment using a life cycle assessment approach: A case study based on composting and a combination for biogas technologies in North Sumatera of Indonesia, Journal of Cleaner Production, Volume 184, 2018, pages 1028–1040.

41 Walker, SM, A McMurray, F Rinaldy, K Brown, and D Karsiwulan. 2018. Compilation of Best Management Practices to Reduce Total Emissions from Palm Oil Production. Winrock International. Report to: Roundtable on Sustainable Palm Oil (RSPO).

42 Id.

CITATIONS / FOOTNOTES (continued)

43 Enström, A., Haatainen, T., Suharto, A., Giebels, M., & Lee, K. Y. (2019). Introducing a new GHG emission calculation approach for alternative methane reduction measures in the wastewater treatment of a palm oil mill. *Environment, Development and Sustainability*, 21(6), 3065–3076.

44 Griscom, B., et al., “Natural climate solutions,” PNAS 114(44), 2017, https://www.pnas.org/content/pnas/114/44/11645.full.pdf.

45 Id.

46 Id.

47 Evans, C. D., Peacock, M., Baird, A. J. et al. Overriding water table control on managed peatland greenhouse gas emissions. *Nature* 593, 548–552 (2021).

48 Muhammad Ansori Nasution, Dhani S. Wibawa, Tofael Ahamed, Ryozo Noguchi, Comparative environmental impact evaluation of palm oil mill effluent treatment using a life cycle assessment approach: A case study based on composting and a combination for biogas technologies in North Sumatera of Indonesia, Journal of Cleaner Production, Volume 184, 2018, pages 1028–1040.

49 Id.