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Oil palm plantations are large sources of nitrous oxide, but where are the data to quantify the impact on global warming?☆

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Oil palm plantations have rapidly expanded over the last 30 years, and now occupy 10% of the world's permanent cropland. The growth of one of the world's most efficient and versatile crop has alleviated poverty and increased food and energy security, but not without side effects. Losses of forest biodiversity hits the news. Although equally important, climate change issues have not reached this limelight. Data on greenhouse gas emissions associated with oil palm production is limited, especially for the potent greenhouse gas nitrous oxide (N_2O). This paper provides an overview of the data availability, and identifies knowledge gaps to steer future research to provide the data required for climate change models and more accurate international and national nitrous oxide emission accounting.

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Introduction

The oil palm (*Elaeis guineensis*) is the most efficient vegetable oil producer globally, and is about five times more productive per area than the second largest oil crop, oil seed rape (*Brassica napus*) [1,2]. Palm oil is the cheapest vegetable oil and used profusely in the food, cosmetic and bioenergy industries [3,4]. With rising global populations and demand for non-fossil fuel energy, oil palm production has risen exponentially, from a total land area of 3.6 million ha in 1961 to 19 million ha in 2018 [5] and has led to the deforestation of 2 million ha between the year 2000 and 2010 [6,7].

Malaysia and Indonesia produce >84% of the global crude palm oil [5]. Production is expanding to African [6] and Latin American countries [8–10]. The cultivation of oil palm has alleviated poverty, both for farming and non-farming households [8,11••,12]. The dark side of this wonder crop is that approximately 50% of oil palm plantations have replaced pristine and secondary forests and peatlands in SE Asia [13]. Recent regulations to minimise deforestation are in place, but difficult to enforce [7]. Environmental and social consequences of palm oil production are critical, often forming trade-offs with economic benefits and are currently not sufficiently addressed by policy makers [10,11••,12,14•].

The focus of this review is the contribution of palm oil production to the long-lived greenhouse gas nitrous oxide (N_2O). The warm climate of the tropics together with high decomposition rates provide ideal conditions for microbial mediated N_2O production [15,16]. It is therefore not surprising that tropical forests are the largest global natural source of soil N_2O emissions [17]. The largest manmade source of N_2O is the agricultural sector, predominately managed soils, which include fertilised plantations. The agricultural sector is responsible for 35–85% of the global anthropogenic N_2O emissions, depending on the regions [18]. Fertilisation with mineral nitrogen compounds and organic rich materials are their main source of N_2O [19]. In temperate climate zones extensive research, spanning 40 plus years, has provided detailed knowledge on the environmental and agronomic impacts on N_2O production and their emission rates from most crops. Contrary, very few studies have investigated the impact of oil palm production on N_2O emissions beyond 6 months periods (Table 1). This paper summarises current knowledge of N_2O emission rates

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Table 1

Peer-reviewed papers studying soil N_2O fluxes using the chamber method over a period > six months.[a] All studies were conducted in Southeast Asia (Indonesia, Malaysia). In oil palm plantations, the fertilised zone represents 10–30% of the plantation area; therefore, sampling should be spatially stratified to cover both, the fertilised and unfertilised areas. Results from studies not using a design spatially stratified according to treatment may overestimate plantation-scale rates, in case of treatment-induced response.

Reference	Soil type	Treatments	Sampling frequency/study length	Post-fertilisation intensive sampling	Spatial stratification in sampling
Aini *et al.* [35]	Mineral	1 smallholder 8-year old plantation fertilised at 33 kg N ha^{-1} y^{-1}	Monthly/13 months	Yes	Yes (2 positions: fertilised area - 0.5 from palm trunk, mid-distance between palms- 4.5 from palm stem)
Sakata *et al.* [61]	Mineral	2 industrial plantations with each 4 treatments (no fert. & no tillage, no fert & tillage, conventional fert., coated fert.)	Bimonthly/15–16 months	No	*No. Sampling restricted to fertilised area. Fluxes not representative of plantation-scale emission rates*
Hassler *et al.* [67]	Mineral	8 smallholder plantations (on 4 loam and 4 clay Acrisols) and 1 industrial plantation fertilised at 48, 88 and 196 kg N ha^{-1} y^{-1}	(Bi)Monthly/12-13 months	Yes	Yes (3 positions: 0.8, 2.5, 5 m from palm stem)
Rahman *et al.* [58]	Mineral	One industrial 13-year old plantation with several water, inorganic & organic fert. treatments	Varying according to experiment/<7 months	Varying according to experiment	*No. Sampling restricted to treated area. Fluxes not representative of plantation-scale emission rates*
Melling *et al.* [39]	Peat	1 industrial 4-year old plantation fertilised at 103 kg N ha^{-1} y^{-1}	Monthly/12 months	No	*No. Sampling restricted to fertilised area. Fluxes not representative of plantation-scale emission rates*
Sakata *et al.* [61]	Peat	1 industrial plantation with 4 treatments (no fert. & no tillage, no fert. & tillage, conventional fert., coated fert.)	Bimonthly/15 months	No	*No. Sampling restricted to fertilised area. Fluxes not representative of plantation-scale emission rates*
Oktarita *et al.* [38]	Peat	1 industrial 3-year old plantation with 3 urea treatments (0, 153, 306 kg N ha^{-1} y^{-1})	Monthly/13 months	Yes	Yes (2 positions: fertilised area - 0.5 from palm stem, mid-distance between palms- 4.5 from palm stem)
Chaddy *et al.* [41]	Peat	1 industrial plantation with 4 ammonium sulphate treatments (0, 31, 62, 124 kg N ha^{-1} y^{-1})	Monthly/48 months	No	*No. Sampling restricted to fertilised area. Fluxes not representative of plantation-scale emission rates.*
Meijide *et al.* [34]	Peat	1 industrial plantation fertilised at 196 kg N ha^{-1} y^{-1}	Bimonthly/15 months	No	Yes (3 positions: 0.8, 2.5, 5 m from palm stem)

[a] Peer-reviewed short-term observations studies (single observation in Ref. [79]; 65-days observation period in Ref. [76] are not presented.

from land clearing, oil palm management and the oil extraction process.

Microbial processes are responsible for N_2O production

Microbial processes in soils and sediments are responsible for around 90% of total global N_2O emissions, with fossil fuel combustion and industrial processes contribution towards the remaining 10% [15]. Nitrous oxide production is a microbial mediated enzyme driven process via nitrification, the aerobic oxidation of ammonia to nitrate; and denitrification, the reduction of nitrate to N_2O and ultimately to inert N_2 (atmospheric nitrogen) under anaerobic conditions [16,20]. In tropical peatlands, other pathways are also important sources of N_2O. DNRA (dissimilatory nitrate reduction) is a preferred process under nitrate limiting conditions, and ANAMOX (anaerobic ammonium oxidation) may contribute to 35% of gross nitrification rates in peats [21]. Similarly in a tropical mineral soil, supporting forests and oil palm plantations, denitrifying bacteria and ammonium oxidising archaea were the main sources of N_2O production [22].

Many groups of bacteria, archaea, also some fungi, have the ability to produce N_2O. Various pathways operate simultaneously in soils and sediments, with many different organisms completing only a few steps of the nitrification, denitrification pathways [16]. The physical and chemical composition of the soil and climate (i.e. precipitation, temperature) largely determines which of the various pathways dominate N_2O production. For example, Espenberg *et al.* [21] reported a shift in microbial community structure, with higher abundance of archaea compared to bacteria in drained peatlands, whereas the opposite, higher bacterial abundance, was the case for natural (undrained) peatlands. Key drivers of N_2O emissions [16,20] are:

(i) a source of carbon (i.e. decomposing leaf litter, decaying soil fauna and manure application, high soil carbon concentration (especially peat), organic fertilisers),

(ii) nitrogen (i.e. nitrogen fertilisers, such as ammonium nitrate, urea and manure, biological nitrogen fixation in legumes or decomposition of soil organic matter),
(iii) low oxygen concentrations (i.e. wet soil, high water table, rainfall, irrigation, fine soil texture (i.e. clay), high microbial respiration rates),
(iv) temperature (enzymatic reactions increase as temperature rises).

Conversion of forests/shrubland to oil palm plantation can change greenhouse gas emission rates

In Indonesia and Malaysia, large areas of forests [23,24] have been cleared to grow oil palm, by burning and mechanical means ('slash and burn'). Burning was banned in the 1990's by both governments, but is still commonplace. Remote sensing has shown that land-use change is associated with burning in many tropical countries, that is, [25] and references within. Clear felling peatlands by burning followed by drainage for crop production is a particular problem, as peat soils store a lot of carbon, in particular the ombrotrophic peats of Indonesia and Malaysia, where most of the oil palms are grown. They have an average carbon content of >30% compared to mineral soils of <10% [26]. Burning does not only remove the vegetation, but can also burn the peat, which exacerbates release of carbon dioxide (CO_2) methane (CH_4), N_2O, and other pollutants (i.e. NO_x), to the atmosphere. The most recent severe, peat fires in Indonesia, in the 2015 El Niño year, emitted more CO_2 to the atmosphere ($\sim$11 Tg day^{-1}) than from fossil fuel combustion from the whole of Europe ($\sim$8 Tg day^{-1}) [27]. However, peat fires also increase in La Niña years [28]. Nitrous oxide is also emitted from fires, but several orders of magnitude smaller (0.001 Tg) than for CO_2. This source of N_2O is not very well quantified [28].

Fire and mechanical felling not only has severe effects on the terrestrial and aquatic biodiversity [14•,29], but also on soil biogeochemical processes. Both processes (slash and burn) temporarily increase the mineralisation of organic matter to ammonium and nitrate. These compounds are converted to N_2O via microbial processes (i.e. nitrification and denitrification [16]) A comparison of logged and unlogged forests on a mineral soil in Malaysia showed that in the first year after logging N_2O emissions increased fivefold [30]. Similar results were observed when converting forest to pasture in Costa Rica [31]; and in Indonesia N_2O emissions from a mineral soil increased threefold after burning [32].

Studies investigating the immediate effect (the period within days of felling to one year) of clear-felling through fire or mechanically are rare. This knowledge gap still needs to be addressed using modern sensors, tracing greenhouse gas concentrations at high temporal frequency; and ideally for several years, to take into consideration interannual meteorological variability [33,34••]. Most studies compare established plantations with natural and degraded forest types [35–37]. For example, N_2O emissions from an N fertilised peatland in Indonesia were 5–10 times larger than from a natural peatland forest [38] and 2–3 times larger than from a Malaysian forest [39] (Table 1).

Once a peatland forest is cleared, the water table needs to be lowered to grow oil palm or other crops. Lowering the water table accelerates peat decomposition and releases large amounts of CO_2 but also N_2O, to the atmosphere over years and decades. Peat decomposition rates depend on the vegetation type. For example, CO_2 emissions from degraded forests were $\sim$50% smaller than from croplands and 30% smaller than from oil palm plantations, whereas N_2O emissions from degraded forests were 50% smaller than from croplands, but 50% larger than from oil palm plantations [37]. A recent review on the impact of landuse change on GHG emissions from tropical peatlands concluded, that N_2O emissions increase exponentially with peat decomposition rates [40]. Nitrous oxide emissions from peat decomposition can be much larger than N_2O emissions triggered by N fertilisation [38] (Table1). Furthermore, the water table level has a stronger influence on N_2O emission rates than N fertiliser input rates, with largest N_2O emissions at high water table [41] (Table 1).

Clear-felling mineral soils also leads to soil organic carbon losses, but loss rates are $\sim$10 times smaller (1 Mg C ha^{-1} y^{-1}) than from peat soils. After converting a secondary forest to plantations on a mineral soil, N_2O emissions were also smaller than from peat soils (<95 g N_2O ha^{-1} y^{-1})[36,42]. These data are highly uncertain and only based on two observations. A much more rigorous study was recently conducted in Indonesia, were CO_2, N_2O and CH_4 fluxes were compared from 1 and 12 year old oil palm plantations grown on mineral soils. The researchers observed that the 1 year old plantation was a significant carbon source (1012 g C m^{-2} y^{-1}), whereas the 12 year old plantation was a carbon sink (−745 C m^{-2} y^{-1}; the negative prefix '- 'means carbon uptake to the ecosystem) [34••]. For N_2O, emissions were two times smaller from the 1 year old (0.11 g N_2O-N m^{-2} y^{-1}) compared to the 12 year old plantation (0.33 g N_2O-N m^{-2} y^{-1}), presumably because of the lower N fertilisation rate applied to the young plantation. The same study included a 12 year old oil palm on peat, which, contrary to the 12 year old plantation on mineral soil, still emitted CO_2 (330 g C m^{-2} y^{-1}) in year 12, and N_2O emissions (0.95 g N_2O-N m^{-2} y^{-1}) were three times larger on peat compared to the 12 year old plantation on the mineral soil. This study demonstrates the large environmental costs incurred by converting peatlands to agricultural production [34••,43•]. The conversion of peatland forests to oil palm plantations produces greenhouse gas emissions so large that the biofuel sustainability label is not valid [34••]. Sustainability either can only be achieved if oil palm plantations replace existing plantations on peatland, or are grown on agricultural and degraded land.

Deforestation and oil palm plantations can cause soil erosion and increase N_2O emissions

Without the protective tree canopy and ground vegetation of a forest, soil erosion increases in oil palm plantations [44]. Erosion rates are particularly high from cleared land (~950 t ha^{-1} y^{-1}) and still at rates of ~90 t ha^{-1} y^{-1} in established oil palm plantations [45]. Sediment loads to rivers flowing through oil palm plantations are 2–8 times larger compared to upstream parts of the river flowing through the forest, carrying with it nitrogen fertilisers, pesticides and herbicides [46]. The consequences are reduced biodiversity [47] and increased dissolved concentrations of N_2O in the rivers [48,49••].

To ameliorate river pollution, riparian buffer strips are mandatory in some countries [14•,50]. Forested buffers can be particularly rich in biodiversity and provide wildlife corridors within in a fragmented landscape [48]. They retain phosphates, nitrates and organic matter in their soil and prevent transfer of these compounds to the river. However, additional nitrogen compounds draining from N fertilised land (oil palm plantations, other fertilised crops and grasslands) into buffer strips can be a potential source for N_2O production [51,52]. These indirect N_2O emissions still needs to be quantified for oil palm plantations.

Oil palm growing requirements, management and yield

The oil palm originates from tropical West Africa, requires a relatively narrow temperature range of 21–32°C, an average rainfall of 150 mm $month^{-1}$, and only withstands dry periods for a few months. Ongoing breeding programmes aim to improve resilience to drought [53]. However, the rather narrow temperature tolerance may lead to an uncertain future for oil palm production in some areas. Climate models have calculated that the increasing climate change predictions for 2050 will reduce the most suitable land for oil palm production by 22% [54]. Converting forests to oil palm and other plantations may accelerate the increase in land surface temperature. Oil palm plantations are much hotter and drier than dense tropical forests [55]. In areas with extensive oil palm production, this 'local' effect can have an impact on the larger region. A land surface temperature increase of 1°C was calculated for the Jambi region, Indonesia [56].

Oil palm is grown at industrial scale (1000–20 000 ha) and by medium and small holders (2–1000 ha) [57]. Seedlings are planted in a triangular design at an approximate density of 120–170 trees/ha. Typically circles of 1.5 m radius around each palm are kept weed free and are fertilised with nitrogen (N), phosphorus (P), potassium (K) and micronutrients (magnesium, boron, copper, zinc) [1,46]. The commonly used N fertilisers urea, ammonium sulphate and ammonium nitrate are applied at rates varying from 48 to 260 kg N ha^{-1} y^{-1}, sometimes at split rates every six months or one annual dose. Nitrogen application rates change with the age of the plantation. Application of N fertilisers trigger the typical elevated response in N_2O emissions commonly observed in agriculturally managed soils in all climate zones [58,59]. For example, a one-year study in Indonesia investigated the impact of urea, and combinations with/without mulch or empty fruit bunches and palm fronds on N_2O emissions, and concluded that organic amendments could reduce N_2O emissions by ~76% [58] (Table 1). However, it is not only the fertiliser type, but also placement of the fertiliser (below or on the soil surface), the soil wetness at the time of fertilisation, soil organic carbon content and soil texture, which can have a large influence on the N_2O emission rate [60,61], (Table 1).

Maximum recorded yield of crude palm oil is 12 t ha^{-1}, but the average yield across Indonesia and Malaysia is only 4 t ha^{-1} [2]. This yield gap could potentially halve by improving management and plant breeding. The average economic lifetime of oil palms span 25–30 years, when the trees are approximately 10 m high. Above this height harvesting heavy fruit bunches is too difficult. The mostly manual harvest is labour intensive, with one person harvesting an area of 8–12 ha [1,62]. Ongoing plant breeding programmes focus on high yielding dwarf oil palm varieties [63].

Fruits are produced from the second and third year onwards, with average yields of fresh fruit bunches in Malaysia of 20–25 tons ha^{-1}, and equivalent to 4 tons ha^{-1} of crude palm oil. They are processed in mills using wet extraction. The resulting palm oil mill effluent (POME) is an organic rich material, traditionally stored in open lagoons, and can be used as a liquid fertiliser [64,65]. These lagoons are large hotspots of CH_4, CO_2 and ammonia emissions to the atmosphere. POME contains reasonably large concentrations of nitrogen and carbon compounds, which suggests, that POME could potentially be a source of N_2O production by microbial denitrification. To date there are no published data. Oil palm producing countries are trying to install biogas capture facilities, to reduce greenhouse gas (GHG) emissions and convert the organic effluent (POME) into valuable electricity, but uptake is currently slow [65,66].

Impact of oil palm management on N_2O emissions and mitigation options

As discussed in the above sections, many environmental and management parameters influence soil N_2O emission rates. For example: (1) Mineral N application (i.e. urea, ammonium sulphate, POME) increase N_2O emissions over short periods, typically for 1–6 weeks [58,67]. However, if the soil is too dry for denitrification to take place there may be delays in the appearance of the N_2O peak [58,68]. (2) The rate of increase in N_2O emissions after fertilisation depends on N application rates and fertiliser type, as demonstrated by Hassler *et al.* [67] comparing N_2O emissions from smallholder and industrial oil palm plantations on mineral soils in Indonesia. Nitrous oxide emissions from smallholder plantations were four times smaller than from industrial plantations, because they applied four times less N fertiliser than the industrial estates [67] (Table 1). The lower fertiliser application rates on smallholder farms are often due to lack of money and distance to fertiliser suppliers [1]. (3) Comparing urea with and without organic fertilisers (a mulch from empty fruit bunches or POME) showed that the combination urea + organic fertiliser reduced N_2O emissions compared to urea alone. This could be a good mitigation strategy for N_2O reductions [58,59]. Other ways to mitigate N_2O emissions from oil palm plantations are:

- Avoid planting on organic soils, as lowering the water table to grow oil palms, will accelerate peat decomposition and releases much more N_2O than from mineral N fertilisers [40,41].
- Adhere to fertiliser recommendations for all macro and micronutrients, as application of too much N creates a surplus of N not required by the crop and instead becomes available for microbial N_2O production; whereas too little N prevents optimised yield and thereby increases the N_2O emission per unit of crop yield [69].
- Match N requirements (and other nutrients) based on leaf analysis prior fertilisation [46] and adopt other available precision farming methods as they become available [69].
- Use slow release N fertilisers, urease and nitrification inhibitors, as these can reduce N_2O emissions [70].
- Develop plant breeding for increased yield, short stem, resilience to drought and high temperatures can improve N uptake efficiency, and thereby reduce soil N_2O emissions.
- Grow cover crops, ideally N fixing plants (legumes, which enables reduced application of mineral N fertilisers). Cover crops also increase the soil organic matter content, reduce erosion, increase biodiversity and pollination [13,71].
- Return empty fruit bunches and palm fronds to the plantation, as they provide a valuable source of C and N, increases the biodiversity of the soil micro-fauna and macro-fauna, and improves soil health [72].

Reporting N_2O emission rates to the IPCC

Research on the impact of oil palm plantation management on N_2O emissions has only started in earnest about 15 years ago [32]. Most studies are either short-term measurements (2–3 weeks) to investigate emissions arising from a fertilisation event; or monthly measurements over 1 year and longer periods [37]. These data have demonstrated the importance of including N_2O emissions in the overall GHG reduction debate. Signatories of the Kyoto protocol are required to prepare emission inventories from all sectors (i.e. energy, industry, agriculture, forestry and other land use, and waste) [19]. Annex I countries are legally bound to prepare emission inventories annually, whereas Non-Annex I countries (developing countries) submit their inventories every four years. The Intergovernmental Panel on Climate Change (IPCC) has provided guidelines to calculate emissions using a three tier system: default values (Tier 1), country specific values (Tier 2), models (Tier 3) [19]. For example, the Tier 1 emission factor (EF) for direct N_2O emissions is 1% of the N fertiliser applied to mineral soils. In wet climates, the default value is 0.6% of organic N inputs and 1.6% of synthetic N inputs. Several studies have demonstrated that the IPCC Tier 1 default EF may not be appropriate for fertilised oil palm plantations, as much larger EFs (i.e. 2.6%) were reported from oil palm plantations on mineral soils in Indonesia [58]. There is urgent need for targeted long-term studies to understand the impact of deforestation and different oil palm management practices on N_2O emissions, in order to develop strategies to reduce N_2O emissions from industrial, medium and smallholder plantations.

Future measurement designs

Based on our research experience we suggest the following strategy to reduce the knowledge gap of N_2O fluxes from oil palm production. It is essential to invest in high temporal frequency of soil N_2O flux measurements (i.e. daily in the first 10–20 days after N fertiliser application) and use large numbers of chambers and plot replications (at least 4) for at least one year [73,74]. To calculate emission factors, it is required to include a control plot without nitrogen application. Such studies also need to include measurements of CH_4 fluxes and soil CO_2 respiration rates and 'activity data' (daily for agricultural management i.e. fertiliser application rate and date, yield, soil physical and chemical properties, daily rainfall and temperature) in order to interpret the N_2O data and inform on mitigation options. Emissions of N_2O from tree stems and the canopy, although smaller than from the soil, should be included [75]. Long-term monitoring of atmospheric N_2O, CH_4, CO_2 concentrations or fluxes from plantations and forests, [34••,76–78] (Table 1), can provide the large scale ($>100\,m^2$) and high frequency (30 min) data to understand inter-annual variability, and changes in management and mitigation [34••] (Table 1). A combination of long-term (ideally high frequency) monitoring with short-term treatment studies, investigating external drivers, are necessary to fully understand greenhouse gas emissions from oil palm plantations.

Conflict of interest statement

Nothing declared.

OECD disclaimer

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Transdisciplinary research on how to optimise landscapes (forests and plantations) for maximum biodiversity or ecosystem function (i.e. GHG) with increasing profits from the oil plam or rubber plantations. The authors conclude that reducing the impact of plantation management on biodiversity and ecosystem function (i.e. GHG emissions) can only be done through well designed policies.

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A multidisciplinary large-scale, long-term ecological experiment has been established to develop viable strategies on how to manage oil palm plantations to benefit the environment and crop yield. This relatively new project includes biodiversity, biogeochemistry (also N_2O fluxes, but not published yet), hydrological measurements through monitoring and manipulation experiments.

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