

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 (N₂O). 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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Current Opinion in Environmental Sustainability 2020, 47:81–88

This review comes from a themed issue on **Climate change, reactive nitrogen, food security and sustainable agriculture**

Edited by **Clemens Scheer**, **David E Pelster** and **Klaus Butterbach-Bahl**

For a complete overview see the [Issue](#) and the [Editorial](#)

Available online 24th September 2020

Received: 01 May 2020; Accepted: 31 August 2020

<https://doi.org/10.1016/j.cosust.2020.08.019>

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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 (N₂O). The warm climate of the tropics together with high decomposition rates provide ideal conditions for microbial mediated N₂O production [15,16]. It is therefore not surprising that tropical forests are the largest global natural source of soil N₂O emissions [17]. The largest manmade source of N₂O is the agricultural sector, predominately managed soils, which include fertilised plantations. The agricultural sector is responsible for 35–85% of the global anthropogenic N₂O emissions, depending on the regions [18]. Fertilisation with mineral nitrogen compounds and organic rich materials are their main source of N₂O [19]. In temperate climate zones extensive research, spanning 40 plus years, has provided detailed knowledge on the environmental and agronomic impacts on N₂O production and their emission rates from most crops. Contrary, very few studies have investigated the impact of oil palm production on N₂O emissions beyond 6 months periods (Table 1). This paper summarises current knowledge of N₂O emission rates

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Table 1

Peer-reviewed papers studying soil N₂O 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 <i>et al.</i> [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 <i>et al.</i> [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 <i>et al.</i> [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 <i>et al.</i> [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 <i>et al.</i> [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 <i>et al.</i> [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 <i>et al.</i> [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 <i>et al.</i> [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 <i>et al.</i> [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 N₂O production

Microbial processes in soils and sediments are responsible for around 90% of total global N₂O 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 N₂O and ultimately to inert N₂ (atmospheric nitrogen) under anaerobic conditions [16,20]. In tropical peatlands, other pathways are also important sources of N₂O. 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 N₂O production [22].

Many groups of bacteria, archaea, also some fungi, have the ability to produce N₂O. 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 N₂O 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 N₂O 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 (CO₂) methane (CH₄), N₂O, 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 CO₂ to the atmosphere (~11 Tg day⁻¹) than from fossil fuel combustion from the whole of Europe (~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 CO₂. This source of N₂O 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 N₂O 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 N₂O emissions increased fivefold [30]. Similar results were observed when converting forest to pasture in Costa Rica [31]; and in Indonesia N₂O 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, N₂O 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 CO₂ but also N₂O, to the atmosphere over years and decades. Peat decomposition rates depend on the vegetation type. For example, CO₂ emissions from degraded forests were ~50% smaller than from croplands and 30% smaller than from oil palm plantations, whereas N₂O 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 N₂O emissions increase exponentially with peat decomposition rates [40]. Nitrous oxide emissions from peat decomposition can be much larger than N₂O emissions triggered by N fertilisation [38] (Table 1). Furthermore, the water table level has a stronger influence on N₂O emission rates than N fertiliser input rates, with largest N₂O emissions at high water table [41] (Table 1).

Clear-felling mineral soils also leads to soil organic carbon losses, but loss rates are ~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, N₂O emissions were also smaller than from peat soils (<95 g N₂O 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, where CO₂, N₂O and CH₄ 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 N₂O, emissions were two times smaller from the 1 year old (0.11 g N₂O-N m⁻² y⁻¹) compared to the 12 year old plantation (0.33 g N₂O-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 CO₂ (330 g C m⁻² y⁻¹) in year 12, and N₂O emissions (0.95 g N₂O-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 N₂O 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 ($\sim 950 \text{ t ha}^{-1} \text{ y}^{-1}$) and still at rates of $\sim 90 \text{ t ha}^{-1} \text{ y}^{-1}$ 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 N₂O 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 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 N₂O production [51,52]. These indirect N₂O emissions still need 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 N₂O 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 N₂O emissions, and concluded that organic amendments could reduce N₂O emissions by $\sim 76\%$ [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 N₂O 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 CH₄, CO₂ 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 N₂O 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 N₂O emissions and mitigation options

As discussed in the above sections, many environmental and management parameters influence soil N₂O emission rates. For example: (1) Mineral N application (i.e. urea, ammonium sulphate, POME) increase N₂O 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 N₂O peak [58,68]. (2) The rate of increase in N₂O emissions after

fertilisation depends on N application rates and fertiliser type, as demonstrated by Hassler *et al.* [67] comparing N₂O 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 N₂O emissions compared to urea alone. This could be a good mitigation strategy for N₂O reductions [58,59]. Other ways to mitigate N₂O 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 N₂O 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 N₂O production; whereas too little N prevents optimised yield and thereby increases the N₂O 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 N₂O 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 N₂O 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 N₂O emission rates to the IPCC

Research on the impact of oil palm plantation management on N₂O 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 N₂O 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 N₂O 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 N₂O emissions, in order to develop strategies to reduce N₂O 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 N₂O fluxes from oil palm production. It is essential to invest in high temporal frequency of soil N₂O 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 CH₄ fluxes and soil CO₂ 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 N₂O data and inform on mitigation options. Emissions of N₂O from tree stems and the canopy, although smaller than from the soil, should be included [75]. Long-term monitoring of atmospheric N₂O, CH₄, CO₂ concentrations or fluxes from plantations and forests, [34^{**},76–78] (Table 1), can provide the large scale (>100 m²) 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

The opinions expressed and arguments employed in this paper are the sole responsibility of the authors and do not necessarily reflect those of the OECD or of the governments of its Member countries.

Acknowledgements

This paper was developed from discussions at a workshop, "Climate Change, Reactive Nitrogen, Food Security and Sustainable Agriculture", held at the Karlsruhe Institute of Technology in Garmisch-Partenkirchen, Germany on 15–16 April 2019. The workshop was sponsored by the OECD Co-operative Research Programme: Biological Resource Management for Sustainable Agricultural Systems, which made it possible for the authors to participate in the workshop. This review was supported by the Sustainable Use of Natural Resources to Improve Human Health and Support Economic Development (SUNRISE) Programme (NE/R000131/1) (UK CEH); by the Deutsche Forschungsgemeinschaft (DFG), project number 192626868, in the framework of the collaborative German–Indonesian research center CRC990 (University of Göttingen); and as part of CIFOR's Global Comparative Study on REDD+ (www.cifor.org/gcs). The funding partners that have supported this research include the Norwegian Agency for Development Cooperation (Norad), the International Climate Initiative (IKI) of the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB) and the CGIAR Research Program on Forests, Trees and Agroforestry (CRP-FTA) with financial support from the CGIAR Fund Donors.

References and recommended reading

Papers of particular interest, published within the period of review, have been highlighted as:

- of special interest
- of outstanding interest

1. Dislich C, Keyel AC, Salecker J, Kisel Y, Meyer KM, Auliya M, Barnes AD, Corre MD, Darras K, Faust H *et al.*: **A review of the ecosystem functions in oil palm plantations, using forests as a reference system.** *Biol Rev* 2017, **92**:1539–1569 <http://dx.doi.org/10.1111/brv.12295>.
2. Woittiez LS, van Wijk MT, Slingerland M, van Noordwijk M, Giller KE: **Yield gaps in oil palm: a quantitative review of contributing factors.** *Eur J Agron* 2017, **83**:57–77 <http://dx.doi.org/10.1016/j.eja.2016.11.002>.
3. Sayer J, Ghazoul J, Nelson P, Klintuni Boedhihartono A: **Oil palm expansion transforms tropical landscapes and livelihoods.** *Global Food Secur* 2012, **1**:114–119 <http://dx.doi.org/10.1016/j.GFS.2012.10.003>.
4. Moreno-Peñaranda R, Gasparatos A, Stromberg P, Suwa A, Puppim de Oliveira JA: In *Stakeholder Perceptions of the Ecosystem Services and Human Well-Being Impacts of Palm Oil Biofuels in Indonesia and Malaysia BT - Biofuels and Sustainability: Holistic Perspectives for Policy-making*. Edited by Takeuchi K, Shiroyama H, Saito O, Matsuura M. Japan: Springer; 2018:133–173 http://dx.doi.org/10.1007/978-4-431-54895-9_10.
5. FAOSTAT: **Production/crops: oil, palm fruit.** *Prod Oil Palm Fruit* 2018. <http://faostat.fao.org>.
6. Ordway EM, Naylor RL, Nkongho RN, Lambin EF: **Oil palm expansion and deforestation in Southwest Cameroon associated with proliferation of informal mills.** *Nat Commun* 2019, **10**:1–11 <http://dx.doi.org/10.1038/s41467-018-07915-2>.
7. Taheripour F, Hertel TW, Ramankutty N: **Market-mediated responses confound policies to limit deforestation from oil palm expansion in Malaysia and Indonesia.** *Proc Natl Acad Sci U S A* 2019, **116**:19193–19199 <http://dx.doi.org/10.1073/pnas.1903476116>.
8. Glinkis EA, Gutiérrez-Vélez VH: **Quantifying and understanding land cover changes by large and small oil palm expansion regimes in the Peruvian Amazon.** *Land Use Policy* 2019, **80**:95–106 <http://dx.doi.org/10.1016/j.landusepol.2018.09.032>.
9. Quezada JC, Etter A, Ghazoul J, Buttler A, Guillaume T: **Carbon neutral expansion of oil palm plantations in the Neotropics.** *Sci Adv* 2019, **5**:1–12 <http://dx.doi.org/10.1126/sciadv.aaw4418>.
10. Furumo PR, Aide TM: **Characterizing commercial oil palm expansion in Latin America: land use change and trade.** *Environ Res Lett* 2017, **12** <http://dx.doi.org/10.1088/1748-9326/aa5892>.
11. Grass I, Kubitzka C, Krishna VV, Corre MD, Mußhoff O, Pütz P, Drescher J, Rembold K, Ariyanti ES, Barnes AD *et al.*: **Trade-offs between multifunctionality and profit in tropical smallholder landscapes.** *Nat Commun* 2020, **11** <http://dx.doi.org/10.1038/s41467-020-15013-5>
 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 palm 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.
12. Azhar B, Saadun N, Prideaux M, Lindenmayer DB: **The global palm oil sector must change to save biodiversity and improve food security in the tropics.** *J Environ Manage* 2017, **203**:457–466 <http://dx.doi.org/10.1016/j.jenvman.2017.08.021>.
13. Gibbs HK, Ruesch AS, Achard F, Clayton MK, Holmgren P, Ramankutty N, Foley JA: **Tropical forests were the primary sources of new agricultural land in the 1980s and 1990s.** *Proc Natl Acad Sci U S A* 2010, **107**:16732–16737 <http://dx.doi.org/10.1073/pnas.0910275107>.
14. Luke SH, Advento AD, Aryawan AAK, Adhy DN, Ashton-Butt A, Barclay H, Dewi JP, Drewer J, Dumbrell AJ, Edi *et al.*: **Managing oil palm plantations more sustainably: large-scale experiments within the Biodiversity and Ecosystem Function in Tropical Agriculture (BEFTA) programme.** *Front For Global Change* 2020, **2**:1–20 <http://dx.doi.org/10.3389/ffgc.2019.00075>
 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 N₂O fluxes, but not published yet), hydrological measurements through monitoring and manipulation experiments.
15. Syakila A, Kroeze C: **The global nitrous oxide budget revisited.** *Greenh Gas Meas Manag* 2011, **1**:17–26 <http://dx.doi.org/10.3763/ghgmm.2010.0007>.
16. Butterbach-Bahl K, Baggs EM, Dannenmann M, Kiese R, Zechmeister-Boltenstern S: **Nitrous oxide emissions from soils: how well do we understand the processes and their controls?** *Philos Trans R Soc B Biol Sci* 2013, **368** <http://dx.doi.org/10.1098/rstb.2013.0122>.
17. Werner C, Butterbach-Bahl K, Haas E, Hickler T, Kiese R: **A global inventory of N₂O emissions from tropical rainforest soils using a detailed biogeochemical model.** *Global Biogeochem Cycles* 2007, **21** <http://dx.doi.org/10.1029/2006GB002909>.
18. Janssens-Maenhout G, Crippa M, Guizzardi D, Muntean M, Schaaf E, Dentener F, Bergamaschi P, Pagliari V, Olivier JGJ, Peters JAHW *et al.*: **EDGAR v4.3.2 Global Atlas of the three major greenhouse gas emissions for the period 1970–2012.** *Earth Syst Sci Data* 2019, **11**:959–1002 <http://dx.doi.org/10.5194/essd-11-959-2019>.
19. IPCC: **2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 4 Agriculture, Forestry and Other Land Use.** 2006.
20. Kapper T, Hetz S, Kolb S, Yoon S, Horn MA, Ho A: **Deforestation for oil palm: impact on microbially mediated methane and nitrous oxide emissions, and soil bacterial communities.** *Biol Fertil Soils* 2020, **56**:287–298 <http://dx.doi.org/10.1007/s00374-019-01421-3>.
21. Espenberg M, Truu M, Mander Ü, Kasak K, Nõlvak H, Ligi T, Oopkaup K, Maddison M, Truu J: **Differences in microbial community structure and nitrogen cycling in natural and drained tropical peatland soils.** *Sci Rep* 2018, **8**:1–12 <http://dx.doi.org/10.1038/s41598-018-23032-y>.
22. Drewer J, Zhao J, Leduning MM, Levy PE, Sentian J, Gubry-Rangin C, Skiba UM: **Linking nitrous oxide and nitric oxide**

- fluxes to microbial communities in tropical forest soils and oil palm plantations in Malaysia in laboratory incubations.** *Front For Global Change* 2020, **3**:1-14 <http://dx.doi.org/10.3389/ffgc.2020.00004>.
23. Carlson KM, Curran LM, Asner GP, Pittman AMD, Trigg SN, Marion Adeney J: **Carbon emissions from forest conversion by Kalimantan oil palm plantations.** *Nat Clim Change* 2013, **3**:283-287 <http://dx.doi.org/10.1038/nclimate1702>.
 24. Gaveau DLA, Sheil D, Husnayaen, Salim MA, Arjasakusuma S, Ancrenaz M, Pacheco P, Meijaard E: **Rapid conversions and avoided deforestation: examining four decades of industrial plantation expansion in Borneo.** *Sci Rep* 2016, **6** <http://dx.doi.org/10.1038/srep32017>.
 25. Adrianto HA, Spracklen DV, Arnold SR, Sitanggang IS, Syaufina L: **Forest and land fires are mainly associated with deforestation in Riau Province, Indonesia.** *Remote Sens* 2020, **12** <http://dx.doi.org/10.3390/RS12010003>.
 26. Batjes NH: **Landmark papers: total carbon and nitrogen in the soils of the world.** *Eur J Soil Sci* 2014, **65**:4-21 http://dx.doi.org/10.1111/ejss.12114_2.
 27. Huijnen V, Wooster MJ, Kaiser JW, Gaveau DLA, Flemming J, Parrington M, Inness A, Murdiyarso D, Main B, Van Weele M: **Fire carbon emissions over maritime southeast Asia in 2015 largest since 1997.** *Sci Rep* 2016, **6** <http://dx.doi.org/10.1038/srep26886>.
 28. Gaveau DLA, Salim MA, Hergoualc'h K, Locatelli B, Sloan S, Wooster M, Marlier ME, Molidena E, Yaen H, DeFries R et al.: **Major atmospheric emissions from peat fires in Southeast Asia during non-drought years: evidence from the 2013 Sumatran fires.** *Sci Rep* 2014, **4**:1-7 <http://dx.doi.org/10.1038/srep06112>.
 29. Wilcove DS, Giam X, Edwards DP, Fisher B, Koh LP: **Navjot's nightmare revisited: logging, agriculture, and biodiversity in Southeast Asia.** *Trends Ecol Evol* 2013, **28**:531-540.
 30. Yashiro Y, Kadir WR, Okuda T, Koizumi H: **The effects of logging on soil greenhouse gas (CO₂, CH₄, N₂O) flux in a tropical rain forest, Peninsular Malaysia.** *Agric For Meteorol* 2008, **148**:799-806 <http://dx.doi.org/10.1016/j.agrformet.2008.01.010>.
 31. Keller M, Veldkamp E, Weitz AM, Reiners WA: **Effect of pasture age on soil trace-gas emissions from a deforested area of Costa Rica.** *Nature* 1993, **365**:244-246 <http://dx.doi.org/10.1038/365244a0>.
 32. Ishizuka S, Tsuruta H, Murdiyarso D: **An intensive field study on CO₂, CH₄, and N₂O emissions from soils at four land-use types in Sumatra, Indonesia.** *Global Biogeochem Cycles* 2002, **16**:22-1-22-11 <http://dx.doi.org/10.1029/2001gb001614>.
 33. Cowan N, Levy P, Maire J, Coyle M, Leeson SR, Famulari D, Carozzi M, Nemitz E, Skiba U: **An evaluation of four years of nitrous oxide fluxes after application of ammonium nitrate and urea fertilisers measured using the eddy covariance method.** *Agric For Meteorol* 2020, **280**:107812 <http://dx.doi.org/10.1016/j.agrformet.2019.107812>.
 34. Meijide A, de la Rua C, Guillaume T, Röhl A, Hassler E, Stiegler C, ●● Tjoa A, June T, Corre MD, Veldkamp E et al.: **Measured greenhouse gas budgets challenge emission savings from palm-oil biodiesel.** *Nat Commun* 2020, **11** <http://dx.doi.org/10.1038/s41467-020-14852-6>
Comparing N₂O, CO₂ and CH₄ fluxes from oil palm plantations of different ages on mineral soil and peat. Unprecedented high quality data and life cycle analysis. An example of how future research on oil palm plantations should be conducted. The conclusions are that oil palms planted on previous forests cannot provide sustainable biodiesel.
 35. Aini FK, Hergoualc'h K, Smith JU, Verchot L: **Nitrous oxide emissions along a gradient of tropical forest disturbance on mineral soils in Sumatra.** *Agric Ecosyst Environ* 2015, **214**:107-117 <http://dx.doi.org/10.1016/j.agee.2015.08.022>.
 36. Shanmugam S, Dalal RC, Joosten H, Raison RJ, Joo GK: **SOC stock changes and greenhouse gas emissions following tropical land use conversions to plantation crops on mineral soils, with a special focus on oil palm and rubber plantations.** *Agriculture* 2018, **8** <http://dx.doi.org/10.3390/agriculture8090133>.
 37. Hergoualc'h K, Verchot LV: **Greenhouse gas emission factors for land use and land-use change in Southeast Asian peatlands.** *Mitig Adapt Strategies Global Change* 2014, **19**:789-807 <http://dx.doi.org/10.1007/s11027-013-9511-x>.
 38. Oktarita S, Hergoualc'h K, Anwar S, Verchot LV: **Substantial N₂O emissions from peat decomposition and N fertilization in an oil palm plantation exacerbated by hotspots.** *Environ Res Lett* 2017, **12** <http://dx.doi.org/10.1088/1748-9326/aa80f1>.
 39. Melling L, Hatano R, Goh KJ: **Nitrous oxide emissions from three ecosystems in tropical peatland of Sarawak, Malaysia.** *Soil Sci Plant Nutr* 2007, **53**:792-805 <http://dx.doi.org/10.1111/j.1747-0765.2007.00196.x>.
 40. Hatano R: **Impact of land use change on greenhouse gases emissions in peatland: a review.** *Int Agrophys* 2019, **33**:167-173 <http://dx.doi.org/10.31545/intagr/109238>.
 41. Chaddy A, Melling L, Ishikura K, Hatano R: **Soil N₂O emissions under different N rates in an oil palm plantation on tropical peatland.** *Agriculture* 2019, **9**:1-18 <http://dx.doi.org/10.3390/agriculture9100213>.
 42. IPCC: **2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Box 4.3A.** 2019.
 43. Pärn J, Verhoeven JTA, Butterbach-Bahl K, Dise NB, Ullah S, ● Aasa A, Egorov S, Espenberg M, Järveoja J, Jauhiainen J et al.: **Nitrogen-rich organic soils under warm well-drained conditions are global nitrous oxide emission hotspots.** *Nat Commun* 2018, **9**:1-8 <http://dx.doi.org/10.1038/s41467-018-03540-1>
The authors conducted a global analysis of the key drivers of N₂O emissions from drained organic soils, and identified temperature and soil nitrate concentrations as key variables to calculate N₂O emissions. N₂O emissions were particularly large in the tropics and subtropics, and urgent action is needed to adopt mitigation strategies.
 44. Guillaume T, Damris M, Kuzyakov Y: **Losses of soil carbon by converting tropical forest to plantations: erosion and decomposition estimated by δ¹³C.** *Global Change Biol* 2015, **21**:3548-3560 <http://dx.doi.org/10.1111/gcb.12907>.
 45. Gharibreza M, Raj JK, Yusoff I, Othman Z, Tahir WZWM, Ashraf MA: **Land use changes and soil redistribution estimation using ¹³⁷Cs in the tropical Bera Lake catchment, Malaysia.** *Soil Tillage Res* 2013, **131**:1-10 <http://dx.doi.org/10.1016/j.still.2013.02.010>.
 46. Pardon L, Bessou C, Nelson PN, Dubos B, Ollivier J, Marichal R, Caliman JP, Gabrielle B: **Key unknowns in nitrogen budget for oil palm plantations. A review.** *Agron Sustain Dev* 2016, **36**:1-21 <http://dx.doi.org/10.1007/s13593-016-0353-2>.
 47. Luke SH, Barclay H, Bidin K, Chey VK, Ewers RM, Foster WA, Nainar A, Pfeifer M, Reynolds G, Turner EC et al.: **The effects of catchment and riparian forest quality on stream environmental conditions across a tropical rainforest and oil palm landscape in Malaysian Borneo.** *Ecology* 2017, **10**:1-14 <http://dx.doi.org/10.1002/eco.1827>.
 48. Mitchell SL, Edwards DP, Bernard H, Coomes D, Jucker T, Davies ZG, Struebig MJ: **Riparian reserves help protect forest bird communities in oil palm dominated landscapes.** *J Appl Ecol* 2018, **55**:2744-2755 <http://dx.doi.org/10.1111/1365-2664.13233>.
 49. Bange H, Hock Sim C, Bastian D, Kallert J, Kock A, Mujahid A, ●● Müller M: **Nitrous oxide (n₂o) and methane (ch₄) in rivers and estuaries of northwestern borneo.** *Biogeosciences* 2019, **16**:4321-4335 <http://dx.doi.org/10.5194/bg-16-4321-2019>
This is one of very few studies that have measured N₂O and CH₄ emissions from tropical rivers and their estuaries. The emission rates are large relative to the areas they occupy. More such measurement are required. This study provides a good experimental measurement plan.
 50. Luke SH, Slade EM, Gray CL, Annamala KV, Drewer J, Williamson J, Agama AL, Ationg M, Mitchell SL, Vairappan CS et al.: **Riparian buffers in tropical agriculture: scientific support, effectiveness and directions for policy.** *J Appl Ecol* 2019, **56**:85-92 <http://dx.doi.org/10.1111/1365-2664.13280>.
 51. Kurniawan S, Corre MD, Matson AL, Schulte-Bisping H, Utami SR, Van Straaten O, Veldkamp E: **Conversion of tropical forests to smallholder rubber and oil palm plantations impacts nutrient**

- leaching losses and nutrient retention efficiency in highly weathered soils. *Biogeosciences* 2018, **15**:5131-5154 <http://dx.doi.org/10.5194/bg-15-5131-2018>.
52. Ullah S, Zinati GM: **Denitrification and nitrous oxide emissions from riparian forests soils exposed to prolonged nitrogen runoff.** *Biogeochemistry* 2006, **81**:253-267 <http://dx.doi.org/10.1007/s10533-006-9040-8>.
 53. Yono D, Purwanti E, Sahara A, Nugroho YA, Tanjung ZA, Aditama R, Dewi C, Sihotang AE, Utomo C, Liwang T: **Physiology and genotyping of adaptive and sensitive oil palm progenies under unwatered stress condition.** *IOP Conf Ser Earth Environ Sci* 2019, **293** <http://dx.doi.org/10.1088/1755-1315/293/1/012012>.
 54. Paterson RRM, Kumar L, Shabani F, Lima N: **World climate suitability projections to 2050 and 2100 for growing oil palm.** *J Agric Sci* 2017, **155**:659-702 <http://dx.doi.org/10.1017/S0021859616000605>.
 55. Meijide A, Badu CS, Moyano F, Tiralla N, Gunawan D, Knohl A: **Impact of forest conversion to oil palm and rubber plantations on microclimate and the role of the 2015 ENSO event.** *Agric For Meteorol* 2018, **252**:208-219 <http://dx.doi.org/10.1016/j.agrformet.2018.01.013>.
 56. Sabajo CR, Le Maire G, June T, Meijide A, Rouspard O, Knohl A: **Expansion of oil palm and other cash crops causes an increase of the land surface temperature in the Jambi province in Indonesia.** *Biogeosciences* 2017, **14**:4619-4635 <http://dx.doi.org/10.5194/bg-14-4619-2017>.
 57. Potter L: *Managing Oil Palm Landscapes A Seven-country Survey of the Modern Palm Oil Industry in Southeast Asia, Latin America and West Africa.* Center for International Forestry Research (CIFOR); 2015 <http://dx.doi.org/10.17528/cifor/005612>.
 58. Rahman N, Bruun TB, Giller KE, Magid J, van de Ven GWJ, de Neergaard A: **Soil greenhouse gas emissions from inorganic fertilizers and recycled oil palm waste products from Indonesian oil palm plantations.** *GCB Bioenergy* 2019, **11**:1056-1074 <http://dx.doi.org/10.1111/gcbb.12618>.
 59. Darras KFA, Corre MD, Formaglio G, Tjoa A, Potapov A, Brambach F, Sibhatu KT, Grass I, Rubiano AA, Buchori D *et al.*: **Reducing fertilizer and avoiding herbicides in oil palm plantations—ecological and economic valuations.** *Front For Global Change* 2019, **2** <http://dx.doi.org/10.3389/ffgc.2019.00065>.
 60. Rahman N, De Neergaard A, Magid J, Van De Ven GWJ, Giller KE, Bruun TB: **Changes in soil organic carbon stocks after conversion from forest to oil palm plantations in Malaysian Borneo.** *Environ Res Lett* 2018, **13** <http://dx.doi.org/10.1088/1748-9326/aade0f>.
 61. Sakata R, Shimada S, Arai H, Yoshioka N, Yoshioka R, Aoki H, Kimoto N, Sakamoto A, Melling L, Inubushi K: **Effect of soil types and nitrogen fertilizer on nitrous oxide and carbon dioxide emissions in oil palm plantations.** *Soil Sci Plant Nutr* 2015, **61**:48-60 <http://dx.doi.org/10.1080/00380768.2014.960355>.
 62. Krishna V, Euler M, Siregar H, Qaim M: **Differential livelihood impacts of oil palm expansion in Indonesia.** *Agric Econ (United Kingdom)* 2017, **48**:639-653 <http://dx.doi.org/10.1111/agec.12363>.
 63. Arolu IW, Rafii MY, Marjuni M, Hanafi MM, Sulaiman Z, Rahim HA, Kolapo OK, Abidin MIZ, Amiruddin MD, Kushairi Din A *et al.*: **Genetic variability analysis and selection of pisifera palms for commercial production of high yielding and dwarf oil palm planting materials.** *Ind Crops Prod* 2016, **90**:135-141 <http://dx.doi.org/10.1016/j.indcrop.2016.06.006>.
 64. Haryani H, Norlindawati AP, Aswanimiyuni A, Azman A, ZEW: **Effect of palm oil mill effluent (POME) on yield and nutritive values of Napier grass.** *Malaysian J Vet Res* 2019, **10**:62-67.
 65. Khairuddin MN, Zakaria AJ, Isa IM, Jol H, Nazri Wan Abdul Rahman WM, Salleh MKS: **The potential of treated palm oil mill effluent (Pome) sludge as an organic fertilizer.** *Agrivita* 2016, **38**:142-154 <http://dx.doi.org/10.17503/agrivita.v38i2.753>.
 66. Iskandar MJ, Baharum A, Anuar FH, Othaman R: **Palm oil industry in South East Asia and the effluent treatment technology—a review.** *Environ Technol Innov* 2018, **9**:169-185 <http://dx.doi.org/10.1016/j.eti.2017.11.003>.
 67. Hassler E, Corre MD, Kurniawan S, Veldkamp E: **Soil nitrogen oxide fluxes from lowland forests converted to smallholder rubber and oil palm plantations in Sumatra, Indonesia.** *Biogeosciences* 2017, **14**:2781-2798 <http://dx.doi.org/10.5194/bg-14-2781-2017>.
 68. Skiba U, Jones SK, Drewer J, Helfter C, Anderson M, Dinsmore K, McKenzie R, Nemitz E, Sutton MA: **Comparison of soil greenhouse gas fluxes from extensive and intensive grazing in a temperate maritime climate.** *Biogeosciences* 2013, **10**:1231-1241 <http://dx.doi.org/10.5194/bg-10-1231-2013>.
 69. Rees RM, Maire J, Florence A, Cowan N, Skiba U, van der Weerden T, Ju X: **Mitigating nitrous oxide emissions from agricultural soils by precision management.** *Front Agric Sci Eng* 2020, **7**:75-80 <http://dx.doi.org/10.15302/J-FASE-2019294>.
 70. Soares JR, Cassman NA, Kielak AM, Pijl A, Carmo JB, Lourenço KS, Laanbroek HJ, Cantarella H, Kuramae EE: **Nitrous oxide emission related to ammonia-oxidizing bacteria and mitigation options from N fertilization in a tropical soil.** *Sci Rep* 2016, **6**:1-11 <http://dx.doi.org/10.1038/srep30349>.
 71. Asbur Y, Purwaningrum Y, Ariyanti M: **Growth and nutrient balance of asystasia gangetica (L.) T. Anderson as cover crop for mature oil palm (Elaeis guineensis jacq.) plantations.** *Chil J Agric Res* 2018, **78**:486-494 <http://dx.doi.org/10.4067/S0718-58392018000400486>.
 72. Tao HH, Snaddon JL, Slade EM, Henneron L, Caliman JP, Willis KJ: **Application of oil palm empty fruit bunch effects on soil biota and functions: a case study in Sumatra, Indonesia.** *Agric Ecosyst Environ* 2018, **256**:105-113 <http://dx.doi.org/10.1016/j.agee.2017.12.012>.
 73. Cardenas LM, Bhogal A, Chadwick DR, McGeough K, Misselbrook T, Rees RM, Thorman RE, Watson CJ, Williams JR, Smith KA *et al.*: **Nitrogen use efficiency and nitrous oxide emissions from five UK fertilised grasslands.** *Sci Total Environ* 2019, **661**:696-710 <http://dx.doi.org/10.1016/j.scitotenv.2019.01.082>.
 74. Pavelka M, Acosta M, Kiese R, Altimir N, Brümmer C, Crill P, Larenova E, Fuß R, Gielen B, Graf A *et al.*: **Standardisation of chamber technique for CO₂, N₂O and CH₄ fluxes measurements from terrestrial ecosystems.** *Int Agrophys* 2018, **32**:569-587 <http://dx.doi.org/10.1515/intag-2017-0045>.
 75. Allen K, Corre MD, Tjoa A, Veldkamp E: **Soil nitrogen-cycling responses to conversion of lowland forests to oil palm and rubber plantations in Sumatra, Indonesia.** *PLoS One* 2015, **10** <http://dx.doi.org/10.1371/journal.pone.0133325>.
 76. Fowler D, Nemitz E, Misztal P, Di Marco C, Skiba U, Ryder J, Helfter C, Cape JN, Owen S, Dorsey J *et al.*: **Effects of land use on surface-atmosphere exchanges of trace gases and energy in Borneo: comparing fluxes over oil palm plantations and a rainforest.** *Philos Trans R Soc B Biol Sci* 2011, **366**:3196-3209 <http://dx.doi.org/10.1098/rstb.2011.0055>.
 77. Leip A, Skiba U, Vermeulen A, Thompson RL: **A complete rethink is needed on how greenhouse gas emissions are quantified for national reporting.** *Atmos Environ* 2018, **174**:237-240 <http://dx.doi.org/10.1016/j.atmosenv.2017.12.006>.
 78. Franz D, Acosta M, Altimir N, Arriga N, Arrouays D, Aubinet M, Aurela M, Ayres E, López-Ballesteros A, Barbaste M *et al.*: **Towards long-term standardised carbon and greenhouse gas observations for monitoring Europe's terrestrial ecosystems: a review.** *Int Agrophys* 2018, **32**:439-455 <http://dx.doi.org/10.1515/intag-2017-0039>.
 79. Ishizuka S, Iswandi A, Nakajima Y, Yonemura S, Sudo S, Tsuruta H, Murdiyarto D: **The variation of greenhouse gas emissions from soils of various land-use/cover types in Jambi province, Indonesia.** *Nutr Cycl Agroecosyst* 2005, **71**:17-32 <http://dx.doi.org/10.1007/s10705-004-0382-0>.