



# Mulching with pruned fronds promotes the internal soil N cycling and soil fertility in a large-scale oil palm plantation

Greta Formaglio · Edzo Veldkamp · Muhammad Damris · Aiyen Tjoa · Marife D. Corre

Received: 18 February 2020 / Accepted: 17 April 2021 / Published online: 4 May 2021  
© The Author(s) 2021

**Abstract** Intensive management practices in large-scale oil palm plantations can slow down nutrient cycling and alter other soil functions. Thus, there is a need to reduce management intensity without sacrificing productivity. The aim of our study was to investigate the effect of management practices on gross rates of soil N cycling and soil fertility. In Jambi province, Indonesia, we established a management experiment in a large-scale oil palm plantation to compare conventional practices (i.e. high fertilization rates and herbicide weeding) with reduced management intensity (i.e. reduced fertilization rates and mechanical weeding). Also, we compared the typical

management zones characterizing large-scale plantations: palm circle, inter-row and frond-stacked area. After 1.5 years of this experiment, reduced and conventional management showed comparable gross soil N cycling rates; however, there were stark differences among management zones. The frond-stacked area had higher soil N cycling rates and soil fertility (high microbial biomass, extractable C, soil organic C, extractable organic N, total N and low bulk density) than inter-row and palm circle (all  $p \leq 0.05$ ). Microbial biomass was the main driver of the soil N cycle, attested by its high correlation with gross N-cycling rates ( $r = 0.93\text{--}0.95$ ,  $p < 0.01$ ). The correlations of microbial N with extractable C, extractable organic N, soil organic C and total N ( $r = 0.76\text{--}0.89$ ,  $p < 0.01$ ) suggest that microbial biomass was mainly regulated by the availability of organic matter. Mulching with senesced fronds enhanced soil microbial biomass, which promoted nutrient recycling and thereby can decrease dependency on chemical fertilizers.

---

Responsible Editor: Vanessa Bailey.

**Supporting Information** The online version of this article contains supplementary material available at (<https://doi.org/10.1007/s10533-021-00798-4>)

---

G. Formaglio (✉) · E. Veldkamp · M. D. Corre  
Soil Science of Tropical and Subtropical Ecosystems,  
Faculty of Forest Sciences and Forest Ecology, University  
of Goettingen, Buesgenweg 2, 37077 Göttingen, Germany  
e-mail: gformag@gwdg.de

M. Damris  
Faculty of Science and Technology, Jambi University, Jl.  
Tribrata, Km 11, Pondok Meja, , Muaro Jambi,  
Jambi, Indonesia

A. Tjoa  
Faculty of Agriculture, Tadulako University, Jl. Soekarno  
Hatta, km 09 Tondo, Palu 94118, Indonesia

**Keywords** Management practices · Gross nitrogen mineralization · Gross nitrification · Microbial biomass · Tropical plantation · Indonesia

## Introduction

Agricultural expansion and intensification in the tropics are major global environmental concerns as they are connected to forest and biodiversity loss, soil degradation, greenhouse gas emissions and reduced ecosystem functioning (Grass et al. 2020; Lewis et al. 2015; Veldkamp et al. 2020). Palm oil is one of the most important cash crops in the tropics since it's the world's leading vegetable oil owing to its high yield and low production costs (Carter et al. 2007; Clough et al. 2016). Oil palm plantations are widespread across the tropics: their area has increased rapidly in the last decades and this increase is predicted to continue in the future (FAO 2017, Pirker 2016). Indonesia is the top producer of palm oil (FAO 2017) with the islands of Sumatra and Kalimantan contributing the largest share (Directorate General of Estate Crop 2017). A substantial part of oil palms is grown in industrial plantations, which are large-scale plantations with intensive management, such as high fertilization rates and herbicide use. In Indonesia, 60% of oil palm plantations are owned by large-scale state and private companies with landholdings ranging from 3000 to 40,000 ha (Lee et al. 2014), as opposed to smallholder plantations with about 4 ha per household (e.g. Jambi province, Sumatra; Clough et al. 2016). The intensive management in large-scale plantations has been linked to negative environmental impacts: high N fertilization rates result in large N<sub>2</sub>O emissions (Hassler et al. 2017; Rahman et al. 2019) and N leaching losses (Formaglio et al. 2020), potentially diminishing water quality (Comte et al. 2012), whilst herbicides remove understory vegetation and reduce soil cover, possibly affecting soil biodiversity (Ashton-Butt et al. 2018) and soil erosion (Moradi et al. 2015). Moreover, oil palm plantations have strongly reduced ecosystem functions (e.g. gas and climate regulation, water regulation and filtration, soil fertility) compared to tropical forests (Clough et al. 2016; Dislich et al. 2017). A reduction in management intensity may diminish some of the negative environmental impacts associated with oil palm cultivation and may moderate the decline of some ecosystem functions. Options to reduce management intensity can include e.g. a reduction in fertilization rates and mechanical weeding instead of using herbicides. The identification of sustainable farming practices in oil palm plantations is a high priority of the

Roundtable for Sustainable Oil Palm (RSPO 2018). Furthermore, reductions in fertilization rates are also in line with the direction of the Indonesian government to support precision farming (e.g. varying rates of fertilizations with age of plantation, soil types and climate; Ministry of Agriculture of Indonesia 2016).

Soil N cycling is an indicator of soil fertility, an important ecosystem function that is very sensitive to management practices (Allen et al. 2015; Corre et al. 2006; Cookson et al. 2006; Lang et al. 2016). The internal soil N cycle consists of microbial-mediated N transformations that regulate mineral N production and retention in the soil, determining the soil's capacity to supply N (Davidson et al. 1991; Hart et al. 1994a) as well as its susceptibility to gaseous and leaching losses (Corre et al. 2014; Formaglio et al. 2020). An optimal management of the internal soil N cycle will maintain crop production and diminish N losses resulting in both ecological and economic benefits. Agricultural management practices, such as fertilization and weeding, affect soil N cycling rates by influencing the inputs of nutrients and organic matter into the soil, and thereby modifying soil biochemical properties and microbial biomass (Allen et al. 2015, 2016; Singh and Ghoshal 2010). Chronic high N fertilization to tropical forest soils represses soil microbial biomass and N immobilization rates but enhances gross N mineralization and nitrification rates as well as N-oxide losses (Baldos et al. 2015; Corre et al. 2010, 2014; Koehler et al. 2009; Müller et al. 2015). Furthermore, N addition can stimulate gross nitrification rates in tropical tree plantations (Silver et al. 2005). On the other hand, herbicide weed control slows down regrowth of understory vegetation by eradicating both above- and belowground biomass, resulting in lower soil cover by vegetation (Darras et al. 2019). As lower understory vegetation can cause lower N uptake and lower inputs of organic matter, the substrate for gross N mineralization, this can result in decreased N mineralization and nitrification rates (Wang et al. 2014). In addition, the removal of understory vegetation may diminish microbial biomass (Pandey and Begum 2010), which is an important factor controlling the internal soil N cycle (Baldos et al. 2015; Corre et al. 2010). Declines in organic matter input and soil microbial biomass, as a consequence of forest conversion to oil palm plantation, have led to decreased gross N mineralization rates in Indonesian soils (Allen et al. 2015). Until now, there

has not been a systematic investigation in oil palm plantations on the effect of management practices on the internal soil N cycle and soil fertility (e.g. soil organic carbon (SOC), total N, microbial biomass, effective cation exchange capacity (ECEC), base saturation, bulk density, among others) and whether these soil properties can be restored by reduced management intensity.

To investigate soil nutrient cycling in an intensively managed oil palm plantation, it is fundamental to account for the spatial variation caused by the standard management practices, since the local-scale heterogeneity in soil characteristics can drive large differences in soil N cycling (Waring et al. 2016). In most large-scale oil palm plantations, there are three distinct management zones (Carron et al. 2015; Haron et al. 1998; Rahman et al. 2018): 1) the area around the palm that is frequently weeded and raked where fertilizer is applied, hereafter called the palm circle; 2) the area between palm rows, which is not fertilized and weeded less frequently to facilitate access to the palms, hereafter called inter-row; and 3) the area where the pruned fronds are piled on every second inter-rows, serving as mulch, hereafter called the frond-stacked area. Decomposition of fronds can be an important source of nutrients and organic matter to the soil (Frazão et al. 2014; Kotowska et al. 2016), and so the frond-stacked area has a potential to support a substantial microbial biomass (Haron et al. 1998), which can promote large gross N mineralization (Huang et al. 2008). In the palm circle, litter inputs are small and mainly derived from the palm roots that are very dense within this management zone (Nelson et al. 2006; Schroth et al. 2000). Gross nitrification in this zone can be high because of periodic fertilization with urea (Silver et al. 2005). Finally, the inter-row has generally lower nutrient inputs than the other zones: below- and aboveground litter input are mainly from weeding of ground vegetation and no fertilizer is applied. In conclusion, we expect that these distinct management zones as well as the management intensity can drive changes in microbial biomass, soil N cycling rates and soil fertility properties. Assessing the link between management practices and soil N cycling rates will aid in optimizing monetary (e.g. fertilizer) inputs and reduce negative environmental effect, in compliance with RSPO criteria.

In a large-scale oil palm plantation on inherently low-fertility Acrisol soil, we investigated whether

management zones differ in gross rates of the internal soil N cycle and soil fertility properties, and whether 1.5 years of reduced fertilization and mechanical weeding increase soil N cycling rates compared to the conventional high fertilization rate and herbicide weed control. Here, we primarily focus on differences among management zones, because the treatments were only initiated 1.5 years earlier and literature suggests that effects on the soil N cycle would probably take longer than 1–2 years to emerge. The first hypothesis that we tested was that the frond-stacked area will have larger SOC and microbial biomass, which drive higher rates of gross N mineralization compared to the palm circle and the inter-row (both with low organic matter input). Our second hypothesis was that reduced fertilization and mechanical weeding stimulate gross N mineralization rates. This hypothesis was based on the above-mentioned studies that high N fertilization rates depressed N-production rates and our expectation that mechanical weeding will enhance organic matter input and microbial biomass. We tested both hypotheses by measuring gross rates of internal soil N cycle using the  $^{15}\text{N}$  pool dilution techniques in a large-scale, spatially replicated oil palm management experiment and stratified according to management zones.

## Materials and methods

### Site description

Our study was conducted in a large-scale, state-owned oil palm plantation located in the Batanghari regency, Jambi province, Indonesia ( $1^{\circ} 43' 8''$  S,  $103^{\circ} 23' 53''$  E, elevation of 73 m above sea level). The plantation was established between 1998 and 2002, encompassed 2025 ha, and the palms were 16–20 years old during our study years of 2017–2018. Planting density was approximately  $142$  palms  $\text{ha}^{-1}$  with 8-m spacing between palms within and between rows. Mean annual air temperature in the study area is  $26.7 \pm 1.0$  °C and mean annual precipitation is  $2235 \pm 385$  mm (1991–2011; climate station at the Jambi Sultan Thana airport of the Meteorological, Climatological and Geophysical Agency). Climatic data measured at the plantation from March 2017 to February 2018 showed a mean daily air temperature of  $26.3$  °C and an annual precipitation of  $2772$  mm. In 2013, nutrient

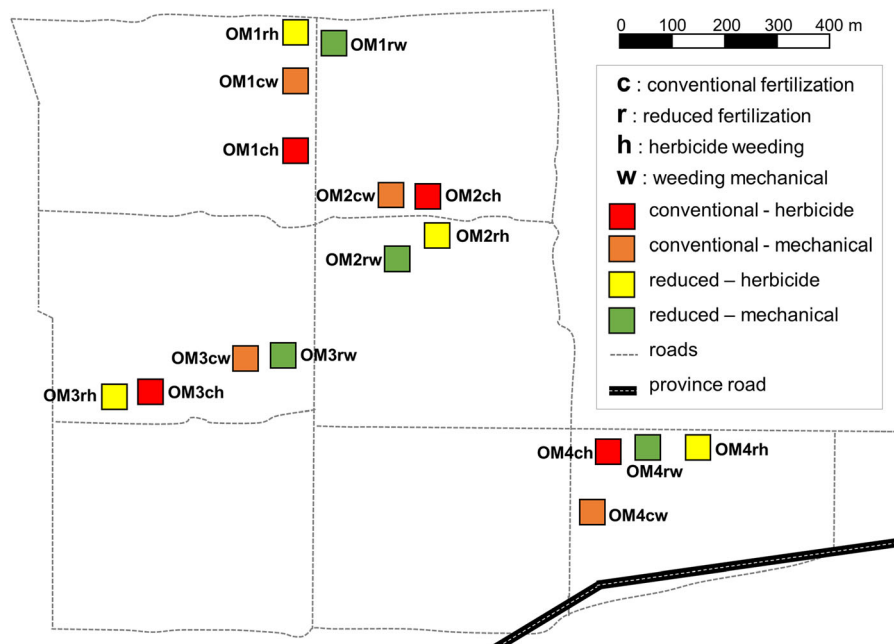
depositions through rainfall in the study area were 12.9 kg N, 0.4 kg P, and 5.5 kg K  $\text{ha}^{-1} \text{yr}^{-1}$  (Kurniawan et al. 2018). The soil in the study area is classified as Acrisol with a loam texture (Allen et al. 2015).

### Experimental design

In November 2016, a full-factorial management experiment with two fertilization rates and chemical and mechanical weed control was established in order to compare high intensity with low intensity management practices. The experimental layout (Fig. 1) was composed of four blocks as replicates (OM1, OM2, OM3, OM4), each with four plots (50 m  $\times$  50 m each) that represented the four treatments: conventional fertilization rate-herbicide (ch), conventional fertilization rate-mechanical weeding (cw), reduced fertilization rate-herbicide (rh), and reduced fertilization rate-mechanical weeding (rw). The conventional fertilization rates were based on rates common to large-scale plantations on Acrisol soils in Jambi province (260 kg N  $\text{ha}^{-1} \text{yr}^{-1}$ , 50 kg P  $\text{ha}^{-1} \text{yr}^{-1}$ , and 220 kg K  $\text{ha}^{-1} \text{yr}^{-1}$ ) whereas the reduced rates were based on the nutrient exports by harvest (136 kg N  $\text{ha}^{-1} \text{yr}^{-1}$ , 17 kg P  $\text{ha}^{-1} \text{yr}^{-1}$ , and

187 kg K  $\text{kg ha}^{-1} \text{yr}^{-1}$ ; see below). Fertilizer sources were urea, triple superphosphate and muriate of potash. All treatments received the same rates of lime (426 kg dolomite  $\text{ha}^{-1} \text{yr}^{-1}$ ) and micronutrients (142 kg micro-mag  $\text{ha}^{-1} \text{yr}^{-1}$  with 0.5%  $\text{B}_2\text{O}_3$ , 0.5% CuO, 0.25%  $\text{Fe}_2\text{O}_3$ , 0.15% ZnO, 0.1% MnO and 18% MgO), as these were the common rates practiced in large-scale plantations on acidic Acrisol soils (Pahan 2010). Fertilizers were applied in the same way as done in large-scale plantations: rates were split in two applications per year (commonly in April and October), and applied within a 2-m radius of the palm circle after the area was raked.

Weed control was done either by herbicide application (glyphosate), commonly used in large-scale plantations, or by mechanical weeding (using a brush cutter) as reduced management practice. Glyphosate was applied at a rate of 1.5 L  $\text{ha}^{-1} \text{yr}^{-1}$  (split in four applications in a year) to the palm circle, and 0.75 L  $\text{ha}^{-1} \text{yr}^{-1}$  (split in two applications in a year) to the inter-row. Mechanical weed control was carried out using a brush cutter in the same areas and frequencies. The mechanical weeding removed only the above-ground biomass, allowing fast ground cover regeneration, while the herbicide eradicated above- and



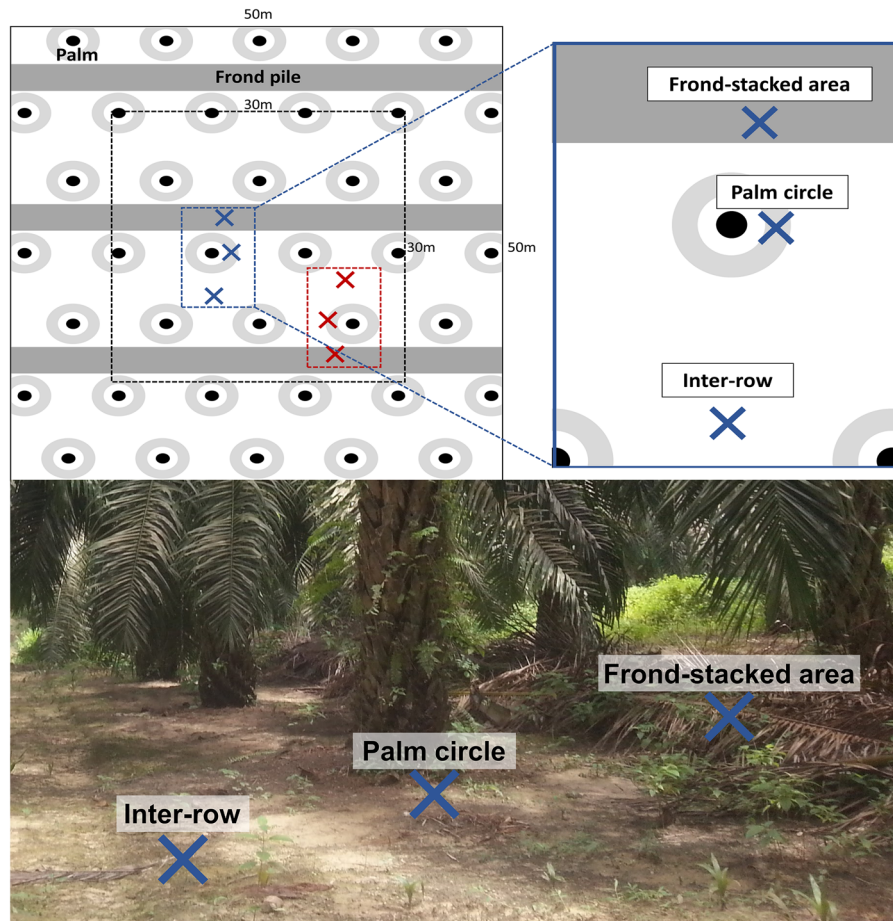
**Fig. 1** Experimental set-up. OM1, OM2, OM3, and OM4 indicate the four blocks, each with the four treatment plots (ch, cw, rh, and rw). Each treatment plot was 50 m  $\times$  50 m

belowground vegetation parts, resulting to slow regeneration of ground cover (Fig. S1).

Within each plot, we randomly selected one palm from the inner 30-m  $\times$  30-m area. We stratified our measurements of gross rates of soil N cycling according to the three distinct management zones (Figs. 2 and S2): within the palm circle, the inter-row and within the frond-stacked area. In total, we measured in 48 sampling points (4 replicate blocks  $\times$  4 treatments  $\times$  3 management zones) in the study site (Figs. 1 and 2). For measurements of the soil biochemical characteristics, another randomly selected palm was added for soil sampling (Fig. 2). Soil samples from the top 5-cm depth were then composited for each management zone per treatment plot, totaling to 48 composite soil samples.

#### Calculation of reduced fertilization rates

The reduced fertilization rates were based on the amount of nutrients (N, P, K) exported from the plantation via harvest. To quantify the nutrient exports, we measured nutrient contents in the harvested fruit bunches from the studied plantation prior to the experiment. We selected 20 harvested fruit bunches at the plantation mill, sampled them for fruits and stalks, and made three composite samples for fruits and three composite samples for stalks. We used a subsample to measure gravimetric moisture content, by oven-drying these plant samples at 60 °C until stable weights were attained (5–7 days); the rest of the samples were oven-dried, ground, and analyzed for total N, P and K contents. Total N contents were determined using a CN analyzer (Vario EL Cube,



**Fig. 2** Soil sampling design at each treatment plot. The blue crosses represent the sampling points for the soil N cycling measurements and the red crosses represent the additional sampling points for the determination of soil biochemical characteristics

Elementar Analysis Systems GmbH, Hanau, Germany). For total P and K contents, samples were pressure-digested in concentrated  $\text{HNO}_3$ , followed by analysis of the digests using the inductively coupled plasma-atomic emission spectrometer (ICP-AES; iCAP 6300 Duo VIEW ICP Spectrometer, Thermo Fischer Scientific GmbH, Dreieich, Germany). The fruits contained on average  $0.5 \text{ g water g}^{-1}$ ,  $7 \text{ mg N g}^{-1}$ ,  $0.9 \text{ mg P g}^{-1}$ , and  $3.8 \text{ mg K g}^{-1}$ ; the stalks contained  $4.6 \text{ g water g}^{-1}$ ,  $1.1 \text{ mg N g}^{-1}$ ,  $1.1 \text{ mg P g}^{-1}$ , and  $62.6 \text{ mg K g}^{-1}$ . Based on the long-term yield records of our studied plantation, mean harvest was 11 fruit bunches  $\text{tree}^{-1} \text{ yr}^{-1}$ , averaging 23 kg (fresh weight) per fruit bunch with 70% fruits and 30% stalks. Using the measured moisture content of the fruit bunch above and the average planting density ( $142 \text{ trees ha}^{-1}$ ), the mean yield was  $17,000 \text{ kg dry fruits ha}^{-1} \text{ yr}^{-1}$  and  $2000 \text{ kg dry stalks ha}^{-1} \text{ yr}^{-1}$ . We multiplied these values with the measured nutrient concentrations to obtain the mean nutrient exports by harvest of  $136 \text{ kg N}$ ,  $17 \text{ kg P}$ , and  $187 \text{ kg K ha}^{-1} \text{ yr}^{-1}$ . These values were used as the basis for the reduced fertilizations rates.

### Soil fertility characteristics

Sampling was conducted in February 2018, 1.5 years since the start of the experiment and four months after the last fertilization and weeding. Soil biochemical characteristics were determined from the composite soil samples (taken from the top 5-cm depth) of each management zone at each treatment plot (Fig. 2). Subsamples of the air-dried, sieved (2 mm) soils were finely ground and analyzed for SOC (after removal of inorganic C, e.g. palm circle, by acid fumigation; Harris et al. 2001) and total N concentrations using a CN analyzer. The air-dried and sieved soils were used to measure pH in a 1:4 soil-to-water ratio, and ECEC by percolating the soils with unbuffered  $1 \text{ mol L}^{-1} \text{ NH}_4\text{Cl}$  and measuring the cations (Ca, Mg, K, Na, Al, Fe, Mn) in percolates using ICP-AES. Soil bulk density in the top 5 cm was measured using the same soil cores, and the values were used to convert the gravimetric moisture content to water-filled pore space, using a soil particle density of  $2.65 \text{ g cm}^{-3}$ .

### Gross rates of internal soil N cycling and microbial biomass

We measured the gross rates of soil N cycling on intact soil cores of the top 5 cm mineral soil, using the  $^{15}\text{N}$  pool dilution technique with in-situ incubation (Davidson et al. 1991). We measured all treatments from one block (Fig. 1) on the same day. At each treatment plot, we took five intact soil cores (8 cm diameter and 5 cm length) at each of the three management zones (Fig. 2). Two cores were injected with five 1-mL  $(^{15}\text{NH}_4)_2\text{SO}_4$  solution (containing  $27 \mu\text{g N mL}^{-1}$  with 95%  $^{15}\text{N}$  enrichment) to measure gross rates of N mineralization and microbial  $\text{NH}_4^+$  immobilization. Two other cores were injected with five 1-mL  $\text{K}^{15}\text{NO}_3$  solution (containing  $28 \mu\text{g N mL}^{-1}$  with 95%  $^{15}\text{N}$  enrichment) to measure gross nitrification, microbial  $\text{NO}_3^-$  immobilization and dissimilatory nitrate reduction to ammonium (DNRA). We used the remaining soil core to determine the background levels of  $\text{NH}_4^+$  and  $\text{NO}_3^-$  in the soil. From each pair of soil cores, one was extracted approximately 10 min after  $^{15}\text{N}$  injection (T0 cores) while the other intact core was extracted after incubation for one day in a loosely closed plastic bag in the field (T1 cores; Fig. S2). The T0 cores were used to correct for reactions that occur immediately after  $^{15}\text{N}$  injection. Soil mineral N extraction from the T0 and T1 cores was done by mixing the soil, removing roots, and placing a subsample into a pre-weighed bottle containing 150 mL  $0.5 \text{ mol L}^{-1} \text{ K}_2\text{SO}_4$  (approximately 1:3 ratio of fresh soil to solution). The bottles were then shaken for 1 h, and the solution was filtered through pre-washed (with  $0.5 \text{ mol L}^{-1} \text{ K}_2\text{SO}_4$ ) filter papers ( $4 \mu\text{m}$  nominal pore size). The extracts were frozen immediately, stored in a freezer, and transported by airfreight to Germany, where they were analyzed. Gravimetric moisture content was determined from each soil core, by oven-drying at  $105 \text{ }^\circ\text{C}$  for one day, and was used to calculate the dry mass of soils extracted for mineral N.

Analyses of  $^{15}\text{N}$  from the extracts were done following the  $^{15}\text{N}$  diffusion procedures outlined by Corre and Lamersdorf (2004). The  $^{15}\text{N}$  enrichment was determined using isotope ratio mass spectrometer (IRMS; Delta Plus, Finnigan MAT, Bremen, Germany); the precisions were 0.009% for  $^{15}\text{N-NH}_4^+$  analysis (from a standard containing 10.6%  $^{15}\text{N}$  in the form of  $(^{15}\text{NH}_4)_2\text{SO}_4$ ) and 0.061% for  $^{15}\text{N-NO}_3^-$

analysis (from a standard containing 11.7%  $^{15}\text{N}$  in the form of  $\text{K}^{15}\text{NO}_3$ ). The  $\text{NH}_4^+$  and  $\text{NO}_3^-$  concentrations in the extracts were determined by continuous flow injection colorimetry (SEAL Analytical AA3, SEAL Analytical GmbH, Norderstadt, Germany):  $\text{NH}_4^+$  was analyzed via salicylate and dichloroisocyanuric acid reaction (Autoanalyzer Method G-102-93) and  $\text{NO}_3^-$  was analyzed with cadmium reduction method with  $\text{NH}_4\text{Cl}$  buffer (Autoanalyzer Method G-254-02). We measured total N in the extracts by ultraviolet-persulfate digestion followed by hydrazine sulfate reduction using continuous flow injection colorimetry. Organic N was calculated as the difference between total N and mineral N ( $\text{NH}_4^+ + \text{NO}_3^-$ ) in the extracts.

We calculated gross rates of soil N cycling following the equations given by Davidson et al. (1991) and Hart et al. (1994b). Gross rates of N mineralization and nitrification were calculated from the  $^{15}\text{NH}_4^+$ - and  $^{15}\text{NO}_3^-$ -injected cores, respectively, based on the dilution of  $^{15}\text{N}$  enrichments in the  $\text{NH}_4^+$  or  $\text{NO}_3^-$  pools between the T0 and T1 cores. Microbial  $\text{NH}_4^+$  immobilization was calculated as the difference between  $\text{NH}_4^+$  consumption and gross nitrification, while  $\text{NO}_3^-$  immobilization was equal to  $\text{NO}_3^-$  consumption (Davidson et al. 1991). This method assumes that  $\text{NO}_3^-$  immobilization is the main consumption process of the  $\text{NO}_3^-$  pool, since DNRA and denitrification are usually low compared to gross nitrification rates (Davidson et al. 1991). The DNRA rates were calculated from the  $^{15}\text{NO}_3^-$ -injected cores following the calculation procedures of Silver et al. (2001). Turnover times of  $\text{NH}_4^+$ ,  $\text{NO}_3^-$  and microbial biomass N (see below) were calculated by dividing the pool with the flux rate.

We determined microbial biomass C and N using the fumigation-extraction method (Brookes et al. 1985; Davidson et al. 1984). We took a subsample (about 25 g fresh soil) from the T1 cores and fumigated it with  $\text{CHCl}_3$  for six days, after which the soil was extracted with  $0.5 \text{ mol L}^{-1} \text{ K}_2\text{SO}_4$  (approximately 1:5 ratio of fresh soil to solution) as described above. The concentrations of C in the extracts were analyzed by ultraviolet-enhanced persulfate oxidation, using a Total Organic Carbon Analyzer (TOC-Vwp; Shimadzu Europa GmbH, Duisburg, Germany) with an infrared detector and total N concentrations in the extracts were measured as described above. Microbial biomass C and N were calculated as the difference of

extractable C and N between the fumigated and unfumigated samples, divided by  $k_C = 0.45$  for microbial biomass C and by  $k_N = 0.68$  for microbial biomass N with a six-day fumigation (Brookes et al. 1985).

Compilation of data on internal soil N cycling, gaseous and leaching losses in large-scale and smallholder oil palm plantations and forest

To gain additional insights on soil N cycling with changes in management intensity and land use, we compared the soil N cycling rates from our present large-scale oil palm plantation with those measured in smallholder oil palm plantations and lowland forest sites (as the reference land use), reported by Allen et al. (2015), located in the same climatic area and soil type as our large-scale plantation site. This earlier work from our group used the same  $^{15}\text{N}$  pool dilution techniques for the same soil depth (top 5 cm) and had similar measurement season (January–March 2013, rainy season) as in our present study. Smallholder oil palm plantations have lower management intensity (i.e. fertilization rates ranged from 48 to 88 kg N, 21–38 kg P and 40–73 kg K  $\text{ha}^{-1} \text{ yr}^{-1}$ ; Allen et al. 2015) and the frond-stacked area is not spatially distinct as in our large-scale plantation. Soil  $\text{N}_2\text{O}$  and  $\text{N}_2$  fluxes are not yet quantified at our studied plantation but  $\text{N}_2\text{O}$  emissions have been reported for frond-stacked area of a large-scale oil palm plantation in Medan, Sumatra (Rahman et al. 2019) and for interrows and palm circle of a plot near our site (Hassler et al. 2017). For this data synthesis, we used these reported  $\text{N}_2\text{O}$  fluxes and we estimated  $\text{N}_2$  emissions using the global  $\text{N}_2\text{O}:(\text{N}_2 + \text{N}_2\text{O})$  ratios of 0.11 for agricultural soils and 0.12 for forest (Scheer et al. 2020). N leaching losses were taken from our earlier studies at the same plots (Formaglio et al. 2020) and the same smallholder oil palm and forest sites (Kurniawan et al. 2018). Our statistical comparison was conducted mainly on the soil N cycling processes, and the N gaseous and leaching losses were provided to support holistic interpretation.

Statistical analysis and comparison with smallholder oil palm plantations and forest

We tested each parameter for homogeneity of variance (using Levene's test) and normality of distribution

(using Shapiro–Wilk test). Log-transformation was used in case of unequal variance. First, we used a linear model to assess the effects of management treatment, spatial pattern (management zone) and their interaction on soil N cycling rates and soil properties. As there was no effect of management treatment  $\times$  spatial zone interaction on any of the parameters and as the most differences were observed among spatial zones, we assessed the effects of management treatments (with four replicate plots each) on soil N cycling rates within each spatial zone. As there were no treatment differences observed on any parameters, we assessed differences among spatial zones with the 16 plots considered as replicates. Differences among spatial zones were tested using one-way analysis of variance with Tukey HSD test for multiple comparisons. For the parameters that showed non-normal distributions, differences among spatial zones were tested using Kruskal–Wallis H test followed by the multiple comparison extension test. To assess the relationships of soil N cycling rates with soil biochemical parameters, we used Spearman rank correlation test on the mean of the four replicate plots per treatment, separated for each spatial zone ( $n = 12$ ; 4 treatments  $\times$  3 management zones). All statistical tests were considered significant at  $p \leq 0.05$ . All statistical analyses were carried out using R version 3.5.1 (R Core Team 2019).

To compare our present measurements of soil N cycling rates in the large-scale plantation with those from the smallholder plantations and reference forest, we averaged the rates from the palm circle and inter-row per treatment plot. The frond-stacked area was analyzed separately because frond-stacked areas were indistinguishable in the smallholder plantations. We converted the soil N cycling rates from soil mass basis ( $\text{mg N kg}^{-1} \text{ soil d}^{-1}$ ) to area basis ( $\text{g N m}^{-2} \text{ d}^{-1}$ ) using the measured soil bulk density, averaged for each management zone. We used the same statistical tests mentioned above.

## Results

### Soil fertility characteristics

Soil fertility parameters in the top 5 cm did not show any treatment effect (all  $p > 0.05$ ) but clearly differed among management zones. The frond-stacked area

had higher extractable C, extractable organic N, SOC, total N, and ECEC compared to the other zones (all  $p \leq 0.04$ ), whereas the inter-row had higher extractable C than the palm circle ( $p = 0.05$ ; Table 1). The palm circle showed a higher ECEC than the inter-row ( $p < 0.01$ ) and higher base saturation and pH compared to the other zones (both  $p < 0.01$ ), whereas the frond-stacked area had higher base saturation than the inter-row ( $p = 0.02$ ) but comparable pH ( $p = 0.44$ ; Table 1). Soil bulk density was lower in the frond-stacked area than the other zones ( $p < 0.01$ ) whereas this was comparable between the palm circle and inter-row ( $p = 0.89$ ; Table 1). The water-filled pore space and soil temperature showed little variation and were comparable among zones (all  $p > 0.05$ ; Table 1).

### Gross rates of soil N cycling and microbial biomass

After 1.5 year from the start of the management treatments, we did not detect any differences in soil N cycling processes among the experimental treatments, stratified according to management zone ( $p > 0.05$ ; Table 2). One exception was  $\text{NH}_4^+$  immobilization in the frond-stacked area, which was lower in the rw than in the cw and rh treatments ( $p \leq 0.04$ ; Table 2). We attributed this difference to a high proportion of gross nitrification relative to gross N mineralization in the rw treatment, resulting in low  $\text{NH}_4^+$  immobilization (Table 2).

In contrast, we detected clear differences in soil N cycling rates among management zones, especially between the frond-stacked area and the other two zones (Table 2). Gross N mineralization, gross nitrification, and  $\text{NH}_4^+$  and  $\text{NO}_3^-$  immobilization rates were larger in the frond-stacked area compared to the palm circle and inter-row (all  $p < 0.01$ ), and gross N mineralization was higher in the inter-row compared to the palm circle ( $p = 0.01$ ; Table 2). The DNRA rates were higher in the palm circle than in the inter-row ( $p = 0.05$ ; Table 2), but they were generally low, ranging only from 3% (frond-stacked area) to 16% (palm circle) of the gross nitrification. Thus, microbial  $\text{NO}_3^-$  immobilization was the main  $\text{NO}_3^-$  retention process. In the frond-stacked area, most of the produced  $\text{NH}_4^+$  was used for microbial  $\text{NH}_4^+$  immobilization, whereas in the palm circle and inter-row the importance of both  $\text{NH}_4^+$  immobilization and gross nitrification as fates of produced  $\text{NH}_4^+$  were



**Table 1** Soil fertility and physical characteristics (means  $\pm$  SE,  $n = 16$  plots) measured in the top 5 cm at the different management zones in a large-scale oil palm plantation in Jambi, Indonesia

Characteristics <sup>a</sup>	Frond-stacked area	Inter-row	Palm circle
Extractable C (mg C kg <sup>-1</sup> d <sup>-1</sup> )	280 $\pm$ 39 <sup>a</sup>	163 $\pm$ 8 <sup>b</sup>	85 $\pm$ 6 <sup>c</sup>
Extractable organic N (mg N kg <sup>-1</sup> )	15.5 $\pm$ 2.2 <sup>a</sup>	6.5 $\pm$ 0.6 <sup>b</sup>	3.9 $\pm$ 0.3 <sup>b</sup>
Soil organic C (g C kg <sup>-1</sup> )	47.6 $\pm$ 5.3 <sup>a</sup>	12.2 $\pm$ 0.6 <sup>b</sup>	11.9 $\pm$ 1.4 <sup>b</sup>
Total N (g N kg <sup>-1</sup> )	2.9 $\pm$ 0.3 <sup>a</sup>	0.9 $\pm$ 0.1 <sup>b</sup>	0.8 $\pm$ 0.1 <sup>b</sup>
Soil C:N ratio	16.0 $\pm$ 0.3 <sup>a</sup>	14.1 $\pm$ 0.2 <sup>b</sup>	15.1 $\pm$ 0.3 <sup>ab</sup>
ECEC <sup>b</sup> (mmolc kg <sup>-1</sup> )	113 $\pm$ 13 <sup>a</sup>	22 $\pm$ 2 <sup>c</sup>	72 $\pm$ 7 <sup>b</sup>
Base saturation (%)	96 $\pm$ 1 <sup>b</sup>	59 $\pm$ 6 <sup>c</sup>	100 $\pm$ 0 <sup>a</sup>
pH (1:4 H <sub>2</sub> O)	5.33 $\pm$ 0.12 <sup>b</sup>	5.17 $\pm$ 0.06 <sup>b</sup>	6.51 $\pm$ 0.05 <sup>a</sup>
Bulk density (g cm <sup>-3</sup> )	0.52 $\pm$ 0.06 <sup>a</sup>	1.20 $\pm$ 0.04 <sup>b</sup>	1.23 $\pm$ 0.04 <sup>b</sup>
Water filled pore space (%)	36.6 $\pm$ 1.3 <sup>a</sup>	34.6 $\pm$ 1.1 <sup>a</sup>	31.5 $\pm$ 0.8 <sup>a</sup>
Temperature (°C)	26.0 $\pm$ 0.3 <sup>a</sup>	25.5 $\pm$ 0.4 <sup>a</sup>	25.8 $\pm$ 0.5 <sup>a</sup>

<sup>a</sup>For each parameter, different letters indicate significant differences among management zones (one-way ANOVA with Tukey HSD or Kruskal–Wallis H test with multiple comparisons extension at  $p \leq 0.05$ )

<sup>b</sup>ECEC = effective cation exchange capacity

comparable (Table 2). The turnover times were comparable among management zones, averaging  $0.23 \pm 0.03$  days for  $\text{NH}_4^+$ ,  $0.34 \pm 0.08$  days for  $\text{NO}_3^-$  and  $7.8 \pm 0.5$  days for the microbial N pool. Across treatments and management zones, gross N mineralization and gross nitrification were correlated ( $r = 0.86$ ,  $p < 0.01$ ,  $n = 12$ ). DNRA did not show any correlation, either with N-cycling processes or with soil fertility parameters (all  $p > 0.05$ ).

Microbial biomass N was higher in the frond-stacked area compared to the other management zones ( $p < 0.01$ ) and lower in the palm circle than in the inter-row (marginally significant,  $p = 0.07$ ; Table 2). Microbial biomass C was also higher in the frond-stacked area than in the other zones ( $p < 0.01$ ; Table 2) and microbial biomass C:N ratio ( $14 \pm 4$ ) did not differ among management zones ( $p = 0.26$ ).

#### Controls on soil N cycle and comparison with smallholder plantations

Gross rates of N mineralization and nitrification were strongly correlated with microbial biomass N ( $r = 0.93$ – $0.95$ , all  $p < 0.01$ ,  $n = 12$ ) which, in turn, was positively correlated with extractable C and extractable organic N ( $r = 0.85$ – $0.87$ ,  $p < 0.01$ ,  $n = 12$ ). Extractable C and extractable organic N were also correlated with SOC and total N ( $r = 0.76$ – $0.89$ ,

$p < 0.01$ ,  $n = 12$ ), of which the latter were correlated with ECEC ( $r = 0.60$ – $0.77$ ,  $p \leq 0.04$ ,  $n = 12$ ).

Compared to the smallholder plantations, gross rates of mineral N production and immobilization were larger in the frond-stacked area of the large-scale plantation (all  $p \leq 0.03$ ; Fig. 3), while the inter-row and palm circle of the large-scale plantation had comparable soil N cycling rates as those in the smallholder plantations (Fig. 3). Mineral N production in the frond-stacked area was twice the rates of the forest, which also drove the larger microbial N immobilization rates in the frond-stacked area than the forest ( $p < 0.01$ ; Fig. 3). DNRA was higher in the forest than in the frond-stacked area ( $p = 0.02$ ); however, this process of N retention (by converting  $\text{NO}_3^-$  to less mobile  $\text{NH}_4^+$ ) was consistently lower than  $\text{NO}_3^-$  immobilization in all land uses (Fig. 3).

## Discussion

### Differences among management zones and effect of management practices

The substantial differences among management zones, notably the frond-stacked area with large extractable C, SOC, extractable organic N, total N and ECEC (Table 1), soil N cycling rates and

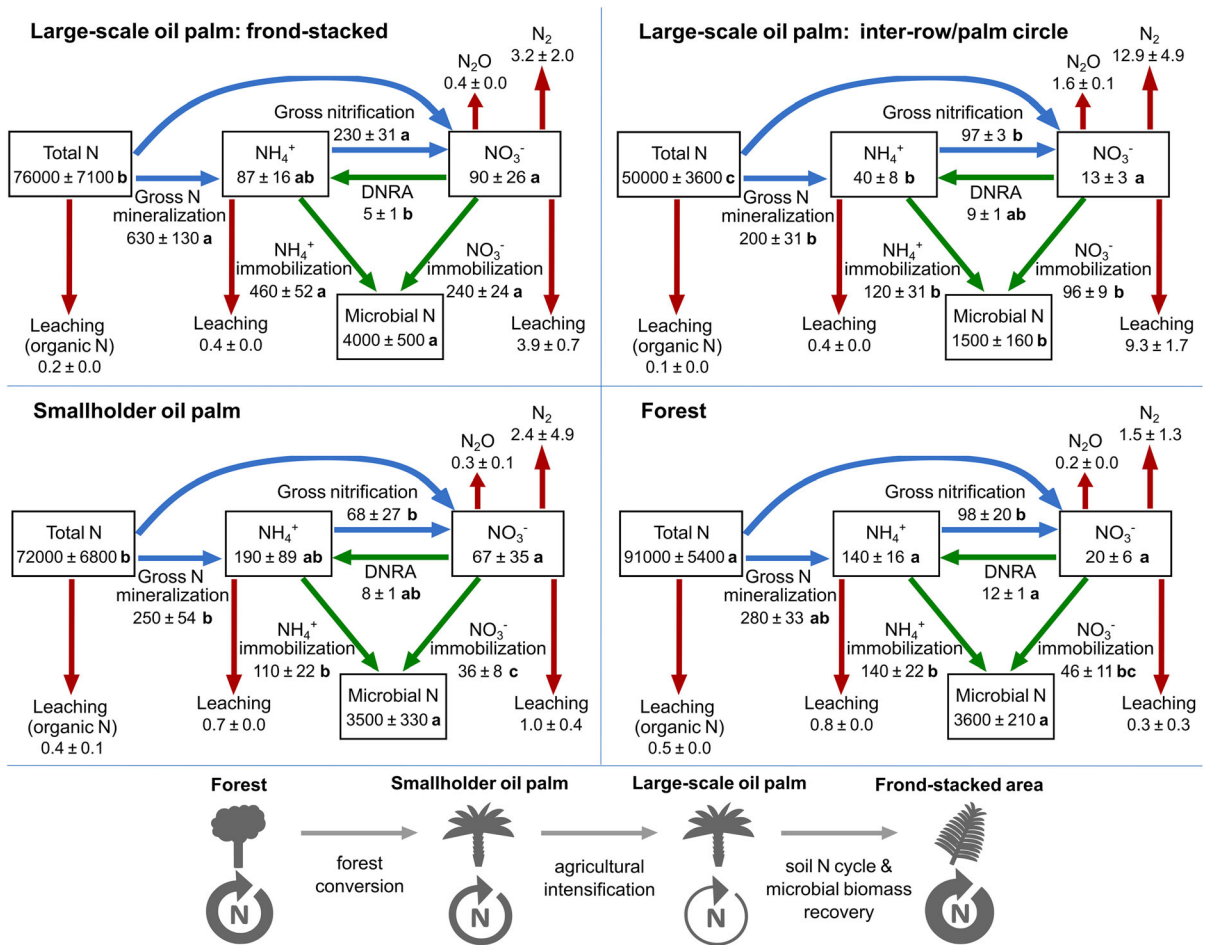
**Table 2** Gross rates of soil N cycling and microbial biomass N and C (means  $\pm$  SE,  $n = 4$  plots) in the top 5 cm for each treatment and management zone in a large-scale plantation in Jambi, Indonesia

Management zone <sup>a</sup>	Treatment <sup>b</sup>	Gross N mineralization mg N kg <sup>-1</sup> d <sup>-1</sup>	NH <sub>4</sub> <sup>+</sup> immobilization mg N kg <sup>-1</sup> d <sup>-1</sup>	Gross nitrification mg N kg <sup>-1</sup> d <sup>-1</sup>	NO <sub>3</sub> <sup>-</sup> immobilization mg N kg <sup>-1</sup> d <sup>-1</sup>	DNRA <sup>c</sup> mg N kg <sup>-1</sup> d <sup>-1</sup>	Microbial biomass N mg N kg <sup>-1</sup>	Microbial biomass C mg C kg <sup>-1</sup>
Frond-stacked area	ch	22.4 $\pm$ 3.3	17.4 $\pm$ 3.4 <sup>ab</sup>	6.4 $\pm$ 2.5	7.9 $\pm$ 2.8	0.2 $\pm$ 0.1	110 $\pm$ 16	780 $\pm$ 96
	cw	32.5 $\pm$ 8.0	20.7 $\pm$ 4.4 <sup>a</sup>	8.1 $\pm$ 3.1	7.5 $\pm$ 2.3	0.3 $\pm$ 0.1	200 $\pm$ 35	2400 $\pm$ 580
	rh	22.4 $\pm$ 7.2	26.8 $\pm$ 2.1 <sup>a</sup>	9.4 $\pm$ 2.2	10.5 $\pm$ 1.9	0.0 $\pm$ 0.0	200 $\pm$ 50	2100 $\pm$ 770
	rw	16.6 $\pm$ 5.2	5.4 $\pm$ 1.7 <sup>b</sup>	12.3 $\pm$ 2.9	10.9 $\pm$ 3.0	0.3 $\pm$ 0.1	120 $\pm$ 20	1300 $\pm$ 300
	Average	<b>24.4 <math>\pm</math> 5.0<sup>A</sup></b>	<b>17.6 <math>\pm</math> 2.0<sup>A</sup></b>	<b>9.0 <math>\pm</math> 1.2<sup>A</sup></b>	<b>9.2 <math>\pm</math> 0.9<sup>A</sup></b>	<b>0.2 <math>\pm</math> 0.1<sup>AB</sup></b>	<b>150 <math>\pm</math> 19<sup>A†</sup></b>	<b>1600 <math>\pm</math> 370<sup>A</sup></b>
Inter-row	ch	4.8 $\pm$ 1.1	3.2 $\pm$ 1.2	1.6 $\pm$ 0.2	1.5 $\pm$ 0.2	0.2 $\pm$ 0.1	43 $\pm$ 11	560 $\pm$ 200
	cw	4.0 $\pm$ 0.6	1.7 $\pm$ 0.5	2.5 $\pm$ 0.5	3.0 $\pm$ 1.4	0.1 $\pm$ 0.0	26 $\pm$ 4	340 $\pm$ 84
	rh	3.8 $\pm$ 0.8	2.5 $\pm$ 0.6	1.2 $\pm$ 0.2	1.2 $\pm$ 0.4	0.0 $\pm$ 0.0	22 $\pm$ 3	400 $\pm$ 78
	rw	4.4 $\pm$ 0.9	2.9 $\pm$ 1.1	1.8 $\pm$ 0.3	1.4 $\pm$ 0.1	0.0 $\pm$ 0.0	27 $\pm$ 5	330 $\pm$ 59
	Average	<b>4.2 <math>\pm</math> 0.8<sup>B</sup></b>	<b>2.6 <math>\pm</math> 0.8<sup>B</sup></b>	<b>1.8 <math>\pm</math> 0.1<sup>B</sup></b>	<b>1.7 <math>\pm</math> 0.4<sup>B</sup></b>	<b>0.1 <math>\pm</math> 0.0<sup>B</sup></b>	<b>29 <math>\pm</math> 4<sup>B†</sup></b>	<b>410 <math>\pm</math> 100<sup>B</sup></b>
Palm circle	ch	2.2 $\pm$ 0.6	1.5 $\pm$ 0.5	1.4 $\pm$ 0.4	1.6 $\pm$ 0.3	0.1 $\pm$ 0.0	19 $\pm$ 3	280 $\pm$ 53
	cw	1.9 $\pm$ 0.4	1.2 $\pm$ 0.1	1.5 $\pm$ 0.2	1.7 $\pm$ 0.5	0.1 $\pm$ 0.0	21 $\pm$ 6	320 $\pm$ 89
	rh	1.8 $\pm$ 0.6	0.9 $\pm$ 0.4	1.2 $\pm$ 0.2	1.0 $\pm$ 0.2	0.1 $\pm$ 0.0	16 $\pm$ 1	210 $\pm$ 68
	rw	3.4 $\pm$ 0.2	1.6 $\pm$ 0.3	1.5 $\pm$ 0.1	1.3 $\pm$ 0.2	0.5 $\pm$ 0.2	24 $\pm$ 3	320 $\pm$ 78
	Average	<b>2.3 <math>\pm</math> 0.3<sup>C</sup></b>	<b>1.3 <math>\pm</math> 0.3<sup>B</sup></b>	<b>1.4 <math>\pm</math> 0.1<sup>B</sup></b>	<b>1.4 <math>\pm</math> 0.1<sup>B</sup></b>	<b>0.2 <math>\pm</math> 0.0<sup>A</sup></b>	<b>20 <math>\pm</math> 2<sup>C†</sup></b>	<b>280 <math>\pm</math> 62<sup>B</sup></b>

<sup>a</sup>Values in bold are the means across treatments for each management zone. Different lowercase letters indicate significant differences among treatments for each management zone, while different capital letters indicate significant differences among management zones across treatments (one-way ANOVA with Tukey HSD or Kruskal–Wallis H test with multiple comparisons extension at  $p \leq 0.05$ , <sup>†</sup>except for microbial N where  $p = 0.07$ ). No letter designation means there were no significant differences among treatments

<sup>b</sup>Treatments: ch = conventional fertilization – herbicide, cw = conventional fertilization – mechanical weeding, rh = reduced fertilization – herbicide, rw = reduced fertilization – mechanical weeding

<sup>c</sup>DNRA = dissimilatory nitrate reduction to ammonium



**Fig. 3** Mean ( $\pm$  SE,  $n = 4$  plots) gross rates of soil N cycling ( $\text{mg N m}^{-2} \text{d}^{-1}$ ), and N pools ( $\text{mg N m}^{-2}$ , in black boxes), measured in the top 5-cm depth, in large-scale and smallholder oil palm plantations and lowland forest (the latter taken from Allen et al. 2015), all on loam Acrisol soils in Jambi, Indonesia. Blue arrows represent soil N production processes, green arrows represent soil N retention processes, and red arrows represent soil N losses that have been quantified in other studies. For each parameter, different letters indicate significant differences among land uses (one-way ANOVA with Tukey HSD or Kruskal–Wallis H test with multiple comparison extension at

$P \leq 0.05$ ). Soil N<sub>2</sub>O emissions ( $\text{mg N m}^{-2} \text{d}^{-1}$ ) in the frond-stacked area were reported by Rahman et al. (2019) for a large-scale plantation in Sumatra; N<sub>2</sub>O emissions in palm circle and inter-row were reported by Hassler et al. (2017) for our studied large-scale plantation and for the same smallholder oil palm and forest sites. N<sub>2</sub> emissions ( $\text{mg N m}^{-2} \text{d}^{-1}$ ) were derived from the global N<sub>2</sub>O:(N<sub>2</sub>O + N<sub>2</sub>) ratios of 0.11 for agricultural soils and 0.12 for forest (Scheer et al. 2020). N leaching losses ( $\text{mg N m}^{-2} \text{d}^{-1}$ , measured at 1.5-m depth) were reported by Formaglio et al. (2020) for our studied large-scale plantation and by Kurniawan et al. (2018) for the same smallholder oil palm and forest sites

microbial biomass (Table 2), supported our first hypothesis, and illustrated the importance of considering management-induced heterogeneity when measuring soil properties. The frond-stacked area had soil N cycling rates that were generally higher than in forests in the same region (Fig. 3), but lower than the rates reported for oil palm plantations and a forest on poorly-drained soils in Malaysia (mineralization:  $1500 \pm 150 \text{ mg N m}^{-2} \text{d}^{-1}$  in oil palm and

$1000 \pm 150 \text{ mg N m}^{-2} \text{d}^{-1}$  in forest, in the top 10 cm of soil; Hamilton et al. 2016). In contrast, soil N cycling rates in the palm circle and inter-row were comparable with rates in smallholder oil palm plantations in the same region (Fig. 3). Relative to the other N transformation rates, DNRA rates were negligible (Table 2) and in the lower range of values reported for smallholder oil palm plantations and forests in the same region (Fig. 3). Since DNRA

mainly occurs in soils with high labile C and high water-filled pore space (Friedl et al. 2018), the low DNRA rates in our plantations likely resulted from low water-filled pore space in all the management zones in combination with low C in the palm circles and inter-rows (Table 1). Comparing with other studies in large-scale oil palm plantations in Southeast Asia with similar age as our studied plantation, one study reported that the frond-stacked area had higher microbial biomass, SOC and N contents (although soil N cycling was not measured) relative to the other management zones (Haron et al. 1998). However, other studies did not detect differences in SOC and N contents between management zones (Tao et al. 2016) or even found higher SOC in the palm circle compared to the frond-stacked area (Carron et al. 2015). In our study site as well as in the study by Haron et al. (1998), the senesced fronds were piled on the inter-row whereas in studies that found contrasting results (Tao et al. 2016; Carron et al. 2015) the fronds were distributed around the palms. The latter practice, however, is uncommon in oil palm plantations in Jambi province, as it hinders easy access to the palms during harvest.

At our site, high SOC and total N in the frond-stacked area were corroborated by high extractable C and organic N (Table 1), which could indicate large organic matter input from decomposing fronds (Frazão et al. 2014). The low bulk density in the frond-stacked area was also in line with the high organic matter contents (Table 1). Approximately 9.8 Mg dry matter ha<sup>-1</sup> yr<sup>-1</sup> of pruned fronds are stacked in this area at a rate of 20–24 fronds tree<sup>-1</sup> yr<sup>-1</sup> (Aljuboori 2013; Corley and Tinker 2016) and their decomposition releases significant amounts of nutrients into the soil (Moradi et al. 2014). In addition, the frond-stacked area differed from the other zones as the soil is covered, has low risk of erosion and has sparse understory vegetation, all influencing organic matter dynamics. The correlation of SOC and total N with ECEC showed the importance of organic matter as the dominant contributor to the ECEC (particularly for the frond-stacked area) of highly weathered Acrisol soils (Veldkamp et al., 2020). The stimulating effect of mulching on soil N cycling, microbial biomass N and soil organic matter has also been shown in other plantations (Huang et al. 2008); in oil palm plantations, mulching with empty fruit bunches from palm oil processing have improved soil

biochemical characteristics, such as SOC, ECEC, base saturation and soil fauna feeding activity (Abu Bakar et al. 2011; Tao et al. 2016). These results suggest that mulching with senesced fronds in the frond-stacked areas of plantations, instead of exporting or burning them, can recover soil N cycling and fertility (i.e. increases in microbial biomass, SOC, total N, ECEC and base saturation; Tables 1 and 2) in this otherwise inherently nutrient poor, Acrisol soils (Allen et al. 2016). Since oil palm can develop considerable root density in the frond-stacked area (Rüegg et al. 2019), high nutrient contents in this zone may contribute to oil palm nutrition, reducing the dependency on chemical fertilizers.

Contrary to our second hypothesis, we did not detect any effect of the management intensity treatments on soil N cycling rates (Table 2) and soil fertility characteristics. This may be due to the fact that the reduced fertilization still added a substantial amount of nutrients, to sustain high production, and that weeding effects on understory vegetation were too small to affect soil properties. The reduced management was established only 1.5 years before we conducted our measurements as opposed to the prior conventional management that had already been employed since the plantation establishment in the last 16–20 years. The understory vegetation responded to the weed management (Fig. S1) with 14% less cover in the inter-rows of the herbicide treatments compared to the mechanical weeding (Darras et al. 2019). However, in both weeding treatments the ground vegetation is removed two times in a year, so that differences in ground vegetation cover were only transitional. Thus, effects of weed management on soil properties will likely be evident only after years of treatment. Similarly, an experiment on understory vegetation manipulation in a large-scale oil palm plantation in Riau province, Indonesia, did not show any effect on soil characteristics after two years of treatment (Ashton-Butt et al. 2018). Other studies that investigated effects of nutrient manipulation on soil N cycling in the tropics did not detect effects after one year of treatment (Corre et al. 2010; Silver et al. 2005) but only after 3–4 years (Baldos et al. 2015; Corre et al. 2014) and more clearly after 9–11 years (Corre et al. 2010; Hall and Matson 1999). It is thus possible that treatment effects on soil nutrient cycling and fertility characteristics only emerge after this management experiment has

continued for several more years. Also, the first three years of our management intensity manipulation did not result in yield difference among treatments (Formaglio et al. 2020); however, a long-term effect on yield is fundamental to evaluate the profitability of the reduced management practices.

#### Controls on soil N cycle and comparison with smallholder plantations and forests

In the frond-stacked area, microbial immobilization was the main consumption process of produced mineral N (Table 2), which was mirrored by a large N demand by a large microbial biomass and extractable C (Table 1 and 2; Hart et al. 1994a). The short turnover times of mineral N and microbial N pools suggest a highly dynamic cycling between labile and organic N pools via microbial immobilization. Comparable short turnover times for  $\text{NH}_4^+$  have been reported for a forest in Puerto Rico ( $0.5 \pm 0.1$  d; Silver et al. 2001) and for coffee agroforestry in Indonesia (0.5 – 1 d; Corre et al. 2006). Microbial immobilization could be an efficient retention mechanism, reducing leaching and gaseous N losses. Indeed, our ancillary study at the same plots show low N leaching in the frond-stacked area (Fig. 3; Formaglio et al. 2020). Gaseous N losses (based from Rahman et al. 2018, Hassler et al. 2017, and Scheer et al. 2020 for  $\text{N}_2$  estimates) were also low in the frond-stacked area relative to the other zones (Fig. 3). Moreover, in the inter-row and palm circle, nitrification became a more important process relative to  $\text{NH}_4^+$  immobilization. For the palm circle, this could be the result of periodic N fertilization, which promotes gross nitrification despite a low microbial biomass (Baldos et al. 2015; Corre et al. 2010; Zhang et al. 2013). It is important to note that our measured soil N cycling rates represented soil conditions beyond the short-term pulse effects of N-fertilizer application, which generally caused elevated mineral N concentrations for up to six weeks following fertilization (Hassler et al. 2017). Thus, the generally comparable soil N cycling rates between the fertilized palm circle and the unfertilized inter-row suggest that excess N from pulse N fertilizer application may have been taken up by the palms (Edy et al. 2020), lost via gaseous emissions (Hassler et al. 2017), or moved down in the soil profile and eventually leached (Formaglio et al. 2020). The low gross N

mineralization in the palm circle illustrated the inherently low N-supplying capacity of the soil in this intensively managed area, and illustrated its dependence on chemical fertilizer inputs to maintain palm productivity.

The microbial biomass was the main predictor of the soil N cycle in our studied plantation, as indicated by the strong correlation of soil N cycling rates with microbial biomass N. Microbial biomass was, in turn, mainly regulated by the input of organic matter as suggested by correlations of microbial N with extractable C and extractable organic N, and with SOC and total N. Other studies on litter manipulation have reported a decrease in microbial biomass with litter removal from tropical forests (Leff et al. 2012; Sayer et al. 2012) and tree plantations (Li et al. 2004; Mendham et al. 2002). In the management zones that received a limited amount of litter, we also detected lower microbial biomass and soil N cycling rates (Table 2). The limited vegetation cover in the palm circle, due to frequent weeding and raking (see Methods section), resulted in lower extractable C (Table 1), which probably constrained microbial biomass compared to the inter-row, and may have led to lower gross N mineralization rates (Table 2). Despite the high base saturation (Table 1), a result of liming and K fertilization, the microbial biomass in the palm circle remained low. These results highlight the importance of litter manipulation in altering the organic matter input into the soil and consequently the soil N cycle, as was shown before in tropical forests (Wieder et al. 2013). Management practices should thus aim at increasing the input of organic matter in order to enhance microbial biomass and promote the soil N cycle.

The palm circle and the inter-row had lower total N and microbial N contents than the smallholder oil palm plantations (Fig. 3), suggesting that the intensive management in the large-scale plantation, such as regular weeding and stacking the frond litter, had a larger impact on reducing organic matter than the lower intensity of management in the smallholder plantations. In contrast, the frond-stacked area had larger gross N mineralization rates than the smallholder oil palm plantations (Fig. 3), illustrating the recuperation of the soil's N-supplying capacity when organic matter input is restored. The larger gross nitrification in the frond-stacked area compared to forest (Fig. 3) could be the result of increased

abundance of nitrifiers in the soils resulting from increased N mineralization of nutrient-rich leaf litter. This is supported by a study in the same area that recorded higher abundance of nitrification-related taxa in oil palm plantations compared to forest (Berkelmann et al. 2018). Furthermore, lower DNRA (relative to nitrification and  $\text{NO}_3^-$  immobilization) in the frond-stacked area compared to forest (Fig. 3) suggests a functional shift, which may be driven in part by changes in microbial community composition. In the same forest and smallholder oil palm sites, the bacterial community in the soil shifted from proteobacterial groups in the forest to *Acidobacteria* in oil palm plantations with higher diversity of the soil prokaryotic communities in oil palm than in forest (Schneider et al. 2015). The larger microbial C and C:N ratio in the frond-stacked area (Table 2) compared to the forests (microbial C of  $514 \pm 48 \text{ mg C kg}^{-1}$  and microbial C:N ratio of  $7.2 \pm 0.3$ ; Allen et al. 2015) may explain the larger N immobilization rates in the frond-stacked area compared to the forest (Fig. 3), as immobilization can be fueled by increased availability of organic matter (Table 1; Booth et al. 2005; Hart et al. 1994a). Altogether, these findings suggest that mulching with senesced fronds in frond-stacked areas of oil palm plantations can be an effective practice to restore soil N cycling rates and microbial biomass size to levels comparable with, or even higher than, the forest.

## Conclusion

At this early stage of this management experiment in a large-scale oil palm plantation, our study revealed that nutrient cycling can be sustained by retaining the litter in the plantation. For this inherently nutrient-poor Acrisol soil, this can reduce dependency on large fertilizer and liming inputs. Management practices should aim at increasing the return of litter and other organic by-products of palm oil production to the soil in order to promote microbial biomass and nutrient recycling. Supporting soil N cycling rates with measurements of functional diversity of microbial community would be an important next step to manage better the functional diversity of the soil microbiome to sustain fertility. This management experiment warrants further investigation on whether long-term reduction in management intensity can minimize the

environmental footprint while maintaining productivity and profit. Our findings on the benefits of using senesced fronds for soil mulching can be used as a field criterion for RSPO certification of soil nutrient management. Investigations on other nutrient-rich by-products of oil palm processing, e.g. empty fruit bunches, are also needed to explore other measures for decreasing dependency on chemical fertilizers while restoring soil nutrient cycling.

**Acknowledgements** This study was funded by the Deutsche Forschungsgemeinschaft (DFG) project number 192626868—SFB 990) in the framework of the Collaborative Research Center 990 EForTS as part of project A05. We thank PT Perkebunan Nusantara VI (PTPN VI) for allowing us to conduct our research in their plantation. We are especially thankful to our Indonesian field and laboratory assistants, Happy Chandra, Fajar Sidik and Sofyan Raden, as well as Kevin Darras and the project Z01 for managing the field implementation of this experiment. We acknowledge Christian Stiegler and the project A03 for the climate data. We also acknowledge Reinhard Langel and Lars Szewc from the Centre for Stable Isotope Research and Analysis (Goettingen University). We thank Andrea Bauer, Martina Knaust, and Kerstin Langs for their assistance in the laboratory analysis. This study was conducted under the research permit 539351/SIP/FRP/E5/Dit.KI/X/2016.

**Authors' contributions** EV and MDC conceptualized the study design, methodologies and laboratory analyses. AT and MD facilitated field access, logistical support, collaborator agreements and material exports. GF conducted the field works and data analysis, and wrote the first draft of the manuscript. MDC and EV revised and commented on the previous versions, and all co-authors suggested and approved the final manuscript.

**Funding** Open Access funding enabled and organized by Projekt DEAL. Deutsche Forschungsgemeinschaft (DFG) project ID 192626868 (SFB 990/2) as part of project A05.

**Availability of data and material** All data of this study are deposited at the EForTS-IS data repository (<https://efforts-is.uni-goettingen.de>), an internal data-exchange platform, which is accessible to all members of the Collaborative Research Center (CRC) 990. Based on the data sharing agreement within the CRC 990, these data are currently not publicly accessible but will be made available through a written request to the senior author.

## Declaration

**Conflict of interest** All authors declare no conflict of interest.

**Consent to participate** All authors approved.

**Consent for publication** All authors approved.

**Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use,

sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

## References

- Abu Bakar R, Darus SZ, Kulaseharan S, Jamaluddin N (2011) Effects of ten year application of empty fruit bunches in an oil palm plantation on soil chemical properties. *Nutr Cycl Agroecosyst* 89(3):341–349. <https://doi.org/10.1007/s10705-010-9398-9>
- Allen K, Corre MD, Kurniawan S, Utami SR, Veldkamp E (2016) Spatial variability surpasses land-use change effects on soil biochemical properties of converted lowland landscapes in Sumatra, Indonesia. *Geoderma* 284:42–50. <https://doi.org/10.1016/j.geoderma.2016.08.010>
- Allen K, Corre MD, Tjoa A, Veldkamp E (2015) Soil nitrogen-cycling responses to conversion of lowland forests to oil palm and rubber plantations in Sumatra, Indonesia. *PLoS ONE* 10(7):e0133325. <https://doi.org/10.1371/journal.pone.0133325>
- Aljuboori AHR (2013) Oil palm biomass residue in Malaysia: availability and sustainability. *Int J Biomass Renew* 1:13–18
- Ashton-Butt A, Aryawan AAK, Hood ASC, Naim M, Purnomo D, Suhardi WR, Willcock S, Poppy GM, Caliman J-P, Turner EC, Foster WA, Peh KSH, Snaddon JL (2018) Understorey vegetation in oil palm plantations benefits soil biodiversity and decomposition rates. *Front For Glob Chang* 1:19. <https://doi.org/10.3389/ffgc.2018.00010>
- Baldos AP, Corre MD, Veldkamp E (2015) Response of N cycling to nutrient inputs in forest soils across a 1000–3000 m elevation gradient in the Ecuadorian Andes. *Ecology* 96(3):749–761. <https://doi.org/10.1890/14-0295.1>
- Bauters M, Verbeeck H, Rütting T, Barthel M, Bazirake Mujinya B, Bamba F, Bodé S, Boyemba F, Bulonza E, Carlsson E, Eriksson L, Makelele I, Six J, Cizungu Ntaboba L, Boeckx P (2019) Contrasting nitrogen fluxes in African tropical forests of the Congo Basin. *Ecol Monogr* 89(1):e01342. <https://doi.org/10.1002/ecm.1342>
- Berkelmann D, Schneider D, Engelhaupt M, Heinemann M, Christel S, Wijayanti M, Meryandini A, Daniel R (2018) How rainforest conversion to agricultural systems in Sumatra (Indonesia) affects active soil bacterial communities. *Front Microbiol* 9:2381. <https://doi.org/10.3389/fmicb.2018.02381>
- Booth MS, Stark JM, Rastetter E (2005) Controls on nitrogen cycling in terrestrial ecosystems: a synthetic analysis of literature data. *Ecol Monogr* 75(2):139–157. <https://doi.org/10.1890/04-0988>
- Brookes PC, Landman A, Pruden G, Jenkinson DS (1985) Chloroform fumigation and the release of soil nitrogen: a rapid direct extraction method to measure microbial biomass nitrogen in soil. *Soil Biol Biochem* 17(6):837–842. [https://doi.org/10.1016/0038-0717\(85\)90144-0](https://doi.org/10.1016/0038-0717(85)90144-0)
- Carron MP, Auriac Q, Snoeck D, Villenave C, Blanchart E, Ribeyre F, Marichal R, Darminto M, Caliman JP (2015) Spatial heterogeneity of soil quality around mature oil palms receiving mineral fertilization. *Eur J Soil Biol* 66:24–31. <https://doi.org/10.1016/j.ejsobi.2014.11.005>
- Carter C, Finley W, Fry J, Jackson D, Willis L (2007) Palm oil markets and future supply. *Eur J Lipid Sci Technol* 109:307–314. <https://doi.org/10.1002/ejlt.200600256>
- Clough Y, Krishna VV, Corre MD, Darras K, Denmead LH, Meijide A, Moser S, Musshoff O, Steinebach S, Veldkamp E, Allen K, Barnes AD, Breidenbach N, Brose U, Buchori D, Daniel R, Finkeldey R, Harahap I, Hertel D, Holtkamp AM, Hörandl E, Irawan B, Jaya INS, Jochum M, Klärner B, Knohl A, Kotowska MM, Krashevskaya V, Kreft H, Kurniawan S, Leuschner C, Maraun M, Melati DN, Opfermann N, Pérez-Cruzado C, Prabowo WE, Rembold K, Rizali A, Rubiana R, Schneider D, Tjitrosoedirdjo SS, Tjoa A, Tschamtko T, Scheu S (2016) Land-use choices follow profitability at the expense of ecological functions in Indonesian smallholder landscapes. *Nat Commun* 7:13137. <https://doi.org/10.1038/ncomms13137>
- Comte I, Colin F, Whalen JK, Grünberger O, Caliman J-P (2012) Agricultural practices in oil palm plantations and their impact on hydrological changes, nutrient fluxes and water quality in Indonesia. *Adv Agron* 116:71–124. <https://doi.org/10.1016/B978-0-12-394277-7.00003-8>
- Cookson WR, Marschner P, Clark IM, Milton N, Smirk MN, Murphy DV, Osman M, Stockdale EA, Hirsch PR (2006) The influence of season, agricultural management, and soil properties on gross nitrogen transformations. *Aust J Soil Res* 44(4):453–465. <https://doi.org/10.1071/SR05042>
- Corley RHV, Tinker PB (2016) *The oil palm*, 5th edn. Wiley, Hoboken, NJ
- Corre MD, Dechert G, Veldkamp E (2006) Soil nitrogen cycling following montane forest conversion in Central Sulawesi, Indonesia. *Soil Sci Soc Am J* 70:359–366. <https://doi.org/10.2136/sssaj2005.0061>
- Corre MD, Lamersdorf NP (2004) Reversal of nitrogen saturation after long-term deposition reduction: impact on soil nitrogen cycling. *Ecology* 85(11):3090–3104. <https://doi.org/10.1890/03-0423>
- Corre MD, Sueta JP, Veldkamp E (2014) Nitrogen-oxide emissions from tropical forest soils exposed to elevated nitrogen input strongly interact with rainfall quantity and seasonality. *Biogeochemistry* 118:103–120. <https://doi.org/10.1007/s10533-013-9908-3>
- Corre MD, Veldkamp E, Arnold J, Wright SJ (2010) Impact of elevated N input on soil N cycling and losses in old-growth lowland and montane forests in Panama. *Ecology* 91(6):1715–1729. <https://doi.org/10.1890/09-0274.1>
- Craine JM, Brookshire ENJ, Cramer MD, Hasselquist NJ, Koba K, Marin-Spiotta E, Wang L (2015) Ecological interpretations of nitrogen isotope ratios of terrestrial plants and

- soils. *Plant Soil* 396:1–26. <https://doi.org/10.1007/s11004-015-2542-1>
- Darras KFA, Corre MD, Formaglio G, Tjoa A, Potapov A, Brambach F, Sibhatu KT, Grass I, Rubiano AA, Buchori D, Drescher J, Fardiansah R, Hölscher D, Irawan B, Kneib T, Krashevskaya V, Krause A, Kreft H, Li K, Maraun M, Polle A, Ryadin AR, Rembold K, Stiegler C, Scheu S, Tarigan S, Valdés-Urube A, Yadi S, Tschardt T, Veldkamp E (2019) Reducing fertilizer and avoiding herbicides in oil palm plantations—ecological and economic valuations. *Front For Glob Chang*. <https://doi.org/10.3389/ffgc.2019.00065>
- Davidson CL, de Gee AJ, Feilzer A (1984) The competition between the composite-dentin bond strength and the polymerization contraction stress. *J Dent Res* 63(12):1396–1399. <https://doi.org/10.1177/00220345840630121101>
- Davidson EA, Hart SC, Shanks CA, Firestone MK (1991) Measuring gross nitrogen mineralization, and nitrification by  $^{15}\text{N}$  isotopic pool dilution in intact soil cores. *J Soil Sci* 42:335–349. <https://doi.org/10.1111/j.1365-2389.1991.tb00413.x>
- Directorate General of Estate Crop (2017) Tree crop estate statistics of Indonesia 2015 - 2017: palm oil
- Dislich C, Keyel AC, Salecker J, Kisel Y, Meyer KM, Auliya M, Barnes AD, Corre MD, Darras K, Faust H, Hess B, Klasen S, Knohl A, Kreft H, Mejjide A, Nurdiansyah F, Otten F, Pe'er G, Steinebach S, Tarigan S, Tölle MH, Tschardt T, Wiegand K (2017) A review of the ecosystem functions in oil palm plantations, using forests as a reference system. *Biol Rev Camb Philos Soc* 92:1539–1569. <https://doi.org/10.1111/brv.12295>
- Edy N, Yelianti U, Irawan B, Polle A, Pena R (2020) Differences in root nitrogen uptake between tropical lowland rainforests and oil palm plantations. *Front Plant Sci* 11:92. <https://doi.org/10.3389/fpls.2020.00092>
- FAO (2017) Food and Agriculture Organization, FAOSTAT. <http://faostat.fao.org/site/339/default.aspx>. Accessed 23 Aug 2019
- Figueiredo V, Enrich-Prast A, Rütting T (2019) Evolution of nitrogen cycling in regrowing Amazonian rainforest. *Sci Rep* 9(1):8538. <https://doi.org/10.1038/s41598-019-43963-4>
- Formaglio G, Veldkamp E, Duan X, Tjoa A, Corre MD (2020) Herbicide weed control increases nutrient leaching compared to mechanical weeding in a large-scale oil palm plantation. *Biogeosciences* 17:5243–5262. <https://doi.org/10.5194/bg-17-5243-2020>
- Frazão LA, Paustian K, Cerri CEP, Cerri CC (2014) Soil carbon stocks under oil palm plantations in Bahia State, Brazil. *Biomass Bioenergy* 62:1–7. <https://doi.org/10.1016/j.biombioe.2014.01.031>
- Friedl J, de Rosa D, Rowlings DW, Grace PR, Müller C, Scheer C (2018) Dissimilatory nitrate reduction to ammonium (DNRA), not denitrification dominates nitrate reduction in subtropical pasture soils upon rewetting. *Soil Biol Biochem* 125:340–349. <https://doi.org/10.1016/j.soilbio.2018.07.024>
- Grass I, Kubitzka C, Krishna VV, Corre MD, Mußhoff O, Pütz P, Drescher J, Rembold K, Ariyanti ES, Barnes AD, Brinkmann N, Brose U, Brümmer B, Buchori D, Daniel R, Darras KFA, Faust H, Fehrmann L, Hein J, Hennings N, Hidayat P, Hölscher D, Jochum M, Knohl A, Kotowska MM, Krashevskaya V, Kreft H, Leuschner C, Lobite NJS, Panjaitan R, Polle A, Potapov AM, Purnama E, Qaim M, Röhl A, Scheu S, Schneider D, Tjoa A, Tschardt T, Veldkamp E, Wollni M (2020) Trade-offs between multifunctionality and profit in tropical smallholder landscapes. *Nat Commun* 11(1):1186. <https://doi.org/10.1038/s41467-020-15013-5>
- Hall SJ, Matson PA (1999) Nitrogen oxide emissions after nitrogen additions in tropical forests. *Nature* 400:152. <https://doi.org/10.1038/22094>
- Hamilton LR, Trimmer M, Bradley C, Pinay G (2016) Deforestation for oil palm alters the fundamental balance of the soil N cycle. *Soil Biol Biochem* 95:223–232. <https://doi.org/10.1016/j.soilbio.2016.01.001>
- Haron K, Brookes PC, Anderson JM, Zakaria ZZ (1998) Microbial biomass and soil organic matter dynamics in oil palm (*Elaeis Guineensis* Jacq.) plantations, West Malaysia. *Soil Biol Biochem* 30(5):547–552. [https://doi.org/10.1016/S0038-0717\(97\)00217-4](https://doi.org/10.1016/S0038-0717(97)00217-4)
- Harris D, Horváth WR, van Kessel C (2001) Acid fumigation of soils to remove carbonates prior to total organic carbon or carbon-13 isotopic analysis. *Soil Sci Soc Am J* 65:1853–1856. <https://doi.org/10.2136/sssaj2001.1853>
- Hart SC, Nason GE, Myrold DD, Perry DA (1994a) Dynamics of gross nitrogen transformations in an old-growth forest: the carbon connection. *Ecology* 75(4):880–891. <https://doi.org/10.2307/1939413>
- Hart SC, Stark JM, Davidson EA, Firestone MK (1994b) Nitrogen mineralization, immobilization, and nitrification. *Methods of Soil Analysis. Part 2. Soil Science society of America Book Series. Microbiological and Biochemical Properties*, Madison, WI, USA
- Hassler E, Corre MD, Kurniawan S, Veldkamp E (2017) Soil nitrogen oxide fluxes from lowland forests converted to smallholder rubber and oil palm plantations in Sumatra, Indonesia. *Biogeosciences* 14:2781–2798. <https://doi.org/10.5194/bg-14-2781-2017>
- Huang Z, Xu Z, Chen C (2008) Effect of mulching on labile soil organic matter pools, microbial community functional diversity and nitrogen transformations in two hardwood plantations of subtropical Australia. *Appl Soil Ecol* 40(2):229–239. <https://doi.org/10.1016/j.apsoil.2008.04.009>
- Koehler B, Corre MD, Veldkamp E, Wullaert H, Wright SJ (2009) Immediate and long-term nitrogen oxide emissions from tropical forest soils exposed to elevated nitrogen input. *Glob Chang Biol* 15(8):2049–2066. <https://doi.org/10.1111/j.1365-2486.2008.01826.x>
- Kotowska MM, Leuschner C, Triadiati T, Hertel D (2016) Conversion of tropical lowland forest reduces nutrient return through litterfall, and alters nutrient use efficiency and seasonality of net primary production. *Oecologia* 180:601–618. <https://doi.org/10.1007/s00442-015-3481-5>
- Kotowska MM, Leuschner C, Triadiati T, Meriem S, Hertel D (2015) Quantifying above- and belowground biomass carbon loss with forest conversion in tropical lowlands of Sumatra (Indonesia). *Glob Chang Biol* 21:3620–3634. <https://doi.org/10.1111/gcb.12979>
- Kurniawan S, Corre MD, Matson AL, Schulte-Bispung H, Utami SR, van Straaten O, Veldkamp E (2018) Conversion of



- tropical forests to smallholder rubber and oil palm plantations impacts nutrient leaching losses and nutrient retention efficiency in highly weathered soils. *Biogeosciences* 15:5131–5154. <https://doi.org/10.5194/bg-15-5131-2018>
- Lang M, Li P, Han X, Qiao Y, Miao S (2016) Gross nitrogen transformations in black soil under different land uses and management systems. *Biol Fertil Soils* 52:233–241. <https://doi.org/10.1007/s00374-015-1070-8>
- Lee JSH, Abood S, Ghazoul J, Barus B, Obidzinski K, Koh LP (2014) Environmental impacts of large-scale oil palm enterprises exceed that of smallholdings in Indonesia. *Conserv Lett* 7(1):25–33. <https://doi.org/10.1111/conl.12039>
- Leff JW, Wieder WR, Taylor PG, Townsend AR, Nemergut DR, Grandy AS, Cleveland CC (2012) Experimental litterfall manipulation drives large and rapid changes in soil carbon cycling in a wet tropical forest. *Glob Chang Biol* 18:2969–2979. <https://doi.org/10.1111/j.1365-2486.2012.02749.x>
- Lewis SL, Edwards DP, Galbraith D (2015) Increasing human dominance of tropical forests. *Science* (New York, NY) 349(6250):827–832. <https://doi.org/10.1126/science.aaa9932>
- Li Y, Xu M, Sun OJ, Wangcheng C (2004) Effects of root and litter exclusion on soil CO<sub>2</sub> efflux and microbial biomass in wet tropical forests. *Soil Biol Biochem* 36:2111–2114. <https://doi.org/10.1016/j.soilbio.2004.06.003>
- Mendham DS, Sankaran KV, O'Connell AM, Grove TS (2002) Eucalyptus Globulus harvest residue management effects on soil carbon and microbial biomass at 1 and 5 years after plantation establishment. *Soil Biol Biochem* 34:1903–1912. [https://doi.org/10.1016/S0038-0717\(02\)00205-5](https://doi.org/10.1016/S0038-0717(02)00205-5)
- Ministry of Agriculture of Indonesia (2016) Guidelines on oil palm replanting. Regulation No: 18/Permentan/KB.330/5/2016
- Moradi A, Teh CBS, Goh KJ, Husni MHA, Ishak CF (2014) Decomposition and nutrient release temporal pattern of oil palm residues. *Ann Appl Biol* 164:208–219. <https://doi.org/10.1111/aab.12094>
- Moradi A, Teh Boon Sung C, Goh KJ, Husni Mohd Hanif A, Fauziah Ishak C (2015) Effect of four soil and water conservation practices on soil physical processes in a non-terraced oil palm plantation. *Soil Till Res* 145:62–71. <https://doi.org/10.1016/j.still.2014.08.005>
- Müller AK, Matson AL, Corre MD, Veldkamp E (2015) Soil N<sub>2</sub>O fluxes along an elevation gradient of tropical montane forests under experimental nitrogen and phosphorus addition. *Front Earth Sci* 3:66. <https://doi.org/10.3389/feart.2015.00066>
- Nelson PN, Banabas M, Scotter DR, Webb MJ (2006) Using soil water depletion to measure spatial distribution of root activity in oil palm (*Elaeis Guineensis* Jacq.) plantations. *Plant Soil* 286:109–121. <https://doi.org/10.1007/s11104-006-9030-6>
- Pahan I (2010) Complete guide to oil palm, 8th edn. Penebar Swadaya, Jakarta
- Pandey CB, Begum M (2010) The effect of a perennial cover crop on net soil N mineralization and microbial biomass carbon in coconut plantations in the humid tropics. *Soil Use Manag* 26(2):158–166. <https://doi.org/10.1111/j.1475-2743.2010.00272.x>
- Pirker J, Mosnier A, Kraxner F, Havlík P, Obersteiner M (2016) What are the limits to oil palm expansion? *Glob Environ Chang* 40:73–81. <https://doi.org/10.1016/j.gloenvcha.2016.06.007>
- R Core Team (2019) R: A language and environment for statistical computing. Foundation for Statistical Computing, Vienna, Austria
- Rahman N, Bruun TB, Giller KE, Magid J, Ven GWJ, Neergaard A (2019) Soil greenhouse gas emissions from inorganic fertilizers and recycled oil palm waste products from Indonesian oil palm plantations. *GCB Bioenergy* 214(2):107. <https://doi.org/10.1111/gcbb.12618>
- Rahman N, de Neergaard A, Magid J, van de Ven GWJ, Giller KE, Bruun TB (2018) Changes in soil organic carbon stocks after conversion from forest to oil palm plantations in Malaysian Borneo. *Environ Res Lett* 13(10):105001. <https://doi.org/10.1088/1748-9326/aade0f>
- RSPO (2018) Principles and criteria. For the production of sustainable palm oil
- Rüegg J, Quezada JC, Santonja M, Ghazoul J, Kuzyakov Y, Buttler A, Guillaume T (2019) Drivers of soil carbon stabilization in oil palm plantations. *Land Degrad Dev* 30(16):1–12. <https://doi.org/10.1002/ldr.3380>
- Sayer EJ, Joseph Wright S, Tanner EVJ, Yavitt JB, Harms KE, Powers JS, Kaspari M, Garcia MN, Turner BL (2012) Variable responses of lowland tropical forest nutrient status to fertilization and litter manipulation. *Ecosystems* 15(3):387–400. <https://doi.org/10.1007/s10021-011-9516-9>
- Schneider D, Engelhaupt M, Allen K, Kurniawan S, Krashevskaya V, Heinemann M, Nacke H, Wijayanti M, Meryandini A, Corre MD, Scheu S, Daniel R (2015) Impact of lowland rainforest transformation on diversity and composition of soil prokaryotic communities in Sumatra (Indonesia). *Front Microbiol* 6:1339. <https://doi.org/10.3389/fmicb.2015.01339>
- Schroth G, Rodrigues MRL, D'Angelo SA (2000) Spatial patterns of nitrogen mineralization, fertilizer distribution and roots explain nitrate leaching from mature Amazonian oil palm plantation. *Soil Use Manag* 16:222–229. <https://doi.org/10.1111/j.1475-2743.2000.tb00197.x>
- Scheer C, Fuchs K, Pelster DE, Butterbach-Bahl K (2020) Estimating global terrestrial denitrification from measured N<sub>2</sub>O:(N<sub>2</sub>O + N<sub>2</sub>) product ratios. *Curr Opin Environ Sustain* 47:72–80. <https://doi.org/10.1016/j.cosust.2020.07.005>
- Silver WL, Herman DJ, Firestone MK (2001) Dissimilatory nitrate reduction to ammonium in upland tropical forest soils. *Ecology* 82(9):2410–2416. [https://doi.org/10.1890/0012-9658\(2001\)082\[2410:DNRTAI\]2.0.CO;2](https://doi.org/10.1890/0012-9658(2001)082[2410:DNRTAI]2.0.CO;2)
- Silver WL, Thompson AW, Reich A, Ewel JJ, Firestone MK (2005) Nitrogen cycling in tropical plantation forests: potential controls on nitrogen retention. *Ecol Appl* 15(5):1604–1614. <https://doi.org/10.1890/04-1322>
- Singh P, Ghoshal N (2010) Variation in total biological productivity and soil microbial biomass in rainfed agroecosystems: impact of application of herbicide and soil amendments. *Agr Ecosyst Environ* 137(3):241–250. <https://doi.org/10.1016/j.agee.2010.02.009>

- Sotta ED, Corre MD, Veldkamp E (2008) Differing N status and N retention processes of soils under old-growth lowland forest in Eastern Amazonia, Caxiuanã, Brazil. *Soil Biol Biochem* 40:740–750. <https://doi.org/10.1016/j.soilbio.2007.10.009>
- Tao H-H, Slade EM, Willis KJ, Caliman J-P, Snaddon JL (2016) Effects of soil management practices on soil fauna feeding activity in an Indonesian oil palm plantation. *Agr Ecosyst Environ* 218:133–140. <https://doi.org/10.1016/j.agee.2015.11.012>
- Veldkamp E, Schmidt M, Powers JS, Corre MD (2020) Deforestation and reforestation impacts on soils in the tropics. *Nat Rev Earth Environ*. <https://doi.org/10.1038/s43017-020-0091-5>
- Wang F, Zou B, Li H, Li Z (2014) The effect of understory removal on microclimate and soil properties in two subtropical lumber plantations. *J For Res* 19(1):238–243. <https://doi.org/10.1007/s10310-013-0395-0>
- Waring BG, Adams R, Branco S, Powers JS (2016) Scale-dependent variation in nitrogen cycling and soil fungal communities along gradients of forest composition and age in regenerating tropical dry forests. *New Phytol* 209(2):845–854. <https://doi.org/10.1111/nph.13654>
- Wieder WR, Cleveland CC, Taylor PG, Nemergut DR, Hinckley E-L, Philippot L, Bru D, Weintraub SR, Martin M, Townsend AR (2013) Experimental removal and addition of leaf litter inputs reduces nitrate production and loss in a lowland tropical forest. *Biogeochemistry* 113:629–642. <https://doi.org/10.1007/s10533-012-9793-1>
- Zhang J, Zhu T, Meng T, Zhang Y, Yang J, Yang W, Müller C, Cai Z (2013) Agricultural land use affects nitrate production and conservation in humid subtropical soils in China. *Soil Biol Biochem* 62:107–114. <https://doi.org/10.1016/j.soilbio.2013.03.006>

**Publisher's Note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.