Dear Dr. Sara Vicca,

on behalf of my co-authors, I express my sincere gratitude for the helpful reviews and comments on our manuscript **bg-2020-15**. We have now incorporated all the changes we stipulated in our answers to the reviewers' comments and from your suggestions. All the line numbers are based on the revised manuscript (not on the marked-up version where the line numbers change).

We hope that our revisions will satisfy your and the reviewers' questions and the standards of Biogeosciences. We look forward to hearing back from you. If there are any questions regarding our manuscript, I would be happy to clarify.

Sincerely yours,
Greta Formaglio

Comments from the editor:

Regarding the short time for the soil to adjust after lysimeters were installed, I would like you to include a brief note about the suitability for nutrient leaching but not for some other soil processes. This to make readers aware and cautious about it when they would conduct similar experiments.

Author's response: in addition to fast cycling in the tropics, the short time period to adjust was also justified by the minimal soil disturbance during the installation of the lysimeter, as we used an auger with the approximate same diameter as the installed lysimeter.

Author's changes in the manuscript: we added this at L 177.

In the Discussion, you mention that fertilization should be avoided during periods of high drainage fluxes. Based on the referee comments, you suggest to modify this to indicate that fertilization during the period of high drainage fluxes should be reduced. Could it be an option to (also) spread the fertilization a bit more in time during that period?

Author's response: yes, indeed that is an option.
Author's changes in the manuscript: we added this at L 432.

I also like to repeat the request by referee 1 to carefully check spelling and grammar.

Author's response: we checked the manuscript thoroughly.

Author's changes in the manuscript: we corrected Table A2, in which the gross N mineralization rates were reported on mass basis (mg N kg^{-1} d^{-1}), instead of being on area-based (mg N m^{-2} d^{-1}).

Comments from Reviewer 1:

My main comment is that the analysis/results of yield are not appropriately considered. The authors refer to previously published studies on the yield aspect but do not actually quote any data/numbers on yield. This is an important point that is missing. Any management options leading to more environmentally friendly or sustainable growing of oil palm will ultimately be scrutinised under the yield aspect. So it is important to include the actual figures in this assessment (even if they have been published elsewhere). Just saying there was no difference is not sufficient. Growers would like to know the actual yield to see that you were not working on a plantation with unusually high or low yield anyway which might have masked any management effects. So a revised version needs results and discussion sections that are expanded with details on yield.
Author's response: thank you for this observation. We agreed that the focus on the yield is essential for the development of long-term more sustainable management practices. The average yield measured was in the same range as the yield reported for large-scale plantations in Indonesia.

Author's changes in the manuscript: Fig. A2 was included and a sentence about the yield was added at L520-525.

General:

There should be no space between number and %. Please revise this throughout the manuscript.
Author's response: corrected.
Author's changes in the manuscript: L45, 138, 139, 152, 153, 219, 227, 230, 281, 282, 316, 318, 336, 337, 363, 364, 365, 366, 367, 394, 395, 539, 540, 566, 567, 993.

The term 'stem' might be more appropriate to use than 'trunk'. Please replace 'trunk' with 'stem' throughout the manuscript.
Author's response: we agree.
Author's changes in the manuscript: changed at L 93, 138, 169, 170, 227, 460.

The term 'conventional' is a bit misleading. Perhaps 'standard practice' or 'standard industry practice' would be a more appropriate term to use?

Author’s response: we prefer to keep the term of conventional practice for consistency with other manuscripts published on this experiment, i.e. Darras et al. 2019, and others in preparation.

Author’s changes in the manuscript: no change.

Generally spelling and grammar need to be checked carefully, some sentences are too long and convoluted.

Author’s response: based on this comment we revised the manuscript and decide to modify the structure of a few sentences to improve clarity.

Author’s changes in the manuscript: some sentence were modified L 66-67, 346-349, 395-400, 411-416, 443-445, 462-465, 491-493.

Specific:

Title remove ’as’.

Author’s response: this is taken out

Author’s changes in the manuscript: L1.

l 39 replace ’have’ with ’has’.

Author’s response: corrected.

Author’s changes in the manuscript: L39.

l 40 remove ’and’.

Author’s response: corrected.

Author’s changes in the manuscript: L 40.

l 45 remove space between 57 and % (see general comment above).

Author’s response: corrected.

Author’s changes in the manuscript: see general comment above.

l 48 introduce N as nitrogen.

l 59 introduce P as phosphor NO3 as nitrate.

Author’s response: we introduced “nitrate” but not the common elements, since N, P, K etc. are all generally known elemental abbreviations.

Author’s changes in the manuscript: L 59.

l 61 comma after reference before ’whereas’.

Author’s response: corrected.

Author’s changes in the manuscript: L60.

l 68 remove ’of’ in front of oil palm.

Author’s response: corrected.

Author’s changes in the manuscript: L 66-67 were revised.

l 80 herbicides needs to be plural.

Author’s response: corrected.

Author’s changes in the manuscript: L79.

l 82 ’herbicide weeding’ perhaps clarify that this is chemical weeding with herbicides as supposed to mechanical weeding.

Author’s response: in this case we meant chemical weeding.

Author’s changes in the manuscript: specified that is chemical weeding at L 81.

l 97 circles needs to be plural.

Author’s response: we prefer to keep it singular for consistency, as it is the management zone mentioned above.

Author’s changes in the manuscript: no change.

l 101 canopy interception will depend on the age of the plantation and whether there is canopy closure or not. Please elaborate here and say that there will be a difference between younger and older plantations.

Author’s response: we agree that the age of the palm is important to determine the level of interception in the inter-row. However, we think that this sentence doesn´t need to be modified because the interception in the inter-row will always be lower than in the palm circle, independent of the age of the palm. Even when the canopy closes, 7-8 years after planting, the interception is lower in the inter-row than in the palm circle (Banabas et al. 2008).

Author’s changes in the manuscript: no change.

l 131 Was the plantation terraced? This should be a discussion point generally as nutrient flows will be different in plantations with even terrain as supposed to terraced plantations. It seems to become more popular (also in Indonesia) to terrace plantations (when replanting) even if the terrain is not that hilly to begin with. This might have potentially large implications on nutrient leaching.

Author's response: the plantation was not terraced and it was not on a slope position.

Author's changes in the manuscript: a sentence added at L 134.

l 135 remove space between number and %.

Author's response: corrected

Author's changes in the manuscript: see general comment above.

l 137 chemically or mechanically weeded? Please clarify.

Author's response: this was already specified in the introduction.

Author's changes in the manuscript: we specified that it was chemically wedded at L 139.

l 142 Is the fertiliser applied in pellets or granules? Broad spread? Please give details.

Author's response: the fertilizers were in granular form and these were banded application within the palm circle, not broadcasted.

Author's changes in the manuscript: specified in L 148, 150.

l 145 Were no EFB (empty fruit bunches) returned to the plantation? This is common practice and would add more organic matter to the plantation in addition to the palm fronds. If it wasn't done in your plantation, it still needs to be discussed in the discussion section.

Author's response: in our studied plantation there is a certain amount of EFB returned to the plantation (mainly in the form of compost). The 2025-ha plantation investigated is owned by the company PTPN6, which has a total of 90122 ha of oil palm plantations in Jambi province. Once the fruits are processed in the mill, the EFB (also in the form of compost or ashes) is redistributed across all the plantations of PTPN6 in a rotation. In addition, within the same plantation, the application of EFB follows a rotation system based on management blocks. Therefore the timing and the amount of EFB distributed are quite complicated to predict. In our experimental plots, we did not include the EFB compost in the treatments. This is for two reasons: 1) our experimental plots encompassed

different management blocks and therefore the different timing and irregular application of EFB might have biased the plots; 2) the aim of the experiment is to compare the most standardized management practices with the reduced management intensity, and the application of EFB is not done regularly throughout the plantations (it is normally applied just to the area next to the mill, for ease of transport by the workers). Since we didn´t include the practice of using EFB in our experiment, we cannot discuss its effects on leaching, but we included this for future systematic evaluation.
Author's changes in the manuscript: EFB added at L 434-437.

l 170 replace ’till’ with ’to’.
Author's response: corrected.
Author's changes in the manuscript: L 172.

l 182 check reference, should only be (2018) in brackets.
Author's response: corrected.
Author's changes in the manuscript: L187.

l 191 not clear what (2018) is suppose to mean? Should there be a reference? And do you mean combined bicarbonate and organic acids? Please clarify (also in Fig 3).
Author's response: yes, the (2018) was from the previous study by Kurniawan et al. (2018).
Author's changes in the manuscript: reference corrected at L 195 and the word “combined” added at L 194 to avoid confusion.

l 205 do you have anything to base your assumption on? Any measurements/references?
Author's response: we don´t have strong references to back down this sentence, therefore we prefer to remove the last part of the sentence
Author's changes in the manuscript: L 207.

l 209 insert ’The’ in front of Expert-N model.
Author's response: corrected.
Author's changes in the manuscript: 212.

l 211 insert ’the’ after using.

Author’s response: corrected.

Author’s changes in the manuscript: L 214.

l 217 add reference for Richards’ equation.

Author’s response: added.

Author’s changes in the manuscript: L 220.

l 224 ’stem’ instead of ’trunk’.

Author’s response: changed

Author’s changes in the manuscript: see general comment above.

l 237 space between 1 and um.

Author’s response: corrected

Author’s changes in the manuscript: L 240.

l 246 remove ’to’ in front of 192.

Author’s response: corrected

Author’s changes in the manuscript: L 249.

l 306 replace ’high’ with ’strong’.

Author’s response: corrected

Author’s changes in the manuscript: L309.

l 318 specify here the months for typical dry and wet season.

Author’s response: we think that specifying the typical months will be confusing. The dry period is clearly indicated in the picture that is referred in the text.

Author’s changes in the manuscript: no changes.

l 424 But as you are saying elsewhere, they would not fertilise in the dry season either. So you might have to elaborate here.

Author’s response: it is true that the farmers don´t fertilise in the dry season, which is also not advisable for the reasons explained in l 429 but they could fertilize for example one month later, avoiding the peaks of drainage. Unfortunately, as explained in the manuscript, this is not practical because it is difficult to predict the period of high drainage

fluxes from the precipitation pattern and so the most viable option to reduce leaching is to reduce fertilization rates and increase nutrient retention efficiency.
Author's changes in the manuscript: no changes.

l 438 Mention EFB, POME, compost or a combination of these as they are all commonly used types of organic fertiliser in oil palm plantations.
Author's response: this is now added.
Author's changes in the manuscript: L 434-437.

l 443 circle closest to the roots for direct uptake of the fertilisers?
Author's response: this was explained in detail later in the manuscript (L 469-470).
Author's changes in the manuscript: no changes.

l 453 replace 'highest' with 'higher'.
Author's response: we replaced with "larger".
Author's changes in the manuscript: L 455.

l 458 trunk = stem
Author's response: corrected.
Author's changes in the manuscript: see general comment above.

l 464 insert 'will' in front of largely.
Author's response: corrected.
Author's changes in the manuscript: L 466.

l 492 replace 'increased' with 'increases'.
Author's response: corrected.
Author's changes in the manuscript: L 494.

l 494 The last part of the sentence doesn't fit the first. Please rephrase.
Author's response: the last part of the sentence was removed to improve clarity, as the study is not investigating soil fertility.
Author's changes in the manuscript: L 501.

l 502 replace ’influence’ with ’effect’.

Author’s response: corrected.

Author’s changes in the manuscript: L 504.

l 505 Please rephrase this sentence, it sounds a bit clumsy and i is not that clear what you are trying to say.

Author’s response: revised as suggested.

Author’s changes in the manuscript: L 505-508.

l 508 Replace ’have’ with ’has’.

Author’s response: corrected.

Author’s changes in the manuscript: L 510.

l 519 Start a new sentence after the reference as the second half doesn’t follow the first.

Author’s response: revised as suggested.

Author’s changes in the manuscript: L 528.

l 525 replace ’conventional’ with ’standard practice’?

Author’s response: we prefer to keep the world “conventional” for consistency throughout the manuscript.

Author’s changes in the manuscript: no changes.

l 527 This is where you need to expand on the yield aspect and include data etc.

Author’s response: we decided that it is to include the yield in L 520-522 where we first mentioned the economic aspects of the treatments (see answer to the first comment above).

Author’s changes in the manuscript: L 520-522.

l 553 Insert ’the’ in front of majority.

Author’s response: corrected.

Author’s changes in the manuscript: L 562.

l 559 Remove ’to’ in from of streams.

Author’s response: corrected.

Author’s changes in the manuscript: L568.

Table 1 call this soil physicochemical parameters as it’s not really biochemical.

Author’s response: SOC, total N, ^{15}N natural abundance are the biochemical characteristics, which include the other chemical parameters.

Author’s changes in the manuscript: no changes.

Table 4 Did you quote the decimals to significant figures?

Author’s response: the difference in values are minute and thus the values (mean ± se) must appropriately have 3 decimal places. If expressed in percentage, this will have 1 decimal place, which is acceptable.

Author’s changes in the manuscript: no changes.

Figures 2,3 and 5 either call the x axis ’month’ or remove ’months’ all together as it is obvious that is a data axis (just add years).

Author’s response: “months” removed from the pictures

Author’s changes in the manuscript: Fig. 1 (L 1003), Fig. 2 (L 1007), Fig. 4 (L 1019).

Figure 3 are RCOO and HCO3 combined or separate? Please clarify. If it is combing perhaps say ’+’?

Author’s response: we prefer to not modify this in the fig. but this is now specified in the fig. caption that this is a combined contribution $RCOO^-$ and HCO_3^-.

Author’s changes in the manuscript: L 1010.

l 1010 with ’unpublished’ do you mean not yet published? If it is in prep, please add, otherwise remove this citation. You are contracting ’reported’ with ’unpublished’.

Author’s response: note revised.

Author’s changes in the manuscript: L 1037-1038.

Comments from Reviewer 2:

Abstract:

It would be interesting to indicate some values of nutrient losses in plots with conventional management practices.

Author's response: we agree with this comment and we added some values.

Author's changes in the manuscript: L 27-32 were revised.

L32: "Our findings signified that mechanical weeding…" should be replaced by "Our findings suggested that mechanical weeding…" because you cannot generalize to Indonesia your results at a single site.

Author's response: we agree with this comment.

Author's changes in the manuscript: we modified "signified" with "suggested" L 32.

Introduction: The Introduction section is clear and informative.

L71-73: Not always the case, see for example eucalypt plantations.

Author's response: we agree that this is not always the case and therefore we will substitute "result" with "can result". See below for a literature review on eucalyptus plantations.

Author's changes in the manuscript: L 72.

Material and methods

The lysimetry design was suitable for the quantification of leaching losses. You might indicate that, even though the time period for soil stabilization was short in your study (only two months from the installation of the ceramic cups to the start of the soil solution collection and four months from the implementation of the factorial management experiment to the collection of the soil solutions), this period was sufficient because the biological processes are rapid in tropical soils.

Author's response: thank you for this observation, indeed the period was quite short but it was enough to show effects on nutrient leaching, also because the soil disturbance was minimized by using an auger with similar diameter as the installed lysimeter.

Author’s changes in the manuscript: this was inserted at L 177-179.

You may be interested in two articles that accurately describe the spatial development of roots in oil palm plantations: Plant and Soil 189: 33-48, 1997 and Plant and Soil 190: 235-246, 1997.

Author’s response: thank you for this comment, we are familiar with these articles. We agree to include one as a reference in the manuscript.
Author’s changes in the manuscript: a sentence to describe root density was inserted at L 97-98.

More information should be given on the water drainage model. How have you dealt with run off from one management zone to another?

Author’s response: it´s not possible to include this in the water model because the different management zones have to be modelled separately, with no interaction with each other. Nevertheless, we expect the runoff to be small in our plantation based on literature review in oil palm plantations and the lack of slope at our site.

Author’s changes in the manuscript: we inserted a table describing all the parameter use to model water drainage (Table A1, see comment below).

The parameterization of the model is rough, without measurements of root profiles and soil hydraulic parameters in each treatment and management zones. Moreover, the validation from soil water potentials is also rough with only two depths (it would have been interesting to include the depth of 1.5 m where soil solutions are collected) and punctual measurements in only two treatments (only 12 tensiometers). It is important to provide a table (in appendix) showing the values given to all the parameters used in the Expert-N water sub-model for each management zone.

Author’s response: we agree that the parametrization of the water model is rough because of the reasons explained. Unfortunately, we could not find an easily accessible, spatially explicit water model that could account for the spatial variability given by the management zones. The commonly used models estimate root water uptake from an estimation of plant evapotranspiration and root density, and therefore cannot partition the root water uptake among management zones. On the other hand, more complicated models require in-depth knowledge of the processes and a large quantity of data that are often not available in literature. Given the limits in our model parameterization, our modeling approach strongly relied on the calibration of the results with field measurements of soil matric potential. We focused on the top 60 cm of the soil because the majority of roots in oil palm are in the top-50-cm depth, so that this is the main zone where the water is exchanged between the soil and the plant and with the atmosphere. Author's changes in the manuscript: the table with all the parameters used in the Expert-N sub-model will be provided in the appendix as Table A1 (L 1031).

Statistical analyses are clearly presented.

Results No specific recommendation, this section is well written.

Discussion

You might be interested by a recent paper providing values for N leaching in oil palm plantations. The three management zones were sampled in the field to validate this model and the order of magnitude is consistent with your results: DOI:10.1002/agj2.20109.

Author's response: thank you for providing this important reference. I will include that in the manuscript.

Author's changes in the manuscript: reference inserted at L 558-560.

The comparison with other perennial tropical plantations is interesting (Table A2). Could you add forest plantations to this appendix (pines, eucalypts, acacias) and rubber plantations if you find data in the literature?

Author's response: nutrient leaching losses in rubber smallholder plantations were measured near our study site by our group: annual N leaching losses were 4 kg N ha^{-1} yr^{-1} (Kurniawan et al. 2018). These data were not included in the table because these plantations were not fertilized. We couldn´t find other data about field-measured leaching losses in rubber plantations or other plantations, just a few data in eucalyptus plantations. Silva et al. 2013 (Forest Ecology and Management 301: 67-78) measured leaching in 2-years-old eucalyptus plantations on sandy soil in Brazil with low fertilization (80 kg N ha^{-1} in 2 years) and lower annual rainfall than our site (1240 mm). They found relatively low leaching: 5.6 kg N ha^{-1} leached in 2 years when the fertilizer was applied 4 times over the 2-year study period, and 8.6 kg N ha^{-1} leached in 2 years when the fertilizer was applied one time at the beginning of the sampling. Another interesting study on nutrient dynamics in eucalyptus plantation is the one of Laclau et al. 2010 (Forest Ecology and Management 259(9):1771-1785) for plantations of different ages in Brazil and Congo, fertilized once with 38 kg N ha^{-1} (Congo) and 120 kg N ha^{-1} (Brazil). The leaching fluxes were in the range of 1-6 kg N ha^{-1} yr^{-1}. Another study by this group, published by Versini et al. 2014 (Geoderma 232-243: 426-436), on 2-years-old eucalyptus plantations in Congo (annual rainfall of 1220 mm and fertilization of 43 kg N ha^{-1} at planting), measured similar leaching losses, equal to 4.4 kg N ha^{-1} yr^{-1}. We decided to not include these data on eucalyptus plantations in Table A2 because: 1) the rainfall was much lower than the one at our site 2) the majority of the data were from young plantations, 3) the plantations were not regularly fertilized.

Author’s changes in the manuscript: no changes.

L515-517: not sure that the amounts of Na taken up by soil macrofauna could be sufficient to explain the differences. It has been demonstrated that oil palm can take up Na in addition/substitution to K (Bonneau, X., Boutin, D., Bourgoing, R., Sugarianto, J., 1997. Le chlorure de sodium, fertilisant idéal du cocotier en Indonésie. Plantations, Recherche, Développement 4 (5), 336–346), as also shown recently in eucalypt plantations.

Author’s response: thank you for providing these interesting references that show that palm and trees in plantations can take up Na from the soil. However, we think that this cannot explain lower Na leaching with mechanical weeding compared to herbicide weeding because it would imply higher Na uptake by the palms with mechanical weeding, which was not investigated.

Author’s changes in the manuscript: no changes.

Tables, Figures and appendices The 4 tables, 5 figures and 3 appendices shown are clear and relevant.

Technical corrections

L329: than in the inter-row.

Author’s response: corrected.

Author’s changes in the manuscript: L 332.

L332: dissolved organic N or total dissolved N?

Author’s response: we meant total dissolved N. We understand that this may be misleading and we decided to remove “dissolved”.
Author’s changes in the manuscript: L 335.

L453: higher?

Author’s response: we modified it with “larger”.
Author’s changes in the manuscript: L 455.

Comments from Reviewer 3:

Specific comments

The abstract should be revised.

Line 23-28 Could you consider the specific data (e.g., low solute concentrations, small drainage…) should be added, and thus increasing the persuasiveness for the readers? (Maybe it is important in the Abstract).

Author's response: we agree that is important to insert some specific data but we want to avoid getting a long abstract. We think that the difference in leaching losses between conventional and reduced management are the most important numbers to be shown so we will include them in the abstract.

Author's changes in the manuscript: revisions at L 37-32.

The introduction is very good. The scientific question is clear.

Line 41 The term "e.g" should be "e.g.".

Author's response: corrected.

Author's changes in the manuscript: L 41.

Line 52-54 Could you provide some references? Thank you.

Author's response: since we don´t have strong evidence to justify this sentence, we will restructure it. We provide a reference on the declining in long-term productivity (Syers 1997).

Author's changes in the manuscript: revised sentence at L 50-52.

Line 57-63 Indeed, high precipitation rate is a critical driver for surface runoff and associated nutrient losses. Particularly for considerable plantations. However, the leaching losses may be offset by a high nutrient cycling due to the rapid uptake of plants.

Author's response: thank you for this observation; this was expanded in the manuscript in the second paragraph.

Author's changes in the manuscript: no changes.

Line 92 How far the radius of the palm circle?

Author’s response: it is 2 m from the palm circle, this was clearly explained in the materials and method but we will also include in the introduction for more clarity.

Author’s changes in the manuscript: we inserted this in L 92.

Line 98-99 Could you describe more details about the root distribution of oil palm? I am not sure the roots of palm only grow around the trunk. I think the root biomass between inter-row area may be high in somewhere.

Author’s response: the root density is higher in the palm circle because it´s closer to the palm stem and because of the repetitive fertilization in this area, whereas the inter-row has the lower root density.

Author’s changes in the manuscript: a sentence about root density is included at L 97-98.

The Materials and methods section is good structure. The content is detailed and makes it easy for readers to understand.

Line 159 Replace the “x” between “the 50 x 50 m” with “_”.

Author’s response: we prefer to not modify this because the symbol “_” may cause confusion to the reader since we want to indicate a mathematical product, normally identified by the symbol “x”.

Author’s changes in the manuscript: no changes.

Line 160 Where is the plant materials from the mechanical weeding? Are they transported far away from the plots?

Author’s response: the plant material is left inside the plot.

Author’s changes in the manuscript: this was inserted in L 156-157.

Line 232 Is the runoff set to 0? Do you mean “no overland runoff”?

Author’s response: yes. For clarity we will insert the term “no overland runoff”.

Author’s changes in the manuscript: L 353.

Line 243 Soil physical-chemical characteristics.

Author’s response: SOC, total N, ^{15}N natural abundance are the biochemical characteristics, which include the other chemical parameters.

Author’s changes in the manuscript: no changes.

Line 247 See comment 1.

Author's response: please see the answer to comment 1.

Line 265 Please simplify the statistical analyses section.

Author's response: although we understand that the statistical analyses section may seem too long, we cannot simplify it without removing essential information. We think that is in line with good scientific practices to report all the statistical analyses used, for reproducibility.

Author's changes in the manuscript: no changes.

The results section is well-organized manner.

However, some statements are so long that they (e.g., the section "3.2 Differences in leaching losses…") should be simplified to delete some non-key contents.

Author's response: we decided included some explanation sentences in the results to guide the reader since we presented a lot of results.

Author's changes in the manuscript: following this comment, the sentence at L 436-439 was revised.

Line 310-311 The drainage flux is low. Do you investigate the stem flow (may be influenced by "funnel effect" of canopy of oil palm?)? Some studies demonstrated that the infiltration was enhanced around the tree trunk.

Author's response: the model used did not allow to parametrize the stem flow and the funnel effect. Nevertheless, the values from the water model were calibrated with field measurements of soil matric potential, reflecting the actual field conditions.

Author's changes in the manuscript: no changes.

Line 346 Why is different between the various elements leaching?

Author's response: the differences in nutrient leaching fluxes between management zones depend on 1) differences in water drainage fluxes (the same of every element) and 2) differences in element concentrations in deep soil-water (which varies for each element). For example, much higher Al concentrations in the inter-row compared to the frond-stacked area resulted in higher Al leaching even if the frond-stacked area have higher water drainage. On the other hand, Mg concentrations were comparable among inter-row and frond-stacked area, but due to the large drainage of the latter Mg leaching was higher in the frond-stacked area.

Author’s changes in the manuscript: no changes.

The discussion section was carefully written and prepared.

Line 391 I recommend the ratios of runoff/interception/evaporation/transpiration to precipitation was supplemented in the Table 2 for better understanding.

Author’s response: we prefer to not include that in Table 2 to have a simpler table and because the ratios can easily be extrapolated

Author’s changes in the manuscript: no changes.

Line 434-438 How to understand the use of organic amendments and slow-release fertilizers? E.g., mulching application? Under the high temperature and precipitation in some tropical areas, the plant materials decompose quickly, and the litterfall may have very short residence time on the ground. Could you provide any information on the standing plant litter in your treatments? Thank you!

Author’s response: in the studied plantation, there were two peaks of leaching due to the overlapping of high drainage fluxes and fertilizer application. Since it is complicated to predict the periods with high drainage, it may be useful to use organic or slow-release fertilizers. These can distribute the nutrient input to the soil over a longer period of time, thus reducing the overlapping of high nutrient input and high drainage, and also avoiding peaks of high nutrient inputs. Indeed, the decomposition in the tropics happens fast but it would still provide nutrients slower than mineral fertilization. The organic amendments more used in oil palm plantations are the waste from the palm oil processing, namely the empty fruit bunches (EFB) or the palm oil mill effluent (but this is normally applyied just close to the mill). In a study on decomposition rates and nutrient release by EFB in oil palm plantation, 75% of the EFB was decomposed in 8 months, with a deposition constant k= 0.2 month^{-1} (Moradi et al. 2014, Ann Appl Biol 164: 208–219). Another organic amendment in the oil palm plantation is the litterfall, which is represented by the frond stack. This can provide plenty of nutrients to the plantation as it can be seen from the high nutrient contents in the frond-stacked area in our manuscript (Table 1). Also, the addition of cut fronds is regular, at a rate of 16 fronds palm^{-1} yr^{-1} in the studied plantation. However, this positive effect on soil fertility is restricted to the frond-stacked area and it is unsure if the palm can benefit from these nutrients. Recent literature (Rüegg et al., 2019) found higher root density under the frond-stacked area compared to the inter-row, indicating that the palm may indeed take up the nutrients from the decomposition of the frond stack.

Author’s changes in the manuscript: no changes.

Line 552-553 Although the mechanical weeding is sustainable way in ecological view, the farmers were reluctant to adopt due to its money-consuming and labor-consuming. Undoubtedly, mechanical weeding is a promising measure to reduce nutrient leaching.

Author’s response: indeed we would expect the farmers to be reluctant to adopt this weeding method because it requires more labor. However, the economic analysis done in Darras et al. (2019) showed that the costs to implement mechanical weeding would be comparable to the ones for herbicide application. In fact, the prolonged use of glyphosate as standard weeding practice has favored woody and resistant understory vegetation that have to be cut periodically with mechanical weeding.

Author’s changes in the manuscript: no changes.

Herbicide weed control increases nutrient leaching compared to mechanical weeding in a large-scale oil palm plantation

Deleted: as

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Abstract

Nutrient leaching in intensively managed oil palm plantations can diminish soil fertility and water quality. There is a need to reduce this environmental footprint without sacrificing yield. We quantified nutrient leaching in a large-scale oil palm plantation on Acrisol soil with factorial treatment combinations of two fertilization rates (260 N, 50 P, 220 K kg ha^{-1} yr^{-1} as conventional practice, and 136 N, 17 P, 187 K kg ha^{-1} yr^{-1}, equal to harvest export, as reduced management) and two weeding methods (conventional herbicide, and mechanical weeding as reduced management). Each of the four treatment combinations was represented by a 2500 m^2 plot, replicated in four blocks. In each plot, soil-pore water was collected monthly at 1.5 m depth for one year in three management zones: palm circle, inter-row, and frond-stacked area. In the palm circle, nutrient leaching was low due to low solute concentrations and small drainage fluxes, resulting from large plant uptake. Conversely, in the inter-row, nitrate and aluminum leaching losses were high due to their high concentrations, large drainage fluxes, low plant uptake, and acidic pH. In the frond-stacked area, base cation leaching was high, presumably from frond litter decomposition, but N leaching was low. Mechanical weeding reduced leaching losses of all nutrients compared to the conventional herbicide weeding, because herbicide decreased ground vegetation, and thereby reduced the efficiency of soil nutrient retention. The leaching of total N was the highest with conventional management (73 ± 20 kg N ha^{-1} yr^{-1}) and the lowest in mechanical weeding with reduced fertilization (32 ± 6 kg N ha^{-1} yr^{-1}) whereas its yield remained comparable among all treatments. Our findings suggested that mechanical weeding and reduced fertilization should be included in the Indonesian Ministry of Agriculture program for precision farming (e.g. variable rates with plantation age), particularly for large-scale plantations, and in the science-based policy recommendations, such as those endorsed by the Roundtable for Sustainable Palm Oil association.

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1 Introduction

Agricultural expansion is a major driver of tropical deforestation (Geist and Lambin, 2002), which has global impacts on reducing carbon sequestration (Asner et al., 2010; van Straaten et al., 2015), greenhouse gas regulation (e.g. Meijide et al., 2020; Murdiyarso et al., 2010), biodiversity (e.g. Clough et al., 2016) and increasing profit gains at the expense of ecosystem multifunctionality (Grass et al., 2020). Oil palm is the most important rapidly expanding tree-cash crop that replaces tropical forest in Southeast Asia (Gibbs et al., 2010; Carlson et al., 2013) due to its high yield with low production costs and rising global demand (Carter et al., 2007; Corley, 2009). Currently, Indonesia produces 57% of palm oil worldwide (FAO, 2018) and this production is projected to expand in the future, threatening the remaining tropical forest (Vijay et al., 2016; Pirker et al., 2016). Forest to oil palm conversion is associated with a decrease in soil fertility, because of high nutrient export via harvest, reduced rates of soil-N cycling, and decreases in soil organic carbon (SOC) and nutrient stocks (Allen et al., 2015; Allen et al., 2016; van Straaten et al., 2015). The decline in soil fertility reinforces the dependency on fertilizer inputs and threatens the long-term productivity of the area (Syers 1997), which could further exacerbate land-use conversion. Leaching can contribute to the impoverishment of soil nutrients as well as reduction in water quality and eutrophication of water bodies. Increased nutrient loads to water bodies due to agricultural expansion and intensification, common in temperate areas (Carpenter et al., 1998), are increasingly reported for tropical regions (Figueiredo et al., 2010; Teklu et al., 2018). Given the typically high precipitation rates, leaching losses can possibly be large in intensively managed plantations in the tropics, although deeply weathered tropical soils also have the capacity to store large quantities of N and P (Jankowski et al., 2018; Neill et al., 2013). Indeed, nitrate (NO$_3^-$), the most leachable form of N, can be retained in the subsoil by anion exchange capacity of highly weathered acidic soils (Wong et al., 1990), whereas P can be fixed to Fe and Al (hydr)oxides of tropical soils (Roy et al., 2016). Nevertheless, there are some evidences of streamwater quality reductions due to oil palm cultivation in Malaysia (Luke

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et al., 2017; Tokuchi et al., 2019), signifying the importance of quantifying nutrient leaching losses in other areas with expansive oil palm plantations, especially in Jambi, Indonesia, one of the hotspots of forest conversion to oil palm in Indonesia (Drescher et al., 2016).

Oil palm plantations can possibly have low leaching losses, as a consequence of high evapotranspiration and thus low drainage fluxes (Tarigan et al., 2020). However, most oil palm plantations are large-scale enterprises that are characterized by intensive management with high fertilization rates and herbicide application. Intensive agriculture in the tropics is associated with high N leaching losses (Huddell et al., 2020). Even in tree-cash or perennial crop plantations, despite their generally higher evapotranspiration and deeper rooting depth than annual crops, high fertilization rates can result in sustained, large nutrient leaching losses (e.g. Cannavo et al., 2013; Wakelin et al., 2011). Large NO_3^- leaching from high N fertilization is always accompanied by leaching of cations (Cusack et al., 2009; Dubos et al., 2017), impoverishing highly weathered tropical soils that are inherently low in base cations (Allen et al., 2016; Kurniawan et al., 2018). Fertilization is necessary to support high yields of oil palm plantations, but reduction in fertilization rates, e.g. to levels that compensate for nutrient export through harvest, may reduce nutrient leaching losses while maintaining high productivity. On the other hand, the use of herbicides for weed control can exacerbate nutrient leaching losses, as prolonged absence of ground vegetation reduces uptake of redistributed nutrients from applied fertilizers far from reach of crop roots (Abdalla et al., 2019). Chemical weeding with herbicides is commonly practiced in large-scale oil palm plantations: the herbicide is placed in the area where the fertilizers are applied, to reduce competition for nutrients and water with ground vegetation, and in the inter-rows, to facilitate access during harvest (Corley and Tinker, 2016). However, herbicide not only eradicates aboveground vegetative parts but also removes roots slowing down regeneration. In contrast, mechanical weeding only removes aboveground

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part, allowing relatively fast regeneration of ground vegetation, which could take up redistributed nutrients and could reduce leaching losses.

To investigate nutrient leaching losses in an oil palm plantation, the spatial structure created by the planting design and by the management practices must be taken into account, which is only partly considered in the sampling designs of previous studies. Three management zones in oil palm plantations can be identified: (1) the palm circle, an area of 2 m radius around the palm´s stem where the fertilizers are applied and weeded; (2) the inter-row, weeded less frequently than the palm circle but unfertilized; and (3) the frond-stacked area, usually every second inter-row, where the cut senesced fronds are piled up. In these management zones, the interplay of water fluxes, root uptake and soil nutrient contents determine the extent of nutrient leaching losses. Root uptake is related to root density, which is high inside the palm circle and lower in the inter-row (Jourdan and Rey, 1997; Lamade et al. 1996). The palm circle despite having direct fertilization have also large water and nutrient uptake (Nelson et al., 2006), such that large leaching losses may only occur following pulse high fertilization and during high drainage (from high precipitation) events (Banabas et al., 2008a). The inter-row experiences higher water input from precipitation than the palm circle because of lower canopy interception (Banabas et al., 2008b), and large water flux within the soil because of low root uptake, stimulating nutrient transport to lower depths. However, as there is no direct fertilizer application on the inter-row, nutrient leaching may be low. The frond-stacked area receives nutrients from decomposition of nutrient-rich fronds (Kotowska et al., 2016) and such mulching with senesced fronds prevents runoff and promotes water infiltration as a consequence of enhanced macroporosity by increased organic matter (Moradi et al., 2015). High water infiltration may generate high water drainage fluxes, resulting in intermediate nutrient leaching losses in the frond-stacked area.

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In this study, we aimed to quantify nutrient leaching losses in an intensively managed, large-scale oil palm plantation, and to assess if reduced intensity of management (i.e. reduced fertilization rates equal to harvest export and mechanical weeding) can reduce leaching losses in oil palm plantations. We tested these hypotheses: (1) leaching losses in the palm circle will be larger than in the other management zones because of direct fertilizer application; (2) leaching losses under herbicide application will be higher than mechanical weeding because of slower regeneration of ground vegetation that can augment nutrient retention; (3) nutrient leaching fluxes under conventional high fertilization rates will be substantial compared to reduced rates because of excessive nutrient inputs. Our study provides a systematic quantification of an important environmental footprint of oil palm production, taking into consideration its spatial variation in management zones, and evaluates the effectiveness of alternative management practices for leaching reduction.

2 Materials and methods

2.1 Study area and experimental design

This study was conducted in a state-owned oil palm plantation in Jambi province, Indonesia (1° 43' 8" S, 103° 23' 53" E, 73 m above sea level). Mean annual air temperature is 26.7 ± 1.0 °C and mean annual precipitation is 2235 ± 385 mm (1991–2011; data from Sultan Thaha airport, Jambi). During our study period (March 2017–February 2018), the mean daily air temperature was 26.3 °C and annual precipitation was 2772 mm, with a dry period between July and October (precipitation < 140 mm month^{-1}). The soil is highly weathered, loam Acrisol soil (Allen et al., 2015) and nutrient inputs from bulk precipitation in the area, measured in 2013, were 12.9 kg N, 0.4 kg P, 5.5 kg K ha^{-1} yr^{-1} (Kurniawan et al., 2018).

This oil palm plantation was established between 1998 and 2002, and so the palms were 16–20 years old during our study period. The plantation has a flat terrain and it encompassed

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2025 ha, with a planting density of approximately 142 palms ha^{-1}, spaced 8 m apart on rows. The rows between palms are used alternately for harvesting operations and to pile-up senesced fronds, which are regularly cut to facilitate harvesting of fruits; this frond-stacked area covers 15% of the plantation. The palm circle, 2 m radius from the stem, wherein fertilizers are applied and chemically weeded four times a year, covers 18% of the plantation. The remaining 67% can be classified as inter-row, which is not fertilized but weeded two times a year.

In November 2016, a two (fertilization rates) by two (weeding methods) factorial management experiment was established in this plantation as part of the framework of the EFForTS project, described in detail by Darras et al. (2019). For fertilization treatments, the conventional rates were 260 N, 50 P, 220 K kg ha^{-1} yr^{-1}, whereas the reduced rates were 136 N, 17 P, 187 K kg ha^{-1} yr^{-1}. Reduced fertilization rates were determined to compensate for nutrient exports via fruit harvest and were based on the nutrient concentrations measured in the fruit bunches multiplied by the annual yield. The fertilizer sources were urea (CH_4N_2O), triple superphosphate ($Ca(H_2PO_4)_2\cdot H_2O$) and muriate of potash (KCl), in granular forms. These were applied according to the plantation's standard practices: split in two applications per year (in April and October), spread in a band within a 2 m radius from the palm, and this area was raked before fertilizer application. For both fertilization treatments, lime (426 kg dolomite ha^{-1} yr^{-1}; $CaMg(CO_3)_2$) and micronutrients (142 kg Micro-Mag ha^{-1} yr^{-1} with 0.5% B_2O_3, 0.5% CuO, 0.25% Fe_2O_3, 0.15% ZnO, 0.1% MnO and 18% MgO) were also applied besides the N, P and K fertilizers, as commonly practiced in large-scale plantations on acidic Acrisol soils (Pahan, 2010). For weeding treatments, the conventional method was the use of herbicide (glyphosate), whereas the reduced method was mechanical weeding using a brush cutter; the cut plant materials were left on the ground. Glyphosate was applied following plantation's standard practice: 1.5 L ha^{-1} yr^{-1} to the palm circle, split four times a year, and 0.75 L ha^{-1} yr^{-1} to the inter-row, split two times a year. The mechanical weeding was carried out in the same areas and

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frequencies as herbicide application. This management experiment comprised of four replicate blocks and each had four plots (50 m x 50 m each) assigned to four treatment combinations: conventional rate–herbicide, conventional rate–mechanical weeding, reduced rate–herbicide, and reduced rate–mechanical weeding.

2.2 Soil water sampling

We collected monthly soil-pore water samples over one year, using suction cup lysimeters (P80 ceramic, maximum pore size 1 µm; CeramTec AG, Marktredwitz, Germany). We installed the lysimeters in January 2017, choosing two palms per plot and sampling in the three management zones: 1) in the palm circle, at 1 m from the palm stem, 2) in the frond-stacked area, at about 4 m from the palm stem, and 3) in the inter-row, at approximately 4 m from the palm stem (Fig. A1). In total, 96 lysimeters were installed (4 treatment plots x 4 replicates x 2 subplots x 3 management zones). The lysimeters were inserted into the soil to 1.5 m depth, so that the soil-pore water was collected well below the rooting depth of 1 m which is common to oil palm plantations on loam Acrisol soils near our study site (Kurniawan et al., 2018). Starting in March 2017, soil water was sampled by applying 40 kPa vacuum (Kurniawan et al., 2018; Dechert et al., 2005) to the lysimeters and collected in dark glass bottles, which were stored in a bucket buried in the field. Although there was only two-month acclimatization of lysimeters between their installation and the beginning of sampling, we considered this to be sufficient as soil disturbance was minimized and biochemical processes are rapid in tropical soils. Once a week, we transferred the collected water into plastic bottles and transported them to the field station, where they were stored frozen. The collection continued over a month until a volume of 100 mL was collected from each lysimeter, or until the end of the month. The frozen water samples were transported by air freight to the University of Goettingen, Germany, where element concentrations were determined. We measured the concentrations of mineral N (NH_4^+ and NO_3^-

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), total dissolved N (TDN) and Cl by continuous flow injection colorimetry (SEAL Analytical AA3, SEAL Analytical GmbH, Norderstadt, Germany), as described in details by Kurniawan et al. (2018). Dissolved organic N (DON) was calculated as the difference between TDN and mineral N. We measured the concentrations of base cations (Na, K, Ca, Mg), total Al, total Fe, total Mn, total S, and total P with an inductively coupled plasma–atomic emission spectrometer (iCAP 6300; Thermo Fischer Scientific GmbH, Dreieich, Germany).

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We determined a partial cation-anion charge balance of the major elements (concentrations > 0.03 mg L^{-1}) in soil-pore water by converting the concentrations to μmol_{charge} L^{-1}. We assumed S to be in the form of sulfate (SO_4^{2-}) and total Al to have a charge of 3^+. We calculated the combined contribution of organic acids ($RCOO^-$) and bicarbonate (HCO_3^-) as the difference between the measured cations and anions (Kurniawan et al., 2018).

2.3 Modeling water drainage

The water balance was modeled using the water sub-model of the Expert-N software, version 5.0 (Priesack, 2005), which was successfully used to estimate drainage fluxes from different land uses in Indonesia (Dechert et al., 2005; Kurniawan et al., 2018). The model inputs were climate data (solar radiation, temperature, precipitation, relative humidity, and wind speed), and soil (texture, bulk density, and hydraulic functions) and vegetation characteristics (biomass, leaf area index, and root distribution). The climate data were taken from the climatological station in the plantation (described in detail by Meijide et al., 2017), and the oil palm biomass was taken from a study on oil palm plantations near our study site (Kotowska et al., 2015). Soil bulk density and porosity in the top 10 cm were measured in each management zone at our study site, whereas for the 10–50 cm depth these were measured in the inter-row. Data for soil bulk density and porosity for the 50–200 cm depth, as well as soil texture, soil hydraulic

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parameters (i.e. water retention curve, saturated hydraulic conductivity and Van Genuchten parameters for the water retention curve), and root distribution were taken from Allen et al. (2015) and Kurniawan et al. (2018), choosing their studied oil palm plantations closest to our study site. The Expert-N water sub-model calculates daily water drainage based on precipitation, evapotranspiration, canopy interception, runoff, and change in soil water storage. Evapotranspiration is calculated using the Penman-Monteith method (Allen, 1998), applying a plant factor of 1.06 (Meijide et al., 2017), with plant transpiration based on leaf area index (LAI), plant biomass, and maximum rooting depth. The canopy interception is calculated from the percentage of throughfall and the maximum water storage capacity of the canopy. Runoff is calculated from soil texture and bulk density, which determine the water infiltration rate, and from the slope, which was 5% (Röll et al., 2019). The vertical water movement is calculated using Richards equation based on soil hydraulic functions (Hillel, 1982).

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To model the drainage in the different management zones, we used the measured soil bulk density and porosity in the top 10 cm and adjusted other input parameters to simulate differences in water balance in each management zone (Table A1). For the palm circle, we set the LAI to 3.65, which is the maximum LAI measured at our site (Fan et al., 2015), to simulate high water uptake in the palm circle (Nelson et al., 2006) and maximum rooting depth to 1 m, which is reported for oil palm plantations near our site (Kurniawan et al., 2018). The percentage throughfall in the palm circle was set to 10% and the water storage capacity of oil palm stem was set to 8.4 mm (Tarigan et al., 2018). For the inter-row, we set the LAI and the maximum rooting depth as half of the palm circle (1.8 LAI, 50 cm rooting depth), as roots are shallower between palms (Nelson et al., 2006); the throughfall was set to 50%, and the palm stem's water storage capacity was set to 4.7 mm (based on canopy storage capacity reported by Tarigan et al., 2018). For the frond-stacked area, the LAI was set to 0.75, which is half of the minimum measured in the studied plantation (Darras et al., 2019), as understory vegetation is absent at

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this zone. Values for interception in the frond-stacked area was set to the same values as the inter-row, whereas the runoff was set to 0 (no overland runoff), as mulching with senesced fronds slows down runoff (Tarigan et al., 2016).

For validation of the Expert-N water sub-model outputs, we measured soil water matric potential at depths of 30 cm and 60 cm over the study period and compared the measured values with the modeled matric potential. Matric potential was measured by installing a tensiometer (P80 ceramic, maximum pore size 1 µm; CeramTec AG, Marktredwitz, Germany) at each depth in each management zone near to two palms in two treatments (i.e. conventional rate–herbicide, and reduced rate–mechanical weeding), for a total of 12 tensiometers. We summed the modeled daily drainage at 1.5 m depth to get the monthly drainage fluxes, which we then multiplied with the element concentrations in soil water to get the monthly nutrient leaching fluxes.

2.4 Soil biochemical characteristics and nutrient retention efficiency

We measured soil biochemical properties in the same sampling locations (Figure A1) at four depth intervals: 0–5 cm, 5–10 cm, 10–30 cm, and 30–50 cm. Soil samples from the same management zone in each plot were pooled to make one composite sample, totaling 192 soil samples (4 treatments plots x 4 replicates x 3 management zones x 4 depths). The samples were air-dried and sieved (2 mm) and measured for pH (1:4 soil-to-water ratio) and for effective cation exchange capacity (ECEC), by percolating the soils with unbuffered 1 mol L^{-1} NH_4Cl and measuring the cations (Ca, Mg, K, Na, Al, Fe, Mn) in percolates using ICP-AES. A subsample was finely ground and analyzed for organic C and total N using a CN analyzer (Vario EL Cube, Elementar Analysis Systems GmbH, Hanau, Germany), and for ^{15}N natural abundance signature using isotope ratio mass spectrometer (IRMS; Delta Plus, Finnigan MAT, Bremen, Germany). We calculated the soil element stocks for each depth by multiplying the element concentration with the measured bulk density and summed for the top 50 cm; other soil

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characteristics (e.g. pH, ECEC, base saturation) in the top 50 cm soil were calculated as the depth-weighted average of the sampled depths.

In addition, we calculated the N and base cation retention efficiency in the soil for each experimental treatment and management zone following the formula: nutrient retention efficiency = 1 – (nutrient leaching loss / soil-available nutrient) (Kurniawan et al., 2018). We used the gross N mineralization rates in the top 5 cm soil (Table A2) as an index of soil-available N whereas soil-available base cations was the sum of the stocks of K, Na, Mg and Ca in the top 10 cm soil, expressed in mol$_{charge}$ m^{-2}.

2.5 Statistical analyses

For soil biochemical properties measured once, we tested for differences among management zones as well as among experimental treatments for the entire 50 cm depth, using the analysis of variances (ANOVA) with Tukey HSD as a post hoc test. The soil variables that showed non-normal distribution or unequal variances, tested with Shapiro–Wilk and Levene’s tests, respectively, were log-transformed prior to the analysis. Base cation and N retention efficiency were also tested for differences between experimental treatments in the same way. For repeatedly measured variables, i.e. soil-pore water solute concentrations and leaching fluxes, we used linear mixed-effects models (LME; Bates et al., 2015) to assess the differences among management zones and treatments. For testing management zone differences, we conducted the LME with management zone as fixed effect and random effects for sampling months and experimental treatments nested with replicate plots, which were also nested with subplots. For testing treatment differences, we calculated for each replicate plot on each sampling month the area-weighted average of the three management zones (i.e. palm circle accounts for 18% of the plantation area, the frond-stacked area 15%, and the inter-row 67%), and LME was carried out with treatment as fixed effect and random effects for sampling months and replicate plots nested

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with subplots. If the residuals of the LME models were not normally distributed, we applied either logarithmic or square root transformation. Differences were assessed with ANOVA (Kuznetsova et al., 2017) followed by Tukey HSD (Hothorn et al., 2008). We also used LME to assess differences in soil water matric potential among management zones, with management zone as fixed effect and measurement days and depth nested with treatment as random effects. Comparability between modeled and measured soil water matric potential for each depth in each management zone ($n = 50$ field measurements) was assessed using Pearson correlation test. All tests were considered significant at $P \leq 0.05$, except for soil pH which we considered a marginal significance at $P = 0.06$. All statistical analyses were performed with R version 3.6.1 (R Core Team, 2019).

3 Results

3.1 Soil biochemical properties and water balance

Soil biochemical properties in the top 50 cm did not differ between experimental treatments (all $P > 0.05$) but strongly differed among management zones (Table 1). The frond-stacked area, where senesced fronds were regularly piled like mulch material, had higher SOC and total N stocks ($P < 0.01$) compared to the other management zones. The inter-row, with regular weeding but without direct fertilizer and lime inputs, showed lower exchangeable base cation contents (i.e. Ca, Mg, K) compared to the other management zones ($P \leq 0.02$) and higher exchangeable Al content than the palm circle ($P = 0.01$). This was reflected in the lower base saturation and higher Al saturation in the inter-row compared to the other zones ($P < 0.01$). Also, inter-row had the lowest ECEC ($P < 0.01$) and marginally lower pH than the palm circle ($P = 0.06$). The palm circle, where fertilizers and lime were applied, had generally comparable exchangeable element contents with the frond-stacked area, except for K, which was higher in the palm circle ($P < 0.01$), and for Mn, which was higher in the frond-stacked area ($P < 0.01$).

There were strong positive correlations between field-measured and modeled soil water matric potential (Fig. 1). The matric potential was generally lowest in the palm circle, intermediate in the inter-row, and highest in the frond-stacked area ($P < 0.01$). This pattern was also reflected in the low drainage flux in the palm circle and high drainage flux in the frond-stacked area (Table 2; Fig. 2). In the palm circle, the low drainage flux had resulted from high plant transpiration and interception whereas the high drainage flux in the frond-stacked area was due to low evapotranspiration and runoff with the senesced frond mulch (Table 2). In ratio to annual precipitation, the calculated annual evapotranspiration was 51%, 31%, and 38% in the palm circle, frond-stacked area, and inter-row, respectively; annual drainage fluxes at 1.5 m depth were 20% of precipitation in the palm circle, 65% in the frond-stacked area, and 43% in the inter-row. Seasonally, the monthly drainage fluxes had two peak periods, May and November, after consecutive days of moderate rainfall, and were lowest during the end of the dry season towards the start of the wet season (Fig. 2).

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3.2 Differences in leaching losses among management zones and treatments

For element concentrations in soil-pore water at 1.5 m depth, treatment differences were exhibited clearly in the palm circle and inter-row (Fig. 3), with the herbicide treatment showing higher element concentrations than the mechanical weeding ($P \leq 0.02$). The frond-stacked area had generally lower ionic charge concentrations compared to the other management zones (Fig. 3). The dominant cations were Al^{3+}, Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+} across experimental treatments and management zones. Among the management zones, Al^{3+} concentrations were highest in the inter-row, intermediate in the palm circle, and lowest in the frond-stacked area ($P < 0.01$). The concentrations of Ca^{2+} were similar in the palm circle and frond-stacked area ($P = 0.42$), and these were higher than in the inter-row ($P < 0.01$). The concentrations of Mg^{2+} and K^{+} were higher in the palm circle than in the other two management zones ($P < 0.01$). The Na^{+} concentrations were higher in the palm circle and inter-row than in the frond-stacked area ($P < 0.01$). As for N, NH$_4^+$ concentrations were lowest in the frond-stacked area, followed by the palm circle, and highest in the inter-row ($P = 0.01$). Across treatments, NH$_4^+$ was 4–18% of TDN whereas DON was 1-7% of TDN. Thus, NO$_3^-$ was the main form of dissolved N, and this was highest in the inter-row, followed by the frond-stacked area, and lowest in the palm circle ($P < 0.01$). The dominant anion was Cl$^-$ with higher concentrations in the palm circle than in the other zones ($P < 0.01$).

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Monthly leaching fluxes showed a common pattern among the major solutes (Fig. 4): there were two peaks of leaching losses (May and November) that followed fertilizer applications, and lower leaching losses during the dry season from July to October. Leaching fluxes of NO$_3^-$ showed similar pattern as its concentrations: higher in the inter-row, followed by the frond-stacked area, and lowest in the palm circle ($P < 0.01$; Fig. 4). Total Al leaching fluxes were also higher in the inter-row than the other zones ($P < 0.01$; Fig. 4). On the other hand, base cation leaching fluxes had opposite patterns as their concentrations: Ca, K, and Mg leaching were higher in the frond-stacked area than the palm circle and inter-row (all $P < 0.01$; Fig. 4). Leaching of Na was higher in both the frond-stacked area and inter-row than the palm circle ($P < 0.01$; Fig. 4).

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Reduced intensity of management clearly influenced nutrient leaching losses (Fig. 5; Table 3). Specifically, mechanical weeding reduced NO$_3^-$ and cation leaching compared to herbicide weed control ($P \leq 0.03$; Fig. 5; Table 3). Leaching of NO$_3^-$ was highest in the conventional fertilization–herbicide treatment and lowest in reduced management treatments ($P \leq 0.02$; Fig. 5). This was also reflected in the leaching fluxes of accompanying cations; specifically, total Al and Ca leaching were higher in conventional fertilization–herbicide treatment than the reduced management treatments (all $P \leq 0.02$; Fig. 5). For the other base cations, mechanical weeding clearly lowered leaching losses compared to herbicide weeding, in particular K and Na leaching in both fertilization rates and Mg leaching in conventional fertilization (all $P \leq 0.03$; Fig. 5).

3.3 Annual leaching losses and nutrient retention efficiency

In proportion to the applied fertilizer, annual leaching losses of TDN (Table 3) were 28% of the applied N in the herbicide treatment for both conventional and reduced fertilization rates, 24% in the mechanical weeding with conventional fertilization, and only 19% in the mechanical weeding with reduced fertilization. The annual leaching of K (Table 3) was 4% of the applied K fertilizer in the herbicide treatment and 3% in the mechanical weeding for both fertilization rates. In this highly weathered Acrisol soils with high capacity for P fixation by Fe and Al (hydr)oxides, there was no leaching of dissolved P (Table 3).

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Both N and base cation retention efficiencies were generally lower in the inter-row compared to the other management zones ($P \leq 0.03$), except for reduced fertilization–mechanical weeding where there were no differences among management zones (Table 4). The area-weighted average N retention efficiency was comparable among experimental treatments ($P = 0.89$) but there was a trend of increasing efficiency with decreasing management intensity (Table 4). Base cation retention efficiency showed clear differences among experimental treatments for each management zones: in the palm circle, it was highest in mechanical weeding and lowest in the herbicide treatment ($P = 0.04$); in the frond-staked area and inter-row, it was lowest in the most intensive management treatment (conventional fertilization–herbicide) and highest in either mechanical weeding or reduced fertilization ($P \leq 0.05$; Table 4). The area-weighted average base cation retention efficiency was also clearly influenced by weeding method, being lowest in herbicide treatment and highest in mechanical weeding both with conventional fertilization (P = 0.03; Table 4).

4 Discussion

4.1 Water model and temporal pattern of nutrient leaching losses

To our knowledge, this study is the first attempt to model drainage fluxes from the different management zones of an oil palm plantation, making our comparisons with literature values limited. Our modeled annual transpiration rate in the palm circle (Table 2) was remarkably similar to the values estimated with the same Penman–Monteith method (827–829 mm yr^{-1}; Meijide et al., 2017; Röll et al., 2019), and our average daily transpiration rate (2.3 mm d^{-1}) was within the range of that measured with drone-based photogrammetry (3 ± 1 mm d^{-1}; Ahongshangbam et al., 2019), all in the same oil palm plantation. Also, the modeled annual runoff in the palm circle and inter-row (Table 2) was within the range of runoff estimates in oil palm plantations in Jambi province (10–20% of rainfall; Tarigan et al., 2016) and in Papua New Guinea (1.4–6% of rainfall; Banabas et al., 2008b). Considering the areal proportions of the three management zones, the weighted-average drainage flux (1161 mm yr^{-1}) was lower than that estimated for smallholder oil palm plantations near our study site (1614 mm drainage flux with 3418 mm precipitation measured in 2013; Kurniawan et al., 2018). However, ratios of drainage flux to annual precipitation were comparable between our study and that by Kurniawan et al. (2018). Also, evapotranspiration rate is higher in large-scale than smallholder oil palm plantations in our study area (Röll et al., 2019), which could have led to lower drainage flux in large-scale plantation. Moreover, in the frond-stacked area, enhanced porosity from organic matter that facilitates water infiltration (Moradi et al., 2015), as indirectly indicated by its low soil bulk density (Table 1), combined with low evapotranspiration and runoff, resulted

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The temporal peaks of nutrient leaching fluxes (May and November; Fig. 4) had resulted from the combined effect of high drainage flux and fertilizer application. High drainage might have stimulated the downward transport of nutrients and decreased their residence time in the soil, and thus their adsorption onto the soil exchange sites (Lohse and Matson, 2005). Although large drainage fluxes usually dilute the nutrient concentrations in the soil-pore water; fertilizer and lime applications maintained high nutrient concentrations as manifested by the parallel peaks of drainage and nutrient leaching fluxes (Figs. 2 and 4). The high NO_3^- leaching following urea-N fertilization (Fig. 4) suggests increased nitrification (Silver et al., 2005), fast NO_3^- transport through the soil column, and reduced anion adsorption capacity, which otherwise would have delayed anion leaching (Wong et al., 1990). The latter was possibly aggravated by the additional Cl^- from fertilization with KCl (Fig. 3), which could saturate the soil anion exchange sites, particularly at this mature plantation with already 16–20 years of high fertilization rates. Large NO_3^- leaching is always accompanied by large leaching of buffering cations (Dubos et al., 2017; Kurniawan et al., 2018), resulting in their similar temporal patterns (Fig. 4). These findings showed that fertilization should be avoided during periods of high drainage fluxes. Generally, the high drainage was a consequence of a protracted period of moderate rainfall (Fig. 2). Prediction of periods of high precipitation and drainage will further be confounded by climate change, which is widening the range between wet and dry seasons and increasing the uncertainties in rainfall intensity and distribution (Chou et al., 2013; Feng et al., 2013). Fertilization during the dry period is also not advisable given the high volatilization

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of applied urea even in acidic soil as this is always accompanied by liming (Goh et al., 2003; Pardon et al., 2016) and the low palm uptake during the dry season (Corley and Tinker, 2016). Thus, spreading the fertilization over a longer period of time and reducing fertilization rates, e.g. at compensatory level equal to harvest export, seem viable options to reduce leaching losses without sacrificing production. One other option is the use of organic amendments, such as empty fruit bunches, compost, palm oil mill effluent, or slow-release fertilizers, which have been shown to reduce N leaching in tropical cropping systems (Nyamangara et al., 2003; Mohanty et al., 2018; Steiner et al., 2008). In addition, organic fertilizer can improve soil fertility in oil palm plantations (Comte et al., 2013; Boafo et al., 2020), as was also evident with mulching of senesced oil palm fronds (i.e. high SOC, total N, ECEC and base saturation in the frond-stacked area; Table 1).

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4.2 Leaching losses in the different management zones

Contrary to our first hypothesis, nutrient leaching losses among management zones were generally large in the inter-row, especially for mineral N (largely NO$_3$; Fig. 3), and lower in the palm circle (Fig. 4). This strikingly large mineral N leaching losses in the inter-row were surprising given that this area did not receive direct fertilizer inputs (see section 2.1). This result suggests that mineral N was transported from the directly fertilized palm circle to the inter-row via surface and subsurface lateral flow as these two zones were just 3 m apart (Fig. A1). Surface transport of mineral N was probably a minor process at our site because of the low runoff (Table 2); in an oil palm plantation in Papua New Guinea, the loss of N fertilizer via surface runoff is only 0.3–2.2 kg N ha^{-1} yr^{-1} (Banabas et al., 2008b). Mineral N was probably predominantly transported to the inter-row via subsurface lateral flow. Acrisol soils are characterized by clay translocation from upper to lower depths that could create an impeding layer conducive to lateral water flow (Elsenbeer, 2001). Indeed, the clay contents of the Acrisol soils at our study

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The palm circle had relatively low N leaching losses (Figs. 3 and 4) despite the direct application of fertilizer. This was probably due to the large root density in this zone that facilitates an efficient nutrient uptake (Edy et al., 2020; Nelson et al., 2006). Hence, the dominant anion in soil-pore water in the palm circle was Cl^- (Fig. 3), enhanced by the applied KCl fertilizer, which was accompanied by high base cation concentrations relative to dissolved Al (Fig. 3). The former was due to the applied micromag fertilizer and dolomite (section 2.1), which increased pH and exchangeable bases and rendered Al in insoluble form (i.e. lower exchangeable Al; Table 1; Schlesinger and Bernhardt, 2013). Despite their high concentrations, the leaching fluxes of base cations in the palm circle (Fig. 4) were constrained by the low water drainage flux due to high evapotranspiration (Table 2).

The frond-stacked area was at the same distance from the palm circle as the inter-row (Fig. A1) but had substantially lower mineral N leaching losses (Figs. 3 and 4). Decomposition of nutrient-rich fronds (Kotowska et al., 2016) resulted in high SOC and N stocks (Table 1), which can support large microbial biomass in this zone (Haron et al., 1998). Thus, the low mineral N leaching in the frond-stacked area may be attributed to immobilization of mineral N by large microbial biomass, converting mobile NO_3^- to less mobile organic N (e.g. Corre et al., 2010). In addition, it could be possible that palm root uptake of nutrients (including mineral N) was higher in the frond-stacked area compared to the inter-row as roots proliferate in nutrient-rich zones (Table 1; Hodge, 2004). This is supported by studies that showed higher root density and higher water uptake under the frond piles compared to the inter-row (Rüegg et al., 2019; Nelson et al., 2006). The high ECEC, base saturation and pH in frond-stacked area (Table 1), despite having no direct lime application, were due to the release of nutrients from decomposition of frond litter, which contain high levels of base cations concentrations (Kotowska et al., 2016). Thus, the larger base cations leaching in the frond-stacked area compared to the inter-row (Fig. 4) merely mirrored their high exchangeable concentrations (Table 1). Finally, the leaching of Al was low in the frond-stacked area (Figs. 3 and 4) because Al becomes insoluble as pH increases (i.e. lower exchangeable Al; Table 1). Altogether, these results highlighted the benefits of piling senesced fronds onto the soil to reduce leaching of mineral N and Al, which otherwise can potentially diminish ground water quality. Oil palm plantations in other areas (e.g. Borneo; Rahman et al., 2018) were reported to practice piling of senesced fronds on every inter-row, which we did not observed in our study region as that is claimed to hinder access to palms during harvest. Nonetheless, our findings implied that increase in the frond-stacked area can contribute to sustainable management practices of oil palm plantations.

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4.3 Leaching losses under different intensity of management

There was a clear influence of management intensity treatments on nutrient leaching losses with a general reduction of leaching in reduced management intensity (Fig. 5; Table 3). In line with our second hypothesis, the weeding methods clearly influenced leaching losses: the mechanical weeding treatment had generally lower nutrient leaching fluxes than the herbicide treatment (Fig. 5; Table 5). Mechanical weeding was associated with more ground vegetation cover (Darras et al., 2019) and higher nutrient retention efficiency than herbicide weeding (Table 4), suggesting that faster regrowth of understory vegetation by mechanical weeding has additionally contributed to the uptake of nutrients and thus reducing leaching losses. This is in line with some studies in temperate forests and a cedar plantation, which showed that understory vegetation can take up excess NO_3^- in the soil (Olsson and Falkengren-Grerup, 2003) and reduce NO_3^- leaching and the mobilization of Ca and Mg (Baba et al., 2011; Fukuzawa et al., 2006). Enhanced understory vegetation in oil palm plantations may also positively impact biodiversity by increasing plant species richness and soil macrofauna diversity and abundance (Luke et al., 2019; Ashton-Butt et al., 2018), which may facilitate uptake and recycling of nutrients. Increase in soil macrofauna might have contributed to lower leaching of Na with mechanical weeding (Fig. 5), since herbivores and decomposers take up a large amount of Na (Kaspari et al., 2009). Yield, in the first three years following the experiment establishment was on average 30 Mg of fresh fruit bunches ha^{-1} yr^{-1} and it was comparable among experimental treatments (Figure A2, Darras et al. 2019). This indicated that the reduced management intensity did not affect productivity at least during the first three years, but the long-term measurment is essential as it may take a longer time for the yield to respond to our experimental the treatments (e.g. Tao et al. 2017). Also, the cost of the two weeding treatments (i.e. herbicide vs mechanical) was comparable because it is a common practice to combine the use of herbicide with the periodic mechanical cutting of resistant ground vegetation (Darras et al., 2019; Pahan, 2010). In addition, the use of glyphosate is associated with possible health risks to workers and

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the environment (van Bruggen et al., 2018). Therefore, these results altogether advocate for a higher sustainability of mechanical weeding over herbicide application.

The reduction of N fertilization rates decreased NO_3^- leaching, supporting our third hypothesis. Comparing conventional and reduced fertilization rates, there were no differences in total N stocks (section 3.1), mineral N levels (Darras et al., 2019), N retention efficiency (Table 4) and oil palm yield (Darras et al., 2019), suggesting that excess N (above harvest export; section 2.1) from high N fertilization was largely lost through leaching (Table 3). The decreased Al and Ca leaching with reduced fertilization can be attributed to the lowered NO_3^- leaching, since these were the accompanying cations (Figs. 4 and 5). Also, a reduction of Ca leaching could have resulted from the lower application rate of triple superphosphate fertilizer, which contains 16% of Ca. The reduced K fertilization had no effect on K leaching (Fig. 5) because K fertilization rate was only reduced by 15% of the conventional rate due to high K requirements of oil palm fruits (section 2.1). We conclude that this mature (16–20 years old) plantation with conventional management was overly fertilized for N, and that a reduction in N fertilization rate may be included in the Indonesian program for precision farming (Ministry of Agriculture of Indonesia, 2016) to reduce environmental footprint of oil palm production.

Comparing the N leaching losses in the studied plantation with other fertilized tropical plantations (Table A3), our plantation had higher N leaching than other large-scale oil palm plantations on similar soils with comparable fertilization rates (Omoti et al., 1983; Tung et al., 2009). However, in these studies the leaching losses were measured in the palm circle (Omoti et al., 1983) or the sampling location was not specified (Tung et al., 2009), such that N leaching may be underestimated as our results showed the high contribution of the inter-row to leaching losses (Figs. 3 and 4). The N leaching fluxes in our plantation were also higher than in smallholder oil palm plantations in the same area, which typically had much lower fertilization rates (Kurniawan et al., 2018). On the other hand, our plantation had lower N leaching losses

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than an oil palm plantation and coffee agroforestry systems on volcanic soils (Banabas et al., 2008b; Cannavo et al., 2013; Tully et al., 2012), which have high inherent nutrient contents, highly porous soils and high infiltration rates. The N leaching losses from our plantation were also lower than in banana plantations, characterized by very high fertilization rates (Wakelin et al., 2011; Armour et al., 2013). Lastly, our values are in the same range as the N leaching estimated for oil palm plantation, using a model that was validated with field measurements (Pardon et al. 2020).

The nutrients leached at 1.5 m depth should be considered lost from uptake of oil palm roots, as the majority of the root mass and the highest root density are in the top 0.5 m depth (Nelson et al., 2006; Schroth et al., 2000; Kurniawan et al., 2018). The high leaching fluxes of NO_3^- and Al implied a risk of groundwater pollution. During the high drainage fluxes following fertilization, NO_3^- concentrations in soil-pore water reached to 20–40 mg L^{-1} in the inter-row (covering 67% of the plantation area), which was close to the 50 mg L^{-1} limit for drinking water (WHO, 2011), and Al concentrations in soil-pore water exceeded the limit of 0.2 mg L^{-1} in 60% of the samples. Nevertheless, before reaching streams and rivers, these NO_3^- and Al concentrations can be diluted by surface flow and retained in the soil along flow paths: NO_3^- can be temporarily adsorbed in the deeper layers of highly weathered soils by its inherently high anion exchange capacity (Harmand et al., 2010; Jankowski et al., 2018) and can be consumed by denitrification (Wakelin et al., 2011). Riparian buffers can mitigate the transport of these agricultural pollutants to streams (Luke et al., 2017; Chellaiah and Yule, 2018). Restoring riparian buffers in former forests converted to oil palm plantations have been listed as one sustainability criteria, endorsed by the Roundtable for Sustainable Palm Oil association (RSPO, 2018), and may provide additional regulation services (Woodham et al., 2019).

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5 Conclusions

Our findings show that nutrient leaching losses in an oil palm plantation differed among management zones, as a result of fertilization, liming, mulching and of different drainage fluxes. The reduction of management intensity, i.e. mechanical weeding with reduced fertilization rates, was effective in reducing nutrient leaching losses without reduction in yield at least during the first three years of this experiment. Long-term investigation of this management experiment is important to get a reliable response of yield and a holistic economic analysis, including valuation of regulation services. Greenhouse gas emissions should also be quantified, as another important parameter of environmental footprint of oil palm production. Our findings and these further investigations should be incorporated into science-based policy recommendations such as those endorsed by the RSPO.

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Data availability

All data of this study are deposited at the EFForTS-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.

Author contribution

GF performed the experiments, analysed the data and wrote the manuscript in consultation with MDC. EV and MDC conceived and planned the experiment. XD helped carry out the water model simulations. AT aided in field activities organization and granting collaborations agreements. All authors contributed to the final version of the manuscript.

Competing interests

No conflict of interest to declare

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Tables and figures

Table 1 Soil physical and biochemical characteristics (mean ± standard errors, *n* = 4 plots) in the top 50 cm depth for each management zone, averaged across experimental treatments. Means within a row followed by different letters indicate significant differences among management zones (one-way ANOVA with Tukey HSD or Kruskal–Wallis H test with multiple comparisons extension at $P \leq 0.05$). Bulk density measured in the top 10 cm of soil, whereas all the other parameters are for the 0–50 cm soil depth: element stocks are the sum of the sampled soil depths (0–5 cm, 5–10 cm, 10–30 cm and 30–50 cm) and the rest are depth-weighted averages, calculated for each replicate plot. ECEC, effective cation exchange capacity

Soil properties		Palm circle	Frond-stacked area	Inter-row
Bulk density	g cm^{-3}	1.37 ± 0.01^{a}	0.89 ± 0.01^{b}	1.36 ± 0.01^{b}
Soil organic C	kg m^{-2}	6.2 ± 0.6^{b}	9.1 ± 0.8^{a}	6.4 ± 0.2^{b}
Total N	g m^{-2}	402 ± 31^{b}	571 ± 39^{a}	426 ± 15^{ab}
soil C:N ratio		15.5 ± 0.5^{a}	15.7 ± 0.3^{a}	15.0 ± 0.5^{a}
^{15}N natural abundance	‰	5.9 ± 0.1^{a}	5.3 ± 0.2^{a}	5.7 ± 0.2^{a}
pH	1:4 (H_2O)	5.05 ± 0.08^{a}	5.00 ± 0.08^{ab}	4.81 ± 0.05^{b}
ECEC	mmol$_c$ kg^{-1}	35 ± 2^{a}	28 ± 2^{a}	18 ± 1^{b}
Base saturation	%	48 ± 3^{a}	46 ± 4^{a}	20 ± 2^{b}
Aluminum saturation	%	52 ± 4^{b}	50 ± 2^{b}	78 ± 2^{a}
Mg	g m^{-2}	32 ± 3^{a}	28 ± 6^{a}	9 ± 1^{b}
Ca	g m^{-2}	169 ± 21^{a}	157 ± 15^{a}	37 ± 5^{b}
K	g m^{-2}	39 ± 13^{a}	13 ± 1^{b}	6 ± 1^{b}
Na	g m^{-2}	1.5 ± 0.4^{a}	0.7 ± 0.2^{a}	0.6 ± 0.2^{a}
Al	g m^{-2}	66 ± 4^{b}	71 ± 4^{ab}	87 ± 3^{a}

Fe	g m^{-2}	1.4 ± 0.2^{a}	1.8 ± 0.4^{a}	1.8 ± 0.5^{a}
Mn	g m^{-2}	0.7 ± 0.1^{b}	1.8 ± 0.3^{a}	0.6 ± 0.2^{b}
H	g m^{-2}	0.2 ± 0.0^{a}	0.2 ± 0.0^{a}	0.2 ± 0.1^{a}

Table 2 Annual water balance simulated from March 2017 to February 2018 for each management zone.

Water flux (mm yr^{-1})	Palm circle	Frond-stacked area	Inter-row
Precipitation	2772	2772	2772
Transpiration	828	448	401
Evaporation	228	214	434
Interception	351	209	209
Runoff	338	0	216
Drainage (at 1.5 m depth)	556	1806	1179

Table 3 Annual leaching losses at 1.5 m depth for each experimental treatment from March 2017 to February 2018. Values are area-weighted averages of leaching losses in each management zone (mean ± standard error, *n* = 4 plots). Means followed by different letters indicate differences among experimental treatments (linear-mixed effect models on monthly values followed by Tukey HSD test for multiple comparisons at $P \leq 0.05$). Treatments: ch = conventional fertilization–herbicide; cw = conventional fertilization–mechanical weeding; rh = reduced fertilization–herbicide; rw = reduced fertilization–mechanical weeding. DON = dissolved organic N; TDN = total dissolved N.

Element leaching (kg ha^{-1} yr^{-1})	ch	cw	rh	rw
NO_3^--N	71.5 ± 20.1^{a}	48.2 ± 13.0^{ab}	36.3 ± 20.1^{b}	30.0 ± 5.7^{b}
NH_4^+-N	1.7 ± 0.2^{a}	1.7 ± 0.1^{a}	1.8 ± 0.1^{a}	1.7 ± 0.2^{a}
DON	0.5 ± 0.5^{a}	0.6 ± 0.3^{a}	0.4 ± 0.1^{a}	0.3 ± 0.0^{a}
TDN	73.6 ± 20.2^{a}	50.4 ± 13.1^{ab}	38.4 ± 8.9^{b}	32.0 ± 5.8^{b}
Ca	26.6 ± 4.3^{a}	19.4 ± 4.4^{b}	18.2 ± 1.8^{b}	17.0 ± 2.1^{b}
Mg	11.6 ± 2.5^{a}	7.7 ± 0.8^{b}	9.1 ± 0.7^{ab}	10.8 ± 3.6^{ab}
K	8.1 ± 1.3^{a}	6.2 ± 0.7^{b}	8.9 ± 0.6^{a}	5.7 ± 1.1^{b}
Na	15.9 ± 3.5^{ab}	13.6 ± 2.4^{b}	18.9 ± 3.1^{a}	13.1 ± 1.2^{b}
Mn	0.3 ± 0.1^{a}	0.2 ± 0.0^{b}	0.2 ± 0.0^{bc}	0.1 ± 0.0^{c}
Total Al	40.8 ± 11.5^{a}	20.8 ± 7.6^{b}	19.9 ± 6.8^{b}	21.8 ± 3.1^{b}
Total S	2.4 ± 0.5^{a}	1.8 ± 0.4^{a}	2.1 ± 0.6^{a}	4.9 ± 3.3^{a}
Total Fe	0.2 ± 0.0^{a}	0.5 ± 0.3^{a}	0.2 ± 0.0^{a}	0.5 ± 0.3^{a}
Total P	0.0 ± 0.0^{a}	0.1 ± 0.0^{a}	0.0 ± 0.0^{a}	0.0 ± 0.0^{a}

Cl	79.7± 15.8^{a}	36.9 ± 8.3^{b}	67.7 ± 8.7^{a}	78.3 ± 7.5^{a}

Table 4 N and base cation retention efficiencies in the soil for each management zone and experimental treatment (means ± standard error, *n* = 4 plots). Means followed by different lowercase letters indicate differences among experimental treatments for each management zone, whereas different uppercase letters indicate differences among management zones for each experimental treatment (one-way ANOVA with Tukey HSD or Kruskal–Wallis H test with multiple comparisons extension at $P \leq 0.05$). Weighted-average is based on the areal coverage of each management zone: 18% for palm circle, 15% for frond-stacked area, and 67% for inter-row. Treatments: ch = conventional fertilization–herbicide; cw = conventional fertilization–mechanical weeding; rh = reduced fertilization–herbicide; rw = reduced fertilization–mechanical weeding. See section 2.4 for calculations of N and base cation retention efficiency.

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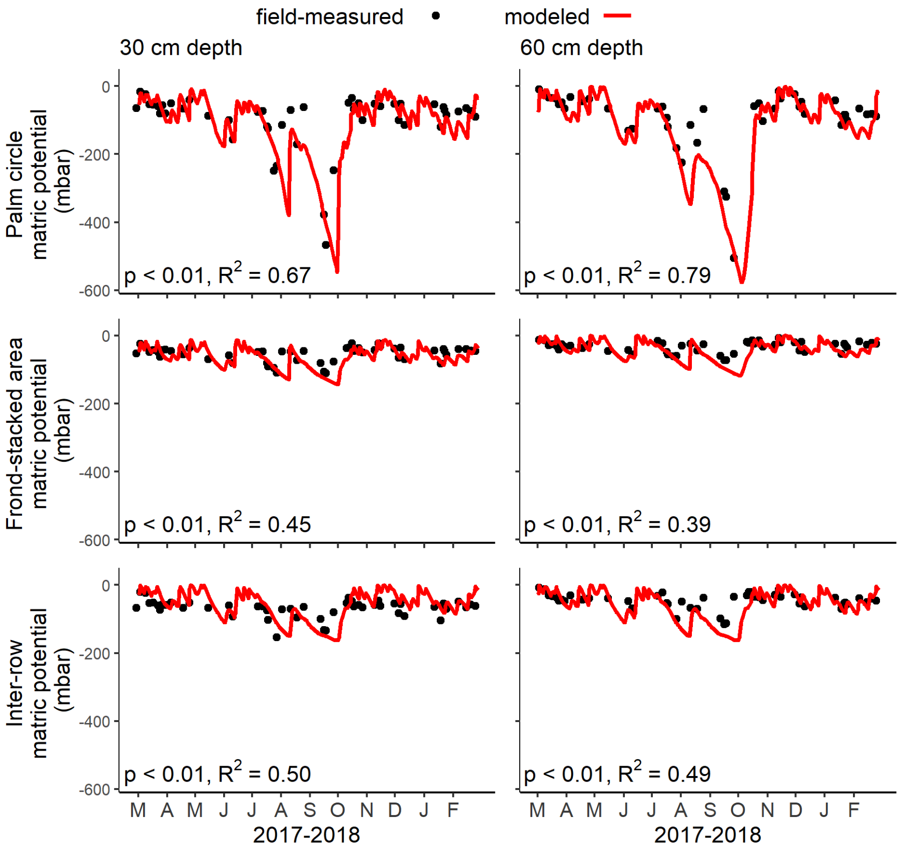
	ch	cw	rh	rw
N retention efficiency (mg N m^{-2} d^{-1} / mg N m^{-2} d^{-1})				
Palm circle	0.987 ± 0.002$^{a\ A}$	0.982 ± 0.007$^{a\ AB}$	0.986 ± 0.003$^{a\ AB}$	0.997 ± 0.000$^{a\ A}$
Frond-stacked area	0.984 ± 0.004$^{a\ A}$	0.989 ± 0.004$^{a\ A}$	0.993 ± 0.001$^{a\ A}$	0.987 ± 0.002$^{a\ A}$
Inter-row	0.877 ± 0.025$^{a\ B}$	0.870 ± 0.022$^{a\ B}$	0.900 ± 0.018$^{a\ B}$	0.906 ± 0.039$^{a\ A}$
Weighted-average	0.925 ± 0.022^{a}	0.934 ± 0.020^{a}	0.945 ± 0.012^{a}	0.946 ± 0.018^{a}
Base cation retention efficiency (mol$_{c}$ m^{-2} yr^{-1} / mol$_{c}$ m^{-2} yr^{-1})				

Palm circle	0.967 ± 0.008$^{ab\ A}$	0.982 ± 0.002$^{a\ A}$	0.937 ± 0.013$^{b\ A}$	0.974 ± 0.010$^{ab\ A}$
Frond-stacked area	0.884 ± 0.013$^{b\ A}$	0.950 ± 0.004$^{a\ A}$	0.960 ± 0.002$^{a\ A}$	0.928 ± 0.016$^{ab\ A}$
Inter-row	0.588 ± 0.086$^{b\ B}$	0.875 ± 0.022$^{a\ B}$	0.704 ± 0.048$^{ab\ B}$	0.822 ± 0.063$^{ab\ A}$
Weighted-average	0.876 ± 0.009^{b}	0.945 ± 0.007^{a}	0.902 ± 0.019^{ab}	0.934 ± 0.012^{ab}

Figure 1 Pearson correlation test between modeled (red line) and field-measured soil water matric potential (black points) (n = 50 field measurements over one year) for each management zone at 30 and 60 cm depths.



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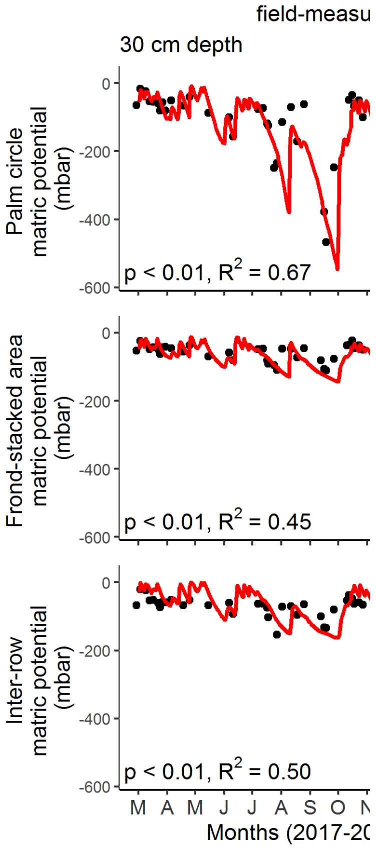
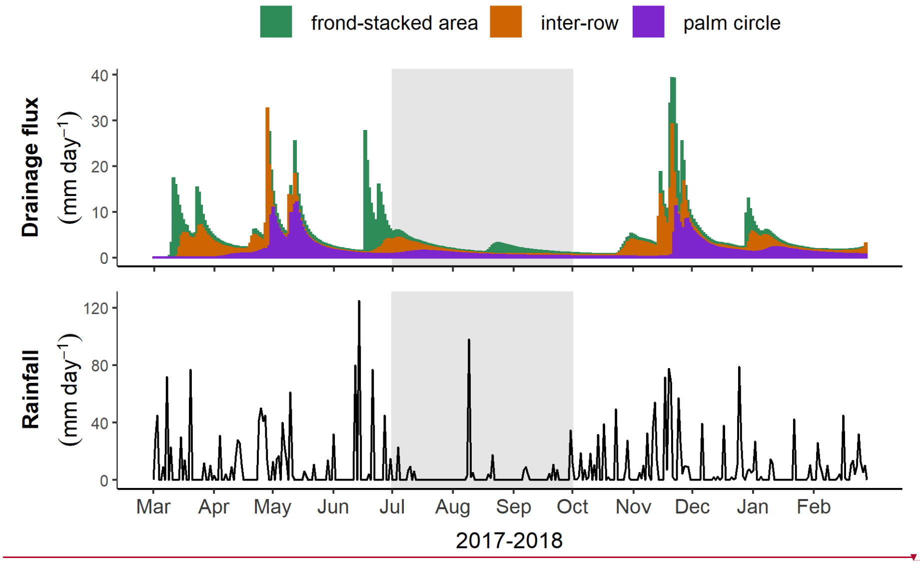


Figure 2 Monthly water drainage at 1.5 m depth, simulated in each management zone, and daily rainfall from March 2017 to February 2018. The gray shaded area represent the dry season (precipitation < 140 mm month^{-1})



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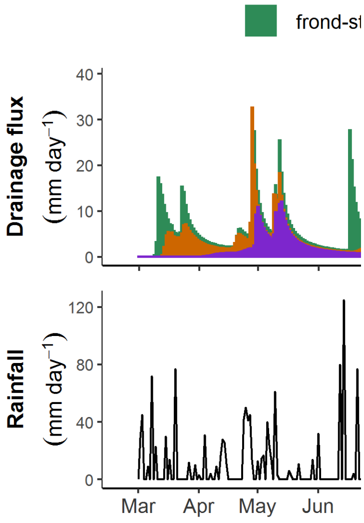


Figure 3. Partial cation-anion charge balance of the major solutes (with concentrations > 0.03 mg L^{-1}) in soil water at 1.5 m depth for each experimental treatment in the different management zones. The combined concentrations of organic acids ($RCOO^-$) and carbonates (HCO_3^-) are calculated as the difference between the measured cations and anions. Treatments: ch = conventional fertilization–herbicide; cw = conventional fertilization–mechanical weeding; rh = reduced fertilization–herbicide; rw = reduced fertilization–mechanical weeding.

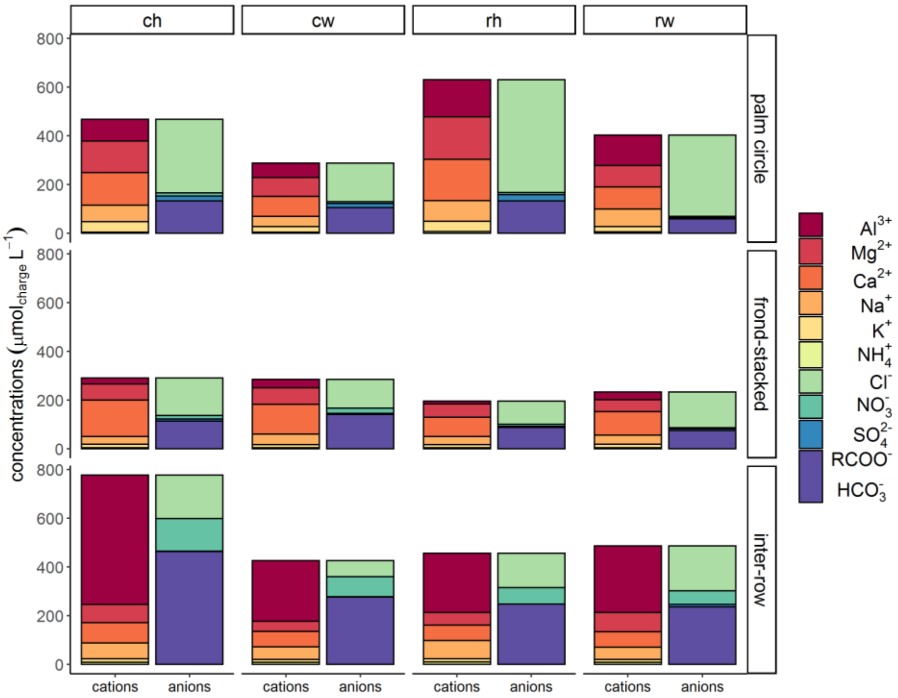
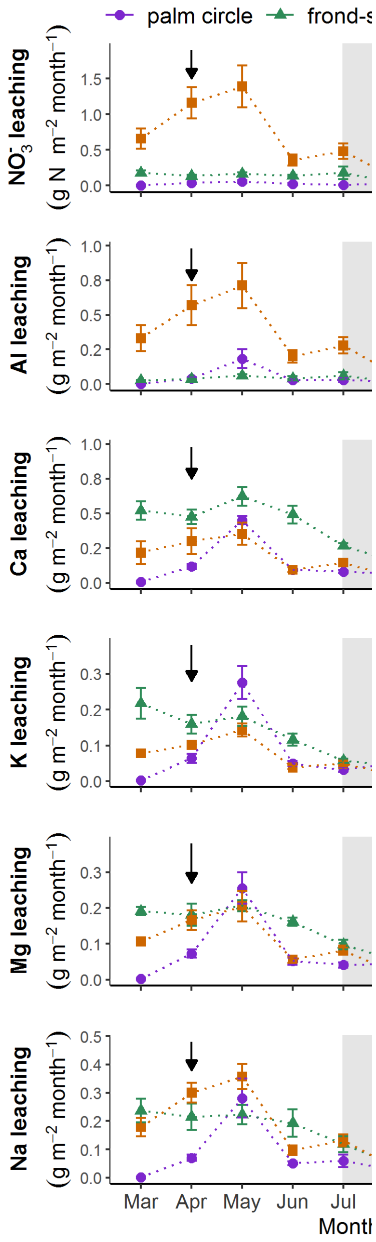


Figure 4 Monthly leaching losses at 1.5 m depth (mean ± standard errors, *n* = 4 plots) for each management zone. Black arrows indicate fertilizer applications and the gray shaded area represents the dry season (precipitation < 140 mm $month^{-1}$).



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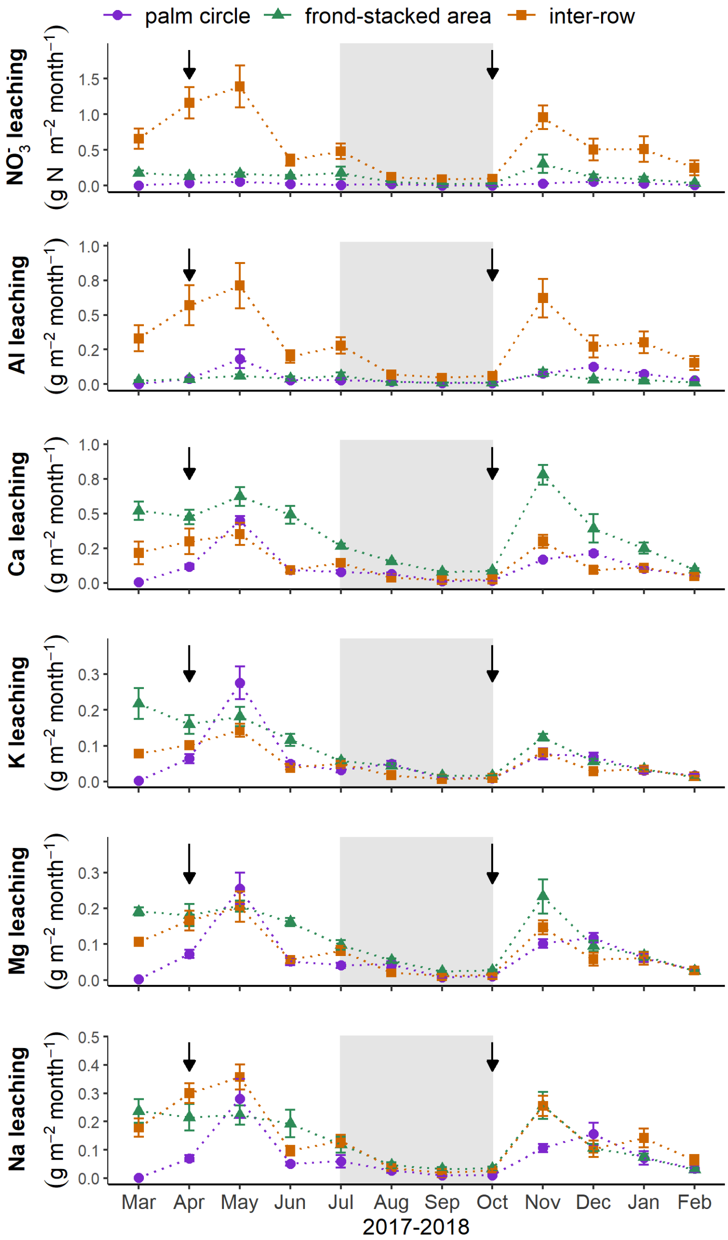
palm circle
frond-stacked area
inter-row
NO_3^- leaching
(g N m^{-2} month^{-1})
0.0
0.5
1.0
1.5
Al leaching
(g m^{-2} month^{-1})
0.0
0.2
0.5
0.8
1.0
Ca leaching
(g m^{-2} month^{-1})
0.0
0.2
0.5
0.8
1.0
K leaching
(g m^{-2} month^{-1})
0.0
0.1
0.2
0.3
Mg leaching
(g m^{-2} month^{-1})
0.0
0.1
0.2
0.3
Na leaching
(g m^{-2} month^{-1})
0.0
0.1
0.2
0.3
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0.5
Mar
Apr
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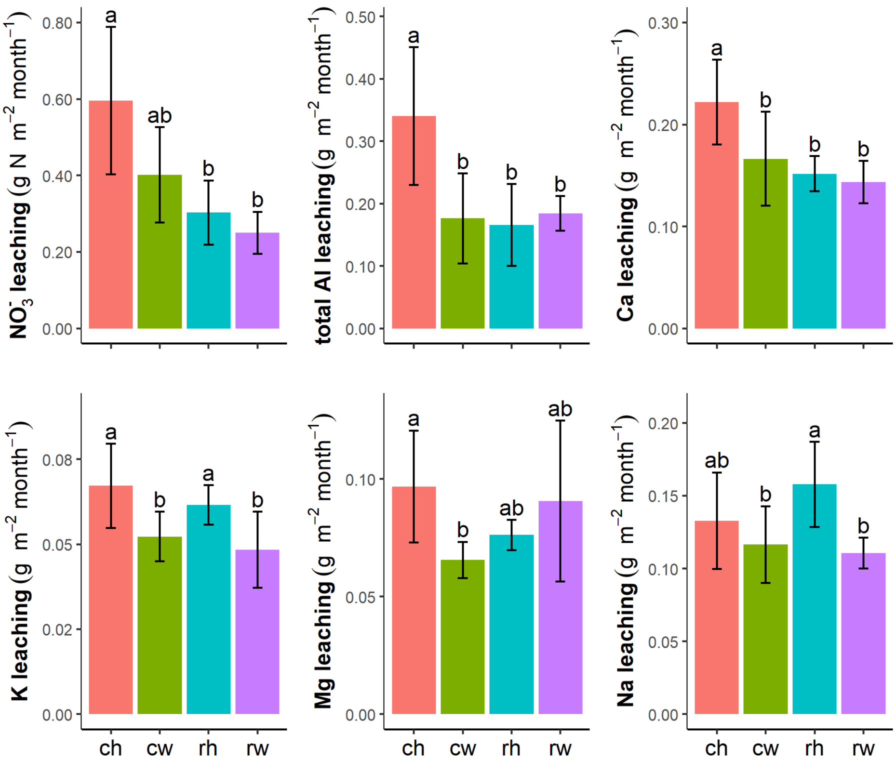
2017-2018

Figure 5 Average monthly leaching losses at 1.5 m depth for each experimental treatment from March 2017 to February 2018. Values are area-weighted averages of leaching losses in each management zone (means ± standard errors, *n* = 4 plots). For each parameter, different letters indicate significant differences among treatments (linear-mixed effect models on monthly values followed by Tukey HSD test for multiple comparisons at $P \leq 0.05$). Treatments: ch = conventional fertilization–herbicide; cw = conventional fertilization–mechanical weeding; rh = reduced fertilization–herbicide; rw = reduced fertilization–mechanical weeding



Appendices

Table A1 Parameters used for the Expert-N water sub-model for each management zone.

	Depth (cm)	**Palm circle**	**Inter-row**	**Frond-stacked area**
Interception				
Saturation capacity (mm d^{-1})		8.4	4.7	4.7
Throughfall (%)		50	10	10
Plant water uptake				
Plant height (cm)		874	874	874
Leaf area index		3.64	1.8	0.75
Leaf number		40	40	40
Aboveground biomass (kg ha^{-1})		47400	47400	47400
Maximum rooting depth (cm)		100	50	50
Crop cover		0.8	0.6	0.6
Root biomass (kg ha^{-1})		15600	15600	15600
Root partition (%)	0–10	29	29	29
	10–30	31	31	31
	30–50	18	18	18
	50–100	15	15	15
	100–150	5	5	5
	150–200	2	2	2
Soil properties				
Bulk density (g cm^{-3})	0–10	1.37	1.36	0.8
	10–30	1.36	1.36	1.26
	30–50	1.52	1.52	1.52
	50–100	1.50	1.50	1.50
	100–150	1.58	1.58	1.58
	150–200	1.46	1.46	1.46
Texture – Clay (%)	0–10	15.8	15.8	15.8
	10–30	24.5	24.5	24.5
	30–50	37.5	37.5	37.5
	50–100	41.0	41.0	41.0
	100–150	43.3	43.3	43.3
	150–200	47.6	47.6	47.6
Texture – Sand (%)	0–10	53.3	53.3	53.3
	10–30	47.6	47.6	47.6
	30–50	35.9	35.9	35.9
	50–100	34.4	34.4	34.4
	100–150	31.7	31.7	31.7

	150–200	29.8	29.8	29.8
Organic matter (%)	0–10	3.2	2.9	8.7
	10–30	2.8	2.6	3.7
	30–50	2.0	1.6	2.0
	50–100	2.5	2.5	2.5
	100–150	2.0	2.0	2.0
	150–200	1.2	1.2	1.2
Porosity (Vol %)	0–10	48.8	48.8	70.0
	10–30	45.7	45.7	45.7
	30–50	41.9	41.9	41.9
	50–100	43.3	43.3	43.3
	100–150	40.3	40.3	40.3
	150–200	45.0	45.0	45.0
Field capacity (Vol %)	0–10	27.2	27.2	27.2
	10–30	27.4	27.4	27.4
	30–50	21.3	21.3	21.3
	50–100	23.1	23.1	23.1
	100–150	24.5	24.5	24.5
	150–200	28.1	28.1	28.1
Wilting point (Vol %)	0–10	18.3	18.3	18.3
	10–30	17.3	17.3	17.3
	30–50	17.9	17.9	17.9
	50–100	17.3	17.3	17.3
	100–150	20.4	20.4	20.4
	150–200	24.5	24.5	24.5
Saturated hydraulic conductivity (mm d^{-1})	0–10	400	400	200
	10–30	200	200	400
	30–50	200	200	300
	50–100	150	150	150
	100–150	260	260	260
	150–200	260	260	260
Van Genuchten α (cm^{-1})	0–10	0.059	0.059	0.059
	10–30	0.025	0.025	0.035
	30–50	0.010	0.010	0.020
	50–100	0.008	0.008	0.015
	100–150	0.021	0.021	0.021
	150–200	0.021	0.021	0.021
Van Genuchten n	0–10	1.70	1.70	1.70
	10–30	1.71	1.71	1.81
	30–50	1.12	1.12	1.25
	50–100	1.09	1.09	1.15
	100–150	1.21	1.21	1.21
	150–200	1.23	1.23	1.23

Table A2 Gross N mineralization rates **(**means ± SE, *n* = 4 plots) in the top 5 cm soil for each treatment and management zone in a large-scale plantation in Jambi, Indonesia. Measurements were done on intact soil cores in February 2018 using the ^{15}N pool dilution technique, as described in details by Allen et al. (2015). Treatments: ch = conventional fertilization–herbicide; cw = conventional fertilization–mechanical weeding; rh = reduced fertilization–herbicide; rw = reduced fertilization–mechanical weeding

Gross N mineralization (mg N m^{-2} d^{-1})				
	ch	cw	rh	rw
palm circle	135 ± 39	115 ± 25	111 ± 34	210 ± 13
frond-stacked area	584 ± 100	845 ± 207	581 ± 188	430 ± 134
inter-row	288 ± 64	239 ± 39	227 ± 51	262 ± 56

Note: These data are not included in the main manuscript to avoid redundant publication as they were already included in another manuscript presently in review.

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Table A3 Literature comparison of annual N fertilization and total N leaching losses across tropical plantations.

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Author	Soil type	rainfall (mm yr^{-1})	Type of plantation management	N applied (kg ha^{-1} yr^{-1})	Total N leaching (kg ha^{-1} yr^{-1})	Percentage N leached (%)
Present study	loam Acrisol	2772	intensive oil palm	260	74	28
Present study	loam Acrisol	2772	intensive oil palm	130	38	28
Omoti et al. 1983	sandy clay Acrisol	2000	intensive oil palm	150	9	6
Kurniawan et al. 2018	loam Acrisol	3418	smallholder oil palm	88	11	12.5
Tung et al. 2009	Acrisol	-	intensive oil palm	128	3 (150 days)	2
Tung et al. 2009	Acrisol	-	intensive oil palm	251	3 (150 days)	1
Banabas et al. 2008	clay loam Andosol	2398	intensive oil palm	100	37	37
Banabas et al. 2008	sandy loam Andosol	3657	intensive oil palm	100	103	103
Cannavo et al. 2013	clay loam Andosol	2678	coffee agroforestry	250	157	63

Tully et al., 2012	clay loam Andosol	2700	coffee agroforestry	120	119	99
Armour et al. 2013	clay Acrisol	1958	intensive banana	476	164	34
Wakelin et al. 2011	loam Acrisol	2685	intensive banana	305	116	38

Figure A1 Lysimeter locations at each treatment plot, with two subplots (blue rectangles) that each included the three management zones (blue crosses): 1) lysimeters in the palm circle were at 1 m from the palm stem, 2) in the frond-stacked area, at about 4 m from the palm stem, and 3) in the inter-row, at approximately 4 m from the palm stem.

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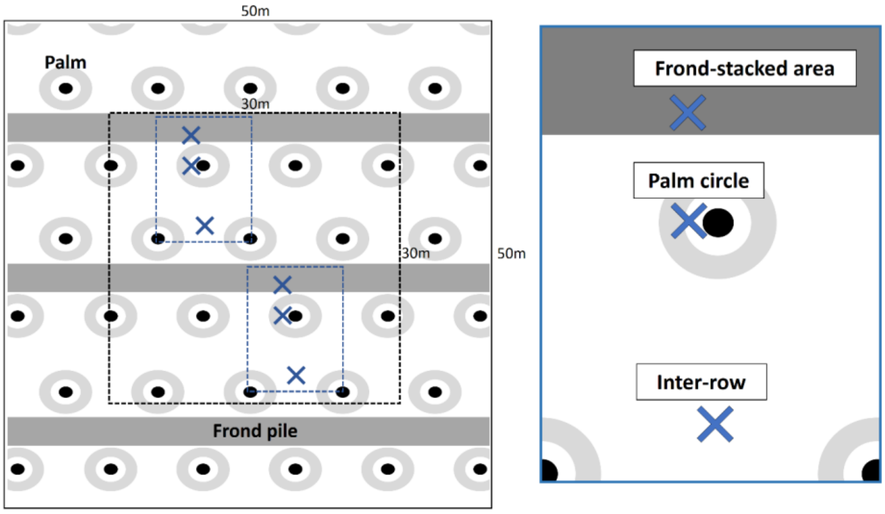

Figure A2 Annual yield of each experimental treatment from 2017 to 2019. Treatments: ch = conventional fertilization–herbicide; cw = conventional fertilization–mechanical weeding; rh = reduced fertilization–herbicide; rw = reduced fertilization–mechanical weeding.

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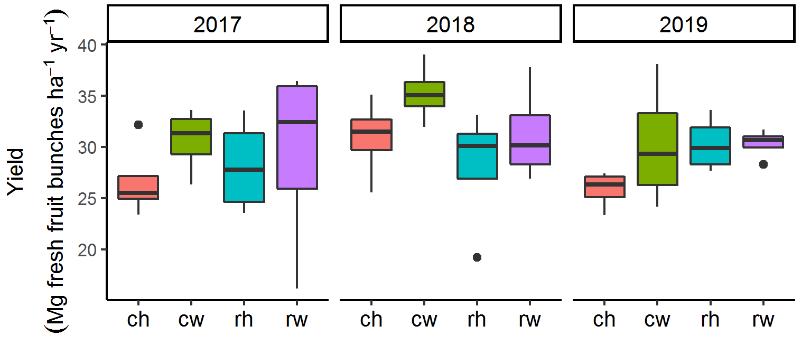

Note: yield was measured by weighing the harvested fresh fruit bunches from each palm in the inner 30 m x 30 m area of each plot.