# *1 Supplementary materials*

## 2 Supplementary Data

### 2.1 Basis for the rates of reduced fertilization

The reduced fertilization rates for nitrogen (N), phosphorus (P) and potassium (K) were based on the exported amount from the harvested fruit bunches. At the PTPN6 mill, we selected randomly 20 harvested fruit bunches, from which we randomly sampled fruits and bunch stalks. We made three composite samples of fruits and stalks separately. From these composite samples, moisture, N, P, and K contents were determined. Gravimetric moisture content was determined by over-drying the samples at 60 °C until stable weights were attained (5-7 days). Total N content was determined from oven-dried and ground samples using a CN analyzer (Vario EL Cube, Elementar Analysis Systems GmbH, Hanau, Germany). Total P and K contents were analyzed from the ground samples by pressure digestion in concentrated $HNO_3$ followed by analysis of the digests using the inductively coupled plasma-atomic emission spectrometer (iCAP 6300 Duo VIEW ICP Spectrometer, Thermo Fischer Scientific GmbH, Dreieich, Germany). The fruits had on average 0.5 g water $g^{-1}$, 0.7% N, 0.9 mg P $g^{-1}$, and 3.8 mg K $g^{-1}$; the stalks contained 4.6 g water $g^{-1}$, 1.1% N, 1.1 mg P $g^{-1}$, and 62.6 mg K $g^{-1}$. The recorded long-term yield average at PTPN6 was equivalent to 17000 kg dry fruits $ha^{-1}$ $yr^{-1}$ and 2000 kg dry stalks $ha^{-1}$ $year^{-1}$ or, on average, 19000 kg dry fruit bunches $ha^{-1}$ yr-$^{1}$. This was calculated from the long-term average harvest record at PTPN6 of 11 fruit bunches $tree^{-1}$ $yr^{-1}$, each 23 kg fresh weight with 70% fruits and 30% stalks (similar as those reported by Corley and Tinker, 2013), and an average of 142 trees $ha^{-1}$. The dry-mass yield multiplied by the nutrient element contents equals to the average harvest exports of 136 kg N, 17 kg P and 187 kg K $ha^{-1}$ $yr^{-1}$.

### 2.2 Specific hypotheses

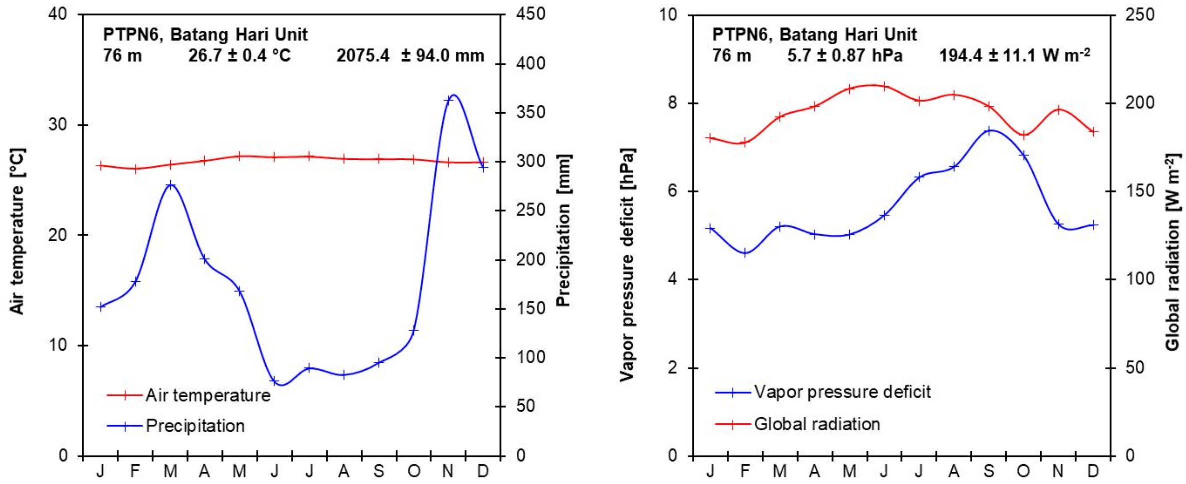
We hypothesized that the reduced fertilization treatments do not affect mineral nitrogen levels in palm circles, so that oil palm productivity (stem growth, leaf area, fresh fine roots biomass, and yields) would be unaffected. Under herbicide spraying, oil palm fine root biomass should decrease due to direct contact with herbicide-sprayed plants. However, there is still natural variation in soil parameters that can be considered in the structural equation model: in palm circles, we hypothesized that soil moisture, base saturation, and mineral nitrogen have a positive influence on oil palm yield, and vegetative productivity variables such as oil palm roots, stem growth, and leaf area index should correlate with it. However, base cations in palm circles and frond-piled areas were already saturated (>93% for all treatment averages), so we decided to leave them out of the structural equation model.

For soil nutrients and functions, we hypothesized that plant cover in the interrows increases nutrient retention and organic matter, leading to a measurable increase in base saturation, microbial biomass, and mineral nitrogen. We expect that plant cover can lead both to higher soil moisture through increased water infiltration and reduced soil evaporation, as well as lower soil moisture due to higher transpiration. Natural variation in soil parameters should show that high bulk density, through lower soil porosity, is associated with reduced water infiltration and higher water moisture. However, we do not expect changes in bulk density during the first two years of the experiment. We did not test effects of plant cover on other variables in the frond-piled area and palm circles because of the low ground vegetation coverage. We hypothesized that increased fertilization rates positively affect mineral nitrogen and base saturation (the negative effect of soil acidification is prevented by liming), but also inhibit microbial biomass and nitrogen mineralization, so that the net effect on mineral nitrogen is null. Correspondingly, we hypothesized that higher microbial biomass will increase mineral nitrogen as a result of its activity on nitrogen mineralization. In the frond-piled area, we hypothesized a positive effect of litter decomposition on nutrient and organic carbon levels in the soil, and hence we predicted higher microbial biomass, mineral nitrogen and base saturation. Mineral nitrogen and base saturation in turn will stimulate plant cover. We did not hypothesize links between oil palm leaf litter decomposition and other variables in the other zones because in practice, oil palm leaf litter only accumulates in the frond-piled area.

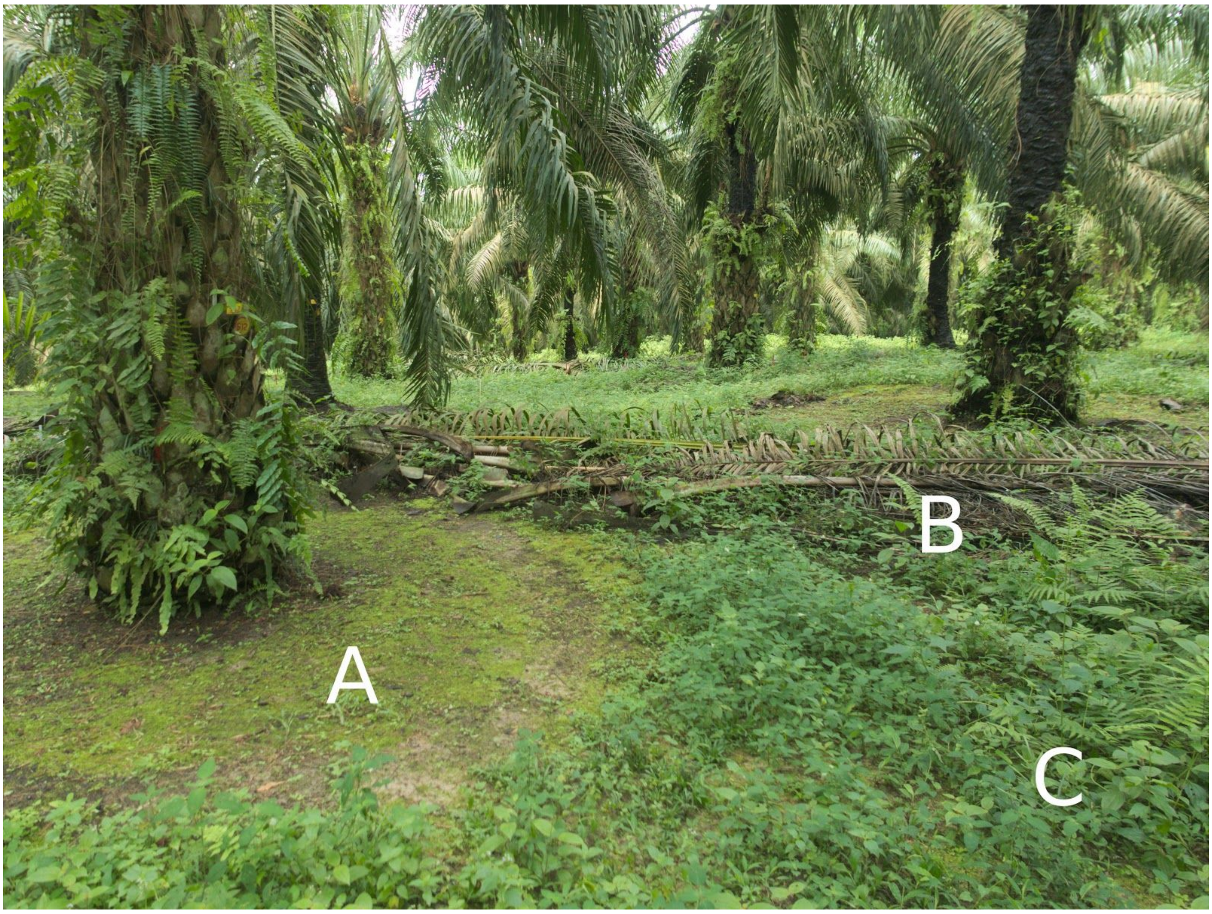
We further hypothesized that mechanical weeding would benefit above-and belowground biodiversity with changes propagating through the trophic chain. Specifically, we predicted that mechanical weeding leads to 1) increased plant cover and species richness, 2) both respectively leading to higher community metabolism of decomposer animals and soil animal groups richness, as well as higher arthropod abundance and insect richness, 3) the latter both respectively leading to higher bird and insectivorous bat vocalization activity, and species and morpho-species richness. We also hypothesized that plant cover and richness respectively increase bird activity and richness, because most birds in oil palm are omnivorous, feeding on fruits and seeds and thus relying on plants. We hypothesized that reduced fertilization would not have immediate effects on vegetation parameters because its application is restricted to palm circles. However, we hypothesized that reduced fertilization will decrease community metabolism of decomposer animals due to a reduced resource supply for the soil food web.

## 3 Supplementary Figures and Tables

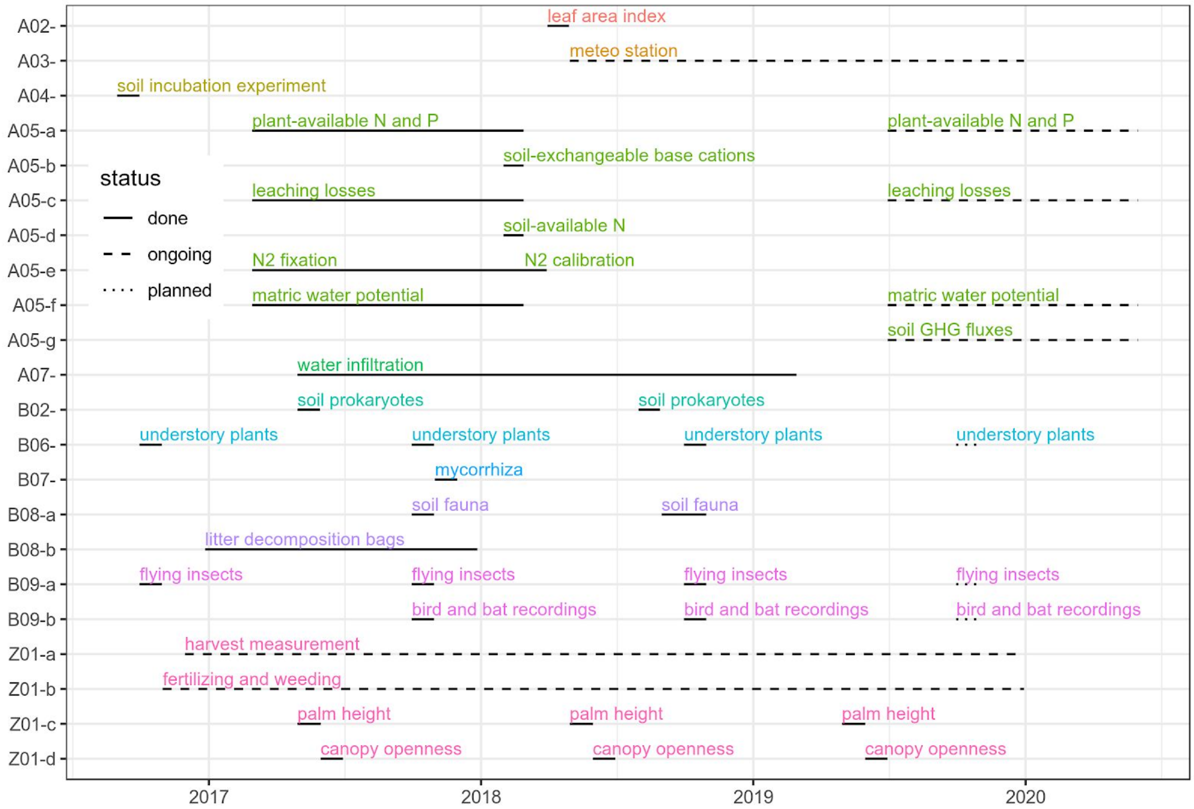
### 3.1 Supplementary Figures



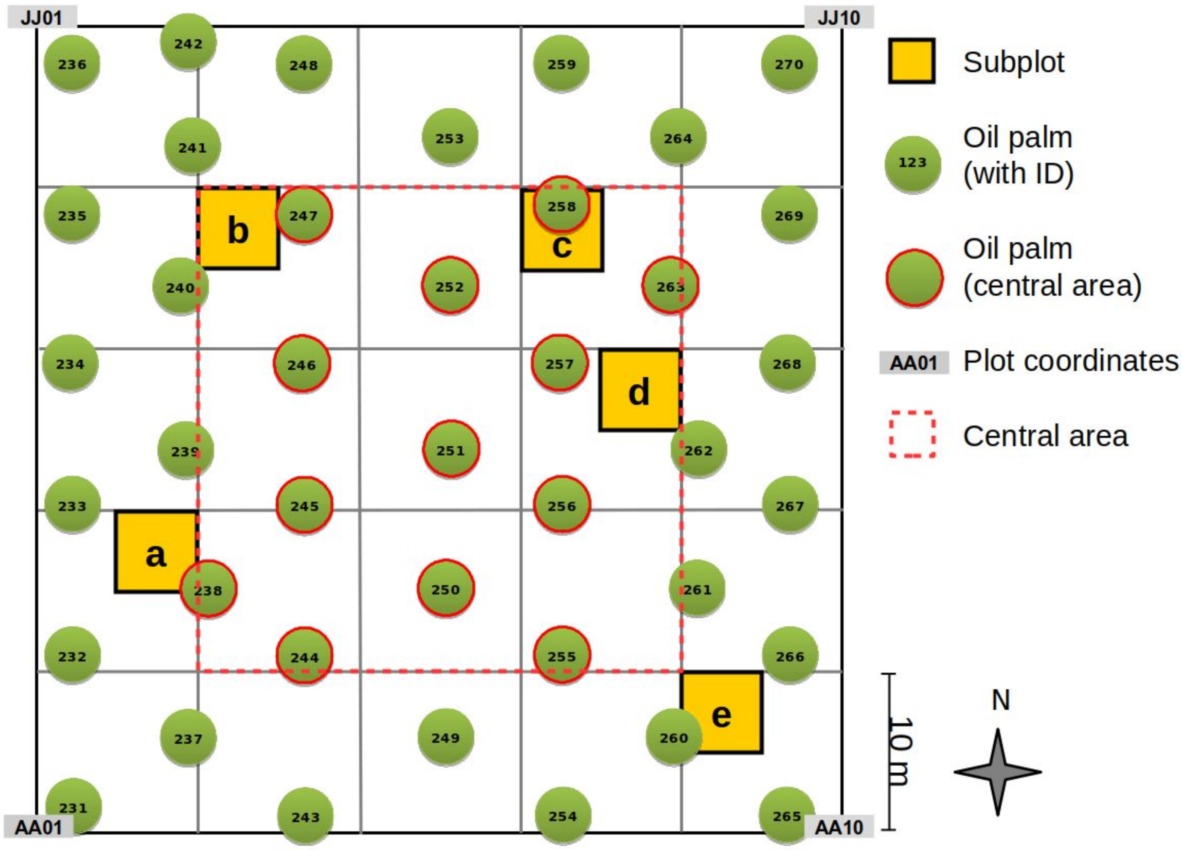

**Supplementary Figure 1:** Averaged climatic variables measured at the PTPN6 meteorological tower during the period March 2014 to May 2019. Left panel: Monthly average air temperature and monthly accumulated precipitation. Due to sensor failure there are no precipitation measurements during the period September 2016 to June 2017. Right panel: Monthly average atmospheric vapour pressure deficit and monthly average global radiation.



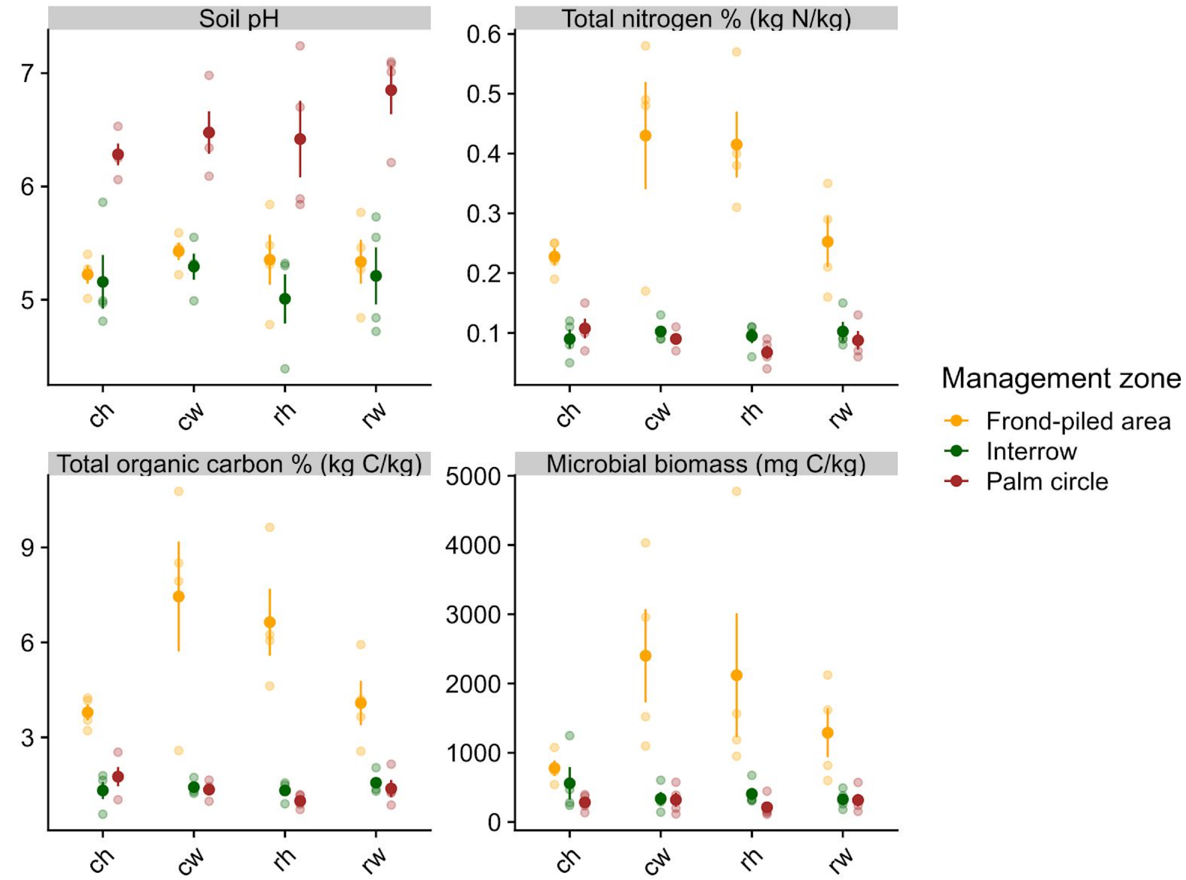

**Supplementary Figure 2.** The three typical management zones in the PTPN6 oil palm plantation. Fertiliser is applied within palm circles (A) which were regularly weeded, cut fronds are stacked on frond piles (B), and the interrows (C) that cover most of the plantation are used for accessing the palms.



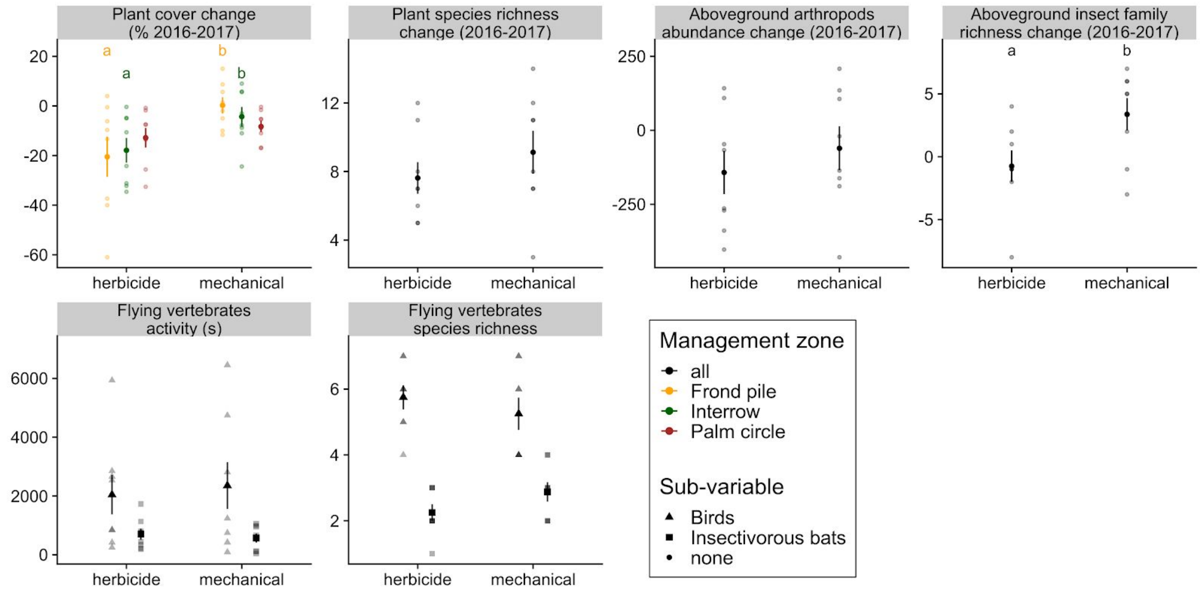

**Supplementary Figure 3.** Calendar of sampling activities carried out in the oil palm management experiment.




**Supplementary Figure 4.** Example plot layout (OM2cw). Coordinate labels are situated at every grid intersection but were omitted here for clarity.




**Supplementary Figure 5.** Additional soil parameters that were not analysed in the main text. Data points are indicated with semi-transparent dots. Mean values are indicated with bigger, opaque dots. Error bars show standard errors of the mean, and significant differences between means are shown with distinct letters, color-coded according to the management zone.




**Supplementary Figure 6.** Responses of aboveground organisms to the weeding treatments. Data points are indicated with semi-transparent dots. Mean values are indicated with bigger, opaque dots. Error bars show standard errors of the mean, and significant differences between means are shown with distinct letters, color-coded according to the management zone.

## 3.2 Supplementary Tables

**Supplementary Table 1.** Taxonomic groups for soil animals. Metabolic rates are shown only for decomposers.

| Group | Rank | General guild | Mean body mass, $\mu$g | Mean individual metabolic rate, J h-1 |
|---|---|---|---|---|
| Annelida | phylum | decomposers | 600599 | 1.31005 |
| Araneae | order | predators | 783 | |
| Blattodea | order | decomposers | 23106 | 0.2573358 |
| Chilopoda | class | predators | 909 | |
| Coleoptera | order | mixed | 337 | |
| Collembola | order | decomposers | 14 | 0.00109 |
| Dermaptera | order | omnivores | 44 | |
| Diplopoda | class | decomposers | 338 | 0.01216 |
| Diplura | order | mixed | 150 | |
| Diptera | order | mixed | 85 | |
| Formicidae | family | omnivores | 689 | |
| Hemiptera | order | mixed | 340 | |
| Hymenoptera | order | predators | NA | |
| Isopoda | order | decomposers | 417 | 0.01764129 |
| Isoptera | class | decomposers | 954 | 0.0277906 |
| Lepidoptera | order | herbivores | 147 | |
| Mesostigmata | order | predators | 14 | |
| Opiliones | order | predators | 768 | |

| | | | | |
|---|---|---|---|---|
| Oribatida | order | decomposers | 8 | 0.00016 |
| Orthoptera | order | herbivores | 2295 | |
| Pauropoda | class | decomposers | 30 | 0.003223414 |
| Prostigmata | order | predators | 8 | |
| Protura | order | decomposers | 20 | 0.00109 |
| Pseudoscorpionida | class | predators | 199 | |
| Psocoptera | order | decomposers | 154 | 0.00594 |
| Schizomida | order | predators | 509 | |
| Staphylinidae | family | predators | 337 | |
| Symphyla | class | decomposers | 170 | 0.00867 |
| Thysanoptera | order | herbivores | 55 | |

**Supplementary Table 2.** Results from the categorical analysis of treatment effects on all the measured variables within the oil palm management experiment.

| Variable | Treatment | Mean | Standard error |
|---|---|---|---|
| Yield increment per palm (kg, 2017-2018) | ch | 30.1 | 10.47 to 49.72 |
| | cw | 32.27 | 15.8 to 48.74 |
| | rh | -0.96 | -18.85 to 16.92 |
| | rw | 12.09 | -23.88 to 48.07 |
| Leaf area index | ch | 2.4 | 2.03 to 2.76 |
| | cw | 2.51 | 2.2 to 2.82 |
| | rh | 2.66 | 2.27 to 3.06 |
| | rw | 2.42 | 2.03 to 2.81 |
| Fresh fine roots (kg/m2) Interrow | ch | 0.58 | 0.51 to 0.66 |
| | cw | 0.72 | 0.49 to 0.95 |
| | rh | 0.47 | 0.36 to 0.58 |
| | rw | 0.5 | 0.45 to 0.54 |
| Stem growth (m, 2017-2019) | ch | 1 | 0.88 to 1.12 |
| | cw | 1.12 | 0.97 to 1.26 |
| | rh | 1.1 | 1.04 to 1.16 |
| | rw | 0.93 | 0.79 to 1.07 |
| Bulk density (g/cm3) Frond-piled area | ch | 0.56 | 0.51 to 0.61 |
| | cw | 0.44 | 0.33 to 0.54 |
| | rh | 0.53 | 0.42 to 0.65 |
| | rw | 0.56 | 0.48 to 0.64 |
| Bulk density (g/cm3) Interrow | ch | 1.23 | 1.2 to 1.26 |
| | cw | 1.2 | 1.14 to 1.26 |

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|---|---|---|---|
| | rh | 1.21 | 1.14 to 1.28 |
| | rw | 1.17 | 1.12 to 1.21 |
| Bulk density (g/cm3) Palm circle | ch | 1.2 | 1.14 to 1.26 |
| | cw | 1.27 | 1.22 to 1.31 |
| | rh | 1.23 | 1.18 to 1.28 |
| | rw | 1.23 | 1.18 to 1.28 |
| Microbial biomass (mg N/kg) Frond-piled area | ch | 109.88 | 91.62 to 128.15 |
| | cw | 196.24 | 155.83 to 236.65 |
| | rh | 199.14 | 141.59 to 256.68 |
| | rw | 115.94 | 92.6 to 139.29 |
| Microbial biomass (mg N/kg) Interrow | ch | 42.82 | 29.79 to 55.85 |
| | cw | 25.64 | 21.26 to 30.03 |
| | rh | 21.57 | 17.52 to 25.62 |
| | rw | 27.27 | 20.87 to 33.67 |
| Microbial biomass (mg N/kg) Palm circle | ch | 18.84 | 14.75 to 22.93 |
| | cw | 21.16 | 13.93 to 28.39 |
| | rh | 15.76 | 14.58 to 16.93 |
| | rw | 24.52 | 20.79 to 28.24 |
| Mineral nitrogen (mg N/kg) Palm circle | ch | 1.08 | 0.86 to 1.3 |
| | cw | 0.97 | 0.81 to 1.14 |
| | rh | 1.02 | 0.73 to 1.3 |
| | rw | 0.92 | 0.74 to 1.11 |
| Water infiltration Interrow (cm/h) | ch | 2.26 | 2.15 to 2.37 |
| | cw | 2.34 | 1.75 to 2.93 |
| | rh | 1.45 | 1.28 to 1.62 |

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|---|---|---|---|
| | rw | 2.27 | 1.97 to 2.57 |
| Belowground animals group richness | ch | 15.75 | 14.5 to 17 |
| | cw | 16.25 | 15.62 to 16.88 |
| | rh | 15.25 | 14.5 to 16 |
| | rw | 17.75 | 16.8 to 18.7 |
| Mineral nitrogen (mg N/kg) Interrow | ch | 0.91 | 0.84 to 0.99 |
| | cw | 0.88 | 0.77 to 0.98 |
| | rh | 0.99 | 0.83 to 1.16 |
| | rw | 0.89 | 0.85 to 0.93 |
| Mineral nitrogen (mg N/kg) Frond-piled area | ch | 5.71 | 5.36 to 6.06 |
| | cw | 4.47 | 3.62 to 5.32 |
| | rh | 4.77 | 4.69 to 4.85 |
| | rw | 4.39 | 3.81 to 4.96 |
| Decomposer animals metabolism (J/h/m2) | ch | 47.25 | 29.9 to 64.6 |
| | cw | 161 | 83.59 to 238.41 |
| | rh | 63.25 | 39.41 to 87.09 |
| | rw | 88 | 60.36 to 115.64 |
| Aboveground arthropods abundance change (2016-2017) | ch | -67.25 | -143.73 to 9.23 |
| | cw | -52 | -182.09 to 78.09 |
| | rh | -217.75 | -340.66 to -94.84 |
| | rw | -69.75 | -162.96 to 23.46 |
| Plant cover change (% 2016-2017) Interrow | ch | -16.6 | -23.49 to -9.71 |
| | cw | -1 | -8.84 to 6.84 |
| | rh | -19.15 | -27.39 to -10.91 |
| | rw | -7.65 | -9.34 to -5.96 |

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|---|---|---|---|
| Plant cover change (% 2016-2017) Palm circle | ch | -10.45 | -16.28 to -4.62 |
| | cw | -9.3 | -12.7 to -5.9 |
| | rh | -15.2 | -21.15 to -9.25 |
| | rw | -7.31 | -10.66 to -3.97 |
| Plant cover change (% 2016-2017) Frond pile | ch | -21.12 | -34.69 to -7.56 |
| | cw | -2.08 | -6.03 to 1.86 |
| | rh | -19.87 | -30.93 to -8.82 |
| | rw | 2.6 | -2.93 to 8.14 |
| Plant species richness change (2016-2017) | ch | 8 | 6.53 to 9.47 |
| | cw | 8.75 | 6.36 to 11.14 |
| | rh | 7.25 | 5.94 to 8.56 |
| | rw | 9.5 | 8.31 to 10.69 |
| Aboveground insect family richness change (2016-2017) | ch | -1.5 | -3.97 to 0.97 |
| | cw | 2.5 | 0.48 to 4.52 |
| | rh | 0 | -0.91 to 0.91 |
| | rw | 4.25 | 2.45 to 6.05 |
| Insectivorous bat activity (s) | ch | 871.5 | 523.01 to 1219.99 |
| | cw | 471.25 | 253.58 to 688.92 |
| | rh | 530 | 385.97 to 674.03 |
| | rw | 658.25 | 427.47 to 889.03 |
| Bird species richness | ch | 6.25 | 5.77 to 6.73 |
| | cw | 5.25 | 4.5 to 6 |
| | rh | 5.25 | 4.77 to 5.73 |
| | rw | 5.25 | 4.5 to 6 |
| Insectivorous bat species richness | ch | 2.25 | 2 to 2.5 |

| | | | |
|---|---|---|---|
| | cw | 3.25 | 3 to 3.5 |
| | rh | 2.25 | 1.77 to 2.73 |
| | rw | 2.5 | 2 to 3 |
| Bird activity (s) | ch | 2619.25 | 1417.16 to 3821.34 |
| | cw | 2382.75 | 1482.18 to 3283.32 |
| | rh | 1464.75 | 809.58 to 2119.92 |
| | rw | 2325.75 | 863.19 to 3788.31 |
| Base saturation (%) Interrow | ch | 55.39 | 40.49 to 70.29 |
| | cw | 70.62 | 61.54 to 79.69 |
| | rh | 48.05 | 36.49 to 59.62 |
| | rw | 59.73 | 41.91 to 77.55 |
| Base saturation (%) Palm circle | ch | 99.34 | 98.88 to 99.8 |
| | cw | 99.81 | 99.73 to 99.88 |
| | rh | 98.95 | 98.39 to 99.5 |
| | rw | 99.8 | 99.7 to 99.9 |
| Base saturation (%) Frond-piled area | ch | 95.79 | 95.33 to 96.26 |
| | cw | 98.64 | 98.03 to 99.26 |
| | rh | 97.13 | 95.43 to 98.83 |
| | rw | 93 | 89.12 to 96.88 |
| Moisture content (%) Interrow | ch | 20.6 | 19.56 to 21.63 |
| | cw | 18.92 | 18.31 to 19.53 |
| | rh | 21.23 | 20.31 to 22.16 |
| | rw | 20.56 | 19.85 to 21.27 |
| Moisture content (%) Palm circle | ch | 20 | 19.14 to 20.87 |
| | cw | 19.32 | 18.07 to 20.57 |

| | | | |
|---|---|---|---|
| | rh | 19.05 | 18.04 to 20.06 |
| | rw | 20.4 | 19.19 to 21.62 |
| Moisture content (%) Frond-piled area | ch | 50.01 | 46.91 to 53.1 |
| | cw | 48.88 | 41.34 to 56.42 |
| | rh | 60.03 | 56.14 to 63.91 |
| | rw | 52.43 | 46.59 to 58.27 |
| Gross margin (% 2017) | ch | 0.72 | 0.7 to 0.73 |
| | cw | 0.75 | 0.74 to 0.76 |
| | rh | 0.79 | 0.78 to 0.79 |
| | rw | 0.78 | 0.75 to 0.81 |
| Gross margin (% 2018) | ch | 0.7 | 0.68 to 0.71 |
| | cw | 0.73 | 0.73 to 0.73 |
| | rh | 0.74 | 0.73 to 0.76 |
| | rw | 0.76 | 0.75 to 0.77 |
| Decomposition (%/8 mo) Interrow | ch | 74.71 | 70.48 to 78.94 |
| | cw | 71.17 | 69.34 to 73 |
| | rh | 73.27 | 68.15 to 78.4 |
| | rw | 74.7 | 71.74 to 77.67 |
| Decomposition (%/8 mo) Palm circle | ch | 67.66 | 63.3 to 72.01 |
| | cw | 74.04 | 70.95 to 77.13 |
| | rh | 80.86 | NA to NA |
| | rw | 77.79 | 75.55 to 80.04 |
| Decomposition (%/8 mo) Frond-piled area | ch | 65.6 | 58.8 to 72.39 |
| | cw | 71.38 | 65.57 to 77.18 |
| | rh | 72.54 | 68.45 to 76.64 |

| | | | |
|---|---|---|---|
| | rw | 72.9 | 69.2 to 76.6 |