Soil CO_2 emissions and net primary production in agricultural plantations on tropical peat

（熱帯泥炭地の農業プランテーションにおける土壌 CO_2 放出量と純一次生産）

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Chapter 1. Introduction

Indonesia has the largest area of tropical peatlands, which covers 2.48×10^7 ha and stores 68.5 Gt of carbon mainly in Sumatra, Kalimantan, and Papua Islands. However, during the last two decades, this carbon-rich ecosystem has been threatened by deforestation and drainage, mainly for agricultural plantations. Land-use change in peatland is usually related to large carbon dioxide (CO_2) emissions due chiefly to drainage, which lowers groundwater level (GWL) and disturbs the peat soil condition. Two major agricultural land uses in Indonesia's tropical peatland during the past several years are oil palm and rubber plantations. Recently, oil palm plantations became the most common agricultural land use in Indonesia, the largest palm oil-producing country in the world. Whereas, rubber plantations, which occupy about 3.6 million ha are the second largest plantation in Indonesia after oil palm plantation. However, field-based information on their carbon (C) balance is still limited on tropical peatland.

Total soil respiration (SR) consists of the autotrophic or root respiration (RR), oxidative peat decomposition (PD), and litter decomposition (LD) components. The two-latter component is usually defined as heterotrophic respiration (HR). Several studies of soil CO_2 emission were conducted on tropical peatland, however, few of them quantify PD or HR from SR separately. Also, there are no data on CO_2 emission through litter or frond decomposition in oil palm plantations on tropical peat. Along with C emission, the conversion of peat swamp forest to plantations also potentially decreases C sequestration through net primary production (NPP) because of vegetation change. However, to our knowledge, there is no field information on above- and belowground NPP in mature oil palm plantations on peat soil.

This study investigated the C dynamics of two main agricultural plantations in Indonesia's tropical peatland, oil palm and rubber plantations, by quantifying soil CO_2 emissions and C sequestration through NPP separately. The objectives of this study were separated into several chapters, 1) to investigate the seasonal variations in total soil respiration (SR) and peat decomposition (PD) in a rubber plantation and determine the contribution of PD to total subsidence (Chapter 2), 2) to quantify the above- and belowground NPP of mature oil palm plantations and determine how much CO_2 was emitted through pruned frond decomposition (Chapter 3), 3) to quantify SR, PD, and NPP of a young oil palm plantation (Chapter 4), and 4) to finally summarize the C dynamics of agricultural plantations on tropical peat.

Chapter 2. Soil CO_2 emissions from a rubber plantation on tropical peat in Central Kalimantan

Soil CO_2 efflux was measured monthly using a closed chamber system from December 2014 to December 2015, in a rubber plantation on peat soil in Central Kalimantan, Indonesia. A strong El Niño event occurred in the period. To exclude root respiration (RR) and directly measure CO_2 efflux through peat decomposition (PD), three trenching plots with four-chamber bases installed in each plot were established in June 2014. For total soil respiration (SR), 12 chamber bases were distributed outside of the trenching plots and categorized into near (1.5 m) and far (3 m) positions from rubber trees to examine the difference of RR. Also, peat surface elevation was measured to determine annual subsidence. To analyze bulk density (BD) and C content, five-peat samples were collected, respectively, at six depths from 0 to 75 cm in the dry season (September 2014) when GWL was low. Simultaneously, groundwater level (GWL) and soil temperature were recorded hourly using automatic data loggers. The annual PD (Mg C ha^{-1} yr^{-1}) was converted to corresponding subsidence (cm yr^{-1}) using BD (g cm^{-3}) and C content (% in mass).

GWL varied seasonally between -1.71 and 0.03 m with a mean annual GWL was -0.69 m. GWL was high in the wet season from December to May and low in the dry season from June to November following a seasonal variation in precipitation. PD showed a large seasonal variation and a negative correlation with GWL. PD increased up to about 10 g C m^{-2} d^{-1} in the dry season and remained low at 0–2 g C m^{-2} d^{-1} during the wet season. Although GWL was lowest in late October 2015, the highest PD was measured in November, just after the first considerable precipitation event in the coming wet season. In contrast, seasonal variation in SR was small after February 2015. The residual between the means of SR and PD showed a different seasonal variation, which increased in the wet season.

The relationship between PD and soil temperature was not significant ($p > 0.05$), whereas SR showed significant positive correlation with soil temperature ($p < 0.05$), but r^2 was low at 0.15. On the other hand, although PD increased linearly as GWL lowered ($p < 0.001$), SR increased logarithmically with GWL lowering both at near and far positions ($p < 0.01$). The regression for PD and SR was improved when the data in November 2015 were excluded, because the data were most probably pulse-like instantaneous CO_2 efflux and were caused by a considerable amount of rain at the beginning of the wet season after a severe drought.

Annual soil CO_2 emissions from December 2014 to December 2015 were calculated from hourly GWL data for each trenching plot (PD) and chamber base (SR), respectively, using the linear (PD) or logarithmic (SR) relationships; data in November

2015 were excluded. Annual CO_2 emissions were 14.1 ± 2.14 and 32.9 ± 10.4 Mg C ha^{-1} yr^{-1} (± 1 standard deviation (SD)), respectively, for PD and SR. SR was not significantly different between near and far positions from tree rows ($p > 0.05$). On the other hand, SR was significantly larger than PD ($p < 0.001$). The residual of SR from PD was 16.1–18.9 Mg C ha^{-1} yr^{-1}, which corresponds to the annual sum of root respiration (RR) and leaf litter decomposition (LD). PD accounted for 43–47% of SR on an annual basis.

Elevation of the peat surface basically varied in parallel to GWL. After correction for GWL variation, annual subsidence rates of 5.64 ± 3.20 and 5.96 ± 0.43 cm yr^{-1} were found from outside and inside of trenching, respectively. There was no significant difference in annual subsidence between inside and outside the trenching ($p > 0.05$). To quantify the contribution of oxidative peat decomposition to the subsidence, annual PD (14.1 Mg C ha^{-1} yr^{-1}) was converted to subsidence using BD and C content of peat at different depths, based on a simple assumption that the peat oxidation occurred only at each depth. The PD subsidence averaged at 1.50 cm yr^{-1} and accounted for 25% of total subsidence inside trenching (5.96 cm yr^{-1}) on average.

Both SR and PD were significantly depended on GWL. PD showed strong negative linearity with GWL, partly because GWL was lowered much by a strong El Niño drought of 2015. The peak of PD was measured in November, just after a lot of rain at the beginning of the wet season probably because of stimulated microbial activity by the rain. SR was measured at near and far positions from rubber trees to examine the spatial distribution of RR. Unexpectedly, however, no significant difference was found in SR between at near and far positions from rubber trees ($p > 0.05$). This result indicates that RR did not decrease with a distance from trees up to 3 m, around the middle of tree rows.

This study was conducted in a strong El Niño year of 2015, in which the dry season was prolonged, and GWL lowered more. Thus, PD was expected to be larger than in normal years without El Niño drought. Ground elevation was sensitive to GWL, thus elevation should be measured at short intervals simultaneously with GWL monitoring to determine annual subsidence correctly. Crucial parameters to interconvert subsidence and oxidative peat decomposition are peat properties such as BD and C content. Therefore, those peat properties should be measured carefully to estimate the contribution of peat oxidation to total subsidence correctly. High subsidence rates usually result from low values of BD and C content.

Chapter 3. Net primary production and CO_2 emission through frond decomposition in oil palm plantations on peat in Sumatra

The study was conducted from February 2018 to July 2019 in two oil palm plantations on peat soil in Sumatra, Indonesia. The first site was an industrial plantation in Riau, Sumatra. The palm tree cultivar was Marihat (M) with a tree density of 148 trees ha^{-1}. In 2019, the tree age was 15 years. The second site was a smallholder plantation in Jambi, Sumatra. The tree density was 125 trees ha^{-1} with two cultivars in the same field, Marihat (*M*) and Sofin (*S*), with a ratio of 4:1 (*M* : *S*). Oil palm trees were planted in 1994 or about 25 years old in 2019.

Net primary production (NPP, Mg C ha^{-1} yr^{-1}) was calculated as all plant biomass produced during a specified period. Aboveground NPP (ANPP) was estimated as the sum of tree canopy (trunks and attached fronds), pruned frond, fruit bunch, and understory vegetation production. Belowground NPP (BNPP) was calculated from the production of coarse and fine roots biomass. Frond decomposition was measured using litter bags of 40 cm x 80 cm. On average, one frond was pruned monthly from one tree both in Riau and Jambi. Fronds immediately after cutting down were collected and separated into two parts (tip and base) because of their large size. In Riau, 100 bags were prepared for each of tips and bases and set on the top of frond heaps in February 2018. However, in total, only 99 bags were retrieved in September 2018, January 2019, and June 2019 as most of the litter bags were missing. In Jambi, 18 bags were prepared for each of tips and bases of the two cultivars (*M* and *S*), respectively. 36 bags in total were set equally on the top of and under frond heaps, respectively, in February 2018. Three bags of each condition were retrieved from the two positions in September 2018, February 2019, and July 2019, respectively. The residual ratio of dry weight or C amount was plotted against elapsed time, and a simple negative exponential equation was fitted to determine the decomposition rate constant (k). Using the k value and initial C amount, C loss through the decomposition of pruned fronds was estimated. Moreover, area-based CO_2 emission was calculated monthly and summed up annually using pruned frond production.

Annual total NPP was estimated to be 17.3 and 13.5 Mg C ha^{-1} yr^{-1} in Riau and Jambi, respectively. The total NPP in Riau was higher than that in Jambi. ANPP was higher in Riau, but BNPP was higher in Jambi. Total NPP was dominated by ANPP (14.0 (Riau) and 9.9 (Jambi) Mg C ha^{-1} yr^{-1}), which accounted for 81 and 73% in Riau and Jambi, respectively. Fruit bunch production contributed most to NPP, accounted for 35 and 34% in Riau and Jambi, respectively. Annual BNPP was 3.32 and 3.60 Mg C ha^{-1} yr^{-1}, respectively, in Riau and Jambi, of which fine root production accounted for 74 and 80 % in Riau and Jambi, respectively.

In Riau, the number of litter bags in the second and third retrieving was different from the first retrieving because some of bags were lost during the study (n = 45, 27, and 27 litter bags, for the first, second, and third retrieving, respectively). Therefore, without distinguishing tip and base parts, all retrieved samples were plotted for decomposition rate calculations. As a result, the frond decomposition rate constant (k) in Riau was estimated to be 1.86 yr^{-1}. Using the k, the pruned frond of *M* in Riau was estimated to be decomposed by 90% in 1.25 years. Annual carbon input through pruned fronds into the plantation was estimated to be 2.54 Mg C ha^{-1} yr^{-1} (= annual pruned fronds (12 fronds $tree^{-1}$) × dry weight (2578 g $frond^{-1}$) × C content (55.5 %) × tree density (148 trees ha^{-1})), whereas annual CO_2 emission through litter or frond decomposition (LD) in Riau was calculated to be 1.48 Mg C ha^{-1} yr^{-1}.

In Jambi, the k values were not significantly different among tip and base parts, top and below heap of pruned fronds, and among two cultivars, *M* and *S*. However, total CO_2 emission through LD should be different between the cultivars because of the different frond size. The frond of *S* was 1.3-1.5 times larger than that of *M*. Therefore, all data for each cultivar (n = 12 for each retrieving, respectively, for *M* and *S*) were used to calculate the k values to be 1.57 and 1.81 yr^{-1} for *M* and *S*, respectively. Using those k values, the pruned fronds of *M* and *S* in Jambi were estimated to be decomposed by 90% in 1.50 and 1.25 years, respectively. Annual C input through pruned frond into the plantation in Jambi for each cultivar was 1.51 and 0.56 Mg C ha^{-1} yr^{-1}, respectively, for *M* and *S*. Annual CO_2 emission through LD was estimated to be 0.80 and 0.32 Mg C ha^{-1} yr^{-1}, respectively, for *M* and *S* in Jambi. In total, annual C input and CO_2 emission through LD in Jambi were estimated to be 2.07 and 1.12 Mg C ha^{-1} yr^{-1}, respectively.

NPP in Riau was higher than in Jambi. Age difference was attributable to this difference. Furthermore, the plantation in Riau was an industrial plantation. Palm tree management, such as cultivar quality and fertilizer application was expected to be better in Riau. In this study, understory vegetation production accounted for 6 and 9% of total ANPP, respectively, in Riau and Jambi, indicating that understory vegetation is not negligible.

CO_2 emission through LD was higher in Riau (1.48) than in Jambi (1.12 Mg C ha^{-1} yr^{-1}). Even for the same cultivar, decomposition rate of *M* was higher in Riau than in Jambi. *S* in Jambi had a higher decomposition rate constant (k) probably because of a lower CN ratio. Annual CO_2 emission through LD in Riau and Jambi accounted for 20 and 15% of heterotrophic respiration from oil palm plantations on tropical peatland.

Chapter 4. Soil CO_2 emissions and net primary production (NPP) of an oil palm plantation on peat in South Kalimantan

Soil CO_2 emissions and NPP were measured in a young oil palm plantation on peat soil in South Kalimantan, Indonesia from September 2018 to March 2020. Oil palm trees were planted in 2013 with a tree density of 147 trees ha^{-1}. Soil CO_2 efflux was measured monthly using a closed chamber system on chamber bases. Total soil respiration (SR) and peat decomposition (PD) were separately quantified by measuring at near (SR, in the root circle (RC)) and far (PD) positions from tree bases. Besides, to estimate the effect of management, far bases were installed in two different areas: frond stacks (FS) and harvesting paths (HP). In total, three bases were installed in RC, FS, and HP, respectively. Before monthly measurement, pruned fronds were removed from chamber bases to exclude CO_2 emission through litter or pruned frond decomposition (LD). Thus, the difference between SR and PD is equivalent to root respiration (RR). Soil subsidence was also estimated from temporal change in peat surface elevation.

Frond decomposition was measured using litter bags with a total of 24 bags for each of tips and bases and set on the top of frond stacks around chamber plots in September 2018. Six bags were retrieved every two months, November 2018, January 2019, March 2019, May 2019, July 2019, September 2019, November 2019, and January 2020. CO_2 emission through LD was estimated using the decomposition rate constant (k) and initial C amount. Moreover, area-based CO_2 emission was calculated monthly and summed up annually using pruned frond production. On average, one frond was pruned nearly bi-monthly from one tree.

NPP (Mg C ha^{-1} yr^{-1}) was estimated as a sum of aboveground (tree canopy, pruned fronds, and fruit bunch production) and belowground NPP (coarse and fine roots). Bulk density (BD) was analyzed from peat samples collected in 0-50, 50-100, 100-150, and 150-200 cm from three plots in the dry season (August 2018), when GWL was low. GWL was measured manually once a month following soil CO_2 efflux measurement.

Mean BD from 3 plots was 0.14 ± 0.04, 0.12 ± 0.04, 0.11 ± 0.03, and 0.17 ± 0.05 g cm^{-3} at a depth of 0-50, 50-100, 100-150, and 150-200 cm, respectively (n = 3). Annual GWL was varied between -0.39 and -1.28 m with a mean of -0.74 m. GWL was high in the wet season from December to June and low in the dry season from July to November following a seasonal variation in precipitation. Soil CO_2 emissions (SR and PD) showed small seasonal variation but were generally higher when GWL was lower. Mean SR was significantly larger ($p < 0.001$) than that of PD, though there was no significant difference between PD in FS and HP ($p > 0.05$). PD showed significant

relationship with GWL ($p < 0.05$), but no in SR. Annual SR and PD were simply estimated as a mean of monthly measurements because their seasonal variations were small. Annual SR was estimated to be 23.1 Mg C ha^{-1} yr^{-1}, whereas annual mean PD from FS and HP was 15.4 Mg C ha^{-1} yr^{-1}. The difference between SR and PD was 7.70 Mg C ha^{-1} yr^{-1}, which nearly corresponds to RR. PD accounted for 67% of SR on an annual basis.

Peat surface elevation relative to the initial value in September 2018 was 0.88 ± 0.33 cm (mean ± 1 SD, n = 3) on February 10, 2019, with GWL of -0.40 m, and -16.5 ± 3.13 cm on February 14, 2020, with GWL of -0.39 m. Because GWL was almost the same, annual subsidence can be simply calculated to be 17.2 ± 3.02 cm yr^{-1}, after adjusting the number of days from 369 to 365 days. Subsidence due to oxidative peat decomposition was separately calculated from PD in FS and HP using BD and C content of surface peat. As a result, subsidence through PD was estimated to be 2.33 cm yr^{-1} and accounted for 14% of total subsidence (17.2 cm yr^{-1}).

The frond decomposition rate constant (k) was estimated to be 1.41 yr^{-1}. Using the k, the pruned frond was estimated to be decomposed by 90% in 1.67 years. Annual carbon input through pruned fronds into the plantation was estimated to be 0.76 Mg C ha^{-1} yr^{-1} from a calculation that annual input of pruned fronds (6 fronds $tree^{-1}$ yr^{-1}) × dry weight (1539 g $frond^{-1}$) × C content (55.4 %) × tree density (147 trees ha^{-1}), whereas annual CO_2 emission through LD was estimated to be 0.38 Mg C ha^{-1} yr^{-1}.

Annual total NPP was estimated to be 10.9 Mg C ha^{-1} yr^{-1}, which was dominated by aboveground NPP (8.51 Mg C ha^{-1} yr^{-1}, 78%). As a young plantation, fruit production was still low. Therefore, the most contribution to total NPP was from tree canopy production (49%). Annual belowground NPP was 2.40 Mg C ha^{-1} yr^{-1}, of which fine root production accounted for 64%.

Soil CO_2 emissions studies in oil palm plantations on tropical peat were commonly separated total soil respiration (SR) with root respiration (RR) to heterotrophic respiration (HR) or peat decomposition (PD) without measure CO_2 emission through litter or frond decomposition (LD) as a part of HR. In this study, HR was estimated as a sum of PD and LD to be 15.8 Mg C ha^{-1} yr^{-1} (15.4 + 0.38 Mg C ha^{-1} yr^{-1}). The contribution of LD was small but would be larger in line with the production growth of oil palm trees. Total NPP in this site (10.9 Mg C ha^{-1} yr^{-1}) was lower than that of HR (15.8 Mg C ha^{-1} yr^{-1}). As a result, if only from these two-contrast carbon effluxes comparison, the oil palm plantation in this site was acted as a C source of -4.9 Mg C ha^{-1} yr^{-1} (= NPP – HR).

Chapter 5. General discussion

To directly measure PD, a trenching was used in a rubber plantation (Chapter 2), whereas, in an oil palm plantation, PD was measured at a far position from tree bases (Chapter 4). We found that trenching was effective to measure PD separately because RR in the rubber plantation was not significantly different between near and far positions from tree bases. In the oil palm plantation, however, RR was decreased with a distance from tree bases.

This is the first study to show up the contribution of CO_2 emission through LD in oil palm plantations on peat soil (Chapters 3 and 4). By quantifying LD separately, HR as a sum of PD and LD could be estimated more accurately. Plantation management was influenced the total NPP as indicated by a higher NPP of an industrial plantation in Riau than that of a smallholder plantation in Jambi (Chapter 3).

Chapter 6. Conclusions

First, in a rubber plantation, in Central Kalimantan, soil CO_2 efflux through oxidative peat decomposition (PD) was measured using chamber method in trenching plots during 2015, a strong El Niño year. PD showed a clear seasonality and linearly increased as groundwater level (GWL) decreased. The linear relationship indicates that annual PD can be simply assessed from only mean annual GWL. Also, the seasonal variation of peat elevation was showed in parallel with GWL. Thus, GWL should be considered carefully to determine peat subsidence for assessing PD.

Second, in mature oil palms, an industrial plantation in Riau and a smallholder plantation in Jambi, Sumatra, annual net primary production (NPP) and CO_2 emission through frond decomposition (LD) were measured from February 2018 to July 2019. In both plantations, total NPP was dominated by aboveground NPP, of which the most contribution was from fruit production. In belowground NPP, the contribution of fine root was higher than that of coarse root, suggesting that fine root NPP should be treated as an important source of NPP. Total NPP of industrial plantation in Riau was higher than that of smallholder plantation in Jambi, which suggests the difference in plantation management influenced NPP.

Third, in a young smallholder oil palm plantation in South Kalimantan, annual PD, LD, and NPP were measured from September 2018 to March 2020. PD showed a significant negative linear relationship with GWL even with the low r^2. NPP was dominated by aboveground NPP, with the most contribution was from tree canopy production. In this site, NPP was low mostly due to plantation immaturity. This plantation was estimated to be a CO_2 source of -4.9 Mg C ha^{-1} yr^{-1} as a result of C balance between NPP and heterotrophic respiration (HR).