Net primary production of oil palm plantations on tropical peat

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SUMMARY

Oil palm plantation is the most common agricultural land use on peatlands in South East Asia. However, the carbon (C) balance of oil palm plantation on peat soil is not well understood. Field studies on net primary production (NPP) of oil palm plantations on peat are scarce. Therefore, we assessed the above-ground and below-ground NPP in two different mature oil palm plantations established on peat. One was an industrial plantation in Riau Province and the other was a smallholder plantation in Jambi Province, Indonesia. Above-ground NPP (ANPP) was calculated from the production of the tree canopy, pruned fronds, fruit bunches and understorey vegetation, whereas below-ground NPP (BNPP) included the production of coarse roots (with trunk bases) and fine roots. Annual total NPP (ANPP + BNPP, as C) was estimated to be 17.3 Mg ha^{-1} yr^{-1} in the industrial plantation and 13.5 Mg ha^{-1} yr^{-1} in the smallholder plantation. The NPP was dominated by ANPP, which accounted for 81 % and 73 % of NPP in the industrial and smallholder plantations, respectively.

KEY WORDS: carbon balance, mature industrial plantation, smallholder plantation

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INTRODUCTION

Tropical peatlands make up only 16–17 % of the global peatland area but store up to 105 Pg of carbon (C), including the recently updated peat C store estimate for Congo Basin peatlands (Page *et al.* 2011, Dargie *et al.* 2017). Thus, they are an important component of the global terrestrial C store. Amongst the countries of South East Asia (SEA), Indonesia has the largest area of peatlands, estimated at 14.9 Mha of which 7.2 Mha (34 %) is located on the island of Sumatra (Wahyunto *et al.* 2014, Warren *et al.* 2017). Indonesia's waterlogged peat soils associated with rainforest have become a massive long-term C sink and currently store about 57.4 Gt of organic C (Page *et al.* 2011, Gumbricht *et al.* 2017). However, this C-rich ecosystem (known as peat swamp forest) is vulnerable to disturbance and becomes a net C source when affected by drainage and land conversion which, in turn, promote peat decomposition and peat fires (Hooijer *et al.* 2012). In the Malay Peninsula, Sumatra and Borneo, the area of peat swamp forest has decreased from 41 % to 29 % of total peatland area over recent decades, mainly in favour of agriculture and plantations (Miettinen *et al.* 2016).

One of the fast-expanding plantation crops on both mineral and peat soils in South East Asia during the last three decades is oil palm. Indonesia is the leading palm oil producing country in the world and oil palm plantation recently became the country's most common agricultural land use (FAOSTAT 2014). Demand for palm oil and related commodities has been increasing rapidly and this may well be a driver of land use change on peatlands (Koh *et al.* 2011). The total area of oil palm plantations on peat soil in Indonesia and Malaysia increased from 0.42 Mha in 1990 to 2.43 Mha by 2010 (Gunarso *et al.* 2013).

The early expansion of oil palm plantations in Indonesia was mainly driven by state-owned and private companies (industrial plantations), but the more recent expansion results mostly from the activities of smallholder farmers (Euler *et al.* 2015). Typically, industrial plantations are well managed, whereas smallholders often have inadequate knowledge of cultivation techniques and limited access to fertilisers due to low income, which results in lower yields (Vermeulen & Goad 2006).

The conversion of forest to plantation potentially reduces C sequestration by lowering photosynthetic capacity and net primary production (NPP) (Kotowska *et al.* 2015). NPP is an essential component of the C and nutrient cycles in terrestrial ecosystems, but is not well understood for oil palm plantations on peat soil. There have been only a limited number of studies on the NPP of oil palm plantations (Melling *et al.* 2008, Kotowska *et al.* 2015, Basuki *et al.* 2018, Wakhid & Hirano 2021), and only three of these reported the NPP of oil palm growing in plantations on peat. The studies of Melling *et al.* (2008), Basuki *et al.* (2018) and

Wakhid & Hirano (2021) were conducted in young plantations (2–7 years old) and did not include direct measurement of some components of NPP such as fine root production, which may seem insignificant but makes a non-negligible contribution to the total NPP of oil palm (Kotowska *et al.* 2015, Violita *et al.* 2016). To our knowledge, there is no previous field information on NPP in mature oil palm plantations on peat soil. The objective of this study was to quantify above-ground and below-ground NPP in mature oil palm established in plantations on peat.

METHODS

Study sites

The field measurements were conducted over a period of 18 months (February 2018 to July 2019) in two mature oil palm (*Elaeis guineensis* Jacq.) plantations on peat soil in Sumatra. One site was located in an industrial plantation in Riau Province, and the other was in a smallholder plantation in Jambi Province (Figure 1). Site characteristics are summarised in Table 1. Both plantations were converted to this land use from secondary peat swamp forest, and were mature in terms of the commonly practised 25-year growth cycle (Corley & Tinker 2003).

Above-ground and below-ground NPP

Total NPP (Mg ha^{-1} yr^{-1}) is the accretion of all above-ground and below-ground plant biomass in a given time period (Kotowska *et al.* 2015). Above-ground NPP (ANPP) was the calculated as the sum of tree canopy (including trunk), pruned frond, fruit bunch, and understorey biomass. Tree canopy NPP was calculated as the cumulative biomass increment (Mg tree^{-1}), between February 2018 and January 2019 for Riau and between March 2018 and February 2019 for Jambi, using the following allometric equation for mature trees (Khasanah *et al.* 2015):

$$\text{Canopy biomass} = 0.0939 \times H + 0.0951 \quad [1]$$

where H (m) is the distance from the base of the tree to the base of the lowest frond in the canopy (Khasanah *et al.* 2015). H was measured in February 2018 and January 2019 in Riau, and in March 2018

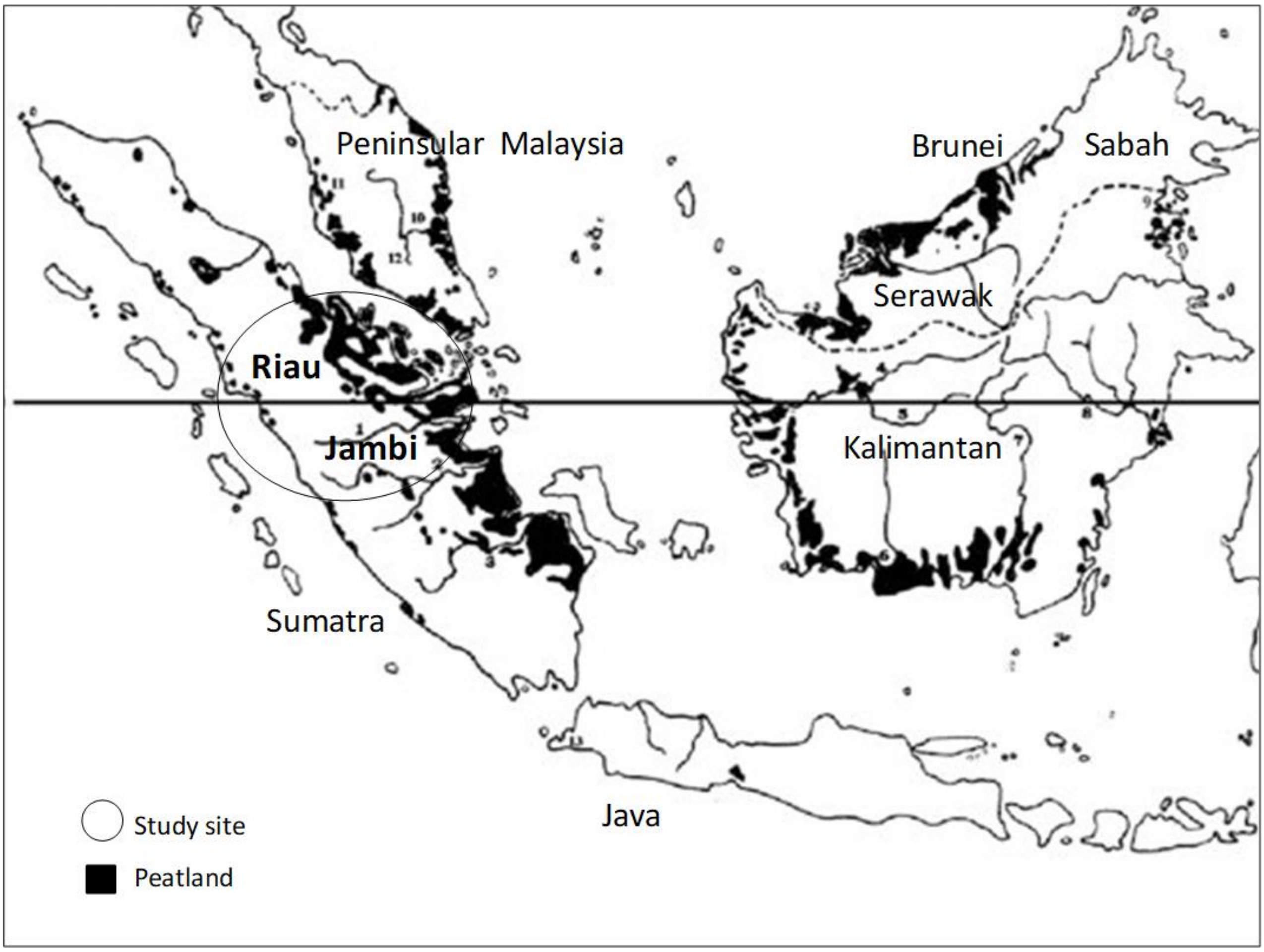

Figure 1. Map of the study site (revised from Posa *et al.* 2011).

Table 1. Site characteristics.

	Industrial (Riau)	Smallholder (Jambi)
Location	Siak Sri Indrapura District, Riau Province (0° 42' 16" N, 101° 42' 52.8" E).	Tanjung Jabung Timur District, Jambi Province (1° 14' 20" S, 103° 35' 23" E).
Annual precipitation in 2018	2046 mm yr^{-1} in the plantation, almost identical to the mean between 2011 and 2018 (2033 ± 339 mm yr^{-1}, mean ± 1 standard deviation (SD)). Monthly precipitation was less than 100 mm in January, May, and July.	1952 mm yr^{-1} at a meteorological station 28 km away, similar to the mean between 2013 and 2018 (2065 ± 401 mm yr^{-1} (BPS-Statistics of Tanjung Jabung Timur Regency 2019). Monthly precipitation was less than 100 mm in June and July.
Annual mean air temperature	27.5°C at a meteorological station 50 km away (BPS-Statistics of Riau Province 2019).	27.9°C at a meteorological station 25 km away (BPS-Statistics of Tanjung Jabung Timur Regency 2019).
Palm tree cultivar(s)	Marihat (*M*).	Marihat (*M*) and Sofin (*S*).
Tree density	148 trees ha^{-1}.	125 trees ha^{-1}. The ratio of the two cultivars was 4 : 1 (*M* : *S*).
Tree age	15 years	25 years
Peat depth	0.8 m	2.0 m
Groundwater level	Annual mean groundwater level (GWL) was -0.5 m, varying seasonally between -0.2 and -0.8 m. GWL was high from November to January and low from May to August.	Annual mean GWL was -0.2 m, varying seasonally between 0.1 and -0.8 m. GWL was high from March to May and low from June to September.
Understorey vegetation	The ground surface was densely covered with fern plants (*Nephrolepis biserrata*), except for a circle of radius 2 m around every tree base. Other understorey vegetation consisted of *Axonopus compressus*, *Asystasia micrantha*, *Peperomia pellucida* and *Asplenium longissimum*.	The ground surface was sparsely covered with *Axonopus compressus*, except for a circle of radius 2 m around every tree base. Other understorey vegetation was similar to that in Riau.
Fertiliser application	Applied twice a year: 139 kg N, 55.5 kg P_2O_5, 222 kg K_2O, 500 kg $CaCO_3$, 278 kg CaO, and 2.96 kg CuZn (ha^{-1} yr^{-1}).	Applied twice a year on average: 64.8 kg N, 64.8 kg P_2O_5, 64.8 kg K_2O and 2 kg MgO (ha^{-1} yr^{-1}). However, fertiliser applications were not regular, depending on the farmer's financial situation.

and February 2019 in Jambi. About 20 % of the total number of trees per ha were randomly selected (32 trees in Riau, 25 trees in Jambi) (Table 1). The industrial plantation in Riau contained only one cultivar (Marihat). In Jambi, the two cultivars Marihat (*M*) and Sofin (*S*) had been planted together in a ratio of roughly 4 : 1 and the trees were selected to include 20 of *M* and 5 of *S*. In the calculation of total NPP, the corresponding weighting factors of 0.8 and 0.2 were applied to the data for *M* and *S* specimens, respectively.

Annual fruit bunch NPP was estimated from yield data recorded by the company in Riau and by the farmer in Jambi. As the yields of the two cultivars at Jambi were not recorded separately, fruit bunch production was assumed to be the same for *M* and *S*. Dry weight and C content of fruit bunches were determined using three fresh fruit bunches of *M* from Riau. When a fruit bunch is harvested, a frond attached just below it is pruned and the pruned fronds are stacked on the ground to return nutrients to the soil (Figure 2). On average in both Riau and Jambi, one frond per tree was pruned every month. At both sites (Riau and Jambi), dry weight and C content were measured for five pruned fronds of each cultivar present. Understorey vegetation biomass was measured, per site, by destructive sampling in three 0.5 m × 0.5 m quadrats placed in each of three management areas, namely: (1) weeded circles of radius 1 m centred on tree bases, (2) inter-rows between frond stacks, and (3) harvesting paths (Figure 2). Thus, there were nine quadrats per site. Understorey vegetation was harvested in September 2018, February 2019 and June 2019 in Riau, and in September 2018, March 2019 and July 2019 in Jambi. The annual NPP of understorey vegetation was calculated as the difference between the maximum and minimum biomass results amongst these samplings (Scurlock *et al.* 2002).

Below-ground NPP (BNPP) was estimated as the sum of biomass production as coarse and fine roots. Coarse root biomass (including trunk base or bottom part of tree; Mg ha^{-1}) was calculated using the following empirical equation (Syahrinudin 2005):

$$\text{Coarse root biomass} = 1.45 \text{ palm age} + 9.88 \qquad [2]$$

This equation was developed for an oil palm plantation on mineral soil with a tree density of 140 ha^{-1}, so the calculated biomass it delivered was adjusted to the tree densities of our sites (148 ha^{-1} and 125 ha^{-1}) by applying factors of 1.06 (148/140) and 0.89 (125/140) for Riau and Jambi, respectively. Annual coarse root NPP was calculated as the annual increment of coarse root biomass. Because no data were available for the C content of coarse roots, the C content of fine roots was assumed to apply also to coarse ones.

Fine root NPP was estimated as the total annual production of fine roots using a simplified decision matrix method following Yuan & Chen (2013). Fine (≤ 2 mm diameter) root biomass was sampled by sequential soil coring within the depth range 0–30 cm using an auger (diameter 2.54 cm). This depth range was chosen because most of the fine roots of oil palm are concentrated near the soil surface (Jourdan & Rey 1997, Jourdan *et al.* 2000, Syahrinudin 2005). Due to resource limitations, core sampling was conducted every six months, in February 2018, September 2018 and February 2019 in Riau and in March 2018,

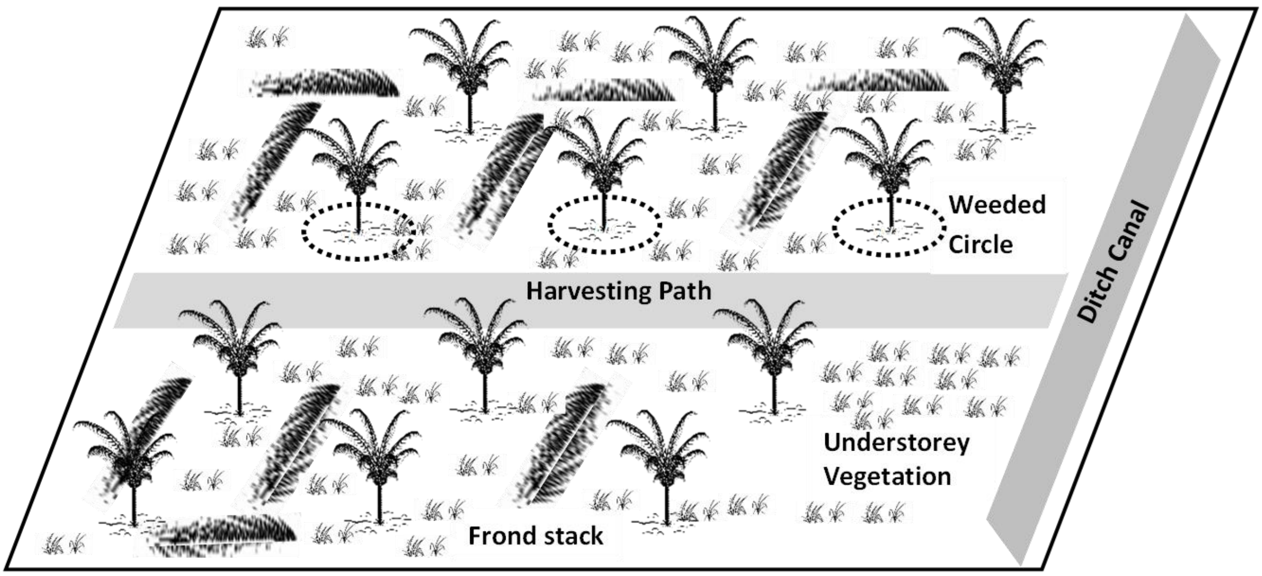

Figure 2. Sampling plot characteristics.

September 2018 and March 2019 in Jambi, around three trees located at different distances from a ditch (only one tree in February 2018 in Riau). February samplings represent the wet season, whereas September coincides with the dry season. In Jambi, two trees of cultivar *M* and one of cultivar *S* were selected. For each tree, three soil cores were collected from each of the weeded circle, understorey vegetation area, frond stack and harvesting path (12 soil core samples per tree). The soil was initially stored in plastic bags, then washed with tap water to separate roots from peat soil. Fine roots were extracted by sieving, then separated into biomass and necromass by visual inspection based on colour and shape (Makkonen & Helmisaari 1999). Fine roots of oil palm trees were rough, rigid, and dark in colour, whereas roots of understorey vegetation were light in colour and soft without a lignified periderm (Leuschner *et al.* 2009). In Jambi, fine root NPP was determined as the sum for *M* and *S* cultivars, considering their relative shares in tree density (80 % vs. 20 %).

To measure the dry weights of frond (leaves and rachises), fruit bunch, fine root and understorey vegetation, samples were dried at 70 °C for at least 48 hours. C concentration was determined by the loss of ignition (LoI) method at 550 °C in a muffle furnace (Thermolyne type 48000, USA) with a conversion factor of 0.58 to convert organic matter to organic C (Agus *et al.* 2011).

Data analysis

Data were compared between sites, cultivars, components and locations by ANOVA and Tukey's HSD test using Excel and R software (R Development Core Team 2019, version 3.5.3).

RESULTS

C content for the different components of NPP ranged from 52 % to 58 %, and was highest in fruit bunches followed by fine roots, fronds, and understorey vegetation (Table 2). Cultivar *M* in Riau tended to have the greatest height increment, followed by *S* and *M* in Jambi, but the differences were not significant (Table 3). Nonetheless, biomass growth of *M* in Riau exceeded that of *S* and *M* in Jambi. Area-based biomass growth (increment of tree canopy biomass per ha) was higher for *M* than for *S* because the tree densities were different. At the Riau site, understorey vegetation biomass in frond stacks was significantly larger than in weeded circles and harvesting paths (Table 4).

Fine root biomass showed significant seasonality in both Riau and Jambi (Table 5). In Riau, fine root biomass in February 2019 (wet season) was significantly higher than in September 2018 (dry season) (Tables 1 and 5). In Jambi, fine root biomass showed no significant difference between February 2019 and September 2018, but in February 2019 it was significantly higher than in February 2018. In contrast to biomass, fine root necromass in Riau showed no significant difference between seasons. Fine root biomass of *S* was significantly higher than that of *M* in Jambi. However, fine root necromass of *M* was significantly lower in Riau than in Jambi. Fine root production (NPP) in Riau showed no seasonal variation between the two periods of sampling (Table 6). In Jambi, the fine root production of *M* and *S* differed significantly between the two periods. Fine root production was not significantly different between cultivars (*M* vs. *S* in Jambi) or between sites (*M* in Riau vs. *M* in Jambi).

Annual total NPP (as C) was estimated to be 17.3 and 13.5 Mg ha^{-1} yr^{-1} in Riau and Jambi, respectively (Table 7). Total NPP was higher in Riau than in Jambi. ANPP was higher in Riau, but BNPP was higher in Jambi. Total NPP was dominated by ANPP (14.0 Mg ha^{-1} yr^{-1} at Riau, 9.9 Mg ha^{-1} yr^{-1} at Jambi), which accounted for 81 % and 73 % of NPP in Riau and Jambi, respectively. Fruit bunch production contributed most to NPP, accounting for 35 % in Riau and 34 % in Jambi. Annual BNPP was 3.32 Mg ha^{-1} yr^{-1} in Riau and 3.60 Mg ha^{-1} yr^{-1} Jambi, of which fine root production accounted for 74 % and 80 %, respectively (Table 7).

Table 2. C content (%) of each measured component of the oil palm plantations in Riau and Jambi (mean ± 1 SD). For Riau, different suffixed letters denote significant differences ($P < 0.05$) according to Tukey HSD test after ANOVA. n/a = data not available.

Component	Riau	Jambi	
		M	*S*
Frond (leaf and rachis)	55.5 ± 0. 9a (n =12)	55.6 ± 1.5 (n = 12)	55.0 ± 1.9 (n = 12)
Fruit bunch	57.7 ± 0.06a (n = 3)	n/a	
Understorey vegetation	51.9 ± 3.2b (n = 9)	53.5 ± 1.8 (n = 9)	
Fine root	56.7 ± 1.1a (n = 6)	n/a	
ANOVA (P value)	< 0.001		

DISCUSSION

The ANPP in Riau was higher than in Jambi. Among the four components of ANPP, the largest one was fruit bunch NPP, which was higher in Riau than in Jambi (Table 7). This difference was attributable to the ages of the trees. Oil palm production usually peaks between the ages of 8 and 16 years and declines after 24 years (Corley & Tinker 2003). Furthermore, the plantation in Riau was industrial. Thus, aspects of plantation management such as cultivar quality, fertiliser application and pest control were expected to be better in Riau. According to data from the Directorate General of Estate Crops, Indonesia Ministry of Agriculture (2017), fruit yield productivity is higher in industrial plantations than in smallholder plantations. Our results for productivity (as C) of 6.13 and 4.53 Mg ha^{-1} yr^{-1} in Riau and Jambi, respectively, were consistent with the official productivity data for industrial plantations in Riau (7.1 Mg ha^{-1} yr^{-1}) and smallholder plantations in Jambi (4.6 Mg ha^{-1} yr^{-1}), which were derived from crude palm oil (CPO) production figures of 4.91 and 3.19 Mg ha^{-1} yr^{-1}, respectively (Directorate General of Estate Crops, Indonesia Ministry of Agriculture 2017) assuming CPO = 20 % of fresh fruit bunch (FFB) mass with dry weight 50 % and C content 57.7 %. The lower tree canopy, fresh fruit bunch and pruned frond NPP in Jambi (Table 7) can also be related to the age (25 years) of the trees. Moreover, frond growth in oil palm tends to decline with increasing tree age (Syahrinudin 2005). Also, pruned frond NPP was partly influenced by the cultivar type; we found differences in different frond size between the two cultivars in Jambi.

The larger biomass in the frond stacks at Riau (about 2 m around the tree base) was due to the dense cover of ferns (*Nephrolepis biserrata*) which was maintained to preserve soil moisture. Also, the frond stack area was usually undisturbed (also called non-traffic inter-row) and enriched by the organic input from decomposition of the pruned fronds (Pauli *et al.* 2014). In contrast, understorey vegetation in weeded circles is weeded, although irregularly, at least twice a year to minimise competition for nutrients. In the harvesting path, the growth of understorey vegetation is suppressed by wheelbarrow and labour traffic. In this study, understorey vegetation production is likely to be underestimated because of weeding. However, it accounted for 6 % and 9 % of total ANPP in Riau and Jambi, respectively, indicating that the growth of understorey vegetation is not a negligible component of the NPP of oil palm plantations.

In contrast to ANPP, BNPP was lower in Riau than in Jambi (Table 7). Coarse root NPP was similar between the two sites because the same allometric equation was used, but the result for Riau was slightly higher owing to higher tree density (Table 1). Fine root NPP was larger than coarse root NPP, and accounted for 14 % and 21 % of total NPP in Riau and Jambi, respectively (Table 7). The larger fine root NPP might be related to the structure of the oil palm root system, which grows fast but has a limited lifespan (Jourdan & Rey 1997). Fine root NPP was lower in Riau than in Jambi (Tables 6 and 7), in line with fine root biomass (Table 5). Old oil palm plantations on mineral soil generally have higher below-ground biomass, including fine roots (Syahrinudin 2005). Since the same types of oil palm trees are grown on peat as on mineral soils, the old

Table 3. Tree height and canopy biomass (mean ± 1 SD; n = 32, 20 and 5 for *M* in Riau, *M* in Jambi, and *S* in Jambi, respectively).

Component		Riau	Jambi	
		M	*M*	*S*
Tree height (m)	Feb / Mar 2018	3.78 ± 1.37	4.03 ± 1.27	4.02 ± 0.65
	Jan / Feb 2019	4.35 ± 1.24	4.38 ± 1.31	4.44 ± 0.71
Height growth (m yr^{-1})		0.57 ± 0.88	0.35 ± 0.24	0.42 ± 0.32
Biomass (Mg $tree^{-1}$)	Feb / Mar 2018	0.45 ± 0.13	0.47 ± 0.12	0.47 ± 0.06
	Jan / Feb 2019	0.50 ± 0.12	0.51 ± 0.12	0.51 ± 0.07
Biomass growth (Mg $tree^{-1}$ yr^{-1})		0.05 ± 0.08	0.03 ± 0.02	0.04 ± 0.03
Tree density (ha^{-1})		148	100	25
Biomass (Mg ha^{-1})	Feb / Mar 2018	66.6	47.3	11.8
	Jan / Feb 2019	74.5	50.6	12.8
Area-based biomass growth (Mg ha^{-1} yr^{-1})		7.9	3.3	1.0

Table 4. Understorey vegetation biomass (mean ± 1 SD, $n = 3$). Different suffixes (a, b, etc.) in the column of site means for Riau (*), and in the columns of seasonal means for Riau and Jambi, respectively, denote significant differences ($P < 0.05$) according to Tukey HSD test after ANOVA.

Area	Biomass (Mg ha-1)							
	Aug 2018 (dry season)		Jan 2019 (wet season)		Jul 2019 (dry season)		Mean	
	Riau	Jambi	Riau	Jambi	Riau	Jambi	Riau*	Jambi
Weeded circle (WC)	1.12 ± 0.88	0.52 ± 0.41	0.62 ± 0.73	1.87 ± 0.65	0.04 ± 0.04	1.43 ± 1.88	0.59 ± 0.54b	1.27 ± 0.69
Harvesting path (HP)	0.62 ± 1.00	1.00 ± 0.17	0.39 ± 0.09	1.94 ± 0.99	0.19 ± 0.07	4.16 ± 2.21	0.40 ± 0.22b	2.37 ± 1.62
Frond stack (FS)	7.76 ± 1.31	1.14 ± 0.71	4.78 ± 1.07	2.52 ± 0.84	4.77 ± 0.99	1.86 ± 1.28	5.77 ± 1.72a	1.84 ± 0.69
Mean	3.17 ± 3.98a	0.89 ± 0.32(b)	1.93 ± 2.47b	2.11 ± 0.36(ab)	1.67 ± 2.69b	2.48 ± 1.46(a)	2.25 ± 3.05	1.83 ± 0.55

ANOVA (*P* values)	Riau	Jambi
Area	<0.001	0.18
Season	<0.01	<0.05
Interaction (area-season)	<0.05	0.23
Site	0.48	

Table 5. Results of Tukey HSD test ($P < 0.05$) and ANOVA for biomass and necromass (Mg ha^{-1}) of fine roots in Riau, Jambi *M* and Jambi *S* (mean ± 1 SD; $n = 12$ for Feb 2018 in Riau, 36 for Sep 2018 and Feb 2019 in Riau, 24 for *M* in Jambi, and 12 for *S* in Jambi). Different suffixes (a, b, etc.) in columns of site mean values (*) denote significant differences between sites ($P < 0.05$), and in columns of seasonal mean values denote significant seasonal variations ($P < 0.05$).

Site	Feb. 2018 (wet season)		Sep 2018 (dry season)		Feb 2019 (wet season)		Mean	
	Biomass	Necromass	Biomass	Necromass	Biomass	Necromass	Biomass*	Necromass*
Riau	2.13 ± 0.08ab	0.50 ± 0.08	0.99 ± 0.4b	0.74 ± 0.64	3.17 ± 1.57a	1.06 ± 0.85	2.10 ± 0.65	0.77 ± 0.45
Jambi *M*	0.52 ± 0.40b	0.61 ± 0.45(a)	2.68 ± 1.91a	1.56 ± 0.94(b)	3.58 ± 2.20a	1.76 ± 0.85(b)	2.26 ± 1.51	1.31 ± 0.71
Jambi *S*	1.35 ± 0.56b	1.41 ± 0.40	5.09 ± 3.11a	1.70 ± 1.19	4.74 ± 3.80a	1.94 ± 0.56	3.73 ± 2.37	1.68 ± 0.71

ANOVA (*P* values)	Biomass in Riau	Necromass in Riau	Biomass *M* in Jambi	Necromass *M* in Jambi	Biomass *S* in Jambi	Necromass *S* in Jambi
Season	<0.001	0.31	<0.001	<0.001	<0.001	0.38
Site (*M* in Riau vs. *M* in Jambi)	0.71	<0.05				
Cultivar (*M* vs. *S* in Jambi)	<0.05	0.11				
Interaction cultivar-season	0.44					

plantation in Jambi can be expected also to have high fine root biomass and NPP (Finér *et al.* 2011). Furthermore, relatively open areas around the tree bases in Jambi would raise soil temperature, probably resulting in higher fine root NPP than in Riau (Gill & Jackson 2000, Majdi & Öhrvik 2004). The seasonality of fine root production in Jambi was consistent with the observation by Kotowska *et al.* (2016) of high fine root production during the dry season in oil palm plantations on mineral soil in Jambi. This seasonality probably reflected the sensitivity of fine roots to the naturally high-amplitude fluctuations of groundwater level (GWL), which were reduced in Riau because of better GWL management in industrial plantations.

The NPP results from this study are compared with values from some previous studies on both peat and mineral soils in Table 8. Our annual NPP (as C) values of 17.3 and 13.5 Mg ha^{-1} yr^{-1} were higher than for a 7-year-old oil palm plantation in Banjarbaru, Indonesia (10.9 Mg ha^{-1} yr^{-1}; Wakhid & Hirano 2021) and for a 5-year-old oil palm plantation in Sarawak, Malaysia (12.01 Mg ha^{-1} yr^{-1}; Melling *et al.* 2008); and much higher than for 2–3-year-old

Table 6. Results of Tukey HSD test ($P < 0.05$) and ANOVA for fine root production (NPP as C) in Riau and Jambi (mean ± 1 SD; n = 12 for Feb–Sep 2018 in Riau, 36 for Sep 2018 to Feb 2019 in Riau, 24 for *M* in Jambi, and 12 for *S* in Jambi). Suffixed lowercase letters indicate significant differences in seasonal production.

Site	February 2018 to September 2018	September 2018 to February 2019	Annual
	Mg ha^{-1} period^{-1}		(Mg ha^{-1} yr^{-1})
Riau	0.65 ± 1.91	1.80 ± 2.09	2.45 ± 2.86
Jambi *M*	1.83 ± 1.56a	0.97 ± 1.32b	2.80 ± 2.33
Jambi *S*	2.48 ± 2.26a	0.62 ± 1.26b	3.10 ± 2.49

ANOVA (*P* values)	Riau	*M* in Jambi	*S* in Jambi
Season	0.10	<0.05	<0.05
Cultivar (*M* and *S* in Jambi)	0.72		
Interaction cultivar-season	0.20		
Site (*M* in Riau vs. *M* in Jambi)	0.76		

Table 7. Net primary production (NPP) based on biomass and carbon (adapted from Wakhid & Hirano 2021).

Components	NPP based on biomass (Mg ha^{-1} yr^{-1})		NPP based on carbon (Mg ha^{-1}yr^{-1})	
	Riau	Jambi	Riau	Jambi
Aboveground NPP (ANPP):				
Tree canopy	7.92	4.25	4.45	2.42
Pruned frond	4.58	3.72	2.54	2.07
Fruit bunch	10.6	7.85	6.13	4.53
Understorey vegetation	1.50	1.60	0.85	0.88
Total	24.6	17.4	14.0	9.9
Belowground NPP (BNPP):				
Coarse root	1.53	1.29	0.87	0.73
Fine root	4.32	5.04	2.45	2.86
Total	5.85	6.34	3.32	3.60
Total NPP (ANPP + BNPP)	30.5	23.8	17.3	13.5

plantations in West Kalimantan, Indonesia (3.7 Mg ha^{-1} yr^{-1}; Basuki *et al.* 2018). The latter study did not quantify fruit bunch NPP because the plantations were immature. Also, neither Melling *et al.* (2008) nor Basuki *et al.* (2018) measured understorey vegetation NPP. Our estimate of NPP was higher than that for peat swamp forest in West Kalimantan, Indonesia (13.2 Mg ha^{-1} yr^{-1}; Basuki *et al.* 2018) and in the Federated States of Micronesia (11.2 Mg ha^{-1} yr^{-1}; Chimner & Ewel 2005). Furthermore, our ANPP (as C) values of 14.0 and 9.9 Mg ha^{-1} yr^{-1} for Riau and Jambi, respectively (Table 7), were higher than two values derived for degraded peat swamp forest in Central Kalimantan (7.9 Mg ha^{-1} yr^{-1}; Miyamoto *et al.* 2016 and 7.3 Mg ha^{-1} yr^{-1}; Saragi-Sasmito *et al.* 2019). There were no previous studies of understorey vegetation NPP in oil palm plantations on peat to compare with.

Our annual NPP values were similar to those derived by Kotowska *et al.* (2015) for oil palm plantations on mineral soil in Jambi, Indonesia (17.3 and 15.1 Mg ha^{-1} yr^{-1}) although that study did not quantify understorey vegetation NPP, which accounted for 5–7 % of total NPP in our study. Amongst the five components quantified by those authors (oil palm tree canopy: 1.9 and 2.6 Mg ha^{-1} yr^{-1}; pruned fronds: 2.5 and 3.3 Mg ha^{-1} yr^{-1}; fruit bunches: 11.5 and 8.5 Mg ha^{-1} yr^{-1}; coarse roots: 0.3 and 0.4 Mg ha^{-1} yr^{-1}; and fine roots: 1.1 and 0.4 Mg ha^{-1} yr^{-1}), only the result for pruned frond NPP was similar to ours. Tree canopy NPP was lower, but fruit bunch production was higher, than in our study. The relatively high fruit bunch production reported by Kotowska *et al.* (2015) is understandable because fruit bunch production is higher on mineral soil than on peat soil (Directorate General of Estate Crops, Indonesian Ministry of Agriculture 2017). Other explanations for dissimilarity between our NPP results and those of Kotowska *et al.* (2015) might include methodological differences (including the use of different allometric equations), age of the plantations (8–15 years in their study), tree densities (not mentioned in their study), and local environments. Their fine root NPP, measured by the ingrowth core method, was much lower (0.4–1.1 Mg ha^{-1} yr^{-1} or 3–6 % of total NPP) than in our study (2.45–2.86 Mg ha^{-1} yr^{-1} or 14–21 % of total NPP); and may be an underestimate because the sampling intervals were relatively long (8–10 months). Sampling intervals for estimating root production are generally several weeks to a few months, with the assumption that any notable change in environmental conditions will be experienced by all samples (Osawa & Aizawa 2012). On the other hand, Yuan & Chen (2013) proposed monthly sampling for their estimation of fine root production. Our results may have large uncertainty arising from changes in environmental conditions during sampling intervals of several months. Results for fine root production obtained using short sampling intervals should be given priority over those derived on the basis of long intervals.

In both plantations, ANPP was the dominant component of total NPP. The contribution of fine root production to BNPP was much higher than that of coarse root production, suggesting that fine root NPP should be treated as an important element of NPP in oil palm plantations. The higher total NPP of the industrial plantation in Riau, as compared to the smallholder plantation in Jambi, indicates that the NPP of oil palm is influenced by plantation management.

Table 8. Comparison of Net Primary Production (NPP as C) with previous studies on peat and mineral soil.

Land use	Age (years)	Type	NPP (Mg ha^{-1} yr^{-1})	References	Notes
Oil palm	7	Smallholder	10.9	Wakhid & Hirano 2021	
Oil palm	5	Smallholder	12.0	Melling *et al.* 2008	
Oil palm	2–3	Smallholder	3.70	Basuki *et al.* 2018	
Forest	-	-	13.2	Basuki *et al.* 2018	
Forest	-	-	11.2	Chimner & Ewel 2005	
Oil palm	8–15	Smallholder	17.3	Kotowska *et al.* 2015	On mineral soil
Oil palm	8–15	Smallholder	15.1	Kotowska *et al.* 2015	On mineral soil
Oil palm	25	Smallholder	13.5	This study	
Oil palm	15	Industrial	17.3	This study	

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AUTHOR CONTRIBUTIONS

The study was conducted by NW under the supervision of TH. AD and FA were involved in the field measurements in Riau and Jambi, respectively. The first draft of the manuscript was written by NW and all authors commented on previous versions of the manuscript.

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