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FACTORS CONTROLLING THE CONTRIBUTION OF NET CARBON LOSS AND TOTAL SUBSIDENCE IN A WATER-MANAGED TROPICAL PEATLAND

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SUMMARY

Acacia plantation on tropical peatland has the issue of subsidence and water management is important to avoid serious subsidence. However, subsidence in the well-managed tropical peatland is seldom reported. Objective of this study is to explore the factors controlling net carbon loss (NCL) and total subsidence (S) and the proportion of NCL in S (P_{ncl}) in a water-managed tropical peatland. Our study site had three major land uses: *Acacia* plantation (sites A1 and A2), buffer zone (site B) and natural forest (site N). Small abandoned canals from a previous era exist throughout the natural forest. New canals were constructed only in *Acacia* plantation, following the contour of the peat dome, with aim to avoid water flow from the high to low elevation. CO_2 flux (peat decomposition), groundwater level (GWL), soil temperature (T_s), relative humidity (RH), and total subsidence (S) were measured from once a month to twice a week at each site. Bulk density (BD) and total organic carbon (TOC) in 30 cm depth of topsoil were measured, and amount of litter fall was measured. GCR was defined as the rising rate of GWL, NCL = CO_2 emission − litter fall, $S_{ncl} = 0.1 \times \text{NCL} / BD / TOC$, and $P_{ncl} = S_{ncl} / S \times 100$. BD (g cm^{-3}) was 0.14 at A1 and A2, 0.11 at B and 0.10 at N, and TOC was 58% for all land uses. Annual cumulative S (cm yr^{-1}) was 6.3 (A1), 8.0 (A2), 3.3 (B) and 2.5 (N). The S significantly correlated with GWL at B and N, but not at A1 and A2, which suggested irreversible subsidence in *Acacia* plantation. NCL (kg C m^{-2} yr^{-1}) was significantly larger at B (1.06 ± 0.18), followed by A1 (0.52 ± 0.38), A2 (−1.14 ± 1.19) and N (−1.63 ± 0.17) ($p < 0.01$), and significantly correlated with T_s ($p < 0.001$, $R^2 = 0.66$). Annual cumulative S_{ncl} (cm yr^{-1}) was almost linear to the P_{ncl} (%), and both were significantly larger at B (1.6 ± 0.5 and 49.0 ± 16.1, respectively), followed by A1 (0.7 ± 0.6 and 11.9 ± 10.1), A2 (−1.8 ± 2.0 and −22.2 ± 25.4) and N (−2.5 ± 0.6 and −98.1 ± 25.3) ($p < 0.01$ and $p < 0.001$, respectively). The P_{ncl} significantly correlated with T_s ($R^2 = 0.90$, $p < 0.001$). In conclusion, water management in our study site could mitigate CO_2 emission, S and P_{ncl} compared with the other reports in *Acacia* plantation on tropical peatland.

***Keywords**: subsidence, net carbon loss, CO_2 flux, water management, tropical peatland*

INTRODUCTION

Acacia plantation for pulp production is one of the agricultural uses in tropical peatland (Miettinen and Liew, 2010), and Indonesia produced 7 million tons of pulp and 10.5 million tons of paper in 2010 (Obidzinski and Dermawan, 2012).

Acacia plantation on tropical peatland has the issue of subsidence (Hooijer *et al.*, 2012). Subsidence is composed of physical processes (shrinkage and consolidation) and chemical processes (net carbon loss (NCL) from peat materials) (Schothorst, 1977), and it is reported that water management is important to prevent serious peat subsidence (Couwenberg *et al.*, 2010, Hooijer *et al.*, 2012). However, subsidence of water-managed tropical peatland has not been thoroughly reported. Objective of this study is to investigate the controlling factors of NCL and total subsidence (S) and the proportion of NCL in S (P_{ncl}) in a water-managed tropical peatland.

METHODS

We studied at a peat dome in Kampar River basin, Riau, Indonesia. The site was opened in 2010 giving in 2012-13 three major land uses: *Acacia* plantation in 2 and 3 year old (A1 and A2, respectively), buffer zone with 2-3 year old *Melaleuca* sp. trees in which had not yet closed canopy (B) and conserved natural forest (N). The canals were constructed only in *Acacia* plantation, following the contour.

Peat samples were taken from top 25 cm soil by peat sampler to measure bulk density (BD, g cm^{-3}) and total organic carbon content (TOC, g C g^{-1}). CO_2 flux (peat decomposition, mg C m^{-2} h^{-1}) was measured by trench method using closed chamber method with three replications from once a month to twice a week in each site. Soil temperature at 4-cm depth (T_s, °C), atmospheric relative humidity (RH, %), total subsidence (S, cm yr^{-1}) and groundwater level (GWL, m) were also measured. Litter was trapped with three replications in each site, and the carbon content of litter was analyzed. Rate of GWL change (GCR, m day^{-1}), NCL (kg C m^{-2} yr^{-1}), subsidence induced by NCL (S_{ncl}, cm yr^{-1}) and proportion of NCL in total subsidence (P_{ncl}, %) were calculated by the following equations:

$GCR = (GWL(i) - GWL(i-1)) / (\text{date}(i) - \text{date}(i-1))$ (Eq. 1)
$\text{NCL} = \text{CO}_2 \text{ emission} - \text{Litter fall}$ (Eq. 2)
$S_{ncl} = 0.1 \times \text{NCL} / BD / TOC$ (Eq. 3)
$P_{ncl} = S_{\text{ncl}} / S \times 100$ (Eq. 4)

RESULTS

BD was the largest at A1 and A2, followed by B and N (Table 1). TOC contents were 0.58 g C g^{-1} for all land uses. Annual cumulative CO_2 emission was the largest at A1, followed by A2, N and B ($p < 0.001$, Table 1). GWL (m) was the deepest at A2, followed by A1, B and N ($p < 0.001$, Table 1). T_s was the highest at B, followed by A1, A2 and N ($p < 0.001$, Table 1). RH was the lowest at B, followed by A1, A2 and N ($p < 0.001$, Table 1). According to the results of step-wise multiple regression for log-transformed CO_2 flux using GWL, GCR, T_s, RH, CO_2 flux was higher for the deeper GWL, the higher GCR (faster rise in GWL), higher T_s, and lower RH, respectively (Table 2).

Annual cumulative NCL was significantly larger at B, followed by A1, A2 and lastly N ($p < 0.01$, Table 3). Especially, NCL at A2 and N were negative, which showed the net carbon increase in these sites. Annual cumulative S was the largest at A2, followed by A1, B and N (Table 2). S was significantly correlated with GWL at B ($p < 0.001$) and N ($p < 0.001$), but not at A1 and A2 (Fig. 2). Annual cumulative S was larger in the deeper average GWL (Table 3). Annual cumulative S_{ncl} (cm yr^{-1}) and P_{ncl} (%) were almost parallel to NCL (Table 3), and both were the significantly largest at B, followed by A1, A2 and N ($p < 0.01$ and $p < 0.001$, respectively, Table 3). The P_{ncl} significantly correlated with the average T_s ($R^2 = 0.90$, $p < 0.001$, Fig. 3).

Table 7 Annual cumulative CO_2 emission, litter fall, bulk density (BD), groundwater level (GWL), soil temperature (T_s) and relative humidity (RH). All the values represent average ± standard deviation.

Plot	CO_2 emission	Litter fall	BD	GWL	T_s	RH
	kg C m^{-2} yr^{-1}		g cm^{-3}	m	°C	%
A1	3.7 ± 0.4^{a}	3.2	0.14	-0.58 ± 0.12^{b}	27.9 ± 1.3^{ab}	65.8 ± 9.6^{b}
A2	$1.7 \pm 0.6_{b}$			-0.93 ± 0.15^{c}	27.0 ± 1.3^{bc}	69.1 ± 8.4^{b}
B	1.1 ± 0.2^{b}	0.0	0.11	-0.33 ± 0.16^{a}	29.1 ± 2.4^{a}	57.2 ± 11.5^{c}
N	1.3 ± 0.2^{b}	2.9	0.10	-0.28 ± 0.12^{a}	25.9 ± 0.8^{c}	78.1 ± 4.9^{a}

Table 8 Results of stepwise multiple generalized linear model for log CO_2 flux using GWL, GCR, T_s and RH.

Plot	Equation	P	R^2
A1	$-0.56 + 0.15 \times T_s - 3.88 \times GWL + 1.18 \times GCR$	< 0.01	0.49
A2	$-1.70 + 0.27 \times T_s - 2.77 \times GWL + 3.73 \times GCR - 0.04 \times RH$	< 0.01	0.73
B	$5.52 - 1.92 \times GWL - 0.02 \times RH$	< 0.05	0.30
N	Not significant		

The annual cumulative CO_2 emission, S and P_{ncl} in A1 and A2 were smaller than the previously reported results in *Acacia* plantation on tropical peatland in the short drainage periods (Table 4). On the other hand, the average *GWL* in A1 and A2 were not different from the previous results, but the standard deviation of *GWL* decreased in A1 and A2 (Table 4).

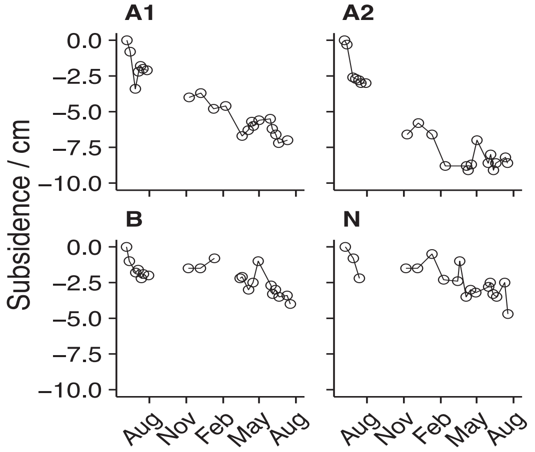

Fig. 1: Time-series of subsidence in *Acacia* plantation (A1 and A2), buffer zone (B) and natural forest (N)

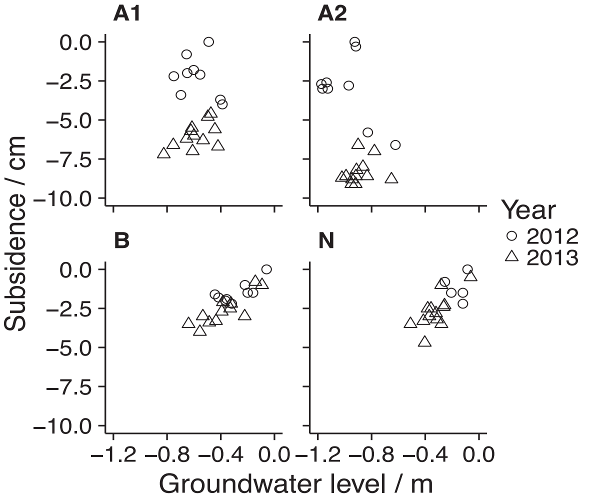

Fig. 2: Relationship between subsidence and groundwater level in *Acacia* plantation (A1 and A2), buffer zone (B) and natural forest (N.

DISCUSSION

CO_2 flux was larger in deeper *GWL* and lower *RH* (Table 1, 2), suggesting that the aerobic condition promoted peat decomposition. Also, CO_2 flux was larger in the higher *GCR* (faster rise of *GWL*, Table 2), indicating that the "soil-drying effect" (Birch, 1958). CO_2 emissions in A1 and A2 were smaller than previous results (Table 4). The average water table depth in our study was similar to previously reported, but with decreased standard deviation of *GWL* (Table 4). This might result in the smaller CO_2 emission in our study due to the decrease of fluctuation of *GWL*.

The S at B and N was significantly correlated with *GWL*, but not at A1 and A2 (Fig. 2). This result indicates the subsidence at B and N was reversible subsidence, while the subsidence in *Acacia* plantation was irreversible subsidence. Also, the annual cumulative S was larger in the deeper average *GWL* within our study site (Table 3), suggesting that higher *GWL* mitigates the annual cumulative S. Note that total subsidence at each land use in our study was very much higher than subsidence in extensive long-term records collected by APRIL.

The P_{ncl} in A1 and A2 were smaller than the previous results (Table 4), resulting from the smaller CO_2 emission. . The largest P_{ncl} was obtained at B, which had the least dense vegetation cover (Table 3). This may be because of following three reasons: 1) small litter fall, 2) high temperature and 3) small *BD* (Table 1). Decrease of *BD* increases P_{ncl} (Eq. 3). Consequently, the difference of *BD* between A1 and B (0.14 and 0.11 g cm^{-3}, respectively) explains 27.2% of the difference of P_{ncl} between them.

Table 9: Annual cumulative net carbon loss (NCL), subsidence induced by NCL (S_{ncl}), total subsidence (S), and proportion of NCL in total subsidence (P_{ncl}). All the values represent average ± standard deviation

Plot	*GWL*	NCL	S_{ncl}	S	P_{ncl}
	m	kg C m^{-2} yr^{-1}	cm yr^{-1}		%
A1	-0.58 ± 0.12 ^{b}	0.52 ± 0.38 ^{a}	0.7 ± 0.6 ^{a}	6.3	11.9 ± 10.1 ^{ab}
A2	-0.93 ± 0.15 ^{c}	-1.14 ± 1.19 ^{b}	-1.8 ± 2.0 ^{b}	8.0	-22.2 ± 25.4 ^{b}
B	-0.33 ± 0.16 ^{a}	1.06 ± 0.18 ^{a}	1.6 ± 0.5 ^{a}	3.3	49.0 ± 16.1 ^{a}
N	-0.28 ± 0.12 ^{a}	-1.63 ± 0.17 ^{b}	-2.5 ± 0.6 ^{b}	2.5	-98.1 ± 25.3 ^{c}

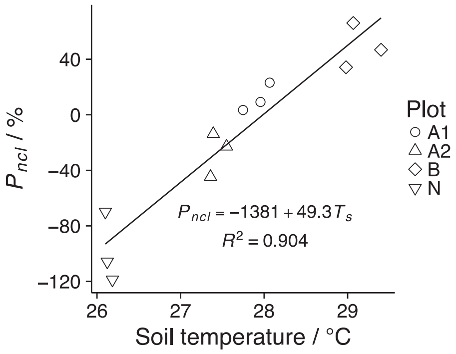

Fig. 3: Relationship between the proportion of net carbon loss in total subsidence (P_{ncl}) and the average soil temperature (T_s)

Table 10: Comparison of drainage year, groundwater level (*GWL*), CO_2 emission, total subsidence (*S*) and proportion of NCL to total subsidence (P_{ncl}) with the published references in *Acacia* plantation on tropical peatland. The values show average ± standard deviation or range.

Reference	Drainage	*GWL*	*S*	CO_2 emission	P_{ncl}
	years	m	cm yr^{-1}	kg C m^{-2} yr^{-1}	%
A1 (this study)	3 to 4	−0.58 ± 0.12	6.3	3.7 ± 0.4	11.9 ± 10.1
A2 (this study)	3 to 4	−0.93 ± 0.15	8.0	1.7 ± 0.6	−22.2 ± 25.4
Hooijer *et al*. (2012)	2 to 5	−0.70 ± 0.20	16.8	17.8	75
Jauhiainen *et al.*(2012)	0 to 5	−0.8		9.4	

CONCLUSION

Water management in our study site could mitigate CO_2 emission, S and P_{ncl} compared with the other reports in *Acacia* plantation on tropical peatland. The largest NCL, S_{ncl} and P_{ncl} were obtained in B, but the closed canopy may be able to improve the NCL, S_{ncl} and P_{ncl} by the increase in litter fall and by decrease in soil temperature in the water-managed tropical peatland.

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