# Effect of hydrological restoration on degraded tropical peat carbon fluxes


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## Summary

Large areas of tropical peat have been drained, resulting in an abrupt change in the carbon sequestration and storing potential. Hydrological restoration by dam construction was made in drainage affected peat swamp forest and deforested burned peat area in Central Kalimantan (Indonesia) in order to slow down water outflow. Peat carbon dioxide fluxes were analyzed both for pre- and post-restoration peat water table level conditions. In forested areas the contribution from autotrophic $CO_2$ production can be high, but oxidation of deposited litter is faster in drainage affected forest than in undrained forest. Restoration of peat hydrology may not instantly affect the reduction of peat $CO_2$ flux rates in forests owing to difficulties in creating near peat surface water table level conditions, and because forest soil results in high autotrophic $CO_2$ production. In open degraded areas near soil surface maintained water table level can potentially reduce $CO_2$ loss from decomposition but carbon loss cannot be stopped until ecosystem C losses are exceeded by vegetation net carbon sequestration.


**Key index words**: carbon dioxide, land use, peat swamp forest, restoration, water table

## Introduction

Tropical peat swamp forest forms one of the most efficient carbon (C) sequestering and storing ecosystems because it combines substantial biomass production capacity and dead biomass conservation in nutrient-poor, waterlogged peat. The estimated current peat carbon store in Indonesia is 26–50 Gt (Page *et al.* 2002). Large areas of tropical peat have been drained, resulting in an abrupt and permanent shift in the ecosystem carbon balance from sink to source (e.g. Page *et al.* 2002; Hirano *et al.* 2007). Decomposition of drained peatlands in Indonesia is estimated to cause 632 Mt $yr^{-1}$ $CO_2$ emissions (range 355–874 Mt $yr^{-1}$), which will likely increase every year for the first decades of the next century unless peatland use practices are changed (Hooijer *et al.* 2006). One of the largest degraded areas on tropical peatland (about 1 Mha) was created in 1996–1998 by the Mega Rice Project (MRP).

The main objectives of this study are to: (1) determine soil $CO_2$ dynamics and cumulative fluxes in relation to peat hydrology in drainage affected forest and deforested tropical peat, (2) determine major patterns in the annual peat WTL conditions after hydrological restoration of drainage affected peat, and (3) to evaluate the effect of hydrological restoration on $CO_2$ fluxes.

## Methods

### *Study site*

Two measurement sites were located near each other in the northeast corner of the ex-MRP area, about 20 km southeast of Palangka Raya City in Central Kalimantan Province of Indonesia. The area is split by two open canals, 25 m wide and 3.5–4.5 m deep. Measurement sites included drainage affected, selectively logged peat swamp forest (DF), and deforested, drained, burned peatland (DBP). The DF site had been cleared of its commercially most valuable timber prior to 1998. The forest floor microtopography included about 10–20 cm high hummocks with adjoining unvegetated depressions with about 50:50 surface ratio. Hummocks were largely formed from tree bases and other vegetation growing on them. The deforested site was treeless as a result of clear felling and consequent fires. The vegetation on the deforested site was dominated by ferns that had colonizing the higher surfaces. About 20–30 cm deep depressions, created by smoldering fires, had remained unvegetated possibly because of excessive wetness during rainy seasons. The mean peat thickness in the area was about 4 metres. The climate is characterized by 24–27°C temperatures, high humidity and high rainfall (overall average ~2800 mm) intensity.

### *Data collection and processing*

Two gas flux monitoring transects oriented perpendicular to the canal direction were established about 1.1 km apart from each other in the selectively logged forest and deforested sites. Both transects consisted of five subplots at about 50 m intervals. Gas flux monitoring on the sites was carried out between April 2004 and December 2006 at intervals of about 2-3 weeks. In June-August 2005, seven dams were constructed in the study area canal system bordering an area of about 13 $km^2$. Water table level loggers (Keller, DCX-22) installed in one depression at the most far-off subplots from the canal recorded peat WTL on the sites. During gas flux measurements, WTL was measured with an audible buzzer apparatus from wells on each subplot.

Two methods were applied for the gas flux measurements. A closed chamber technique was applied for measuring $CO_2$ on depressions (method described in Jauhiainen *et al.* 2005). In this, four air samples were collected at 5-minute intervals from aluminum frames closed air-tightly by a 37 $dm^3$ headspace during a 20-minute incubation period. Evacuated glass vials (12 ml) were used for sample storing by filling each vial with 20 ml of the sample air. For $CO_2$ analysis a gas chromatograph (Agilent 6890N) equipped with a flame ionization detector (FID) was used. The other method applied for measuring $CO_2$ emissions from hummocks and high surfaces was a portable infrared gas analyzer (PP Systems, model EGM-4) connected to a 30 cm diameter soil respiration chamber that enclosed the peat surface during 81-second incubation periods.

Carbon dioxide fluxes were calculated from a linear change of gas concentration inside the closed chamber as a function of measurement time. Non-linear regression models were fitted to $CO_2$ data from each subplot, and WTL was applied as an explanatory factor. The 3–5 most representative subplots on both microtopographical surface types, based on $R^2$ values, were selected for further analysis. Gas fluxes at respective diurnal WTLs were summed together to produce cumulative gas fluxes for one year periods. Cumulative fluxes on hummocks and depressions were proportioned to microtopography surface ratio (50:50) on both sites. Mean gas fluxes were used for the DF site hummocks because goodness of fit for modeled gas fluxes with WTL in hummocks was low.

## Results

### *Peat water table level*

Deforested (DBP) site WTL annual mean, minimum (-21 vs. -33 cm), median (-14 vs. -26 cm), and mean 4-month dry season WTL (-40 vs. -52 cm) were higher after canal blocking. In the forested DB site, annual mean (-43 vs. -47 cm), minimum (-100 vs. -155 cm), and median (-35 vs. -39 cm) WTL were also higher after canal blocking. In general, the greatest difference in the peat WTL was found in the annual minimum WTL, which was 55 cm higher in the forest and 68 cm higher in the deforested site after restoration. Precipitation during the one-year period before restoration was 3215 mm in comparison to 2857 mm rainfall after restoration, and timing of dry and wet seasons was comparable during the two years.

### *Regression models*

All gas flux data for each subplot were pooled together in the regression analyses since the GHG fluxes did not differ markedly ($P > 0.05$) at comparable soil water table level conditions before and after restoration. $CO_2$ flux maximum rates in the DF site depressions were clearly higher in comparison to the clear-felled site. The WTL resulting in the maximum $CO_2$ flux in the DF depressions was deeper and covered wider WTL range than in the DBP site.

### Cumulative gas fluxes

Annual cumulative $CO_2$ fluxes differed between the DF and DBP sites at ($P < 0.001$) level between hummocks and high surfaces, and ($P < 0.01$) level in depressions. By using the 50:50 surface ratio in microtopography, cumulative fluxes between the sites differed ($P < 0.001$) during both years. There were no marked differences ($P > 0.05$) in the hummock/high surface or depression cumulative gas balances in either of the sites between year before and after restoration.

## Discussion

### *CO2 fluxes*

Hummocks in the DF site are in an elevated position in forest floor microtopography which creates sufficiently moist conditions in surface peat and therefore makes them appropriate for root growth and seedling germination. Hummock surfaces resulted in high $CO_2$ emission rates even in nearly waterlogged conditions, which is largely (not quantified in this study) from autotrophic root respiration of trees. In bare forest floor depressions gas fluxes responded more clearly to peat WTL which is proposed to result from the smaller share of autotrophic respiration in comparison to emissions from organic matter decomposition. Comparable gas flux response in hummocks and depressions has been found in an undrained peat swamp forest, but with about 320 $mg\ m^{-2}\ h^{-1}$ lower maximum $CO_2$ flux rate in comparison to DF site (Jauhiainen *et al.* 2005). Tree roots in the DF site need to extend deep in the peat and cover a spatially large area in order to secure water availability in dry conditions, which may increase proportionally litter deposition in oxic situation in deeper peat layer, and thus contribute to the resulted high $CO_2$ loss maximum that was resulted in deep WTL conditions and covered a wide WTL range in the model.

Lower $CO_2$ fluxes at the sparsely vegetated BDP site, in comparison to the forest, can be explained by low root respiration and low deposition of fresh litter into peat. After clear felling a large amount of fresh debris remains in and on the surface peat, but if the subsequent litter deposition is low, decomposition rate slows down over time (Wösten *et al.* 1997). $CO_2$ flux maximum in fern dominated high surfaces at the site was about 100 $mg\ m^{-2}\ h^{-1}$ lower compared to depressions, which indicates low root respiration contribution to the fluxes and relatively low microbial activity in peat near the surface. High exposure to sun may promote over-heating and over drying in high surfaces, which probably reduces microbial activity in the uppermost peat profile. In the DBP site $CO_2$ emission was highest when the depth of the oxic peat profile was relatively wide (WTL deep), and this likely reflects conditions in which oxic peat horizon depth and peat moisture conditions are optimal for aerobic decomposition.

Drainage affected forest cumulative $CO_2$ effluxes were among the highest measured in tropical peat (~2000 g $CO_2$-C $m^{-2}$). Forest floor $CO_2$ emissions of a comparable scale have been detected in Sarawak (2130 g C $m^{-2}y^{-1}$) by Melling *et al.* (2005). Undrained peat swamp forest floor $CO_2$ emissions have varied between 953–1200 g C $m^{-2}$ $y^{-1}$ (Inubushi *et al.* 2003; Jauhiainen *et al.* 2005). The DBP site annual $CO_2$ efflux (711–758 g C $m^{-2}$ $yr^{-1}$) are somewhat higher than annual $CO_2$-C emissions from agricultural uncultivated peat (526 g C $m^{-2}$) in the same area (Jauhiainen *et al.* 2004), but it is lower than in more voluminous vegetation-covered oil palm (1540 g $m^{-2}$) and sago plantation (1110 g $m^{-2}$) soil emissions (Melling *et al.* 2005).

### *Peat water table level and gas fluxes*

The peat swamp forest main water storage is in permanently waterlogged subsurface peat below the usual water fluctuation zone. This peat is relatively well decomposed and has lower hydraulic conductivity compared to the more permeable surface peat (Takahashi *et al.* 2002). Water runoff through the top horizon was more efficient in the DF forest site which still had a 15–30 cm deep highly porous, fibric horizon on top. High WTL conditions prevailed longer in the DBP site because the peat is characterized by a collapsed peat macro-pore structure, and it is well decomposed and compacted up to the peat surface. Therefore dams can act as barriers restricting water outflow during the dry season especially in the forest area, and thus decrease depth and duration of the lowest water level conditions.

Restoration of peat hydrology may not instantly effect the reduction of peat $CO_2$ flux rates in forests owing to difficulties in creating near peat surface WTL conditions in porous peat, and because forest soil results in high autotrophic $CO_2$ production. The main positive outcome from nearer peat surface stabilized hydrological conditions is likely created by enhanced C-storing potential through avoided drought stress and maintained sufficient net photosynthesis in the vegetation (Hirano *et al.* 2007). This would increase litter deposition and duration of recently deposited litter in a decomposition slowing, waterlogged environment also near the peat surface, while the deeper carbon stores would not be exposed to oxic conditions. In clear felled sites higher WTL did not show any immediate response in the cumulative $CO_2$ flux. However, peat C losses can be expected to decrease with long term stabilized near peat surface hydrology conditions. Instant benefit from higher WTL is greater water availability for vegetation that promotes forest regeneration potential.

## Conclusions

Uncontrolled drainage causes enhanced dead biomass oxidization in peat owing to increased thickness of the aerobic peat profile, which leads to peat subsidence. Long term waterlogging is difficult to achieve in peat that has porous surface peat. In drainage affected forested areas, the contribution from autotrophic $CO_2$ production can be high, but oxidation of deposited litter is faster than in undrained forest. The main positive outcome from higher WTL conditions in forest is likely to be improved ecosystem level C-storing potential through avoided drought stress and thus maintained net carbon sequestration resulting in sufficient litter deposition in frequently and long-term water logged conditions. In open degraded areas, such as the DBP site, near soil surface maintained WTL can potentially reduce $CO_2$ loss from decomposition but carbon loss cannot be stopped until ecosystem C losses are exceeded by vegetation net carbon sequestration. Forest regeneration is a long process, but investments into hydrological restoration are important both for reducing the fire hazard and in creating conditions for forest vegetation re-establishment.

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