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Originally it was planned to study 'Review on CH_4 and N_2O fluxes from tropical land use changes' under Deliverables D.3.2. Just before starting the work, the project team noticed a recent publication of a similar nature of study in a public domain. Therefore the research team decided to study changes in soil CH_4 fluxes from the conversion of tropical peat swamp forests.

Changes in soil CH_4 fluxes from the conversion of tropical peat swamp forests: a meta-analysis

Hergoualc'h Kristell and Verchot Louis V.

Center for International Forestry Research (CIFOR)
Jl. CIFOR, Situ Gede. Bogor 16115, Indonesia

Abstract

Currently 25% of all deforestation in insular Southeast Asia occurs in peat swamp forests. When peatlands are deforested, drainage ditches are often constructed to lower the ground-water level, which may result in decreased methane (CH_4) production and increased CH_4 consumption by peat soils. Our aim was to evaluate how tropical peat swamp forest conversion affected soil CH_4 emissions. Average CH_4 fluxes and associated water table depths and correlation between both were calculated from the literature for common land use treatments. In addition, we used a meta-analysis statistical approach to compare soil CH_4 fluxes before and after land-use change. Mean rates of soil CH_4 emissions amounted to average values of 28.5 ± 9.7 kg C ha^{-1} y^{-1} and 155.1 ± 82.4 kg C ha^{-1} y^{-1} in virgin peat swamp forests and rice fields, respectively; whereas in the other land uses, mean soil CH_4 fluxes (9.9 ± 5.4 kg C ha^{-1} y^{-1}) were significantly lower. Methane fluxes were positively correlated ($r = 0.54$; $P = 0.0149$) with the water table depth. The significant overall effect size of land-use change on emissions of CH_4 was -0.4 ± 0.2 indicating a small decrease of CH_4 emissions with the conversion of virgin peat swamp forests to another land use, including rice cultivation. A similar analysis would be required on soil emissions of N_2O. It's important to stress however that the overall decrease in CH_4 emission from peat swamp forests conversion would never offset the simultaneous increase in soil CO_2 emissions due to accelerated decomposition of the peat.

Keywords
Carbon, Climate change, Greenhouse gas, Land-use change, Southeast Asia

1. Introduction

Despite covering only about 0.25% of the Earth's land surface, tropical peatlands contain around 3% of the global soil carbon (C) stocks and at least 20% of global peat C [*Page et al.*, 2004; *Page and Banks*, 2007]. The largest area of tropical peatlands occurs in Southeast Asia, where they are found in Indonesia, Malaysia, Brunei and Thailand [*Rieley and Ahmad-Shah*, 1996]. In their natural state, lowland tropical peatlands support a growth of swamp forest overlying peat deposits up to 20 meters thick [*Page et al.*, 1999]. Peat soils are characterized by high C contents over the full depth of the peat deposit and very low bulk densities (< 0.2 g cm^{-3}) [*Andriesse*, 1988]. Anaerobic conditions in the soil limit decomposition of the litter, leading to peat accumulation and also channel a small fraction of the excess organic matter (OM) into methane (CH_4) [*Jauhiainen et al.*, 2005], which is a greenhouse gas (GHG) with a global warming potential (GWP) 25 times stronger than carbon dioxide (CO_2) [*Forster et al.*, 2007] over a 100 year time horizon.

Between 2000 and 2010, 25% of all deforestation in insular Southeast Asia occurred on peatlands [*Miettinen et al.,* 2011]. This deforestation is driven by wood production and demand for land on which to establish small- and large-scale agriculture including oil palm and timber plantations [*Hooijer et al.*, 2006]. Accessible peat swamp forests of Southeast Asia are often logged, legally or not. Cutting canals in order to extract the logged wood is a widespread practice in the region that results in a subsidence of the peat dome [*Kool et al.*, 2006], a fall of the water tables and consequently induces changes in the carbon cycle. When peatlands are reclaimed for other uses, the forest is cleared and the land is prepared for cultivation, often using fire. Drainage ditches are often constructed to lower the ground-water level and the soil may be compacted with heavy machinery to allow anchorage of trees and to increase the bearing capacity of the soil [*Andriesse*, 1988; *Wösten et al.*, 1997]. Increased aeration due to drainage may result in decreased CH_4 production and increased CH_4 consumption by peat soils [*Melling et al.*, 2005]. Large areas of tropical peatlands will continue to be cleared to establish oil palm and *Acacia* plantations [*Barr*, 2001; *Miettinen*, 2004; *Hooijer et al.*, 2006, *Germer and Sauerborn*, 2008] and to a lesser extent, sago palm and rubber.

Our aim was to evaluate how land-use change (LUC) in tropical peat swamps of Southeast Asia affected soil fluxes of CH_4. As a first step, we reviewed studies on soil CH_4 fluxes of six land-use (LU) types prevalent in Southeast Asia: virgin peat swamp forest, drained forest, fire-damaged forest, mixed croplands & shrublands, rice fields and oil palm plantations. From this compilation we proceeded to a meta-analysis in order to compare CH_4 fluxes before and after LUC.

2. Materials and Methods

2.1. Data collection, calculation and presentation

We collected data from a variety of published sources including journal articles, theses and reports. Mean annual CH_4 fluxes and associated water table depths were calculated for the different LU treatments. We also explored correlations between soil fluxes of CH_4 and two important abiotic factors, soil temperature and water table level, by LU treatment. Given the high variation in the responses of soil CH_4 fluxes to LUC among sites, we used a meta-analysis statistical approach to compare CH_4 fluxes before and after LUC. We used data from studies with paired observations on the same site. Six bibliographic references were included in the meta-analysis, considering 16 case studies of conversion from a virgin peat swamp forest to another LU. In the meta-analysis, the control treatment was the virgin peat swamp forest and the “other land-use” treatment included all other land-uses than virgin peat swamp forest.

2.2. Statistics Analysis

Statistical analysis was performed using the software *InfoStat* [2004], with a probability level of 0.05 to test the significance of the treatments effects. For multiple comparisons between land-use types the non parametric Kruskal Wallis test was performed since CH_4 fluxes were no-normally distributed. The distribution of CH_4 fluxes was tested using the Shapiro-Wilks test.

Meta-analysis was used to evaluate the response of CH_4 fluxes to land-use change (LUC) in tropical peatlands. Only the studies comparing a virgin peat swamp forest to another land use on the same site were included in the analysis. The magnitude of the effect of LUC on CH_4 fluxes was evaluated using the Hedges’s g metric (bias-corrected standardized mean difference) as defined by *Borenstein et al.* [2009]. Positive Hedge’s g values indicated that LUC increased the value of the variable with respect to that in virgin peat swamp forest; negative values indicated that LUC decreased the value of the variable. According to *Borenstein et al.* [2009], Hedge’s g values of 0.2 or less indicate a small effect size; values around 0.5 indicate a medium effect and 0.8 or above indicate a large effect size. The overall effect size was calculated using a random effects model which allows that the true effect could vary from study to study [*Borenstein et al.*, 2009], rather than using a fixed effect model for which the true effect size is assumed to be shared by all the included studies. A t-test was used to assess the significance of

individual and overall LUC effect sizes on soil fluxes of CH_4. The meta-analysis was performed with the software Comprehensive Meta Analysis version 2.2.048 [Biostat Inc., New Jersey, USA].
Throughout the manuscript uncertainties estimates are reported as standard errors except those of CH_4 fluxes from individual studies which are reported as standard deviations for the purpose of the meta-analysis.

3. Results and discussion

Mean rates of soil CH_4 emissions in virgin peat swamp forests from all available studies (Table 1) ranged from 0.2 to 72.3 kg C ha^{-1} y^{-1}, with a mean rate across all sites of 28.5 ± 9.7 kg C ha^{-1} y^{-1} (n = 8). In rice fields, emissions of CH_4 amounted to an average value of 155.1 ± 82.4 kg C ha^{-1} y^{-1} (n = 4). In the other LUs, mean soil CH_4 fluxes (9.9 ± 5.4 kg C ha^{-1} y^{-1}, n = 17) were significantly lower (P = 0.0047) than in virgin peat swamp forests and rice fields. Mean soil temperature was higher in the other LUs (27.1°C) than in the virgin peat swamp forest (25.7°C) and mean water table level was the highest in the rice fields (-3.3 cm), followed by the virgin peat swamp forest (-13 cm) and other LUs (-30.6 cm). Methane fluxes were positively correlated (r = 0.54; P = 0.0149) with the water table depth indicating increased emissions with increased water level. The effect size of LUC on emissions of CH_4 (Figure 1) ranged from -2.2 ± 0.7 (conversion of virgin peat swamp forest to a drained forest) to 1.2 ± 0.7 (conversion of virgin peat swamp forest to an abandoned rice field). Positive effect sizes (i.e. increased CH_4 fluxes) were associated with conversions to rice fields and a sago palm plantation. The overall effect size was -0.4 ± 0.2 and was significantly different from zero (P = 0.0425) indicating a small decrease of CH_4 emissions with the conversion of virgin peat swamp forests to another LU, including rice cultivation.
Our study confirms that soil water table depth is one of the key factors governing soil emissions of CH_4 as observed elsewhere in northern [*Lai*, 2009] and tropical [*Jauhiainen et al.*, 2005] peatlands. The overall decrease in soil CH_4 emissions resulting from LUC in tropical peatlands may however also be associated with changes in other factors such as soil temperature and vegetation type. Currently available data on CH_4 fluxes in tropical peatlands are yet insufficient to proceed to such an analysis. In order to assess how deforestation of tropical peat swamps may affect climate change, it is necessary to compare the overall decrease in soil CH_4 emission observed here to the associated changes in soil nitrous oxide (N_2O) and heterotrophic CO_2 emissions. Autotrophic soil CO_2 emissions also called root respiration are already integrated in biomass C stocks assessments generally used for quantifying CO_2 losses from the vegetation. Very few studies have quantified all three GHG in changing land uses on tropical peat and almost none has partitioned soil respiration into autotrophic and heterotrophic components. Therefore much more research is needed in this area. Using the data from *Melling et al.* [2005], the conversion of a virgin peat swamp forest into an oil palm plantation on peat fertilized at a rate of 100 kg of N ha^{-1} y^{-1} would represent a decrease in soil CH_4 fluxes of 0.33 kg C-CH_4 ha^{-1} y^{-1} or 0.01 Mg of CO_2eq ha^{-1} y^{-1} (applying the CH_4 GWP of 25 over a time horizon of 100 y [*Forster et al.*, 2007]). The same conversion would lead to an increase in soil N_2O emissions of 0.5 kg N-N_2O ha^{-1} y^{-1} or 0.23 Mg of CO_2eq ha^{-1} y^{-1} (applying the N_2O global warming potential of 298 over a time horizon of 100 y [*Forster et al.*, 2007]). With increased soil N_2O emissions 20 times larger than the respective decreased soil CH_4 emissions, when both expressed in CO_2 equivalent, it's clear that converting the peat swamp forest into the oil palm plantation is harmful for the climate. Finally, a comparison between mean annual soil CO_2 and CH_4 emissions in the six LU types prevalent in Southeast Asia as defined in this study [*Hergoualc'h and Verchot*, 2011] demonstrated that the decrease in CH_4 emissions arising from deforestation of peat swamp forest was negligible compared with the corresponding release of CO_2 into the atmosphere due to intense decomposition of the peat in aerobic conditions.

Table 1: Annual soil fluxes of CH_4 (standard deviation SD and n number of average values used to calculate annual fluxes) in different land uses (LU) on tropical peatlands.

Ref[a]	Country	Sf[b]	Sl[c] (months)	LU	LUT[d]	CH_4 (kg C ha^{-1} y^{-1})	SD	n	Altitude (m)	Rainfall (mm y^{-1})	Ta[e] (°C)	Ts[f] (°C)	WT[g] (cm)
1*	Indonesia	1	12	Forest	F	63.1	55.7	3	10	2582	26.7	-	3.3
2*	Indonesia	12	11	Forest	F	44.7	79.6	11	3	2500	26.5	-	0
3*	Indonesia	12	12	Forest	F	10.6	5.5	3	30	1852	26.7	-	-
3*	Indonesia	12	12	Forest	F	12.8	6.0	3	30	2292	26.4	-	-
3*	Indonesia	12	12	Forest	F	13.0	6.1	3	30	2560	25.9	-	-
4*	Malaysia	12	24	Forest	F	72.3	40.1	4	-	-	-	-	-
5*	Indonesia	12	12	Forest	F	12.0	4.0	3	3	3133	26.5	-	-10
6*	Malaysia	12	12	Forest	F	0.2	0.4	12	-	2163	27.2	25.7	-45.3
1*	Indonesia	12	12	Drained Forest	DF	8.8	9.1	12	10	2582	26.7	25.5	-18.1
1*	Indonesia	12	12	Cassava	C&S	25.4	54.6	12	10	2582	26.7	27.1	-23.5
1*	Indonesia	12	12	Upland rice	R	27.2	24.3	12	10	2582	26.7	27.2	-13
1*	Indonesia	12	12	Lowland rice	R	371.4	752.6	12	10	2582	26.7	27.1	5.2
1*	Indonesia	1	24	Coconut	C&S	-0.9	0.9	2	10	2582	26.7	-	-43
1*	Indonesia	1	24	Pineapple	C&S	0.0	0.0	2	10	2582	26.7	-	-19
1*	Indonesia	1	12	Pineapple	C&S	0.9	4.6	3	10	2582	26.7	-	-50
2*	Indonesia	12	12	Rice	R	196.0	291.7	11	3	2500	26.5	-	-2
2*	Indonesia	12	12	Rice-Soybean	R	26.0	43.7	11	3	2500	26.5	-	-
3*	Indonesia	12	12	Drained Forest	DF	8.3	3.2	3	30	2560	25.9	-	-
3*	Indonesia	12	12	Drained Forest	DF	9.4	3.8	3	30	2331	26.3	-	-
3	Indonesia	12	12	Abandoned cropland	C&S	0.8	-	-	30	2331	26.3	-	-
4*	Malaysia	12	24	Sago palm	C&S	90.7	53.9	10	-	-	-	-	-
5*	Indonesia	12	12	Abandoned cropland	C&S	6.0	7.0	3	3	3133	26.5	-	-15
5*	Indonesia	12	12	Abandoned rice	C&S	19.0	5.0	3	3	3133	26.5	-	2.1
6*	Malaysia	12	12	Sago palm	C&S	0.2	2.3	12	-	2928	32.1	27.8	-27.4
6*	Malaysia	12	12	Oil palm	OP	-0.2	0.5	12	-	2471	30.5	27.8	-60.2
7	Indonesia	12	12	Drained Forest	DF	-1.6	0.6	4	30	2560	25.9	-	-47
7	Indonesia	12	12	Drained Forest	DF	-2.8	0.7	4	30	2331	26.3	-	-43
7	Indonesia	12	12	Burnt Forest	FF	1.5	1.0	3	30	2560	25.9	-	-33
7	Indonesia	12	12	Burnt Forest	FF	2.1	1.1	3	30	2331	26.3	-	-21

[a] 1, Furukawa et al. (2005); 2, Hadi et al. (2005); 3, Hirano et al. (2009); 4, Inubushi et al. (1998); 5, Inubushi et al. (2003); 6, Melling et al. (2005); 7, Jauhiainen et al. (2008). References followed by * were included in the meta-analysis. [b] Sampling frequency per year. [c] Length of the experiment. [d] Land use type classification used for the calculation of mean annual CH_4 fluxes (F: virgin peat swamp forest, FF: fire-damaged forest, C&S: mixed croplands and shrublands, DF: drained forest, R: Rice fields, OP: oil palm plantation). [e] Air temperature. [f] Soil temperature. [g] Water table depth.

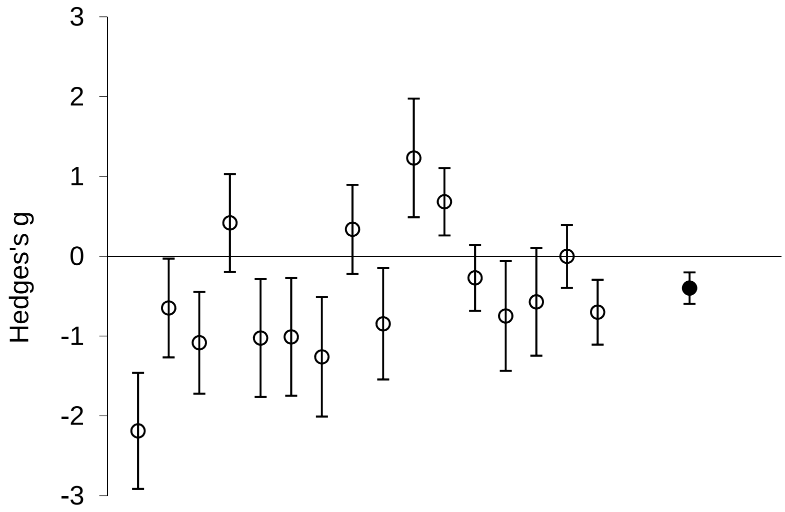

Figure 1: Mean effect size (Hedges's g) and standard error of individual (open circle) and overall (closed circle) land-use change on soil emissions of CH_4 in tropical peatlands.

4. Conclusion

The fate of tropical peat swamp forests is a major concern within the framework of climate change because of the high amount of carbon they currently store and could carry on storing, and the consequences of LUC for GHG release into the atmosphere. These ecosystems are therefore an important issue for climate change mitigation mechanisms, such as REDD (Reducing Emissions from Deforestation and forest Degradation). Quantifying GHG emissions from LUC requires studies on all three GHG (N_2O, CH_4 and CO_2) achieved simultaneously in changing land uses on tropical peat. The meta-analysis achieved with the few studies available in the literature indicated a small overall decrease of soil CH_4 fluxes due to conversion of virgin peat swamp forests. Such an analysis on the response of soil N_2O emissions to LUC in tropical peatlands is still inexistent and would be very useful. Finally it is important to underline that the overall decrease in CH_4 emission from peat swamp forests conversion would never offset the corresponding increase in soil CO_2 emissions due to accelerated decomposition.

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