© Suoseura — Finnish Peatland Society
Helsinki 2012

ISSN 0039-5471
Suo 63(3–4): 93–105 — Research articles

Diffusion GHG fluxes at tropical peatland drainage canal water surfaces

Kasvihuonekaasujen diffuusio kuivatuskanavissa trooppisilla soilla

Jyrki Jauhiainen & Hanna Silvennoinen

Jyrki Jauhiainen, Department of Forest Sciences, University of Helsinki, P.O. Box 27, 00014 University of Helsinki, Finland, e-mail: jyrki.jauhiainen@helsinki.fi
Hanna Silvennoinen, Norwegian University of Life Sciences, Department of Plant and Environmental Sciences, Fougnerbakken 3, 1432 Aas, Norway.

Data on greenhouse gas (GHG) exchange between water surfaces and the atmosphere above tropical peatland drainage canals are lacking in the literature. We quantified diffusion fluxes of CO_2, CH_4 and N_2O between the water surface and the atmosphere for two typical reclaimed peatland sites. One site was an industrial pulp wood plantation in the Kampar Peninsula (Sumatra) and the other was an abandoned peatland area in Kalimantan (Borneo). Drainage canal fluxes were measured by using floating closed chambers during both the wet and dry seasons. Fluxes at the sites were determined across a range of conditions that were created by varying land use histories, and also by canal biotic environment and hydrological features. Gas fluxes in the canal systems were influenced by their respective surrounding peatland areas, the season, and canal management. Fluxes of all three gases were higher at the more recently reclaimed settled (undisturbed) canals of the Kampar site in comparison to the Kalimantan site. In general, the mean flux from the canals ranged from 9–16, 0.1–1.1 and 0–0.003 g m^{-2} d^{-1} for CO_2, CH_4 and N_2O, respectively. A cumulative equivalent annual emission of these three GHGs from canals was nearly three times higher at the Kampar site (13.8 kg CO_{2e} m^{-2} y^{-1}) than that at the Kalimantan site (4.8 kg CO_{2e} m^{-2} y^{-1}). Mean fluxes of the three gases and the cumulative annual emission at the Kampar site were higher in the settled canals in comparison to the disturbed canals when both dry and wet season fluxes were calculated. The fluxes of CH_4 and N_2O especially decreased when canals had been recently cleaned (i.e. were in disturbed condition). In terms of their relative global warming potentials (GWP), CO_2 was the most important of the three GHG's both at the Kalimantan site settled canal (69% of the fluxes were attributed to CO_2) and at the disturbed canals at the Kampar (82%) site, whereas CH_4 dominated in settled canals at the Kampar site at 61% contribution to the total annual emission. CH_4 contributed 31% to the total cumulative equivalent annual emission at the Kalimantan settled canal. N_2O had only a minor role (0–2% of the cumulative fluxes) at the sites. On a unit area basis, GHG emissions from the drainage canals formed were generally higher emission sources in comparison to the surrounding peatland, and proportional contributions from the three GHG species to the total were more diverse in canals than on land.

Key words: tropical peat, drainage canal, CO_2, CH_4, N_2O, surface diffusion

Introduction

Lowland peatlands in Southeast Asia cover 24.8 million hectares (Mha), equivalent to 6% of the global peatland area (Page et al. 2011). The peat carbon store in Southeast Asia is 68.5 Gt, which is 11–14% of the global peat carbon store. These substantial peat deposits are result from the continuous organic matter inputs from evergreen lowland forests under waterlogged conditions. Since 1990, 5.1 Mha of a total 15.5 Mha of peatland in the Peninsular Malaysia and the islands of Borneo and Sumatra have been deforested, drained and burned and most of the remaining peat swamp forest has been intensively logged (Langner & Siegert 2009, Miettinen & Liew 2010). Over the same period industrial palm oil and pulpwood (*Acacia*) plantations expanded dramatically from 0.3 Mha to 2.3 Mha, an increase from 2 to 15% of the total peatland area. By 2008, only 10% of the peatlands of the Peninsular Malaysia, Borneo and Sumatra remained in an intact or slightly degraded condition (Miettinen & Liew 2010).

Greenhouse gas (GHG) dynamics of tropical ombrotrophic peatland consist of CO_2 uptake via photosynthesis and losses through autotrophic respiration of vegetation, CO_2, CH_4 and N_2O emissions from dead organic matter decomposition (heterotrophic respiration), and fluvial export of dissolved organic carbon (DOC) and particulate organic carbon substrates (POC) (Jauhiainen et al. 2005, 2008, 2012b, Moore et al. 2011). In drainage systems, such as canals, both the canal floor and the water column can form an important GHG store. Moreover, gases in canals, especially CH_4, can be released by diffusion through the water body, by ebullition and also by gas transport through certain vegetation types that grows on flooded peatland (Frenzel & Rudolph 1998, Saarnio & Silvola 1999). Increasing peat carbon losses from drained SE Asian peatlands have been found to contribute substantially to global GHG emissions (Couwenberg et al. 2010, Hooijer et al. 2010, Murdiyarso et al. 2010). The approximate range of decomposition net carbon loss emissions from peatland drained for agriculture is from ~4000 g CO_2 m^{-2} y^{-1} to ~6000 g m^{-2} y^{-1} at water table depths of around 0.7 m (Melling et al. 2005, Murdiyarso et al. 2010, Herchoualc'h & Verchot 2011, Jauhiainen et al. 2012a). Carbon dioxide emissions from tropical peat has had an outstanding global warming impact (>90%) when concurrent CO_2, CH_4 and N_2O fluxes at peat surfaces are compared across various land use types (Jauhiainen et al. 2012b).

Land use changes on wet tropical peatland ecosystems necessitate establishing drainage systems on peat. Drainage canals are used for lowering the water table in order to increase the aeration of surface peat for growing production plants. The surface areas and the volumes of canals are proportionally much smaller in comparison to the surrounding drained land. Organic substrates and particulate organic matter in the drainage water may become concentrated in the canal by accumulation on the canal floor and decomposing there, when they are not leached out of the system with runoff (Moore et al. 2011). Published research on GHG dynamics of tropical peatland water surfaces (Hadi et al. 2001, Inubushi et al. 2003, Furukawa et al. 2005, Jauhiainen et al. 2005) have hitherto not quantified fluxes from drainage canals. However, emissions from canal water may contribute significantly to the overall GHG budget by indirectly ventilating gases formed in the surrounding drained land and also by directly emitting gases formed within the canals from DOC and POC that have originated from peatland.

We studied CO_2, CH_4 and N_2O effluxes from water surfaces to the atmosphere. These diffusive fluxes were explicitly derived from the organic matter of surrounding ecosystem via three different mechanisms: 1) via indirectly exhausting gases formed in the peatland, 2) by releasing gases dissimilated from autochtonous (from carbon entered in the canal system by photosynthesis of canal vegetation), and 3) by releasing gases dissimilated from allochtonous material in the canal water column and canal floor peat or "sediment".

The focus of this study was to quantify the overall peat derived GHG fluxes from drainage canals as affected by land use and canal management, rather than to provide information on partitioning between the three possible production routes described above.

The specific land uses in the two canal systems in this study include industrial pulp wood plantation drained in the Kampar Peninsula (Sumatra) in the year 2000 and an abandoned peatland area that was cleared and drained in Kalimantan (Borneo) in early 1990s. The water table in the Kampar plantation canal system is managed by operational needs. Most of the canals had not been disturbed for several years lasting the whole timber growing phase but they were cleaned by excavators prior to the removal of timber. The water table at the Kalimantan abandoned area canal is uncontrolled and the wet and dry season levels may differ greatly. We quantified fluxes and annual emissions for three GHGs that diffused from the canal water surfaces. This was done by measuring gas flux during the wet and dry seasons across a range of conditions, which were created by land use history, biotic environment and hydrological events.

Material and methods

Sites

The Kalimantan study site (2°20’26.74”S, 114°2’16.48”E) was about 20 km distance from Palangka Raya city in Central Kalimantan Province, of Indonesia. The climate in the area is characterized by a relatively unvarying temperature, high humidity, and high rainfall intensity. The mean monthly temperature varies between 24 and 27°C. The mean annual rainfall varies between 1900 and 3000 mm along this part of the southern coast of Borneo, with an overall mean of around 2700 mm in the study area. The wettest months are December, January and February, whereas the driest months are August and September. The mean evapotranspiration is fairly constant, which gives an annual total of around 1350 mm, and it usually exceeds the mean monthly rainfalls of the July to September dry period. The Kalimantan site is inside the so called Ex-Mega Rice Project (EMRP) area, close to its northwest corner. The EMRP area comprises about 1 000 000 ha, and represents one of the largest continuous areas of degraded tropical peatland in the region. This area was clear-felled and drained for food production purposes in the mid-1990s, but many parts have since been abandoned as unsuitable for the intended agricultural production. Repeated fires have consumed several decimeters of the surface peat, all the trees and the larger bushes in the area. Subsequently, the area was proliferated by ferns, such as *Stenochlaena palustris*. The peat depth in the monitoring site was about 4 meters. The Kalimantan site was established on a large drainage canal originally built for water table management of the area. The studied canal is part of an approximately 4600 km long nonfunctional water management system and the total length of the studied ‘main primary’ canal network in the area is 1129 km. The canal had originally been constructed to be about 15 m wide at the bottom with a maximum depth of 4.5 m. Currently the area between canal banks is partly overgrown by ferns (*Stenochlaena sp.*) and sedges (*Lepironia articulata*) and has typically a less than 2 m of width water track in the middle (Fig. 1). Canal banks currently grow trees, mostly Tumih (*Combretocarpus rotundatus*), which also introduce litter into the canal system. The water table of the canal is not controlled and the canal enhances drainage from the surrounding degraded peatland area.

The Kampar study site was located in an *Acacia* (pulp wood) plantation on peatland in the Kampar Peninsula, Riau Province, Indonesia (0º26’06.9”N, 101º53’01.4”E). This part of eastern Sumatra has a mean annual rainfall of around 2500 mm and a mean daytime air temperature of around 28ºC. The Kampar Peninsula contains contiguous peat deposits of around 700 000 hectares. Prior to clearance of ~160 000 ha for plantation development from the year 2000 onwards, the area was peat swamp forest. The site area was not affected by fire immediately prior to, during, or after land use change. The plantation area is drained by a rectangular system of canals, 5 to 8 metres wide, over 3 metres deep and spaced 500 to 800 m apart, to lower the water table to a level suitable for growth of the plantation crops (Fig. 1). Jauhiainen et al. (2012a) provides further information on the peat characteristics on the peat dome, which has a peat thickness that ranges from 4–9 m (mean 6 m). *Acacia* grown on the plantation is fertilized, but quantities, timing or locations of possible fertilization events close to monitoring locations are not known. Flux monitoring was done within an area with distance between the most distant monitoring locations about 30 km. Flux data were collected under two typical canal

Figure 1. Typical view inside settled canals at the Kalimantan (left) and Kampar (right) sites with some gas flux monitoring equipment in use.

Kuva 1. Tyypillinen ruoppaamaton kanava Kalimantanilla (vasen) ja Kamparilla (oikea) sekä kaasunäytteiden keräyslaitteita.

management conditions, which were settled canal systems within *Acacia* tree growth phase areas and disturbed canals. In this case disturbed canals had recently been cleared by excavators for timber transportation, next to harvest ready and recently harvested areas. The largest part of the canal system was in the settled condition and has been for ~5 years *Acacia* growing phase. Certain stretches of the canal system are actively used for timber extraction. In the analysis on this study, 80% of the canals were proportioned to be in the settled condition and 20% in the disturbed condition at the Kampar site. Typical characteristics of settled canals were clear water, some locations had floating algae and vegetation (*Utricularia sp.*) on the surface, and the canal banks were overgrown by ferns (*Stenochlaena sp.*) that also floated on the canal water. In contrast, disturbed canals had been recently cleaned by removing organic materials by excavators in order to ease transportation of felled wood from the harvesting area. Disturbed canal banks and water were typically free of vegetation and the water was usually turbid due to suspended debris.

Data collection at the two sites was carried out daytime in September 2007 (dry season data) and in April 2008 (wet season data). Basic characteristics of the canal systems during the monitoring are provided in Table 1 and photographic views at two settled canals are shown in Fig. 1.

Sampling

Air samples were taken from 25 locations at the Kalimantan site and from 18 locations at the Kampar site. Closed chambers, cylindrical in shape, with the dimensions (D×H) 23 × 27 cm were used for the flux data collections. The chambers, constructed of electroplated steel, were painted light gray on their outside surfaces in order to avoid temperature build-up. Each chamber was open at the bottom and had about a 3 cm diameter hole in the top. The chambers were placed on polystyrene rafts (Fig. 1). Prior to sampling, 12 ml glass vials (Labco Extainer) were filled with nitrogen (99.5% N_2) and made airtight by sealing them with a rubber septa. The air sampling chambers were set floating on the water and the hole on their tops were sealed by a rubber stopper into which temperature and air sampling probes had been fitted. For each gas flux determination, four 60 ml air samples were drawn into syringes at 10 min intervals over the applied 40 min deployment time. Air volume taken from each chamber during the deployment time was not compensated because the sampled air volume was only 2.4% of the original air volume in the chamber, and thus the sampling was not assumed to cause a notable pressure difference inside the system mounted on a floating raft. During sampling, sample vials were flushed with 40 ml of the sample air and then over-pressurized with the remaining 20 ml. During transportation the impenetrability of gas samples in each vial was ensured by an additional hot-melt glue seal applied on/around the caps. Samples were analyzed within three weeks from the sampling event. Four chambers were sampled simultaneously at each sampling location in order to get representative gas flux determinations.

Analysis

For CO_2 and CH_4 analysis we used an Agilent 6890N GC (gas chromatograph) (Agilent Technologies Deutschland GmbH, Waldbronn, Germany) equipped with an autosampler (Gilson 222XL, Gilson Inc., Middleton, WI, USA), a peristaltic pump (Minipuls 3, Gilson Inc., Middleton, WI, USA) for sample transfer, a Hayesep Q column for gas separation with a flame ionization detector (FID) for CH_4, an electron capture detector (ECD) for determining CO_2 and N_2O. Each CO_2, CH_4 and N_2O flux reading was analyzed for linearity based on concentrations in consecutive air samples drawn from the closed chamber during deployment time. The temporal increase in gas concentrations in each chamber deployment was also compared with the deviation in standard gas concentrations. A sample was rejected when one or more of the following events occurred: when the GHG flux change in three sampled concentrations were not linear, when there remained less than three samples for forming the flux readout, and when the change in sampled gas concentration within the deployment time was smaller than the deviation in the standard gas samples. Gas fluxes in the replicate chambers were checked for highly differing values prior to the data analysis. Flux data from some 20% of the samples were lost due to computer failure during the gas analysis.

The collected data provides first emission results for tropical drainage canal systems. Mean fluxes and simple cumulative estimates are provided, but statistical analyses were limited to a comparison of the mean fluxes (at 95% confidence interval) in the conditions that prevailed during the gas sampling. A cumulative annual flux for each GHG species at the Kalimantan site canal was calculated as the sum of respective mean dry season and wet season fluxes both of which were each scaled up to six months long periods. Cumulative annual fluxes for each GHG species for both canal types at the Kampar site are given as a cumulative sum of mean flux proportioned over 365 days. They were also expressed by proportioning the cumulative fluxes to the estimated relative share of settled canals (80%) and disturbed canals (20%) each in sampling area.

The presented GHG fluxes should be considered as minimal levels because other gas emission pathways, such as ebullition and transport through

Table 1. Summary of canal water depth, water surface width and water flow rates during surface GHG sampling.

Taulukko 1. Yhteenveto kanavien veden syvyydestä, vesipinnan leveydestä ja vedenpinnan nopeudesta kaasunäytteiden ottamisen aikana.

Site	Water character	Min.	Max.	Mean	Dry season mean	Wet season mean
Kalimantan Settled	Depth (m)	0.1	2	0.7	0.46	0.9
	Surface width (m)	1	7	3.8	3.4	4.4
	Surface flow rate (cm s^{-1})	0	10	3.1	0.9	6.2
	Temperature (ºC) at 20 cm depth	26.6	33.1	28.4	29.0	27.5
Kampar Settled	Depth (m)	1.1	3.5	2.0	1.4	2.4
	Surface width (m)	-	-	8	-	-
	Surface flow rate (cm s^{-1})	0	60	15.5	7.5	20.6
	Temperature (ºC) at 20 cm depth	28.4	32.2	30.4	31.0	30.9
Kampar Disturbed	Depth (m)	1.1	2.0	1.7	1.6	1.7
	Surface width (m)	-	-	8	-	-
	Surface flow rate (cm s^{-1})	0.1	10	4.1	2.9	10
	Temperature (ºC) at 20 cm depth	29.2	31.0	30.4	30.3	30.8

vegetation were not monitored. Moreover, visible gas bubbles surfacing on canal waters (ebullition) was noticed at several locations during the data collections.

Results and discussion

Fluxes in settled canals at the two sites

Based on all flux readouts of the data, fluxes of each of the three GHG species were markedly higher at the Kampar site settled canals in comparison to the settled canal at the Kalimantan site (Table 2, Fig. 2). Mean fluxes for the settled canals at the two sites differed (p=0.025) for CO_2 and CH_4, and p= 0.028 for N_2O. Although substrate dynamics of organic matter on dry land and material transfer into canal system were not quantified in this study, settled canals at the two sites have likely been influenced by the organic substrates released from the surrounding peat, and also by live vegetation on the canal banks and in the water. It can be expected that peat substrates released into the canal from the surrounding land system

Table 2. Water surface diffusion flux characteristics of three GHG species at the Kalimantan and Kampar sites. The mean of four replicate chamber fluxes at each monitoring location are used in the calculation. Data for settled canals and disturbed canals for the Kampar site are separated.

Taulukko 2. Vesipinnan diffuusiokaasuvuo kolmelle kasvihuonekaasulle Kalimantanin ja Kamparin mittausalueilla. Laskennan perusteena on käytetty mittauspisteiden neljän rinnakkaisen kammion vuon keskiarvoa. Kamparin aineistossa on eritelty ruoppaamattomat ja ruopatut kanavat.

Site	GHG	Season	N	Min.	Max.	Mean	S.E.	S.D.
Kalimantan settled	CO_2 ($mg\ m^{-2}\ d^{-1}$)	dry	14	2568	22355	8386	1297	4853
		wet	11	1706	15716	9804	1354	4492
		all	25	1706	22355	9010	931	4656
	CH_4 ($mg\ m^{-2}\ d^{-1}$)	dry	13	3	1311	299	112	405
		wet	11	0	12	6	1	3
		all	24	0	1311	164	67	328
	N_2O ($\mu g\ m^{-2}\ d^{-1}$)	dry	14	–79	103	–1	16	60
		wet	11	–29	41	2	7	22
		all	25	–79	103	0	9	46
Kampar settled	CO_2 ($mg\ m^{-2}\ d^{-1}$)	dry	5	1874	22075	11810	3927	8781
		wet	8	5751	40034	19222	4583	12963
		all	13	1874	40034	16372	3256	11740
	CH_4 ($mg\ m^{-2}\ d^{-1}$)	dry	5	0	5076	1405	988	2209
		wet	8	15	4358	866	536	1515
		all	13	0	5076	1073	484	1744
	N_2O ($\mu g\ m^{-2}\ d^{-1}$)	dry	5	1034	22047	5397	4163	9309
		wet	8	99	4883	1152	560	1584
		all	13	99	22047	2785	1640	5914
Kampar disturbed	CO_2 ($mg\ m^{-2}\ d^{-1}$)	dry	4	9055	21345	13508	2774	5547
		wet	1	878	878	878	-	-
		all	5	878	21345	10982	3316	7415
	CH_4 ($mg\ m^{-2}\ d^{-1}$)	dry	4	3	389	111	93	187
		wet	1	3	3	3	-	-
		all	5	3	389	89	75	169
	N_2O ($\mu g\ m^{-2}\ d^{-1}$)	dry	4	66	3195	891	768	1537
		wet	1	190	190	190	-	-
		all	5	66	3195	751	611	1367

Note. Kampar disturbed canal wet season flux characteristics (mean ± S.D.) for the three GHG species in the replicate samples in the only monitoring location were; 979±994 mg CO_2 $m^{-2}\ d^{-1}$, 3.68±0.32 mg CH_4 $m^{-2}\ d^{-1}$, and 252±281 µg N_2O $m^{-2}\ d^{-1}$.

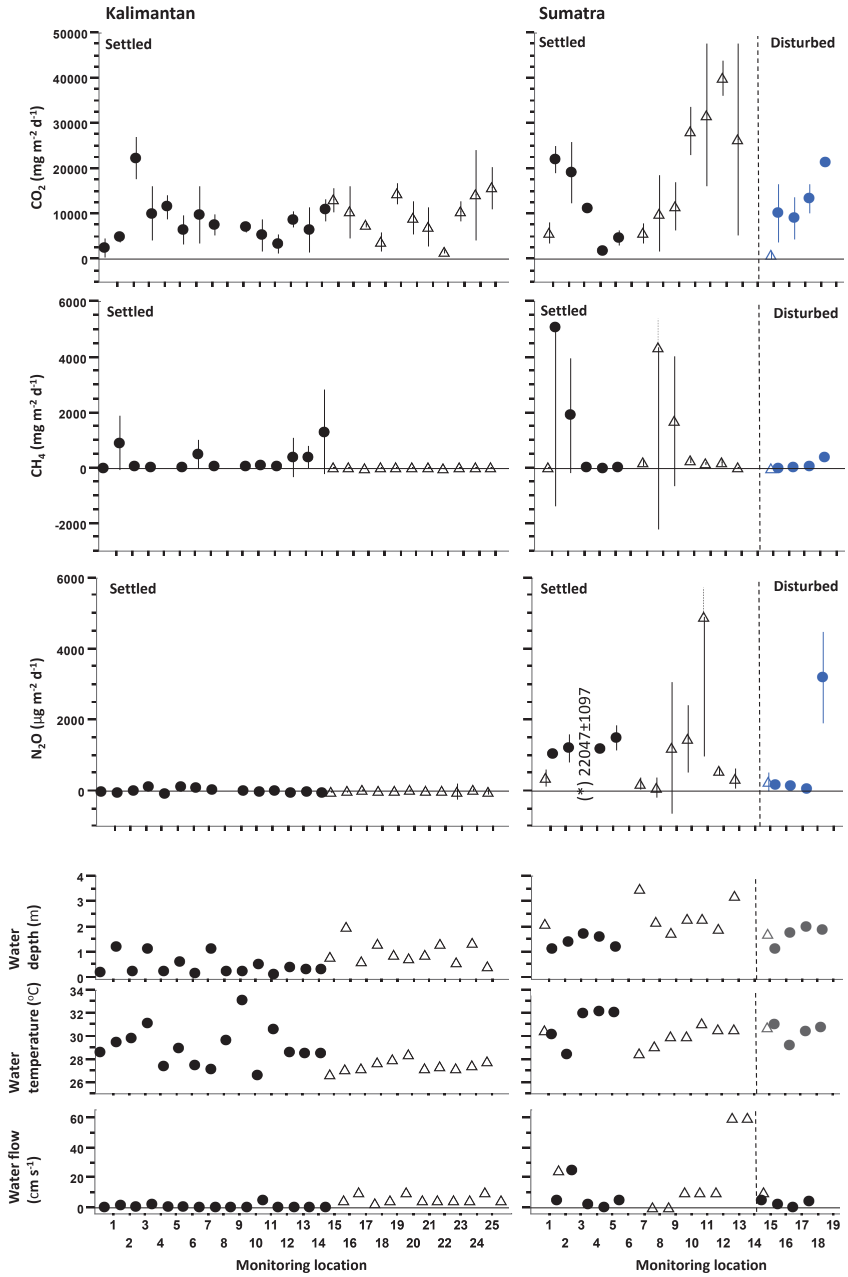

Figure 2. Mean (S.D.) fluxes for CO_2, CH_4 and N_2O at the Kalimantan canal (25 locations) and the Kampar canals (18 locations) for replicated samples at various canal water depths, temperature and flow rate conditions. Symbols separate daytime dry season fluxes (closed dots) in September 2007 and day time wet season fluxes (open triangles) in April 2008, and also settled and disturbed canals at the Sumatra site are separated. One large N_2O flux at Sumatra (monitoring location 4) is denoted by a number.

Kuva 2. Keskimääräinen CO_2, CH_4 and N_2O kanavien vuo (±keskihajonta) Kalimantanilla (25 paikkaa) ja Sumatralla (18 paikkaa) kolmelle rinnakkaiselle kammiolle kanavissa vallinneissa vedensyvyyden, lämpötilan ja virtausnopeuden olosuhteissa. Suljetut ympyrät ovat kuivan kauden ja avoimet kolmiot sadekauden arvoja. Sumatran ruopattujen kanavien arvot ovat numeroilla 15–18. Yksi N_2O emissio Sumatralla (mittauspaikka 4) on ilmaistu numeroarvolla.

at the Kalimantan site are poorer, i.e. relatively more recalcitrant, than the substrates released at the Kampar site. In addition, the Kampar site peatland had not been affected by fire and the land is usually covered with *Acacia* trees grown for rotations lasting about five years. Although the Kalimantan site area had been clear-felled and drained only a few years before the Kampar site, repeated fires had exposed its older recalcitrant peat by burning several decimeters off the peat surface and also largely by preventing growth of seedlings (Page et al. 2002, Langner & Siegert 2009). One consequence of the differing land use histories at these two sites is higher mean surface peat bulk density (0.15 g cm^{-3}; Jauhiainen et al. 2012b) in Kalimantan peatland area compared to the Kampar site (0.09 g cm^{-3}; Jauhiainen et al. 2012a). An indication of the poorer quality of surface peat substrates at the Kalimantan site was the lower mean respiratory CO_2 flux at barren peat surfaces (7200–14 400 mg m^{-2} d^{-1}, from Jauhiainen et al. 2008) compared to the Kampar peatland (~26 000 mg m^{-2} d^{-1}, Jauhiainen et al. 2012a) at comparable water table depth of 0.8 m. Mean wet season and also mean dry season canal CO_2 fluxes in the canal at the Kalimantan site (8400–9800 mg m^{-2} d^{-1}) and in the settled canals at the Kampar site (12 000–19 000 mg m^{-2} d^{-1}) had a lower range of fluxes compared to those found in their respective surrounding land areas. However, CH_4 and N_2O fluxes (especially effluxes) in settled canals were higher than fluxes in the surrounding land at these sites (Jauhiainen et al. 2012b, c).

The few existing tropical peatland studies on fluvial organic carbon only focused on substrate transfer into river systems and to the sea (Meyer 1986, Alkhatib et al. 2007, Bauma et al. 2007, Moore et al. 2011). However, detailed studies on the subject outside rivers or quantification of organic substrate origin are still to be made. Moore et al. (2011) studied the release of DOC and POC substrates from canals to same river system on the Central Kalimantan peat dome and they found DOC to contribute from 88 per cent to 94 per cent of the total organic carbon concentration in the river water. The observation by those authors can be interpreted as the POC transport from degraded peatland to canals as being minor compared to DOC and fine particle (≤ 0.45µm) carbon forms. However, it is possible that the more coarse POC substrates form silt on the canal floor or become largely decomposed into smaller size particles before entering the river system.

Fixed carbon sources include peat and recalcitrant carbon materials. Renewable carbon sources include litter released from vegetation in the canal water and that which grows on the canal banks. In general, both these carbon sources are considered important in feeding substrates into aquatic systems (Fearnside & Pueyo 2012). Therefore vegetation, i.e. trees, ferns and sedges on the canal banks and in the settled canals, form a likely and important litter source for decomposers in the canals. In the settled canal system, vegetation on the canal banks provide sources of cellulose and hemicellulose substrates for anaerobic and aerobic decomposition processes. Carbon substrate contributions from vegetation were not quantified in this study.

GHG fluxes during dry and wet seasons in settled canals

GHG fluxes were tested for differences between dry season and wet season in the data collected from settled canal systems. The only significant difference at the Kalimantan site was in the mean CH_4 flux, which was clearly higher ($p=0.026$, $n=23$, $F=5.704$, $df=1$) during the dry season (299±112 mg m^{-2} d^{-1} than during the wet season (6±1 mg m^{-2} d^{-1}). The dry season mean water flow rate (0.9 m s^{-1}) at the Kalimantan site was 14.5% of the rate (6.2 m s^{-1}) during the wet season. Oxygen may have become depleted from the relatively shallow non-turbulent water which would lead to reduced CH_4 oxidation, i.e. an increase in CH_4 release (Table 1). During the wet season water depth and flow rates in the canal were higher, and CH_4 oxidation is more likely to be increased in the more turbulent waters.

The Kampar site settled canal GHG fluxes did not differ markedly between samples collected both during the dry and the wet seasons. Mean CH_4 and N_2O fluxes in the settled canals at the Kampar site were higher for the dry season in comparison to the wet season, but this was largely due to some high individual fluxes obtained from some monitoring locations (Table 2, Fig. 2). The seasonal flux dynamics were the opposite for CO_2 whereby the wet season flux mean and also most of the flux readouts were higher though not statistically significant during the wet season than for the dry season (Table 2, Fig. 2). The seasonal differences in the CO_2 fluxes may be related to hydrology events in the managed canal system, even though no obvious explanation to these differences is available within this study. Water management practices at the plantation aim at maintaining stable water levels close to the *Acacia* roots and thus the water flow is partly artificial. Water outflow from the surrounding land into the canals is less likely during the dry season due to lower precipitation. It may be the case that canal CO_2 fluxes during the wet season increase because CO_2 is constantly flushed from *Acacia* rooting zone in land areas into the canal. In follow-up studies possible seasonal gas transfer in waters moving between the canal and draining land should be monitored.

Dry season GHG fluxes in the two canal types at Kampar

Dry season mean GHG fluxes were compared in settled and disturbed canal types at the Kampar site. The small amount of data available from the wet season monitoring at the disturbed canals limited the possibility for statistically robust wet season data comparisons between the two seasons to be made. Mean dry season CO_2 fluxes in settled and disturbed canals were similar to (Table 2, Fig. 2). Although the mean CH_4 and N_2O fluxes during the dry season were lower in the disturbed canals than in the settled canals, the differences were not statistically significant due to the high variations in the flux data measured (Table 2, Fig. 2). Prior to gas sampling, operational canal cleaning of disturbed canals had agitated the canal floor and may have degassed much of the CH_4 and N_2O storage, which would have resulted in lower flux rates (Table 2).

Variation in GHG fluxes

Flux data interpretation based on the monitored hydrological parameters is restricted by the complexity of the monitored canal water characteristics. These variations can be caused by water depth, temperature and flow rate in comparison to the variation in the flux rates at each monitoring location (Table 1, Fig. 2). CO_2 fluxes always have some deviation around the mean values in each monitoring location. CH_4 and N_2O fluxes were typically close to zero with only modest deviation, but at some monitoring locations both the mean and the deviations around the mean for CH_4 and N_2O fluxes ere high (Fig. 2). Variations in the settled canal GHG fluxes were clearly higher at the Kampar site in comparison to variations in the Kalimantan site canal. This difference may be caused by differences between the 18 different canals and few monitoring locations at the Kampar site compared to only one canal with 25 monitoring locations at Kalimantan site (Table 2, Fig. 2). Upstream activities at actively managed plantation canal systems may also influence water quality and gas fluxes at downstream locations. Sampled canal section surrounding the Kalimantan peatland was quite invariable, and the canal waters and GHG fluxes in it might have been influenced by seasonal precipitation differences which have major influences on water quality and water flow rates between wet seasons and dry seasons (Jauhiainen et al. 2008, Moore et al. 2011).

Annual GHG fluxes

CO_2 equivalent fluxes (CO_{2e}) calculated on an annual basis show that CO_2 was the most important GHG species at the Kalimantan site because it accounted for 69% of the total emissions (4800 g CO_{2e} m^{-2} y^{-1}), whereas the remaining 31% was attributed to CH_4 emissions (Table 3). At the Kampar site, the annual emission from the proportioned two canal types was 14 000 g CO_{2e} m^{-2} y^{-1}, where 40% of the total could be attributed to CO_2, 58% to CH_4 and 2% to the N_2O, respectively (Table 3). When comparing the two canal types at the Kampar site, the most important GHG species that contributed to the annual total emissions were CH_4 in the settled canals at 61% and CO_2 in the disturbed canals at 82%. N_2O had only a minor role (0–2% of the total fluxes) at these studied sites. The surrounding land area of the monitoring canal at the Kalimantan canal site had cumulative total emissions of 2900 g CO_{2e} m^{-2} y^{-1}, where CO_2 accounted for 98.5%, CH_4 0.2%, and N_2O 1.3% of the total (Jauhiainen et al. 2008, 2012b). The annual daytime heterotrophic emission as CO_{2e} at the Kampar site land area was 9400 g CO_{2e} m^{-2} y^{-1}, and the contributions to the total were 93.3% from CO_2 , 0.3% from CH_4 and 6.4% from N_2O (Jauhiainen et al. 2012a, c). Annual CO_{2e} fluxes at the Kalimantan site were 68% higher than that in the surrounding drained area per square unit area. The corresponding comparison for canals in the Kampar site was 47% higher. Total GHG emissions in the canal systems can thus differ substantially from emissions from the surrounding peatland areas, and in this study CH_4 made a considerable contribution to the total CO_{2e} emission value.

For development of data quality

Detailed GHG flux data requires close and detailed gas flux and environmental parameter monitoring throughout the year in order to separate possible diurnal or seasonal flux characteristics from the specific monitoring location dependent characteristics. This study did not take into account GHG ebullition emissions or GHG storage in the water or emissions through vegetation in the canals. These sources should also be included in a complete canal system estimate because ebullition was visible in settled canal systems at both sites and also sedge communities occupied over 50% of the canal floor surface area at the Kalimantan site. Deep rooting sedges and other plants that populate waterlogged peatland have been found to play an important role in releasing CH_4 into the atmosphere from temperate and boreal peatlands (Frenzel & Rudolph 1998, Saarnio & Silvola 1999, Strack et al. 2006). The gas storage in canal water occurs within the peatland areas and are usually released into the atmosphere inside the area or immediately after passing outlets, and thus it creates a GHG component within the area. In order to obtain a more complete presentation on spot level canal GHG dynamics, the origin of organic carbon and nitrogen substrates would have to be quantified, i.e. vegetation litter input, POC and DOC inputs from monitored canal surrounding land, and substrates transported with waters coming from upstream.

Table 3. Cumulative annual (365 d) CO_2, CH_4 and N_2O fluxes as CO_2 equivalents (mg CO_{2e} m^{-2} y^{-1}), cumulative total emission of the three GHG species, and relative contributions of each GHG species to the total. Estimate is based on flux data, which include both seasons in Table 2. Flux estimates for the three GHG species are also given by proportioning the measurements of the two canal types at the Kampar site.

Taulukko 3. Kumulatiivinen vuoden (365 päivää) CO_2, CH_4 ja N_2O vuo kanavissa CO_2 ekvivaletteina (CO_{2e}), yhteenlaskettu kolmen kaasun kumulatiivinen emissio, ja kunkin kaasun suhteellinen osuus kokonaisemissiosta. Sumatran kahdelle kanavatyypille on laskettu erikseen kokonaisemissio suhteutettuna kanavatyyppien osuuteen alueella. Lukujen lähtöarvot perustuvat taulukon 2 keskimääräisiin päivävuoarvoihin (sade- ja kuivakausiaineisto yhdistetty).

	Flux, g m^{-2} y^{-1} [Emission GWP contribution to the total, %]			
Site	CO_2	CH_4 as CO_{2e}	N_2O as CO_{2e}	Total CO_{2e}
Kalimantan settled	3289 [69]	1499 [31]	0.023 [0]	4788
Kampar settled	5976 [37]	9793 [61]	300 [2]	16069
Kampar disturbed	4008 [82]	814 [17]	81 [2]	4903
Kampar settled and disturbed proportionally	5582 [40]	7997 [58]	256 [2]	13836

Note 1. Radiative forcing in 100 years perspective, i.e. CO_2 = 1 equivalent, CH_4 = 25 equivalent, N_2O = 298 equivalent (Solomon et al. 2007), applied in calculation of CO_{2e}.
Note 2. Proportion of Kampar canal type coverage is set to 80% for settled canals and 20% for disturbed canals for the total area.

Conclusions

GHG fluxes in tropical peatland canal systems were found to differ from those at the surrounding peatland areas, and the unit area rates and the total emissions were generally higher in the canals. The contribution of each GHG species to the cumulative equivalent flux in the canals was also more varied than that of the land areas, where CO_2 is the dominant GHG species. GHG dynamics in the canal system is influenced by the peat quality of the surrounding land areas through substrates transferred into water. Although it was not quantified in this study, carbon released from the vegetation growing within the canal or on the canal banks may form an important carbon source and its contribution to the fluxes should be quantified when canal carbon balance are estimated in the future. Water volume and the flow rate can differ seasonally and man-made disturbances may change the flux considerably in the canal system.

Acknowledgements

We thank the SBMSP and TROPEASS projects for financial support.

References

Alkhatib, M., Jennerjahn, T. C. & Samiaji, J. 2007. Biogeochemistry of the Dumai River estuary, Sumatra, Indonesia, a tropical blackwater river. Limnology and Oceanography 52: 2410–2417.

Bauma, A., Rixena, T. & Samiajib, J. 2007. Relevance of peat draining rivers in central Sumatra for the riverine input of dissolved organic carbon into the ocean. Estuarine, Coastal and Shelf Science 73(3–4): 563–570.

Couwenberg, J., Dommain, R. & Joosten, H. 2010. Greenhouse gas fluxes from tropical peatlands in south-east Asia. Global Change Biology 16: 1715–1732.

Fearnside, M. & Pueyo, S. 2012. Greenhouse-gas emissions from tropical dams. Nature Climate Change 2: 382–384.

Frenzel, P. & Rudolph, J. 1998. Methane emission from a wetland plant: the role of CH_4 oxidation in *Eriophorum*. Plant and Soil 202: 27–32.

Furukawa, Y., Inubushi, K., Ali, M., Itang, A. M. & Tsuruta, H. 2005. Effect of changing groundwater levels caused by land-use changes on greenhouse gas emissions from tropical peatlands. Nutrient Cycling in Agroecosystems 71: 81–91.

Hadi, A., Haridi, M., Inubushi, K., Purnomo, E., Razie, F. & Tsuruta, H. 2001. Effects of land-use change on tropical peat soil on the microbial population and emission of greenhouse gases. Microbes and Environments,16: 79–86.

Hergoualc'h, K. & Verchot, V. 2011. Stocks and fluxes of carbon associated with land use change in Southeast Asian tropical peatlands: A review. Global Biogeochemical Cycles 25: GB2001, doi:10.1029/2009GB003718.

Hooijer, A., Page, S., Canadell, J.G., Silvius, M., Kwadijk, J., Wösten, H. & Jauhiainen, J. 2010. Current and future CO_2 emissions from drained peatlands in Southeast Asia. Biogeosciences 7: 1505–1514.

Inubushi, K., Furukawa, Y., Hadi, A., Purnomo, E. & Tsuruta, H. 2003. Seasonal changes of CO_2, CH_4 and N_2O fluxes in relation to land-use change in tropical peatlands located in coastal area of South Kalimantan. Chemosphere 52(3): 603–608.

Jauhiainen, J., Limin, S., Silvennoinen, H. & Vasander, H. 2008. Carbon dioxide and methane fluxes in drainage affected tropical peat before and after hydrological restoration. Ecology 89: 3503–3514.

Jauhiainen, J., Hooijer, A. & Page, S. E. 2012a. Carbon dioxide emissions from an Acacia plantation on peatland in Sumatra, Indonesia. Biogeosciences 9: 1053–1071.

Jauhiainen, J., Silvennoinen, H., Hämäläinen, R., Kusin, K., Limin, S., Raison, R. J. & Vasander, H. 2012b. Nitrous oxide fluxes from tropical peat with different disturbance history and management. Biogeosciences 9: 1337–1350.

Jauhiainen, J., Hooijer, A. & Page, S. E. 2012c. Greenhouse gas emissions from a plantation on thick tropical peat. Proceedings of the 14^{th} International Peat Congress, Peatlands in balance, Stockholm 3–8. 6. 2012, IX tropical peatlands, 3 Social and economic uses of

tropical peatlands, extended abstract No. 220.
Jauhiainen, J., Takahashi, H., Heikkinen, J. E. P., Martikainen, P. J. & Vasander, H. 2005. Carbon fluxes from a tropical peat swamp forest floor. Global Change Biology 11: 1788–1797.
Langner, A. & Siegert, F. 2009. Spatiotemporal fire occurrence in Borneo over a period of 10 years. Global Change Biology 15: 48–62.
Melling, L., Hatano, R. & Goh, K. J. 2005. Soil CO_2 flux from three ecosystems in tropical peatland of Sarawak, Malaysia. Tellus 57B: 1–11.
Meyer, J. L. 1986. Dissolved organic carbon dynamics in two subtropical blackwater rivers. Archiv für Hydrobiologie 108: 119–134.
Miettinen, J. & Liew, S. C. 2010. Degradation and development of peatlands in peninsular Malaysia and in the islands of Sumatra and Borneo. Land Degradantion and Development 21: 285–296.
Moore, S., Gauci, V., Evans, C. D. & Page, S. E. 2011. Fluvial organic carbon losses from a Bornean blackwater river. Biogeosciences 8: 901–909.
Murdiyarso, D., Hergoualc'h, K. & Verchot, L. V. 2010. Opportunities for reducing greenhouse gas emissions in tropical peatlands, PNAS 107(46): 19655–19660.
Page, S. E., Rieley, J. O. & Banks, C. J. 2011. Global and regional importance of the tropical peatland carbon pool. Global Change Biology 17: 798–818.
Page, S. E., Siegert, F., Rieley, J. O., Boehm, H. D. V., Jaya, A., & Limin, S. 2002. The amount of carbon released from peat and forest fires in Indonesia during 1997. Nature 420: 61–65.
Saarnio, S. & Silvola, J. 1999. Effects of increased CO_2 and N on CH_4 efflux from a boreal mire: a growth chamber experiment. Oecologia 119: 349–356.
Solomon, S., Quin, D., Manning, M., Marquis, M., Averyt, K., Tignor, M. M. B. Miller, H. L.-R., Chen, Z. (eds) 2007. Climate Change 2007. The Physical Science Basis – Summary for Policymakers, Contribution of working group I to the fourth assessment report of the IPCC Cambridge University Press, Cambridge, 18 pp.
Strack, M., Waller, M . F. & Waddington, J. M. 2006. Sedge succession and peatland methane dynamics: A Potential Feedback to Climate Change. Ecosystems 9: 278–287.

Tiivistelmä: Kasvihuonekaasujen diffuusio kuivatuskanavissa trooppisilla soilla

Trooppisten soiden vesipintojen ja ilmakehän välinen kasvihuonekaasujen dynamiikka on saanut varsin vähän huomiota, eikä kuivatettujen turvemaiden kuivatuskanavien kasvihuonekaasujen päästöistä ole julkaistua tietoa. Tässä tutkimuksessa seurattiin kuivatuskanavien vedenpinnan ja ilmakehän välistä hiilidioksidin (CO_2), metaanin (CH_4) ja dityppioksidin (N_2O) kaasudiffuusiota trooppisilla turvemailla kahdessa kanavajärjestelmässä sade- ja kuivakausien aikana.

Ensimmäinen mittauspaikka oli teollisessa mittakaavassa sellupuuta tuottavan akaasiaplantaasin kanavajärjestelmä Kamparin niemimaalla (Sumatra), ja toinen mittauspaikka oli kanava hylätyllä kuivatusalueella Kalimantanilla (Borneo) Indonesiassa. Plantaasilla kasvihuonekaasuja mitattiin sekä ruoppaamattomissa kanavissa (akaasiapuiden kasvuvaiheessa), että puuston korjuun vuoksi vastikään ruopatuissa kanavissa. Plantaasialue oli raivattu suosademetsästä ja kuivatettu alle kymmenen vuotta ennen mittauksia. Turvetta ei maankäyttömuutoksen yhteydessä ollut poltettu, ja kanavien vedenpinta oli säädelty. Hylätty suoalue oli raivattu ja kuivatettu noin 15 vuotta ennen mittauksia, alueen turpeen pinta oli palanut useaan otteeseen, kasvillisuus oli sanikkaisvaltaista, ja alueen kanavien vedenpinta ja virtaukset vaihtelivat ympäröivän turvemaan hydrologian mukaan kuiva- ja sadekausina.

Tulokset osoittivat kanavien kaasudynamiikan olevan yhteydessä ympäröivän alueen turpeen ominaisuuksiin, kanavien reunamien kasvillisuuteen, veden virtaamiin sekä kanavien käyttöön. Keskimääräiset kaasuvuot kanavissa olivat plantaasilla ja hylätyllä turvemaalla 9–16g CO_2 m^{-2} d^{-1}, 0.1–1.1g CH_4 m^{-2} d^{-1} ja 0–0.003 g N_2O m^{-2} d^{-1}. Kolmen kaasun kumulatiiviset kaasuvuot (hiilidioksidiekvivalentteina) olivat lähes kolme kertaa suurempia plantaasin ruoppaamattomissa kanavissa (13.8 kg CO_{2e} m^{-2} y^{-1}) Kamparilla kuin ruoppaamattomassa kanavassa Kalimantanilla (4.8 kg CO_{2e} m^{-2} y^{-1}). Plantaasilla kanavien keskimääräiset kolmen kaasun kaasuvuot sekä niiden yhteenlaskettu kumulatiivinen vuo olivat suuremmat ruoppaamattomissa kanavissa puiden kasvatusalueilla kuin ruopatuissa kanavissa. Erityisesti N_2O ja CH_4 kaasujen vuot olivat pienempiä ruopatuissa kuin ruoppaamattomissa kanavissa.

CO_2 muodosti tärkeimmän kumulatiivisen diffuusiokaasulähteen CO_2-ekvivalenttina (CO_{2e}) muodostaen kolmen kaasun päästöistä 69 % hylätyn suoalueen kanavassa ja 82 % plantaasin ruopatuissa kanavissa, kun taas CH_4 muodosti 61 % plantaasin ruoppaamattomien kanavien päästöstä. Kalimantanin hylätyllä kuivatusalueella metaanin osuus kumulatiivisista kokonaispäästöistä oli 31 %. N_2O:lla havaittiin olevan vähäinen osuus (0–2 %) kumulatiivisiin kokonaispäästöihin tutkituissa kanavissa. Yksikköalaa kohti arvioituna kanavien kasvihuonekaasupäästöt olivat suuruusluokaltaan vastaavia tai jopa korkeampia kuin ympäröivän suoalueen turvepintojen vuot. Kolmen mitatun kaasun suhteelliset osuudet kumulatiivisina päästöinä arvioituna vaihtelivat enemmän kanavissa kuin ympäröivillä kuivatetuilla suoalueilla.

Received 11.6.2012; Accepted 12.11.2012