Methane emissions from peat soils

(organic soils, histosols)

Facts, MRV-ability, emission factors

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John Couwenberg, Greifswald University
Wetlands International, Ede, August 2009
www.wetlands.org
Produced for the UN-FCCC meetings in Bonn, August 2009.

Summary

Huge reductions of carbon dioxide (CO_2) and nitrous oxide (N_2O) emissions can be attained by rewetting drained peatlands. A post-2012 framework aiming at peatland rewetting must, however, also address associated methane (CH_4) emissions.

The scientific data base for methane (CH_4) emissions from peatland is much larger than that for CO_2 or N_2O. The data show that, once anaerobic conditions are given, the availability of fresh plant material is the major factor in methane production. Old (recalcitrant) peat plays only a subordinate role.

The annual mean water level is a surprisingly good indicator for methane emissions, but at high water levels the cover of aerenchymous shunts (gas conductive plant tissue) becomes a better proxy. Ideally, both water level and cover of aerenchymous shunts should be assessed to arrive at robust estimates for methane emissions.

The available data provide sufficient guidance for arriving at consistent Tier 1 methodologies as presented in this report. For higher Tier approaches, vegetation provides a promising basis for development of more detailed emission factors. Vegetation is a strong indicator for mean water levels and can provide – with extra attention for aerenchymous shunts – a robust proxy for accurate and spatially explicit estimates of methane emissions over large areas.

Introduction

Drainage of peat soils results in carbon dioxide (CO_2) and nitrous oxide (N_2O) emissions of globally 2-3 Gt CO_2-eq per year (Joosten & Couwenberg 2009), a volume that should urgently be addressed in a post-2012 climate framework. Many of these emissions can be avoided by peatland rewetting and restoration (Trumper *et al.* 2009).

Rewetting of peatlands suppresses aerobic CO_2 and N_2O emissions but also leads to increased methane (CH_4) emissions. Some parties to the UNFCCC are hesitant to include peatland rewetting as an activity in a UNFCCC and Kyoto post-2012 framework because conclusive IPCC guidance is lacking and the availability of data on CH_4 emissions from peatlands assumed to be limited.

Reporting of methane emissions under the UNFCCC is not new. The IPCC (2006) guidelines on reporting emissions from croplands (Vol. 4, Ch. 5) provides a detailed Tier 1 approach for assessing methane emissions from rice cultivation. Methane emission factors are provided in Vol. 4, Ch. 2 for biomass burning based on a review by Andrea & Merlet (2001). Vol. 4, Ch. 10 gives detailed guidance on methane emissions from livestock and manure management. Also methane emissions from the waste sector are covered by the IPCC (2006) guidelines (Vol. 5). So there is no general reluctance to address methane.

The lack of IPCC guidance for CH_4 emissions from peatlands is easily explained: until now the development of peatland CH_4 emission factors has not been opportune. Pristine peatlands do produce methane but these emissions are not anthropogenic and thus irrelevant under the UNFCCC. On the other hand, land use on peat soils (for forest, cropland, grassland and peat extraction) has always involved peatland drainage resulting in negligible methane emissions (but substantial CO_2 and N_2O emissions). Rewettingof drained peatlands as climate mitigation measure presents a new challenge, however: addressing methane emissions.

Fortunately this task is not insuperable: the scientific data base for methane emissions from peatland is much larger than those for CO_2 or N_2O (for which IPCC default values are available, see Couwenberg 2009) and recently several high quality reviews on the subject have been published (Couwenberg *et al.* 2009, Lay 2009, Saarnio *et al.* 2009).

This report looks at methane emissions from wet peatlands, discusses the mechanisms behind these emissions, and presents tentative emission factors.

1. Rewetting of drained peatlands

In its fourth assessment report, IPCC (2007) estimated emissions from the land use sector (AFOLU, Agriculture, Forestry and Other Land Use) to amount to >30% of total anthropogenic greenhouse gas emissions. More than 25% of those were estimated to originate from peatland fires and degradation of drained peat soils. Peatland rewetting reduces fire risk as well as emissions from ongoing degradation of drained peat soils. Undrained peatlands are a natural source of methane (Aselmann & Crutzen 1989, Gorham 1991), however, and rewetting will reinstate methane emissions that then are of anthropogenic origin and thus must be reported and accounted.

2. Methane dynamics in peatlands

In peatlands decomposition of organic matter is incomplete and peat accumulates. Incomplete cycling and conservation of peat is caused by waterlogging with its associated low temperatures, anaerobic conditions and small microbial populations. Under anaerobic conditions microbial decomposition does continue, but such anaerobic degradation of organic material is slow. It is carried out stepwise by a complex foodweb of specialised micro-organisms, each producing specific intermediate substrates (Whalen 2005, Lai 2009). The final step in anaerobic decomposition is then performed by methanogenic *Archaea*, methane producing micro-organisms.
The actual amount of methane emitted to the atmosphere depends on the balance between methane production and consumption and the mode of methane transport.

methane production
Literature reviews (Segers 1998, Whalen 2005, Lai 2009) reveal that
- most methane in peat columns is derived from recently fixed (young) carbon,
- methane production decreases when labile substrates are depleted, for example with depth below the water table,
- methane production can be stimulated substantially with addition of intermediate substrates.

These observations lead to the conclusion that, once anaerobic conditions are given, the quality and supply of the substrate is the major factor in methane production. Substantial amounts of methane are only produced when labile carbon substrates are amply available and old (recalcitrant) peat plays only a subordinate role as a substrate for methane production (Chanton *et al.* 1995, Hornibrook *et al.* 1997, Charman *et al.* 1999, Clymo & Bryant 2008).
Large variation has been found in the temperature sensitivity of methane production (Segers 1998, Whalen 2005). Likely this is due to varying temperature response within the anaerobic foodweb (Whalen 2005). At temperatures below -5° C methane production is consistently low.
While most methanogenic Archaea grow only under a narrow pH range between 6 and 8, some are known to occur under more acid conditions as well (Garcia *et al.* 2000, Whalen 2005, Lai 2009). Quantitative assessments of the effect of pH on methanogenesis arrive at inconsistent results (Whalen 2005).

methane consumption
Only part of the methane produced is emitted to the atmosphere. Considerable amounts are consumed by methanotrophic bacteria (Hanson & Hanson 1996; Segers 1998). The re-oxidation of methane is mainly confined to the zone close to the water table, where neither the supply of oxygen nor of methane is limited. Similarly, methane consumption occurs in the oxygenated zone surrounding plant roots (Fig. 1). The potential for methane oxidation by methanotrophics is typically an order of magnitude larger than the potential for methane production by methanogens (Segers 1998). As a result, methanotrophic bacteria can limit the amount of methane that is released to the atmosphere substantially.
Data and insight on the influence of temperature and pH on methanotrophs are still incomplete and dependencies uncertain (Whalen 2005).

methane transport
Methane gas is emitted from the peat to the atmosphere via three main pathways: diffusion, ebullition and plant mediated transport (Fig 1).
Diffusion of methane is slow and overall, diffusive efflux from peatlands is small compared to the other two pathways (Kiene 1991, Lai 2009). Methane diffusion does play an important role in providing the methanotrophic community in the aerobic near-surface zone with methane from the anaerobic zone below (Whalen 2005).

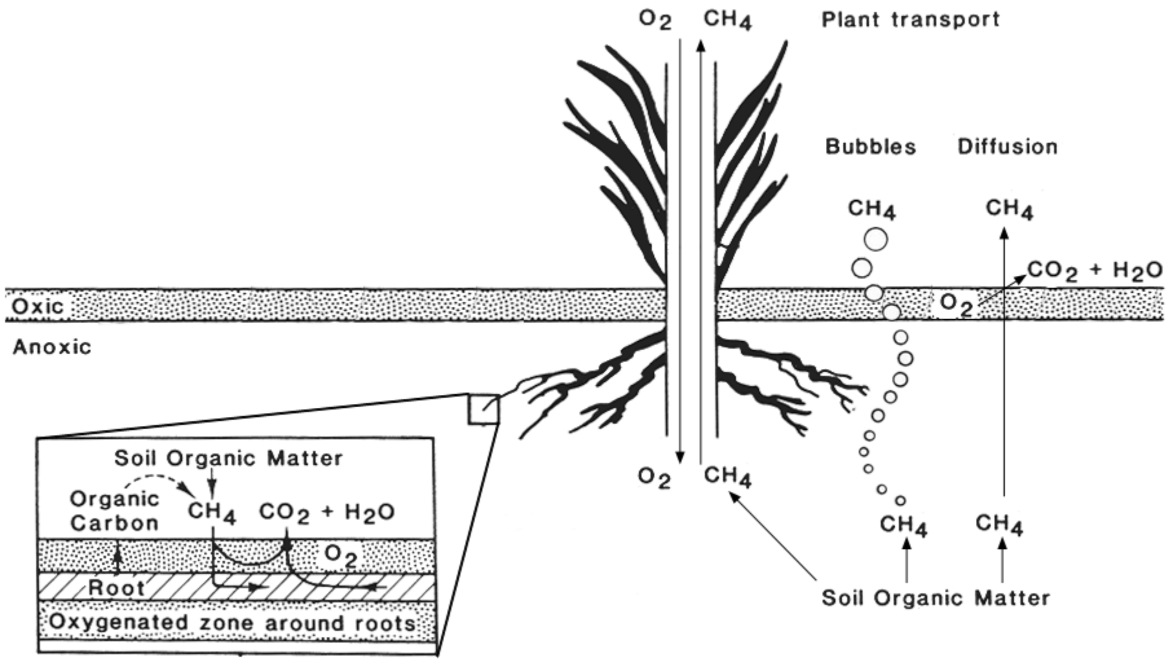

Fig. 1. Production, re-oxidation and emission of CH_4 from a vegetated peatland site (after Kiene 1991, see also Whalen 2005, Lai 2009, Li *et al.* 2009).

Ebullition refers to methane released to the atmosphere in form of bubbles. Methane bubbles commonly occur in water saturated peat layers, where they remain trapped and grow in size. When a certain threshold pressure is reached, a sudden release of the trapped methane occurs (Kellner *et al.* 2004). Often this release is associated with changes in water level (Strack *et al.* 2005), barometric pressure (Kellner *et al.* 2004, Tokida *et al.* 2007b, Comas *et al.* 2008) and temperature (Beckmann *et al.* 2004) as well as mechanical disturbance (Fechner-Levy & Hemond 1996). Ebullition events are also observed during spring thaw when methane trapped under ice is released to the atmosphere (Moore & Knowles 1990, Hargreaves *et al.* 2001, Tokida *et al.* 2007a). The rapid transfer of methane bubbles through the aerobic near surface layer means there will be little or no consumption by methanotrophs.

Diffuse ebullition can be measured using the eddy covariance technique or even closed chambers of sufficient size. Their localised extent and episodic nature make *large* ebullition events hard to detect by closed chamber measurements (Glaser *et al.* 2004, Comas *et al.* 2007, Denmead 2008), however, and also the eddy covariance technique may not be suitable for measuring these emissions (Tokida *et al.* 2007b). Quantification is therefore difficult. Glaser *et al.* (2004) use surface deformations to calculate a total flux of 136 g CH_4 m^{-2} from three large degassing events during a summer drought that exceeds remaining annual fluxes by an order of magnitude. The role of these large ebullition events in rewetted peat sites needs further research and quantification.

Many wetland plants possess aerenchymous tissue (Fig. 2) that allows for transport of oxygen into the root zone as an adaptation to rooting in waterlogged soils. Whereas this oxygen allows for oxidation of methane in the root zone (Chanton *et al.* 1992), at the same time methane is transported through the aerenchyma out into the atmosphere, bypassing the aerobic zone (Fig. 1; see Whalen 2005 for a review). Plant species displaying this alternative methane emission pathway, or shunt, are referred to as ‘chimney’ or ‘shunt species’. This ‘shunt flow’ occurs both as diffusive flux as well as through much more effective pressure driven internal gas flow from younger leafs through the aerenchyma down to the rhizomes and then back out to the atmosphere through the older leaves (Brix *et al.* 1992).

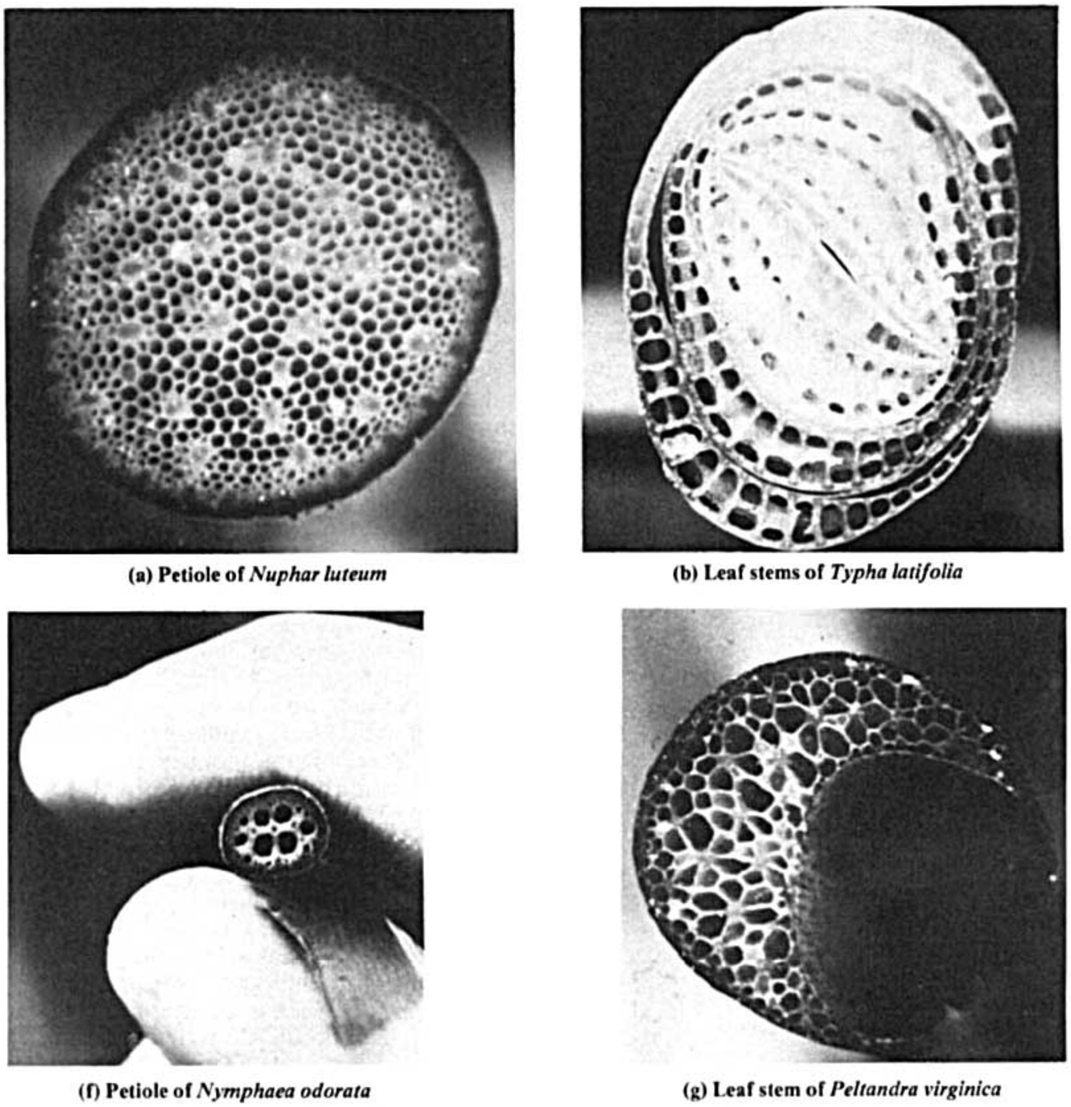

Fig. 2. Stem cross-sections of aquatic plants showing coarse aerenchymous tissue that allows for methane transport from the anaerobic root zone directly into the atmosphere (from Sebacher *et al.* 1985)

The contribution of shunt species to overall methane emissions can be assessed using various experimental set-ups and has been estimated at 25-97% (see Whalen 2005 for a review). Plants acting as shunts in methane emission include for example *Nymphaea*, *Nuphar*, *Calla*, *Peltandra*, *Sagittaria*, *Cladium*, *Glyceria*, *Scirpus*, *Eleocharis*, *Eriophorum*, *Carex*, *Scheuchzeria*, *Phragmites* and *Typha* (Sebacher *et al.* 1985, Chanton *et al.* 1992, Schimel 1995, Shannon *et al.* 1996, Frenzel & Rudolph 1998, Verville *et al.* 1998, Yavitt & Knapp 1998, Grünfeld & Brix 1999, Frenzel & Karofeld 2000, Greenup *et al.* 2000, Arkebauer *et al.* 2001). In addition, methane emission through pneumatophores and prop roots has been observed (Purvaja *et al.* 2004, Kreuzwieser *et al.* 2003, Pulliam 1992) as well as through aerenchyma of Alder trees, albeit only as slower diffusive flux (Rusch & Rennenberg 1998). The relative effectiveness of different plant species in transporting methane through their aerenchyma needs further study.

3. Annual methane emissions

Whereas instantaneous methane emissions frequently show high variability in time and space (Whalen 2005), these fluctuations seem to be levelled out over larger areas and time spans. Measuring methane emissions using closed chambers is much more straightforward and much less cumbersome than measuring carbon dioxide emissions – only part of the available data was processed to produce Fig. 4. Yet, reverting to actual measurements to assess fluxes over large areas is impractical and proxies are needed (Joosten & Couwenberg 2009).

In order to estimate methane emissions on a large scale, easily assessable environmental parameters are required that possibly explain much of the variation between sites. While pH, C/N ratio, temperature and atmospheric pressure certainly affect production, consumption and transport of methane, dependencies and dynamics are complex and simple rules cannot be derived for situations in the field. On the other hand, water level and the absence/presence of shunt species are easily established also for larger areas (Joosten & Couwenberg 2009) and provide robust indicators for methane emissions (Fig. 3).

Methanogenic and methanotrophic micro-organisms in the peat soil are well adapted to adverse conditions and remain at the same depth below surface also when water levels fluctuate (Kettunen *et al.* 1999). At higher water levels the thickness of the methane production zone increases while the thickness of the methane oxidation zone decreases, and vice versa (Whalen 2005, Lai 2009). The overall result of this water level dependency and stress resistance of the microbial community is that the annual mean water level is a surprisingly good proxy for methane emissions (Fig. 3, 4).

Significant methane emissions occur only at mean annual water levels above -20 cm, a rule that applies to boreal as well as temperate peatlands and to bogs and fens alike (Fig 4). Water levels above the peat surface often result in lower methane emissions, because of enhanced methane consumption in the oxygenated water column (Fig 4, Bubier 1995) and lower cover of shunt species.

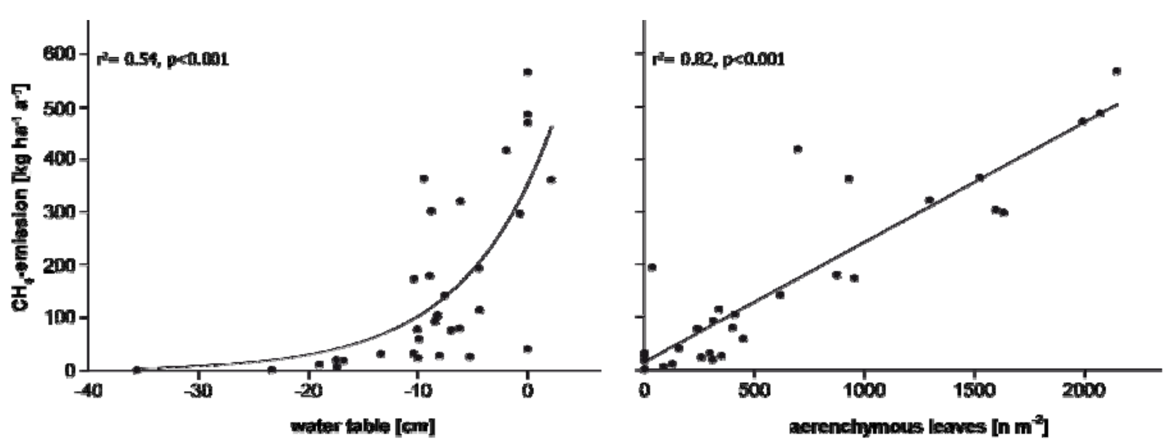

Fig. 3. Annual methane emissions from the Kendlmühlfilze (Germany) – a disturbed bog site under restoration – in relation to mean annual water level and density of aerenchymous leaves that act as shunts (or short cuts) for methane emission from the anaerobic zone directly to the atmosphere (after Drösler 2008).

The actual amount of methane that can be emitted to the atmosphere depends on the balance between methane production and consumption. As explained, this balance is determined by the water level. At high water levels, the ability to by-pass the high methane oxidation potential in the aerobic near surface layer seems more important, however. The cover of aerenchymous shunts is then a better proxy for emissions than the mean annual water level (Fig. 3). Ideally, both water level and cover of aerenchymous shunts should be assessed to arrive at robust estimates for methane emissions (Drösler 2008).

Mapping peatland waterlevels over large areas by direct measurements (and extrapolations) is expensive and time-consuming (and likely inaccurate). Instead, vegetation cover can be used as a good proxy for waterlevels that can be mapped using remote sensing (Joosten & Couwenberg 2009). Vegetation mapping can focus on the presence of aerenchymous shunts as well, thereby providing a robust basis for accurately estimating methane emissions over large areas.

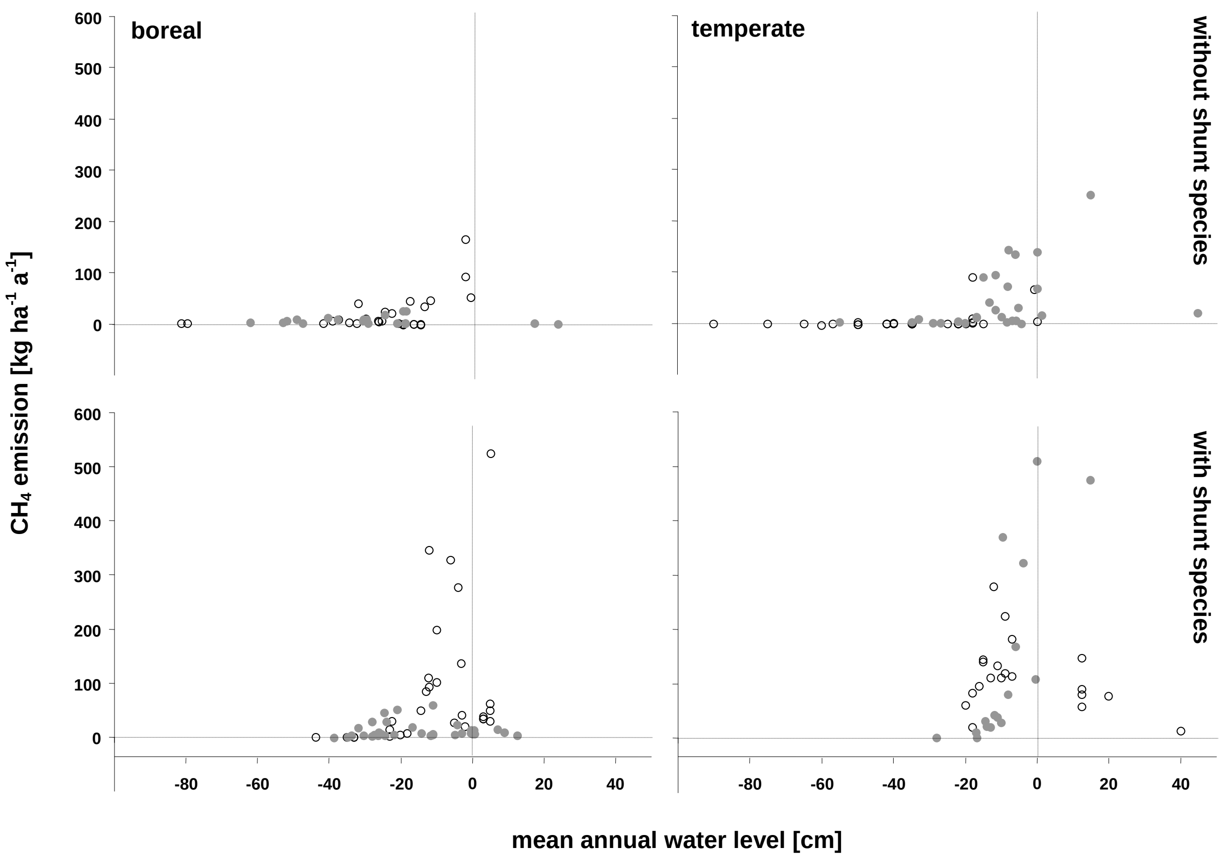

Fig. 4. Annual methane emissions from boreal (left) and temperate (right) raised bogs (●) and fens (○) in relation to water level and absence (top) or presence (bottom) of shunt species.
Data from Alm *et al.* 1997; Augustin & Merbach 1998; Augustin 2003; Augustin & Chojnicki 2008; Augustin *et al.* 1996a; Augustin *et al.* 1996b; Bortoluzzi *et al.* 2006; Bubier *et al.* 1993; Drösler 2005; Flessa *et al.* 1998; Gauci & Dise 2002; Hendriks et al 2007; Jacobs *et al.* 2003; Jungkunst & Fiedler 2007; Laine *et al.* 1996; Maljanen *et al.* 2004; Müller *et al.* 1997; Nykänen *et al.* 1995; Scottish Executive 2007; Shannon & White 1994; Sommer et al 2003; Tauchnitz et al 2008; Tuittila et al 2000; Van den Bos 2003; Van den Pol-Van Dasselaar et al 1997; Van den Pol-Van Dasselaar et al 1999; Van Huissteden et al 2006; Von Arnold 2004; Von Arnold *et al.* 2005a; Von Arnold *et al.* 2005b; Von Arnold *et al.* 2005c; Waddington & Roulet 2000; Whiting & Chanton 2001; Wickland *et al.* 2001; Wild *et al.* 2001.

For (sub)tropical peatlands data on annual methane emissions are still poor, but comparison of flux measurements from south-east Asia with those from temperate and boreal Europe reveals that fluxes are comparatively low (Fig. 5), which is likely due to the recalcitrance of tropical peats (Couwenberg *et al.* 2009). Emissions from rice paddies on tropical peat are high, but fall within the IPCC (2006) default range (Couwenberg 2009).

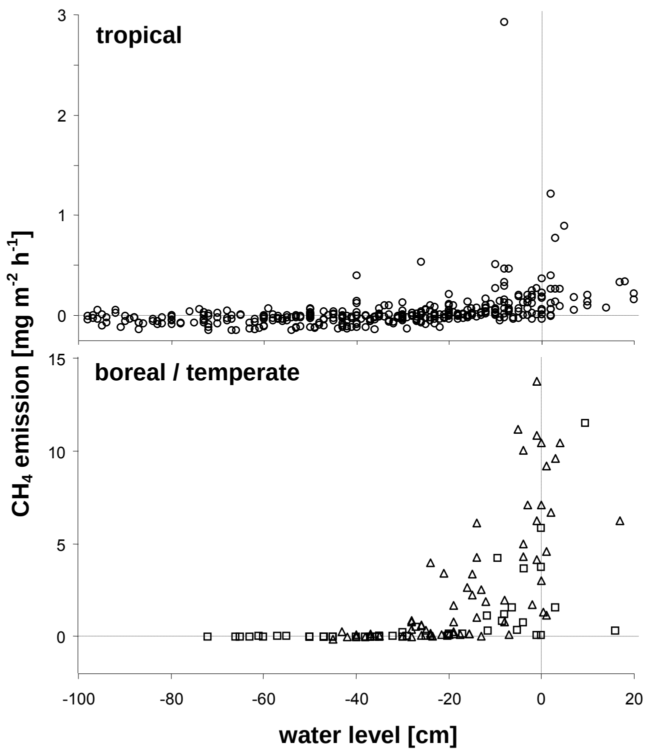

Fig. 5. Top: hourly methane fluxes from tropical peat soil in relation to water level. Negative values denote net uptake from the atmosphere by the soil. Bottom: same for (Δ) boreal and (□) temperate sites Note the fivefold difference in scale. (From Couwenberg *et al.* 2009.)

4. Emission factors

With respect to aerenchymous shunts, current published data only allows for distinguishing between their presence and absence (Fig 4), which nevertheless results in distinct emission classes (Fig. 4). In a Tier 1 approach, distinction can, for example, be restricted to 'dry' and 'wet' peatlands, where 'wet' means a mean annual water level of -20 cm or higher (Tab. 1).

Tab. 1. Emission factors for methane from peatlands following a first, simplified Tier 1 approach. 'Dry' means a mean annual water level below -20 cm, 'Wet' one above – 20 cm.

	kg CH_4 ha^{-1} a^{-1} mean (range)	
	Dry	Wet
Boreal	8.6 (-1.1 – 51)	56 (-1.7 – 525)
Temperate	0.2 (-4.0 – 9.0)	122 (-0.2 – 763)

In a more sophisticated approach, a differentiation can be made between generally nutrient poor, acidic raised bog peat and often more nutrient and base rich fen peat (cf. Joosten & Clarke 2002). The lower nutrient content and higher acidity of the bog peat would suggest lower methane production and emission (Lai 2009). This is indeed so for boreal peatlands and becomes most obvious when comparing bogs and fen with aerenchymous shunts (Fig. 4, Tab. 2). In temperate peatlands no differentiation between bogs and fens can be made on the basis of the available data (Fig. 4). Taking the presence/absence of shunt-species into account, Tab. 2 presents emission factors for methane on a more detailed level.

Tab. 2. Emission factors of methane from peatlands addressing climate, peatland type and vegetation. 'Dry' means a mean annual water level below -20 cm, 'Wet' one above – 20 cm.

		kg CH_4 ha^{-1} a^{-1} mean (range)		
		Dry	Wet	
			Without shunts	With shunts
Boreal	Bogs	8.6 (-1.1 – 51)	24 (-1.7 – 164)	12 (3.1 – 59)
	Fens			123 (6.6 – 525)
Temperate		0.2 (-4.0 – 9.0)	50 (-0.2 – 250)	170 (0 – 763)

Availability of comparable data for tropical peatlands is still limited. Current knowledge suggests emissions will be small after rewetting (Fig. 5, Couwenberg *et al.* 2009).

Rewetting of previously drained peat soils may lead to excessive initial methane emissions when vegetation is flooded and dies off to become substrate for methanogens (Augustin & Chojnicki 2008). On the longer run there will be a clear climate benefit from rewetting drained peatlands, however, even in case of such mishaps (Augustin & Chojnicki 2009), but certainly when cutover peatlands are concerned (Tuittila 2000; Wilson *et al.* 2008).

5. Conclusions

Huge reductions of CO_2 and N_2O emissions can be reached by rewetting drained peatlands. A post-2012 framework aiming at peatland rewetting must, however, also address the associated methane (CH_4) emissions. The IPCC does not provide conclusive guidance in this respect because CH_4 emissions were until now irrelevant (pristine peatlands) or non-existent (drained peatlands).

The scientific data base for methane emissions from peatland is much larger than that for CO_2 or N_2O. The data show that, once anaerobic conditions are given, the quality and supply of the organic material is the major factor in methane production. Substantial amounts of methane are only produced when fresh plant material is amply available. Old (recalcitrant) peat plays only a subordinate role.

Methane is emitted via three main pathways: diffusion, ebullition and plant mediated transport. Both the role of large ebullition events and the effectiveness of different plant species in transporting methane through their aerenchyma need further study.

Whereas methane emissions show high variability in time and space, these differences seem to be levelled out over larger areas and time spans. The annual mean water level is a surprisingly good proxy for methane emissions. At high water levels, the ability to by-pass the high methane oxidation potential in the aerobic near surface layer becomes more important and the cover of aerenchymous shunts becomes a better proxy for emissions than the mean annual water level. Ideally, both water level and cover of aerenchymous shunts should be assessed to arrive at robust estimates for methane emissions.

The available data and insight provide sufficient guidance for arriving at a consistent Tier 1 methodology. In a tentative Tier 1 approach, distinction is made only between 'dry' and 'wet' peatlands, where 'wet' means a mean annual water level of -20 cm or higher. In a more complex approach, additional differentiation can be made between sites with and without shunt species and – at least in the boreal zone – between nutrient poor, acidic (bogs) and more nutrient and base rich sites (fens).

For higher Tier approaches development of more detailed emission factors on the basis of vegetation looks promising. Vegetation is a strong indicator for mean water levels and can provide - with extra attention for aerenchymous shunts - a robust proxy for accurately and spatially explicitly estimating methane emissions over large areas (Joosten & Couwenberg 2009).

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Mission:

To sustain and restore wetlands, their resources and biodiversity for future generations.

HEADQUARTERS
PO Box 471
6700 AL Wageningen
The Netherlands
Tel.: +318-660910
Fax: + 31 318-660950
E-mail: post@wetlands.org
Website: http://www.wetlands.org

AFRICA

Senegal
Rue 111, Zone B, Villa N° 39B
BP 25 581 Dakar - Fann, Senegal
Tel.: +221 33 869 1681
Fax: +221 33 825 1292
E-mail: wetlands@orange.sn
Website: http://Afrique.wetlands.org

Mali
PO Box 97
Mopti/Sévaré, Mali
Tel.: +223 21 420 122, Fax: +223 21 420 242
E-mail: malipin@afribone.net.ml
Website: http://Afrique.wetlands.org

Guinea-Bissau
c/o Gabinete de Planificação Costeira (GPC)
(Coastal Planning Office)
CP 23, 1031 Bissau-Codex
Guinea-Bissau
Tel.: +245 20 12 30 / Mobile: +245 72 00 562
Fax: +245 20 11 68
E-mail: gpc@sol.gtelecom.gw /
joaosa2003@hotmail.com
Website: http://Afrique.wetlands.org

Kenya
ICIPE Campus, Kasarani Road
P.O. Box 3502-00100 Nairobi, Kenya
Tel.: +254 20 8562246
Fax: +254 20 8562259
E-mail: Oliver.Nasirwa@Birdlife.or.ke
Website: http://Afrique.wetlands.org

AMERICAS

Argentina
25 de Mayo 758 10 I (1002)
Buenos Aires, Argentina
Tel./Fax: +54 11 4312 0932
E-mail: deblanco@wamani.apc.org
Website: http://LAC.wetlands.org

Panama
Ramsar CREHO
City of Knowledge / Ciudad del Saber
House 131 A
Apdo. Postal 0816 - 03847 Zona 3
Panamá, Rep. de Panamá
Tel.: +507 317 1242
Fax: +507 317 0876
E-mail: julio.montesdeocalugo@wetlands.org
Website: http://LAC.wetlands.org

NORTH ASIA
Room 501, Grand Forest Hotel, No. 3A
Beisanhuan, Zhonglu Road
Beijing 100029, People's Republic of China
Tel.: +86 10 62058405/18 or 62377031
Fax: +86 10 620 77900
E-mail: ckl@wetwonder.org,
zxh@wetwonder.org
Website: http://www.wetwonder.org

Japan
6F NCC Ningyocho Building, 3-7-3 Ningyo-cho,
Nihonbashi, Chuo-ku, Tokyo 103-0013, Japan
Tel: +81 3 5332 3362, Fax: +81 3 5332 3364
E-mail: info@wi-japan.org
Website: http://www.wi-japan.org

OCEANIA

Canberra - Australia
PO Box 4573
Kingston ACT 2604
Australia
Tel.: +61 2 6260 8341, Fax: +61 2 6232 7727
E-mail : doug.watkins@wetlands-oceania.org
Website: http://oceania.wetlands.org

Brisbane - Australia
c/o Queensland Herbarium
Brisbane Botanic Gardens, Mt Coot-tha Road
Toowong, QLD 4066, Australia
Tel.: +61 7 3406 6047, Fax: +61 7 3896 9624
E-mail: roger.jaensch@wetlands-oceania.org
Website: http://oceania.wetlands.org

Fiji
PO Box S6, Superfresh, Tamavua, Suva, Fiji
Mobile: +679 9 255 425, Fax: +679 332 2413
E-mail: apjenkins@wetlands-oceania.org
Website: http://oceania.wetlands.org

SOUTHEAST ASIA

Indonesia
P.O.Box 254 / BOO
16002 Bogor, Indonesia
Tel.: +62 251 8312189
Fax: +62 251 8325755
E-mail: admin@wetlands.or.id
Website: http://www.wetlands.or.id

Project office in Southern Kalimantan
Jl. Menteng 25 No. 31
Palangka Raya 73112
Central Kalimantan, Indonesia
Tel.: +62- (0)536-38268
Fax: +62 (0)536-29058
E-mail: aluedohong@yahoo.com
Website: http://www.wetlands.or.id

Project office in Aceh
Jl. Persatuan 2 No 15, Desa Lambheu
Keutapang Dua, Banda Aceh, Indonesia
Tel.: +62 651 740 1981, Tel.: +62 811167027
Website: http://www.wetlands.id

Malaysia
3A39, Block A, Kelana Centre Point Jalan SS7/19
47301 Petaling Jaya, Selangor, Malaysia
Tel: +60 3 7804 6770, Fax: +60 3 7804 6772
E-mail: malaysia@wetlands.org.my
Website: http://malaysia.wetlands.org

Thailand
Prince of Songkla University
Faculty of Environmental Management
PO Box 95, Kor Hong Post Office
A. Hat Yai, Songkhla Province
90112 Thailand
Tel: +66 74 429307, Fax: +66 74 429307
E-mail: asae-s@psu.ac.th /
asaesayaka@yahoo.com

SOUTH ASIA

India
A-25, 2nd Floor
Defence Colony, New Delhi 110024, India
Tel.: +91 11 24338906, 32927908
Fax: +91 11 24338906
E-mail: wi.southasia@wi-sa.org
Website: http://south-asia.wetlands.org

EUROPE

Black Sea Region
PO Box 82, 01032 Kiev, Ukraine
Tel./Fax: +380 44 2465862
E-mail: kv@wetl.kiev.ua
Website: http://blacksearegion.wetlands.org

Russia
Postal address:
c/o WWF 232, FLIP-Post, Suite 25
176 Finchley Road
London NW3 6BT, United Kingdom
Visiting address:
Nikoloyamskaya Ulitsa, 19, Str. 3
Moscow 109240, Russia
Tel.: +7 495 7270939
Fax: +7 495 7270938
E-mail: oanisimova@wwf.ru
Website: http://russia.wetlands.org

France
Tour du Valat - Centre de recherche pour la conservation des zones humides méditerranéennes
Le Sambuc - 13 200 Arles, France
Tel.: +33 (0)4 90 97 20 13
Fax: +33 (0)4 90 97 20 19
E-mail: bossuet@tourduvalat.org
Website: www.tourduvalat.org

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www.wetlands.org