The effect of an exceptionally wet summer on methane effluxes from a 15-year re-wetted fen in north-east Germany

V. Huth, A. Günther, G. Jurasinski and S. Glatzel

Faculty of Agricultural and Environmental Sciences, University of Rostock, Germany

SUMMARY

Re-wetting minerotrophic fens has become an important strategy to mitigate climate change in Germany. However, recent studies report raised methane (CH_4) effluxes during the first years after flooding. A minerotrophic fen in north-east Germany that was re-wetted 15 years ago was exposed to exceptionally heavy rainfall and freshwater flooding in August 2011. We measured CH_4 effluxes from wetland vegetation stands dominated by *Phragmites australis* (Cav.) Trin. ex Steud., *Typha latifolia* L. and *Carex acutiformis* Ehrh., using the closed-chamber method, fortnightly from March 2011 to March 2012 with extra sampling during the flooding. The respective annual effluxes of CH_4 (mean ± 1 standard error) from the three vegetation types were 18.5 ± 1.3, 21.1 ± 1.2 and 47.5 ± 5.0 g m^{-2} a^{-1}, with the August effluxes contributing 40 %, 50 % and 10 % of the annual effluxes. Despite the freshwater flooding in August, annual CH_4 effluxes from the 15-year re-wetted fen are similar to those reported from pristine fens. These results are promising because they indicate that, although CH_4 effluxes are elevated after re-wetting, they may return to values typical for pristine fens after 15 years. Hence, re-wetting can achieve the purpose of reducing greenhouse gas effluxes from drained minerotrophic fens.

KEY WORDS: emergent macrophytes; freshwater flooding; heavy rainfall; peatland

INTRODUCTION

The greenhouse gas (GHG) methane (CH_4) is an important driver of anthropogenic radiative forcing (Forster *et al*. 2007). While agricultural activities have increased the global atmospheric CH_4 concentration during the last century, pristine peatlands are natural sources of CH_4 (Dise 1992, Melloh & Crill 1996). The reported climatic impact of pristine peatlands is a slight warming or a slight cooling depending on the balance of carbon (C) sequestration and CH_4 effluxes (Frolking *et al*. 2006). However, about 99 % of north-east Germany's fens had been intensively drained by 1990 (Gelbrecht *et al*. 2001). While natural peatlands are regarded as C sinks (Frolking *et al*. 2006), drainage has converted them into C sources owing to high carbon dioxide (CO_2) emissions (Couwenberg *et al*. 2011). Drained fens in north-east Germany have been re-wetted since the mid-1990s to restore their ecosystem functions including (primarily) the habitat function for rare biota and the C sequestration function as an important climate change mitigation strategy (Erwin 2009).

However, recent studies indicate that re-wetting of drained fens may cause large CH_4 effluxes if, as is common, the ecosystem is flooded (i.e. water table ranging above the ground surface), which counteracts the reduction of CO_2 and nitrous oxide (N_2O) effluxes (Augustin & Chojnicki 2008, Höper *et al*. 2008, Glatzel *et al*. 2011). Litter from dead and drowned vegetation has been identified as a source of increased CH_4 effluxes (Hahn-Schöfl *et al*. 2010). Assessment of the success of measures to mitigate GHG release depends on knowledge about the duration of these increased CH_4 effluxes after re-wetting. This assessment is complicated by differences in CH_4 effluxes among plant species (Chanton *et al*. 1993, Couwenberg & Fritz 2012) and intra-annual differences in precipitation with resulting fluctuations in ground water table.

The Trebel valley mire in north-east Germany is a complex of minerotrophic fens and one raised bog. The plant composition already reflects the altered hydrology caused by re-wetting 15 years ago. Since then, the average water table of the mire system has remained within the range 0–20 cm below ground surface (Bönsel & Sonneck 2011).

The exceptionally wet summer of 2011 gave us the opportunity to measure the effect on CH_4 effluxes of natural prolonged flooding with freshwater under high summer temperatures. The three types of vegetation available in the fen parts of the mire system were stands dominated by *Phragmites australis* (Cav.) Trin. ex Steud., *Typha latifolia* L. and *Carex acutiformis* Ehrh. As these vegetation stands are better adapted to inundation than the grassland communities of drained fens we hypothesise that, despite the summer flood, CH_4 effluxes from the 15-year re-wetted fen are similar to those reported for pristine fens in similar climate zones.

METHODS

Site description

The study site is in the Trebel valley mire system close to the town of Tribsees (54° 06′ N, 12° 44′ E; Figure 1), within a re-wetted area of more than 3000 ha. The climate is humid with a continental influence, mean annual (1991–2010) air temperature 9.1 °C and mean annual (1981–2010) precipitation 626 mm (both calculated from the available German Weather Service data). For August, mean temperature is 19.1 °C, mean precipitation is 64 mm and net precipitation is slightly positive at +50 to +100 mm (Klämt & Schwanitz 2002). The fen is a typical percolation mire of the southern Baltic region. The peats are mainly of reed and sedge origin with thickness in the range 4 – 6 m. Deep (~1.5 m) drainage ditches allowed high-intensity grassland use until the fen was re-wetted in 1997. Since that time the water table has remained close to the ground surface (Bönsel & Sonneck 2012) and the vegetation of the study site has shown a typical shift from managed grassland with plants such as *Agrostis* spp. L., *Alopecurus geniculatus* L. and *Phleum pratense* L. to a re-wetted state with reeds (*P. australis* and *Phalaris arundinacea* L.), and stands dominated by *Carex* spp. L. or *Typha* spp. L. (Bönsel & Sonneck 2011) where the only remaining land use is hunting/shooting.

Study design

In November 2010, three GHG measurement plots were established in vegetation stands dominated by *P. australis*, *T. latifolia* and *C. acutiformis*, respectively (Figure 1). Each plot consisted of three measurement locations arranged at ~2 m intervals along a boardwalk. The measurement locations were marked with permanent collars (h = 20 cm, d = 63 cm) sunk into the peat surface to a depth of 5–10 cm. We installed the boardwalks and collars four months before the first measurements were made. In mid-July 2011, we installed collars at two additional locations close to the boardwalk in each vegetation stand, and we carried out additional measurements during August 2011. We did not cut the vegetation, as cutting may alter internal gas transport in convective and diffusive plants (Van der Nat & Middelburg 2000, Ding *et al*. 2004).

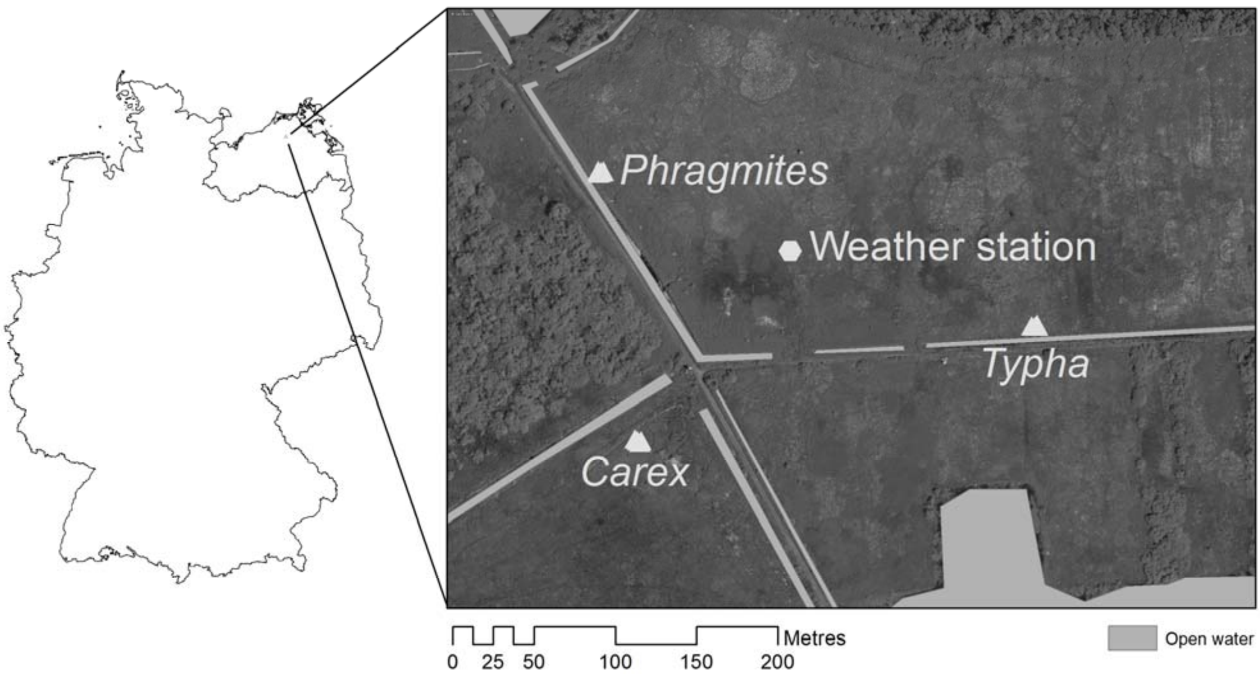

Figure 1. Maps showing (left) the location of the study site in north-east Germany, and (right) the study site (54° 06′ N, 12° 44′ E) at larger scale with locations of measurement plots (triangles) in *Phragmites*, *Typha* and *Carex* stands.

We sampled CH_4 effluxes fortnightly throughout the year with flexible, height adjustable, opaque, dynamic closed chambers (d = 63 cm) that could cover plants up to 2.3 m tall. The chamber material was flexible thermoplastic polyurethane, white outside and black inside, which is normally used in agriculture for covering silage. The chamber wall was stabilised with rings of plastic tubing to ensure full volume when installed in the field. The chambers were sealed onto the collars by pressing the lowest (or two lowest) ring(s) (depending on vegetation height) around the collars. During (rare) strong winds we added a tension belt. We tested the chamber for air tightness in the laboratory and found no significant concentration loss during a two-hour enclosure time. Five gas samples per location were taken at ten-minute intervals with evacuated gas flasks (12 ml Exetainer, Labco Ltd.) that were attached to the chamber with a short (< 2 cm) silicone rubber tube. The average temperature change inside the chambers during the 40-minute deployment time was < 2 °C. To account for diurnal variability, sampling was carried out at randomised times of day (Ding *et al*. 2004), but usually between 8 a.m. and 4 p.m. Gas samples were analysed for CH_4 concentration in the laboratory, within one week, using a gas chromatograph (Shimadzu Auto System). We collected water samples from the plots during the fortnightly gas measurements. The water table in each vegetation stand was recorded hourly by automated loggers (Solinst, Canada) submerged in dipwells. Other environmental variables were logged hourly by a weather station (F&C, Germany) located in the middle of the study site (Figure 1).

Data analysis

R 2.15.0 (R Development Core Team 2012) was used for all statistical analyses. Mean values ± 1 standard error are given. The R-package "flux" was used to derive effluxes from the chamber concentration data (Jurasinski *et al.* 2012). The parameters of the model with best linear fit (greatest R^2) were used to obtain the change in concentration in the chamber headspace over the sampling time (dc/dt) using four out of five values. When none of the models had $R^2 \geq 0.9$ the associated efflux was discarded. Effluxes lying beyond four standard deviations of the mean of effluxes from each vegetation stand were regarded as outliers and excluded from further analyses.

We estimated annual effluxes with a Monte Carlo repeated sampling procedure using the function auc.mc in the R-package "flux". This function linearly integrates the effluxes over the covered time period many times, each time leaving out a specified number of measurements (jackknife method); we used (n - 2) measurements in all cases. From the resulting distribution of seasonal efflux estimates *per* sampling location we calculated the mean (best estimate) and the standard deviation (providing an estimate of error introduced by temporal variation in sampling and by missing high/low effluxes during regular sampling campaigns). The best estimates *per* sample location were averaged to generate the reported annual efflux values. The reported standard errors were calculated from the propagated standard deviations of the best estimates (law of error propagation). To extract the effect of the flood, we estimated whole-year effluxes (a) including and (b) excluding all August 2011 measurements.

Because the single-plot data were not normally distributed in all cases, differences in efflux and environmental variables amongst the four plots were tested for significance using the pair-wise Wilcoxon rank test with Bonferroni adjustment of P values. Generalised linear models of water table *vs*. CH_4 efflux were constructed to explain variability within the vegetation stands.

RESULTS

In Mecklenburg-Western Pomerania, the summer of 2011 was the wettest in the last 30 years. Total precipitation during July and August was 392 mm, which is three times the long-term mean. As a result, the Trebel valley was flooded in August with the water table 10 cm (*Phragmites*), 20 cm (*Typha*) and 40 cm (*Carex*) above the peat surface. In contrast, the median water table for the whole study period was -7.7 cm (*Phragmites*) (i.e. below the surface), 5.7 cm (*Typha*) and 3.7 cm (*Carex*) above the peat surface. Mean temperatures in 2011 were 8.9 °C for the study year and 17.0 °C for August, i.e. cooler than the annual (9.1 °C) and August (19.1 °C) long-term means. Analyses of fen water samples revealed mesotrophic conditions (total N < 1 mg L^{-1}, Table 1). The peat is strongly decomposed (H9–H10 on the von Post scale) with low SOC and C/N quotient, less pronounced at the *Carex* stands (Table 1).

Of 311 flux measurements, 110 were discarded on the basis of the efflux estimation criteria and six were eliminated by outlier detection. At the *Phragmites* and *Typha* plots, CH_4 effluxes remained below 5 mg m^{-2} h^{-1} during most of the measurement period, but rose to 15–20 mg m^{-2} h^{-1} in August–September (Figure 2). The effluxes from these two vegetation types did not differ significantly from one another during the measurement year. CH_4 effluxes at the *Carex* plot were significantly higher ($P < 0.01$) and ranged from 5 to 20 mg m^{-2} h^{-1} during the growing season (May–November).

Table 1. Plot characteristics under the three vegetation types. For peat: degree of decomposition (von Post scale), Soil (peat) Organic Carbon (SOC, C/soil, g/g) and C/N quotient estimated from cores (n = 5) of the uppermost 30 cm of peat. For fen water: nitrate and ammonium concentrations (µmol L^{-1}), pH and electrical conductivity (EC, µS) during the year of measurements (n = 22 for each vegetation type); means ± one standard deviation are given.

		P. australis	*T. latifolia*	*C. acutiformis*
Peat	decomposition	H9–H10	H9–H10	H9–H10
	SOC	0.3 ± 0.07	0.3 ± 0.05	0.4 ± 0.02
	C/N	11.3 ± 0.0	11.4 ± 0.1	13.0 ± 0.4
Fen water	nitrate	21.7 ± 8.9	35.9 ± 15.3	12.6 ± 5.4
	ammonium	8.4 ± 4.7	47.4 ± 47.6	15.2 ± 6.8
	pH	8.3 ± 0.4	8.2 ± 0.3	7.9 ± 0.3
	EC	534 ± 58	732 ± 177	484 ± 56

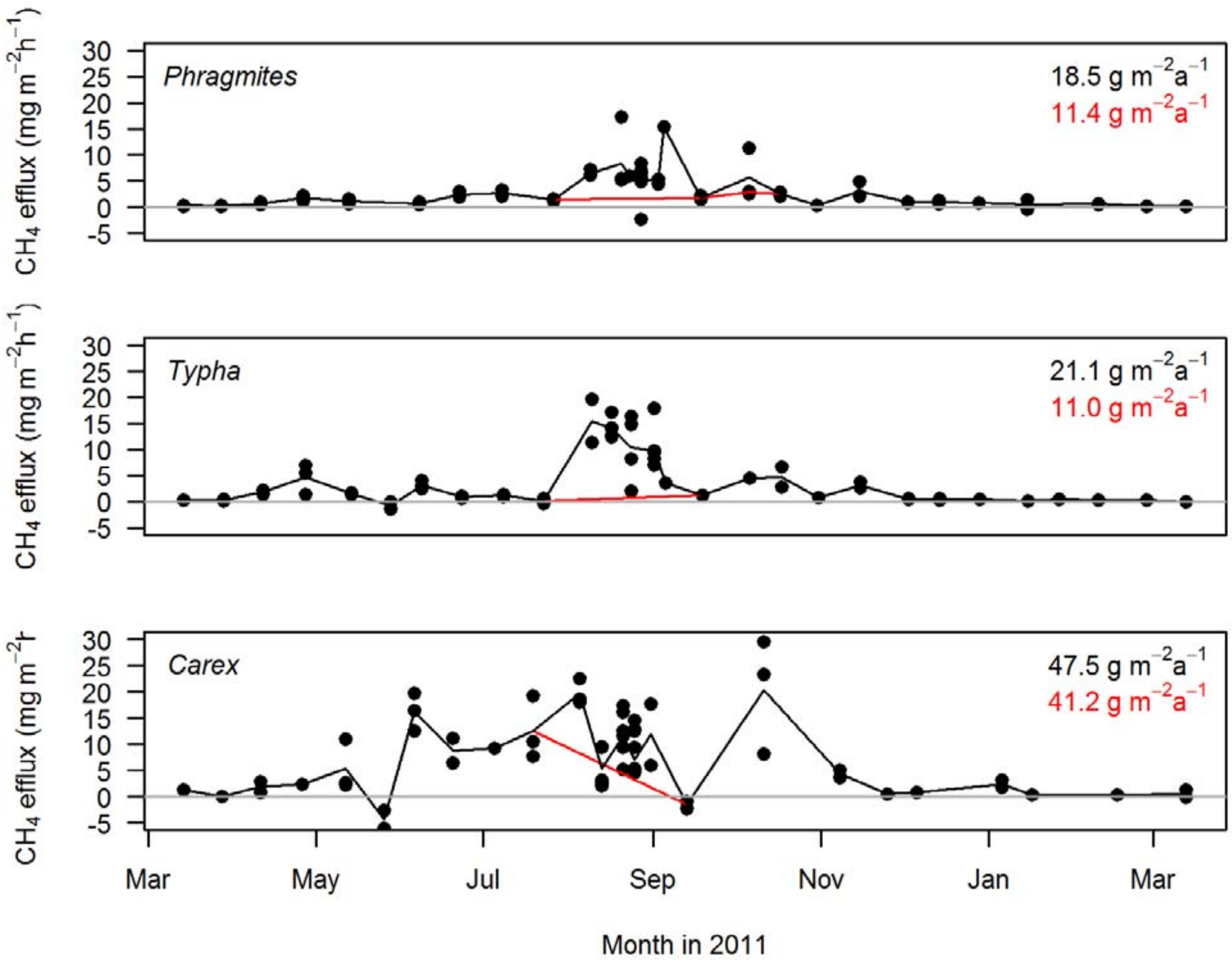

Figure 2. Course of CH_4 efflux from the three types of vegetation during the measurement period in 2011. Dots represent single measurements, black lines connect daily means of all measurements, red lines connect the daily means flanking the August measurements. Annual effluxes at the top right of each graph (black: all measurements, red: August measurements excluded) were calculated by the jackknife method described in the Methods section. Note that the last measurement before the start of August was on 23rd July, and the first measurement after the end of August was on 13th September; the red lines for *Typha* and *Carex* stands span this period. The red line for the *Phragmites* stand continues until 11th October because one large efflux measurement in September was excluded by outlier detection after the August measurements were removed from the dataset.

The annual CH_4 efflux estimates (mean ± one standard error, derived by the jackknife method) of the *Phragmites*, *Typha* and *Carex* plots were 18.5 ± 1.3, 21.1 ± 1.2 and 47.5 ± 5.0 g m^{-2} a^{-1}, respectively (18.4, 21.0 and 48.0 g m^{-2} a^{-1} when integrating all measurements). To test the influence of the August flooding on the annual efflux estimates, we re-estimated the annual CH_4 effluxes leaving out the August CH_4 measurements (Figure 2), which yielded the results 11.4 ± 0.6, 11.0 ± 1.0 and 41.2 ± 8.0 g m^{-2} a^{-1}. The August measurements were thus responsible for 40 %, 50 %, and 10 % of the annual CH_4 effluxes from the *Phragmites*, *Typha* and *Carex* plots, respectively.

DISCUSSION

The *Carex* stand showed the highest effluxes observed at the study site. *Carex* transports oxygen (O_2) to the rhizosphere by diffusion (Ding *et al*. 2004). In contrast, *Phragmites* and *Typha* are able to transport O_2 to the rhizosphere by convective flow (Brix *et al*. 1992), which may result in effective oxidation of CH_4 before it is released to the atmosphere when the O_2 demand of the soil exceeds the O_2 supply by the plants (Fritz *et al*. 2011). Since the study site was flooded in summer and saturated during the rest of the year a strong O_2 demand during the study period was likely.

CH_4 effluxes from the study site (18–48 g m^{-2} a^{-1}) are similar to CH_4 effluxes from boreal pristine fens (12–66 g m^{-2} a^{-1}, Dise 1992; 27–63 g m^{-2} a^{-1}, Martikainen *et al*. 1995; 20–35 g m^{-2} a^{-1}, Nykänen *et al*. 1995) and temperate pristine fens (55–120 g m^{-2} a^{-1}, Melloh & Crill 1996). In contrast, CH_4 effluxes from other fens in north-east Germany that were re-wetted less than five years before CH_4 measurements are an order of magnitude greater when the ecosystem is flooded (up to 493 g m^{-2} a^{-1}, derived from Augustin & Chojnicki 2008; up to 267 g m^{-2} a^{-1}, Höper *et al*. 2008; 147 g m^{-2} a^{-1}, derived from Glatzel *et al*. 2011). Our findings suggest that CH_4 effluxes become similar to those from pristine fens 15 years after re-wetting, even with a summer flood.

Water table is recognised as a major control for both annual (Fiedler & Sommer 2000, Couwenberg *et al*. 2011) and seasonal CH_4 effluxes (Hargreaves & Fowler 1999, Jungkunst *et al*. 2008, Huth *et al*. 2012). Generalised linear modelling of water table *vs*. CH_4 effluxes explained 12 % ($P < 0.01$, *Phragmites*), 42 % ($P < 0.001$, *Typha*) and 11 % ($P < 0.05$, *Carex*) of the overall CH_4 variability (R^2 values) in this study. Hence, the impact of freshwater flooding on CH_4 effluxes at the *Phragmites* and *Carex* plots was small, whereas it explained almost half of the CH_4 efflux variability at the *Typha* plot. The peat is similar among the measurement locations (Table 1), but the *Typha* stand has a larger fraction of easily decomposable grassland type understorey (e.g. *Poa trivialis*, L., unpublished results) than the *Phragmites* and *Carex* stands. Therefore, the difference in water table response may indicate that, in contrast to the *Phragmites* and *Carex* stands, the *Typha* stand is not yet fully established.

This study highlights the finding that, if the water table is close to the ground surface (Bönsel & Sonneck 2012) and the shift in vegetation composition already reflects the altered hydrology (Bönsel & Sonneck 2011), as it does in the Trebel valley mire, then the CH_4 effluxes from re-wetted fens become similar to those from pristine fens even under extremely wet conditions. Therefore, our results are very promising because they show that re-wetting projects can reduce GHG effluxes within 15 years.

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Author for correspondence:
Vytas Huth, Landscape Ecology and Site Evaluation, Faculty of Agricultural and Environmental Sciences, University of Rostock, Justus-von-Liebig-Weg 6, 18059 Rostock, Germany
Tel: +49 381 498 3232; Fax: +49 381 498 3222, email: vytas.huth@uni-rostock.de