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Effect of reed canary grass cultivation on greenhouse gas emission from peat soil at controlled rewetting

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BGD

11, 13309–13341, 2014

Effect of reed canary grass cultivation on GHG emission from peat soil

S. Karki et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



Abstract

Cultivation of bioenergy crops in rewetted peatland (paludiculture) is considered as a possible land use option to mitigate greenhouse gas (GHG) emissions. However, bioenergy crops like reed canary grass (RCG) can have a complex influence on GHG fluxes. Here we determined the effect of RCG cultivation on GHG emission from peatland rewetted to various extents. Mesocosms were manipulated to three different ground water levels (GWL), i.e., 0, -10 and -20 cm below the soil surface in a controlled semi-field facility. Emissions of CO₂ (ecosystem respiration, ER), CH₄ and N₂O from mesocosms with RCG and bare soil were measured at weekly to fortnightly intervals with static chamber techniques for a period of one year. Cultivation of RCG increased both ER and CH₄ emissions, but decreased the N₂O emissions. The presence of RCG gave rise to 69, 75 and 85 % of total ER at -20, -10 and 0 cm GWL, respectively. However, this difference was due to decreased soil respiration at the rising GWL as the plant-derived CO₂ flux was similar at all three GWL. For methane, 70–95 % of the total emission was due to presence of RCG, with the highest contribution at -20 cm GWL. In contrast, cultivation of RCG decreased N₂O emission by 33–86 % with the major reductions at -10 and -20 cm GWL. In terms of global warming potential, the increase in CH₄ emissions due to RCG cultivation was more than off-set by the decrease in N₂O emissions at -10 and -20 cm GWL; at 0 cm GWL the CH₄ emissions was offset only by 23 %. CO₂ emissions from ER obviously were the dominant RCG-derived GHG flux, but above-ground biomass yields, and preliminary measurements of gross photosynthetic production, show that ER could be more than balanced due to the uptake of CO₂ by RCG. Our results support that RCG cultivation could be a good land use option in terms of mitigating GHG emission from rewetted peatlands, potentially turning these ecosystems into a sink of atmospheric CO₂.

Effect of reed canary grass cultivation on GHG emission from peat soil

S. Karki et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



1 Introduction

Peatlands cover 3% of the world's area but contain 30% of the soil organic carbon (Parish et al., 2008), signifying an important role in the global carbon cycle. About 15% of the world's peatlands have been drained for different human purposes mostly for agriculture and forestry and to a lesser extent for peat extraction (Joosten, 2009). Drained peatlands are major sources of CO₂ emissions and estimated to account for about 6% of the total anthropogenic CO₂ emission (Joosten, 2009). In order to reduce the large emissions of CO₂ from drained peatlands, extensive rewetting projects have been implemented in Europe and North America (Höper et al., 2008), and rewetted organic soils have been included in the guidelines for national greenhouse gas (GHG) inventories by the Intergovernmental Panel on Climate Change (IPCC, 2014). In addition, agricultural use of wet and rewetted peatlands for crop growth (paludiculture) is considered as a possible land use option that may indirectly reduce the CO₂ emissions on rewetted organic soils by biomass production for energy purposes (Joosten et al., 2012; Günther et al., 2014).

Reed canary grass (RCG) is one of the suitable biomass crops for paludiculture (Wichtmann and Tanneberger, 2011). These plants thrive in wet soils due to aerenchyma tissues (Kercher and Zedler, 2004; Askaer et al., 2011) that transport oxygen to the roots in otherwise anaerobic soil compartments. However, cultivating wetland plants like RCG may influence the overall GHG balance by a combination of contrasting effects. First of all, RCG can stimulate the processes of GHG production by increasing the labile soil organic carbon pool, e.g., via root exudates (Ström et al., 2003; Bastviken et al., 2005). Next, the transport of oxygen to anaerobic zones stimulates heterotrophic degradation of organic matter, but at the same time stimulates oxidation of CH₄ (Kao-Kniffin et al., 2010) and suppress CH₄ production due to increase in redox potential (Laanbroek, 2010; Sutton-Grier and Megonigal, 2011). RCG may further increase the emissions of reduced soil gasses as the aerenchyma tissues act as a conduit for the direct transport of, e.g., CH₄ and N₂O produced in soil (Joabs-

BGD

11, 13309–13341, 2014

Effect of reed canary grass cultivation on GHG emission from peat soil

S. Karki et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



son et al., 1999; Jørgensen et al., 2012). Also, RCG can decrease N₂O emissions by assimilation of mineral N which reduces the availability of electron acceptors (nitrate) for denitrifying microorganisms (Roobroeck et al., 2010). In summary, the introduction of RCG at rewetted peatlands may cause a change in the patterns and underlying mechanisms of GHG emission, which is rather complex.

In the natural state, GHG emissions from rewetted peatlands are predominantly controlled by the position (depth) of the water table (IPCC, 2014). Basically, due to slow diffusion of oxygen in water (10 000 times slower than in air), ground water level (GWL) has a strong control on the oxic/anoxic soil boundary and thereby on the biogeochemical processes involved in GHG fluxes (Dinsmore et al., 2009; Karki et al., 2014). However, the presence of aerenchymatous plants may strongly interact with GWL in being decisive for the resulting GHG emissions from rewetted peatlands. The objective of the present study was to document the initial effect of RCG cultivation on the resulting GHG emissions of CO₂, N₂O and CH₄ from peat soils rewetted to various extents. To accomplish this, the GHG emissions of all three gases were measured in an annual study with peat soil mesocosms with RCG and bare soil rewetted to constant GWL of 0, -10 and -20 cm in a controlled semi-field facility.

2 Materials and methods

2.1 Site description

Soil cores were collected from a fen peatland in the Nørre Å river valley, Denmark (56°44' N, 9°68' E). The peatland was drained to a depth of 60–70 cm in early 20th century and since then used for agricultural purposes. RCG experimental plots were established at the site in 2009 (Kandel et al., 2013). The top soil layer (0–20 cm) at the study site had the following main properties: highly decomposed peat soil corresponding to H9 on the von Post scale; bulk density, 0.29 g cm⁻³; total organic carbon, 37.8 % and total nitrogen, 3.2 % (Karki et al., 2014).

2.2 Experimental design

A total of 30 intact soil cores for mesocosm study were collected in May 2012 by inserting PVC pipes of 60 cm depth and 30 cm diameter into the soil. Half of the soil cores were collected from RCG plots and the other half were collected from a grass field surrounding the RCG plots. The upper 5 cm of the soil and litter layer was removed from the grass field before inserting the PVC pipes and these soil cores were kept bare during the experiment. The soil cores were retrieved with help of a mini excavator and transported to semi-field facilities at AU-Foulum (Karki et al., 2014). The bottom of the PVC pipes were covered with net to allow for free water movement and the pipes were then installed in plastic cylinders (diameter, 37 cm; height, 70 cm). The plastic cylinders were filled with gravel at the bottom 10 cm and the space between the PVC pipes and the wall of the cylinders (ca. 3 cm) was filled with sand. The whole set up was then installed in a trench at the semi-field facility with the soil surface at ground level.

Mesocosms with bare soil and RCG were randomly divided into three groups and were manipulated to three different GWL of 0, -10 and -20 cm below the soil surface. Water table was adjusted by fitting a rubber tubing (diameter, 1 cm) to the bottom of each plastic cylinder and placing the other end of the rubber tubing at different heights corresponding to the level of GWL treatment. Water was supplied in the space between the PVC pipes and the wall of the cylinders every day for one hour by a drip irrigation system. Further details on mesocosm incubations and the semi-field facility were given by Karki et al. (2014).

Due to poor regrowth of RCG (both under mesocosms and field conditions), initial weed biomass was uprooted and new RCG seeds were spread on 21 June 2012. RCG was fertilized with surface application of 0.6 g N, 0.1 g P and 0.5 g K per mesocosm on 23 July 2012. After the regrowth of RCG in spring 2013, RCG was fertilized with the same amount of fertilizer on 30 April and again in 28 June 2013. RCG plants were harvested twice, first on 29 October 2012 and then on 27 June 2013. In bare soil mesocosms, emerging weeds were uprooted and mosses were eliminated by applica-

BGD

11, 13309–13341, 2014

Effect of reed canary grass cultivation on GHG emission from peat soil

S. Karki et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



tion of iron sulphate (FeSO_4) on 29 August 2012. No fertilizer was added to bare soil mesocosms.

2.3 Gas measurements and flux calculation

Dark PVC chambers (diameter, 30 cm; height, 50 cm) equipped with fans and pressure equilibration vents were used for the measurement of CO_2 , CH_4 and N_2O (Karki et al., 2014). Gas measurements were carried out between 10:00 and 13:00 LT at weekly to fortnightly intervals during July 2012 to July 2013. Four gas samples (10 mL) were drawn from the chamber headspace with polypropylene syringes during 45 min of chamber enclosure and transferred to evacuated 6 mL Exetainers. Gas samples were analysed with an Agilent 7890 gas chromatograph connected to a CTC CombiPAL automatic sample injection system (Agilent, Nærum, Denmark). Fluxes were calculated with the HMR method (Pedersen et al., 2010) in the statistical software R (R Core Team, 2013) as non-linear increase in gas concentration over time was often observed with non-steady state chambers for used gas measurement (Davidson et al., 2002). Thus according to statistical HMR analysis fluxes were calculated either by non-linear or linear models (Pedersen et al., 2010). Out of the total of 435 fluxes for each gas, the non-linear approach was applied for 41, 40 and 18 % of CO_2 , CH_4 and N_2O fluxes from RCG mesocosms and 22, 16 and 22 % of CO_2 , CH_4 and N_2O fluxes from bare soil mesocosms. In bare soil at 0 cm GWL, approximately 3% of the CH_4 fluxes were discarded due to episodic release of CH_4 presumably by ebullition.

2.4 Biomass measurement

Biomass development was monitored through the non-destructive measurement of ratio vegetation index (RVI). RVI was determined for each mesocosm using a SpectroSense 2+ fitted with SKR1800 sensors (Skype Instruments, Powys, UK) as described by Görres et al. (2014). RVI measurements were done on the same days as GHG sampling except in winter when the soil was covered with snow or frozen. The

Effect of reed canary grass cultivation on GHG emission from peat soil

S. Karki et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



total above ground dry biomass from each mesocosm was also determined after each harvest by oven drying at 60 °C to constant weight. After the harvest in 2013, species composition from each mesocosm was determined on dry weight basis to quantify the contribution of volunteer weeds in the total biomass.

2.5 Environmental parameters and pore water analysis

Soil temperature at 5 cm depth and soil moisture was measured by temperature and time domain reflectometry (TDR) probes installed permanently in one of the five replicates for each GWL treatment. Soil temperature was measured automatically every hour while soil moisture measurements with TDR (volumetric water content, VWC) were done on every gas sampling occasion. The instrumented mesocosms also had Pt probes installed at 20 cm depth to measure soil redox potential. Soil redox potential was measured at fortnightly intervals from mid-April to July 2013 with a portable pH meter (PHM220, Radiometer) by gently pushing a double junction calomel reference electrode (REF251, Hach Lange) into the soil. Measured redox potential were converted to standard hydrogen electrode potential (Eh) by addition of +245 mV (Kjaergaard et al., 2012).

A piezometer (length, 65 cm; diameter, 2 cm) with the screen all the way down was installed in the instrumented mesocosms. Approximately 30 mL of soil water was sampled monthly from these piezometers except for February to April 2013 where water inside the piezometers was frozen. Water samples were analysed for ammonium, nitrate, and sulphate content. Ammonia and nitrate content were measured using an auto-analyzer (Bran+Luebbe GmbH; Norderstedt, Germany) and sulphate was determined by ion chromatography on a Dionex ICS-1500 IC-system (Dionex Corp., Sunnyvale, CA, USA).

BGD

11, 13309–13341, 2014

Effect of reed canary grass cultivation on GHG emission from peat soil

S. Karki et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



2.6 Cumulative GHG fluxes

For the mesocosms with RCG, CO₂ emissions from ecosystem respiration (ER) were modelled as a function of GWL, temperature, and biomass (RVI) by Model 1 (Karki et al., 2014); for bare soil mesocosms Model 2 excluding RVI was applied:

$$ER = (b_1 + b_2 \text{ GWL}) \cdot \exp\left(b_3 \left(\frac{1}{10 - T_0} - \frac{1}{T - T_0}\right)\right) \cdot (b_4 + \text{RVI}) \quad (1)$$

$$ER = (b_1 + b_2 \text{ GWL}) \cdot \exp\left(b_3 \left(\frac{1}{10 - T_0} - \frac{1}{T - T_0}\right)\right) \quad (2)$$

where T_0 is a notional zero respiration temperature, here fixed to -46.02°C (Lloyd and Taylor, 1994), T is the air or soil temperature ($^\circ\text{C}$), RVI is the ratio vegetation index, GWL is water table depth below the soil surface (cm) and b_1 , b_2 , b_3 and b_4 are model parameters.

All model parameters were estimated by non-linear regression in SigmaPlot 11 (Systat Software, Chicago, IL, USA). Using the obtained model parameters, continuous temperature data and linearly interpolated RVI data, hourly rates of CO₂ emissions were reconstructed for each GWL. These hourly emissions values were summed to yield the annual flux from 10 July 2012 to 9 July 2013. The uncertainty of annual fluxes were addressed by deriving the minimum and maximum cumulative fluxes from upper and lower values of model parameters \pm standard errors (SE) (Elsgaard et al., 2012). For model evaluation the Nash–Sutcliffe modelling efficiency (ME) was calculated according to:

$$ME = 1 - \frac{\sum_{i=1}^n (\text{Mes}_i - \text{Mod}_i)^2}{\sum_{i=1}^n (\text{Mes}_i - \overline{\text{Mes}})^2} \quad (3)$$

where Mes_i and Mod_i are measured and modelled values, respectively, and \overline{Mes} is the mean of measured values (Haefner, 2005).

Cumulative CH_4 and N_2O fluxes were calculated by the linear interpolation method between the sampling dates using the trapezoidal rule (Petersen et al., 2012). Linear interpolation method was used as there were no common models to predict CH_4 and N_2O fluxes for vegetated and bare soil plots. Cumulative fluxes were calculated for each individual mesocosm and then averaged for each GWL treatment ($n = 5$). Total GHG emissions were calculated by summing annual CO_2 , CH_4 and N_2O emissions at each GWL; CH_4 and N_2O emissions were converted to CO_2 equivalents by multiplying with 28 and 265, respectively, according to the global warming potential (GWP) of the three GHG (Myhre et al., 2013). The plant-derived total GHG emission at each GWL was estimated as the difference between the total GHG emissions from RCG mesocosms and bare soil mesocosms. The uncertainty of annual plant derived GHG emissions was calculated following the law of error propagation as the square root of the sum of the squared standard errors of plant and bare soil emissions.

2.7 Statistical analysis

Statistical analyses were done using R version 3.0.2 (R Core Team, 2013). Data were analyzed using a linear mixed model including the fixed effect of vegetation (bare soil/RCG), GWL, date and their two-way interactions. The model also included the random effect of each experimental unit. Prior to analysis, gas flux data were log-transformed after addition of a constant (minimum fluxes of CH_4 and N_2O) to obtain normal distribution and variance homogeneity. Dates were treated as repeated measurements and autocorrelation of CorAR1 structure was applied to CH_4 and N_2O fluxes while compound symmetry was applied to CO_2 fluxes (Oehlert, 2000). A similar model was run to determine the effect of GWL on RVI development. One-way ANOVA was used to test the difference in mean yield between the treatments. Significance of all tests was accepted at $P < 0.05$.

BGD

11, 13309–13341, 2014

Effect of reed canary grass cultivation on GHG emission from peat soil

S. Karki et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



3 Results

3.1 Environmental conditions

The average air temperature during the study period was 6.9°C and total precipitation was 667 mm (Fig. 1). Snowfall started in early December 2012 and was observed till end of March 2013 with intermittent freezing and thawing events. The soil was frozen and covered with ice till mid-April 2013. The average soil temperature (5 cm depth) in RCG treatments was 7.4, 7.7 and 7.6°C at 0, -10 and -20 cm GWL, respectively; for bare soil treatments it was 7.5, 7.4 and 7.9°C at 0, -10 and -20 cm GWL, respectively. The average volumetric soil water content during the measurement period was 82 ± 5%, 67 ± 3%, and 58 ± 3% from RCG treatments at 0, -10 and -20 cm GWL, respectively, and 83 ± 4%, 62 ± 6%, and 55 ± 7% from bare soil treatments at 0, -10 and -20 cm GWL, respectively (mean ± standard deviation, $n = 22$). Average soil redox potential was -115, -27, and 40 mV from RCG treatments at 0, -10 and -20 cm GWL, respectively, and -118, -51, 151 mV from bare soil treatments at 0, -10, and -20 cm GWL, respectively (Fig. 2).

3.2 Biomass yield and RVI

The mean biomass yield was 6.0 and 6.6 Mg ha⁻¹ across all GWL in 2012 and 2013, respectively (Fig. 3). During the first year there was a good stand of RCG but during the second year weed biomass became established especially at 0 cm GWL; this was notably marsh foxtail (*Alopecurus geniculatus* L.) and grasses (*Poa* sp.) which made an important contribution to the total biomass at the time of harvest.

The pattern of RVI development was similar among the different GWL treatments; peak values of RVI occurred in late August 2012, where after RVI started to decline due to plant senescence. RVI started to increase again during the regrowth of biomass in spring 2013 (Fig. 4).

BGD

11, 13309–13341, 2014

Effect of reed canary grass cultivation on GHG emission from peat soil

S. Karki et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



3.3 Pore water properties

The annual variation in soil water sulphate concentrations ranged from 1.3 to 56.9 mg L⁻¹. Generally, similar SO₄²⁻ concentrations were found in bare soil and RCG mesocosms at 0 and -10 cm GWL, but at -20 cm GWL consistently higher SO₄²⁻ concentrations were found in the bare soil mesocosms (Table 1). For ammonium the concentrations ranged from 0.1 to 10.2 mg L⁻¹ and higher NH₄⁺ concentrations were generally found in bare soil mesocosms than in RCG mesocosms at 0 and -10 cm GWL. In the bare soil treatments the level of NH₄⁺ was lower at -20 cm GWL than at 0 and -10 cm GWL, but in RCG treatments NH₄⁺ concentrations were similar at all the three GWLs (Table 1). The concentration of nitrate was low (< 3.1 mg L⁻¹) across all treatments; the highest NO₃⁻ levels were generally seen at bare soil treatments at -20 cm GWL (Table 1).

3.4 Measured GHG fluxes

The emission of CO₂ was measured as ER in RCG and bare-soil treatments in order to evaluate the contribution of RCG in the total ER at the different GWLs. The emissions of CO₂ were different between RCG and bare soil mesocosms ($p < 0.001$) and also between the three GWL treatments ($p < 0.001$) (Table 2). CO₂ emissions decreased consistently with higher GWL both from RCG and bare soil mesocosms. The emissions showed expected seasonal variation with highest CO₂ fluxes during summer time ($p < 0.001$) (Fig. 5a and b). CO₂ emissions ranged from 20 to 485 mg m⁻² h⁻¹ across all GWL in bare soil and from 55 to 1700 mg m⁻² h⁻¹ in RCG treatments. Among the air and soil temperature at 5 cm, CO₂ emissions were better correlated with soil temperature in bare soil, but with the air temperature in RCG treatments.

Methane fluxes were significantly affected both by vegetation and GWL (Table 2). CH₄ emissions were highest at 0 cm GWL both from RCG and bare soil treatments (Fig. 5c and d). CH₄ emissions from RCG treatments showed temporal variation ($P <$

BGD

11, 13309–13341, 2014

Effect of reed canary grass cultivation on GHG emission from peat soil

S. Karki et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Effect of reed canary grass cultivation on GHG emission from peat soil

S. Karki et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

0.001) with highest emissions during summer time (Fig. 5c). Peak emissions of CH₄ from RCG treatments were observed in August 2012 across all GWL levels, ranging from 4.4 to 8.9 mg CH₄ m⁻² h⁻¹. During November to early April (i.e., winter season), CH₄ emissions from RCG treatments were below 0.1 mg m⁻² h⁻¹ and even occasional uptake (25 % of total fluxes measured) of CH₄ was recorded. From bare soil treatments, CH₄ fluxes were generally low and fluctuated between apparent net emission and net uptake except for few episodic peak events, generally from 0 cm GWL. These peak events were considered to represent unsystematic ebullition events.

N₂O fluxes from RCG treatments were generally low, fluctuating in a range between -0.02 to 0.07 mg m⁻² h⁻¹ except for peak events after fertilizer application (Fig. 5e). Emission peaks of 0.4, 0.7 and 0.4 mg N₂O m⁻² h⁻¹ were observed at 0 cm GWL immediately after the first, second and third fertilization events, respectively. Smaller peak emissions of 0.4 and 0.2 mg N₂O m⁻² h⁻¹ were observed at -10 cm GWL after the first and second fertilization event, but at -20 cm GWL, peak emission after the fertilizer application was absent. N₂O emissions from bare soil treatments generally were higher and ranged from -0.02 to 1.9 mg m⁻² h⁻¹. Most of the N₂O emission in bare soil mesocosms was measured during the winter period from November 2012 to April 2013 accounting for more than 70 % of the cumulative emission at 0 and -10 cm GWL and more than 50 % at -20 cm GWL.

3.5 Annual GHG emissions and contribution of plants to annual GHG emissions

The estimated parameters for CO₂ flux models are presented in Table 3 showing also that the modelling efficiency was considerably higher for the RCG treatments than the bare soil treatments. Annual CO₂ emissions decreased consistently with raising GWL towards the soil surface both in RCG and bare soil treatments (Fig. 6). In contrast, CH₄ emissions increased systematically both from RCG and bare soil treatments in response to raising GWL (Fig. 6). The annual N₂O emissions showed a contrasting response to raising GWL in bare soil and RCG treatments; in bare soil treatments

lower N₂O emissions occurred in response to raising GWL, but in RCG treatments there was a tendency of higher N₂O emissions in response to raising GWL (Fig. 6).

The presence of plants contributed 69–85 % of the total CO₂ emissions from the RCG mesocosms (Fig. 6). The highest contribution was observed at 0 cm GWL and the contribution decreased at lower GWL. RCG likewise contributed more than 70 % of total CH₄ emissions with the highest contribution of 95 % observed at –20 cm GWL. Thus at this GWL (–20 cm) CH₄ emission was negligible from bare soil treatments (0.2 g CH₄ m⁻² yr⁻¹) whereas the emissions was substantial from RCG treatments (4.1 g CH₄ m⁻² yr⁻¹). In contrast to CO₂ and CH₄ emissions, cultivation of RCG reduced the annual N₂O emissions despite the application of mineral N fertilizer in RCG mesocosms (Fig. 6). At –10 and –20 cm GWL, RCG eliminated 82–86 % of the N₂O emissions as compared to bare soil treatments; from 0 cm GWL the reduction corresponded to 33 % of the N₂O emissions. In terms of GWP, the increase in CH₄ emissions due to RCG cultivation was more than off-set by the decrease in N₂O emissions at –10 and –20 cm GWL, but apparently not at 0 cm GWL where CH₄ emissions were off-set by only 23 % (Fig. 7). CO₂ emissions from ER, though, were the dominant RCG-derived GHG fluxes (Fig. 7).

4 Discussion

During the present study, the effects of RCG cultivation on GHG emission from rewetted peatland was evaluated by comparison of planted and unplanted (bare-soil) mesocosms. One concern of using this plant exclusion method for GHG studies is the difference in soil moisture regime and temperature that may develop between planted and bare soil treatments which may result in different decomposition rates of soil organic matter (Kuzyakov, 2006). With our experimental setup, we were able to control the GWL throughout the measurement period and this resulted in soil moisture contents (VWC) that were similar between RCG and bare soil treatments at each GWL; this was generally also seen for the soil redox potential and pore water sulphate concentration at least

BGD

11, 13309–13341, 2014

Effect of reed canary grass cultivation on GHG emission from peat soil

S. Karki et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Effect of reed canary grass cultivation on GHG emission from peat soil

S. Karki et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



at 0 and –10 cm GWL. The average soil temperature difference between the RCG and bare soil treatments was found to be less than 1 °C; however during the annual study we observed some seasonal difference in soil temperature especially during spring days (higher temperature in RCG treatments) and summer days (lower temperature in RCG treatments) which was attributed to the RCG cultivation. Yet, the differences in moisture and temperature regime between the planted and bare-soil mesocosms were considered to be modest and pertinent for an evaluation of the effects of RCG on total GHG emissions.

Monitoring of environmental variables was achieved by instrumentation of one out of five replicate mesocosms at each GWL. We assumed that the measured variables were representative for all replicates and that the instrumentation did not lead to any bias. This was substantiated by the absence of any systematic deviations in measured GHG fluxes from the instrumented and non-instrumented replicates. Thus, the average difference in annual fluxes with and without instrumentation was less than 15 %.

4.1 CO₂ emissions

Plants can enhance CO₂ flux from ER directly by above- and below-ground respiration and indirectly by enhancing the decomposition of soil organic matter by the supply of easily degradable root exudates to the soil (priming effect) (Kuzakov et al., 2001; Van Huissteden et al., 2006). In vegetated soils ER is essentially balanced by photosynthetic CO₂ uptake, and therefore CO₂ emissions from ER does not represent the net ecosystem exchange (NEE) of CO₂. Rather than quantifying NEE, an important result of the present study was that plant-derived ER from RCG mesocosms (the major part of total CO₂ emissions) was similar at all three GWL (Fig. 7) substantiating the results of Lafleur et al. (2005) and Riutta et al. (2007) who reported autotrophic respiration to be independent of water table depth. Thus, the observed increase in the contribution of plants in total ER with rising GWL was promoted mainly by decreasing soil respiration at the higher GWL (Fig. 6). The observed contribution of RCG to total CO₂ emissions (on average 76 %) was higher than the values of 55 % previously reported by Shurpali

et al. (2008). Yet, the studies by Shurpali et al. (2008) was carried out in a drained peatland with an average GWL of -65 cm which would favor soil respiration to a larger extent than in our soils with GWL no deeper than -20 cm. In accordance with this we also observed a larger soil respiration at -20 cm than at 0 cm GWL.

4.2 Methane emissions

Methane fluxes from soil is the result of CH_4 production, consumption and transport (Lai, 2009). Plants play a key role on CH_4 fluxes as they have potential to influence all three processes (Joabsson et al., 1999). CH_4 emissions were higher from RCG than bare soil treatments even though the GWL was raised to the soil surface. Plant roots release organic compounds to soil, which are easily available carbon sources to anaerobic microbial consortia eventually producing the precursors (acetate or H_2/CO_2) for methanogenesis (Ström et al., 2003). Such fresh organic carbon is suggested to be important substrates for methanogenesis as peat carbon is shown to be more recalcitrant to anaerobic decomposition (Tuittila et al., 2000; Hahn-Schöfl et al., 2011).

Methane produced in soil can be emitted to the atmosphere by diffusion, ebullition (release of gas bubbles) and plant-mediated transport (Whalen, 2005; Lai, 2009). Indeed, RCG can transport CH_4 from soil to the atmosphere directly through its aerenchyma tissue, thereby bypassing the microbial methane oxidation layer in the soil. On an annual basis it has been estimated that RCG may actually transport 70% of the total CH_4 emissions from a natural wetland in Denmark (Askaer et al., 2011). In the absence of plant-mediated transport, diffusion expectedly would be the dominant pathway of CH_4 emissions in bare soil treatments. CH_4 transport through diffusion is a slow but important process for bringing CH_4 in contact with the CH_4 oxidizing microbial community (Whalen, 2005; Lai, 2009). In our study there was negligible CH_4 emissions from bare soil at -20 cm GWL, aligning with the results of Schäfer et al. (2012) who reported this drainage depth to be sufficient to suppress diffusive CH_4 emissions due to methane oxidation and reduced methanogenesis.

BGD

11, 13309–13341, 2014

Effect of reed canary grass cultivation on GHG emission from peat soil

S. Karki et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The transport of oxygen by aerenchyma plants to anoxic soil compartments has been reported to increase the redox potential which could suppress the CH₄ emission (Sutton-Grier and Megonigal, 2011). However, in our study neither the redox potential nor the sulphate content was consistently increased by the presence of plants suggesting the role of substrate availability and transport of CH₄ through RCG to be important for controlling CH₄ emissions from the RCG treatments.

It is possible that we could have underestimated the total CH₄ emission from bare soil treatments at 0 cm GWL as episodic CH₄ release through ebullition was not taken into account in the annual balance. Ebullition events were identified by occasional erratic time courses of CH₄ concentrations during the flux measurements; however as these events were generally associated with the initial (time 0 and 15 min) CH₄ measurements it was believed to represent artifacts created during chamber deployment. Yet, episodic release of CH₄ may be more important in bare soil than in vegetated soil as plants may reduce the soil concentration of CH₄ by mediating CH₄ transport and also by rhizospheric oxidation of CH₄; these processes reduce the potential formation of CH₄ bubbles (Chanton, 2005). Tentatively accounting for the observed episodic CH₄ release, a total of 0.04 g m⁻² of CH₄ was released during the study; this was a negligible contribution to the annual CH₄ flux from bare soil at 0 cm GWL. However, as ebullition events are short-lived and unsystematic they could easily be missed by the chamber measurements (Coulthard et al., 2009).

4.3 N₂O emissions

Annual fluxes of N₂O (0.2–0.4 g N₂O m⁻² yr⁻¹) from RCG were within the range (–0.4–0.8 g N₂O m⁻² yr⁻¹) reported for undisturbed Danish riparian wetland (Audet et al., 2014). However, annual fluxes were higher in bare soil (0.6–2.0 g N₂O m⁻² yr⁻¹) as compared to RCG treatments. Thus, RCG decreased the annual N₂O emissions, contradictory to the finding of Hyvönen et al. (2009) where fertilization in RCG increased the N₂O emissions by 90%. However, in their study N₂O emissions were quite low

BGD

11, 13309–13341, 2014

Effect of reed canary grass cultivation on GHG emission from peat soil

S. Karki et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Effect of reed canary grass cultivation on GHG emission from peat soil

S. Karki et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



($0.01 \text{ g N}_2\text{O m}^{-2} \text{ yr}^{-1}$) from the soil without vegetation (Hyvönen et al., 2009). Their site was an abandoned peatland (Hyvönen et al., 2009) probably with limited nitrification because of a high C/N ratio (42.3) (Klemmedtsson et al., 2005) compared to our peat soil with rich N content (3.2 %) and a low C/N ratio (11.6). Thus, the ecosystem studied

5 by Hyvönen et al. (2009) might have been more N limited at the unfertilized sites than was the case for our study site. This, in turn, could cause a more pronounced response to N fertilization in the studies of Hyvönen et al. (2009).

The effect of RCG cultivation on N_2O emissions was highly dependent upon the GWL. At 0 cm GWL, there was least effect of RCG cultivation on N_2O emissions due to

10 peak emissions observed after fertilization. Peak emission observed after fertilization events suggest that N_2O emission was limited by mineral N content at 0 cm GWL. Saari et al. (2013) and Silvan et al. (2002) also reported a significant increase in N_2O emission after addition of inorganic nitrogen in riparian wetland due to favorable conditions for denitrification.

Previous studies have reported that winter emissions significantly contributed to annual N_2O emissions (Maljanen et al., 2004; Regina et al., 2004). Such emissions in

15 winter have been related to the physical release of N_2O that is produced and trapped under frozen surface layers and the emissions of newly produced N_2O (de novo emissions) at the onset of thaw stimulated by increased biological activity and changes in physical and chemical soil conditions (Risk et al., 2013). Significant emissions at all

20 GWL were observed in winter from bare soil treatments, but not from RCG treatments. After harvesting, there was regrowth of RCG and also other volunteer grasses which survived throughout the winter and which may have competed with microorganisms for available N. Maljanen et al. (2004) also observed higher N_2O emissions from bare soil

25 as compared to vegetated plots during winter and likewise related the low emission in vegetated plots to low mineral N content due to uptake of nitrate by plants. Bare soil treatments indeed had a higher availability of mineral N (Table 1), and could be more prone to physical damage by freeze and thaw cycles due to lack of plant cover; both these factors stimulate the biological activities related to N_2O emissions as substanti-

ated by the observed slight increase also in CO₂ emissions coinciding with increased N₂O emission especially at 0 and –10 cm GWL.

4.4 Effect of RCG cultivation on GHG balance from rewetted peatland

Two of the major concerns of growing wetland plants like RCG in rewetted peatland are the possible increase in CH₄ emissions due to supply of fresh plant material and transport of CH₄ by aerenchyma tissue (Ström et al., 2003; Askaer et al., 2011) and the possible increase in N₂O due to application of N fertilizers (Maljanen et al., 2010). However, in the present experiment, cultivation of RCG decreased N₂O emission to an extent that could offset the increase in CH₄ emission at –10 and –20 cm GWL, but apparently not at 0 cm GWL; the latter case being due to peak emissions in N₂O after fertilization events in RCG. Regarding the overall emission, the CO₂ emissions from ER was clearly the dominant RCG-derived GHG flux. Yet, CO₂ flux from ER would to a large extent be counterbalanced by gross photosynthesis which expectedly was similar at all GWL treatments (based on the similar biomass yields), though CO₂ flux from photosynthesis was not measured in this annual study. Yet, a photosynthetic uptake of 6.2 kg CO₂ m⁻² was measured from RCG mesocosms at 0 cm GWL during the growing season from May to September 2013 (S. Karki, unpublished results) reflecting that RCG potentially can turn the rewetted ecosystem into a sink of atmospheric CO₂. Adaptation or selection of RCG varieties that thrive especially well under distinct climate and shallow GWL conditions could further help to fulfill this potential.

5 Conclusions

The present study to our knowledge is the first to compare the annual GHG emission from RCG and bare soil treatments of rewetted peatland at controlled GWL. The following conclusions were derived: (i) soil respiration decreased with increasing GWL from –20 to –10 to 0 cm, but RCG-derived ER was similar at all three GWL resulting in

BGD

11, 13309–13341, 2014

Effect of reed canary grass cultivation on GHG emission from peat soil

S. Karki et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Effect of reed canary grass cultivation on GHG emission from peat soil

S. Karki et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



the highest contribution of RCG to total ER (85 %) at 0 cm GWL, (ii) cultivation of RCG increased CH₄ emission at all GWLs, but relatively most at –20 cm GWL, (iii) N₂O emissions decreased at –10 and –20 cm of GWLs due to RCG cultivation especially during winter; winter emissions were an important component of annual emission from bare soil, (iv) in terms of GWP, the increase in CH₄ emissions due to RCG cultivation was more than off-set by the decrease in N₂O emissions at –10 and –20 cm GWL, (v) CO₂ emissions from ER (the dominant RCG-derived GHG flux) could be balanced by photosynthetic CO₂ uptake at all three GWL as indicated by the large and similar above-ground biomass yields at all GWL, signifying a potential of RCG cultivation to turn the rewetted peatland into a sink of atmospheric CO₂.

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Effect of reed canary grass cultivation on GHG emission from peat soil

S. Karki et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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BGD

11, 13309–13341, 2014

Effect of reed canary grass cultivation on GHG emission from peat soil

S. Karki et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

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Effect of reed canary grass cultivation on GHG emission from peat soil

S. Karki et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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Effect of reed canary grass cultivation on GHG emission from peat soil

S. Karki et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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Effect of reed canary grass cultivation on GHG emission from peat soil

S. Karki et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)



[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



Table 1. Concentration of sulphate, ammonium, and nitrate (mg L^{-1}) in ground water samples collected from piezometers from bare soil and reed canary grass (RCG) mesocosms at different ground water levels (GWL).

Treatment and date	SO_4^{2-} (mg L^{-1}) at GWL			NH_4^+ (mg L^{-1}) at GWL			NO_3^- (mg L^{-1}) at GWL		
	0 cm	-10 cm	-20 cm	0 cm	-10 cm	-20 cm	0 cm	-10 cm	-20 cm
Bare soil									
26 Jul 2012	20.7	33.4	54.2	0.9	0.7	0.0	0.4	0.6	0.7
24 Aug 2012	6.6	10.0	56.9	1.4	2.0	0.1	0.2	0.1	2.0
26 Sep 2012	41.7	13.5	52.9	3.4	4.3	0.3	0.1	< 0.1	1.8
5 Nov 2012	2.7	1.8	46.2	3.6	3.5	0.7	< 0.1	0.1	0.5
30 Nov 2012	2.1	4.7	41.9	4.0	3.2	0.8	< 0.1	< 0.1	0.1
4 Jan 2013	2.3	4.0	29.7	2.9	3.8	0.4	0.1	0.3	1.0
6 May 2013	1.3	1.4	22.7	5.1	4.6	0.7	0.7	0.1	0.6
11 Jun 2013	2.0	2.1	18.1	5.8	3.8	0.2	< 0.1	< 0.1	0.6
16 Jul 2013	1.3	1.4	17.2	10.2	5.9	0.6	< 0.1	< 0.1	2.5
RCG									
26 Jul 2012	10.4	11.4	9.9	2.9	1.2	2.0	2.9	0.4	0.1
24 Aug 2012	3.8	2.4	9.2	0.2	0.1	0.5	< 0.1	< 0.1	0.1
26 Sep 2012	2.0	10.6	3.9	0.6	0.2	0.9	0.1	0.1	0.1
5 Nov 2012	5.6	3.6	2.3	0.8	0.1	1.0	< 0.1	< 0.1	< 0.1
30 Nov 2012	4.1	3.2	3.9	0.6	0.4	0.8	0.5	0.2	0.1
4 Jan 2013	2.3	3.5	5.3	1.5	0.1	0.7	0.1	0.5	0.1
6 May 2013	2.0	1.8	3.5	1.7	0.4	0.2	< 0.1	3.1	< 0.1
11 Jun 2013	3.4	4.5	4.7	0.3	0.8	0.1	< 0.1	0.1	0.3
16 Jul 2013	3.3	1.8	10.6	1.5	1.5	0.1	0.1	< 0.1	0.3

Effect of reed canary grass cultivation on GHG emission from peat soil

S. Karki et al.

Table 2. Statistical main effects of vegetation (i.e., reed canary grass cultivation or bare soil), ground water level (GWL), and date on fluxes of CO₂, CH₄ and N₂O as explored with linear mixed models.

Variables	CO ₂			CH ₄			N ₂ O		
	DF	<i>F</i> value	<i>P</i> value	DF	<i>F</i> value	<i>P</i> value	DF	<i>F</i> value	<i>P</i> value
Vegetation	1	956.2	< 0.001	1	165.8	< 0.001	1	0.5	< 0.001
GWL	2	32.2	< 0.001	2	15.4	< 0.001	2	3.1	0.02
Date	28	75.6	< 0.001	28	25.8	< 0.001	28	< 0.1	< 0.001

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Effect of reed canary grass cultivation on GHG emission from peat soil

S. Karki et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Table 3. Parameter estimates (b_1 , b_2 , b_3 and b_4) for CO₂ flux models. Uncertainties shown in parentheses are standard error of parameter estimates. Also shown are correlation coefficients (r) between observed and modelled data and modeling efficiencies (ME).

Treatment	CO ₂ flux model	b_1 (mg CO ₂ m ⁻² h ⁻¹)	b_2 (mg CO ₂ m ⁻² h ⁻¹ cm ⁻¹)	b_3 (K)	b_4	r	ME
Reed canary grass	Model 1	49.6 (3.8)	0.4 (0.1)	259.1 (15.5)	5.0 (0.7)	0.90	0.82
Bare soil	Model 2	79.1 (6.9)	5.7 (0.5)	286.4 (24.1)	na	0.68	0.46

na: Not applicable.

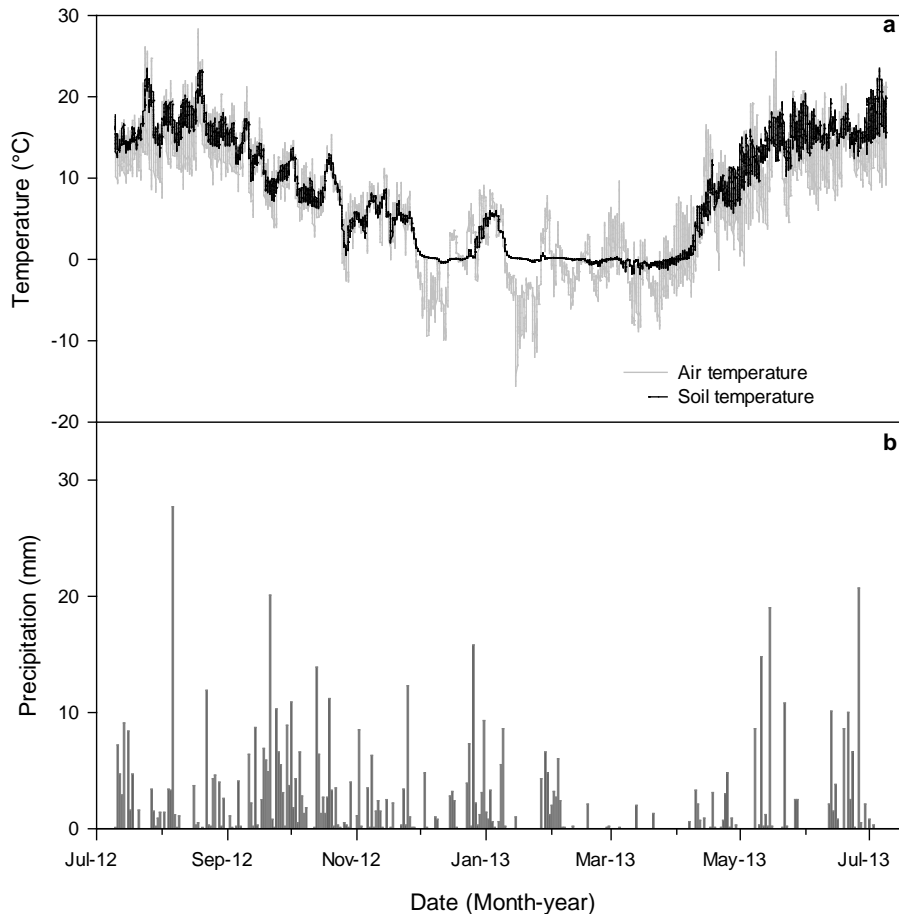


Figure 1. (a) Hourly air temperature at 2 m height at the semi-field facility and hourly average soil temperature at 5 cm depth across all mesocosm treatments, and (b) daily precipitation at the semi-field facility during the study period (July 2012 to July 2013).

BGD

11, 13309–13341, 2014

Effect of reed canary grass cultivation on GHG emission from peat soil

S. Karki et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Effect of reed canary grass cultivation on GHG emission from peat soil

S. Karki et al.

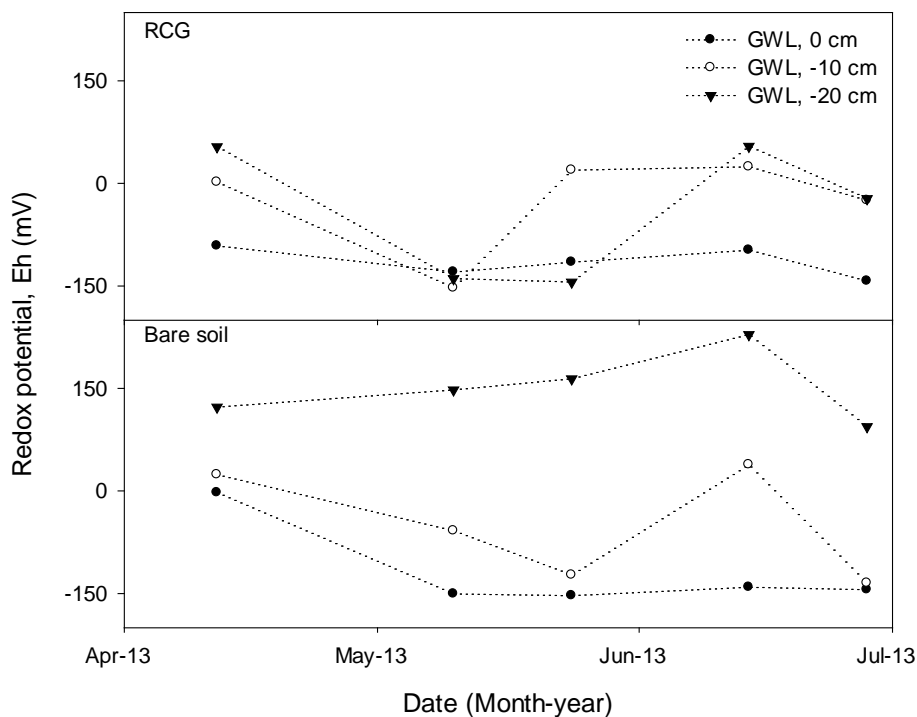


Figure 2. Redox potential (Eh) at different ground water levels (GWL) from reed canary grass (RCG) and bare soil mesocosms. Eh was measured at 20 cm soil depth from April to July 2013.

Effect of reed canary grass cultivation on GHG emission from peat soil

S. Karki et al.

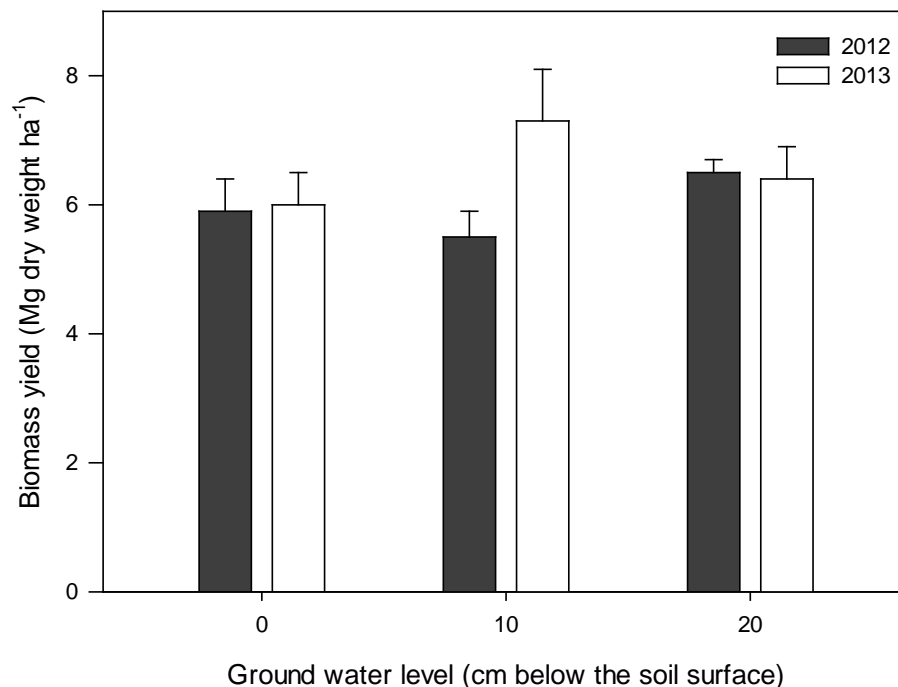


Figure 3. Mean dry biomass yield (Mg ha⁻¹) from mesocosms at different ground water level in 2012 and 2013. Error bars show standard error ($n = 5$).

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Effect of reed canary grass cultivation on GHG emission from peat soil

S. Karki et al.

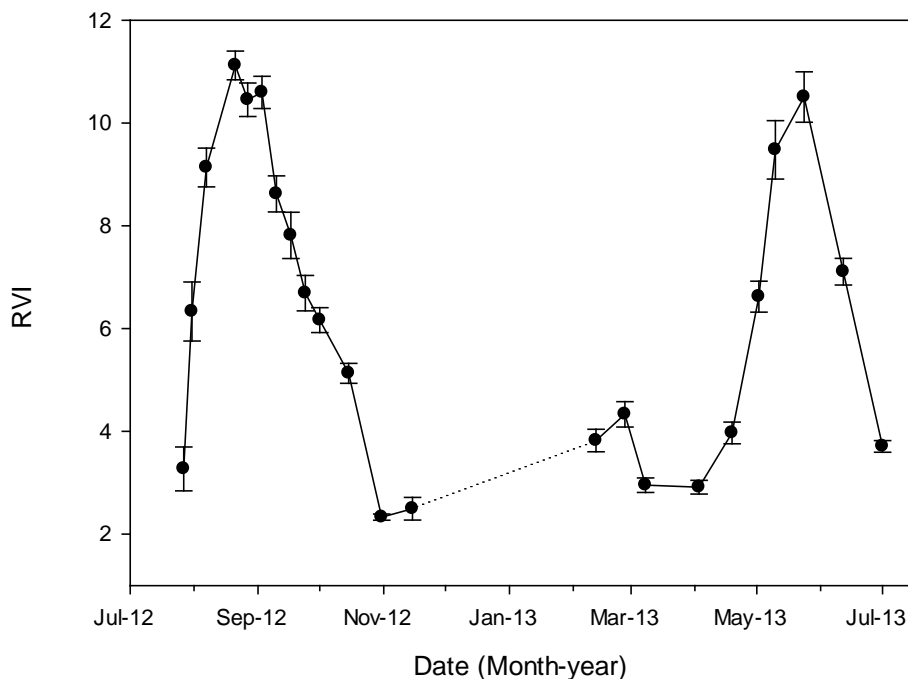


Figure 4. Average ratio vegetation index (RVI) development during the measurement period across all ground water levels. Error bars show standard error ($n = 15$). Dotted line represent the winter period when RVI was not measured due to ice and snow.

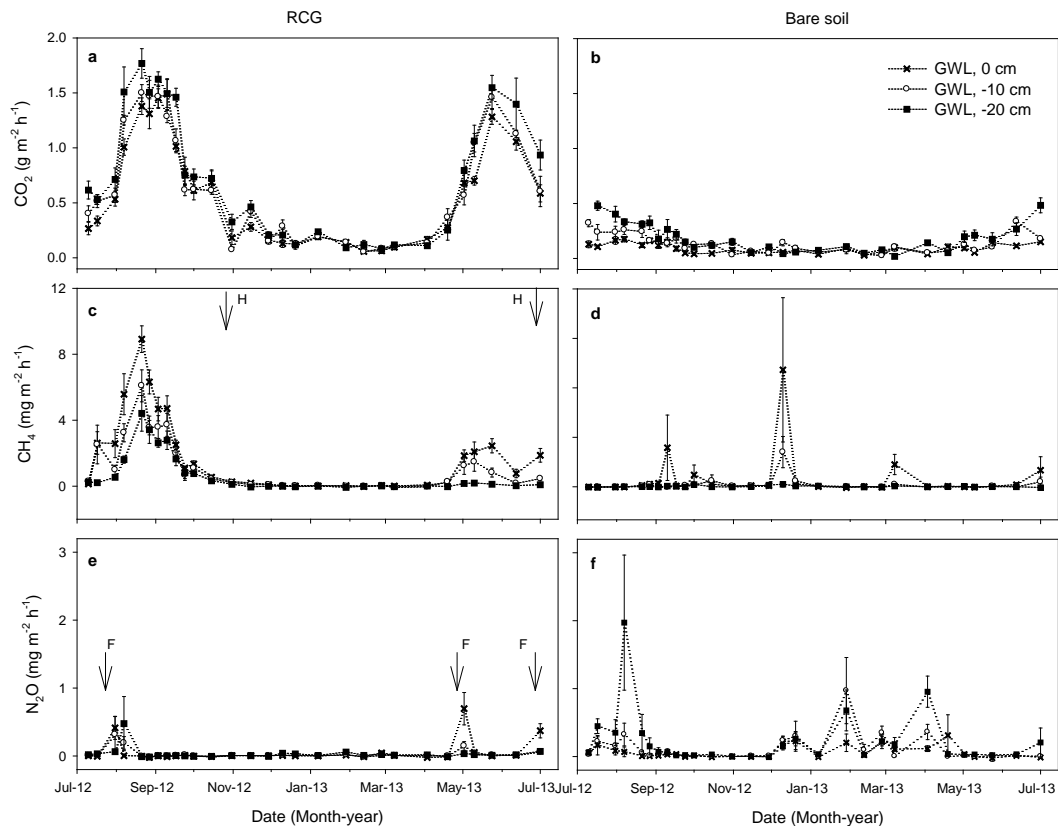


Figure 5. Time course of greenhouse gas fluxes from the rewetted peat soil mesocosms during July 2012 to July 2013 in treatments with RCG cultivation (left panels) and bare soil (right panels). Data are shown for (a, b) CO₂ fluxes from ecosystem respiration, (c, d) CH₄ fluxes, and (e, f) N₂O fluxes. All data are mean and standard error of five replicates from each of the three ground water levels (GWL) at 0, -10 and -20 cm. Arrows marked by H indicate the times of harvest and arrows marked by F indicate the times of mineral fertilization.

Effect of reed canary grass cultivation on GHG emission from peat soil

S. Karki et al.

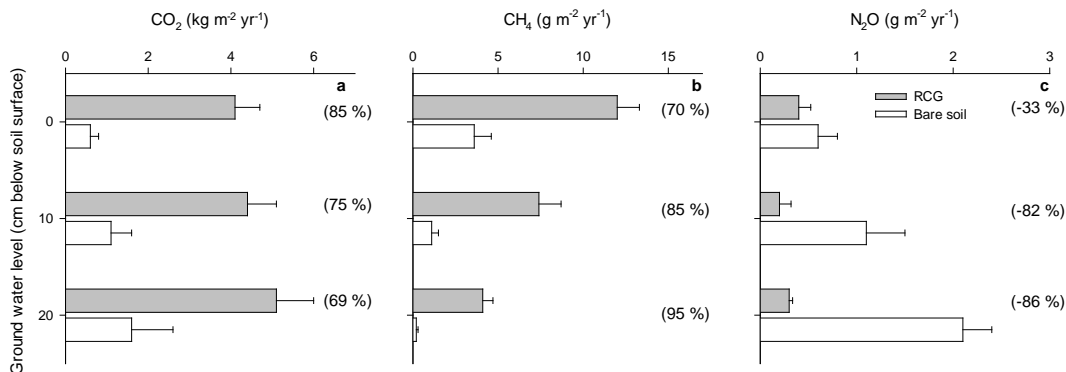


Figure 6. Annual fluxes of **(a)** CO₂ from ecosystem respiration, **(b)** CH₄, and **(c)** N₂O from the rewetted peat soil mesocosms during July 2012 to July 2013 in treatments with RCG cultivation (gray bars) and bare soil (white bars) at ground water levels of 0, –10 and –20 cm. Error bars for CO₂ data show the standard error (SE) derived from SE of model parameters. For CH₄ and N₂O, data are shown as mean and SE of individual mesocosms ($n = 5$). Numbers in parentheses indicate the contribution of RCG in total emission at the different GWLs.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Effect of reed canary grass cultivation on GHG emission from peat soil

S. Karki et al.

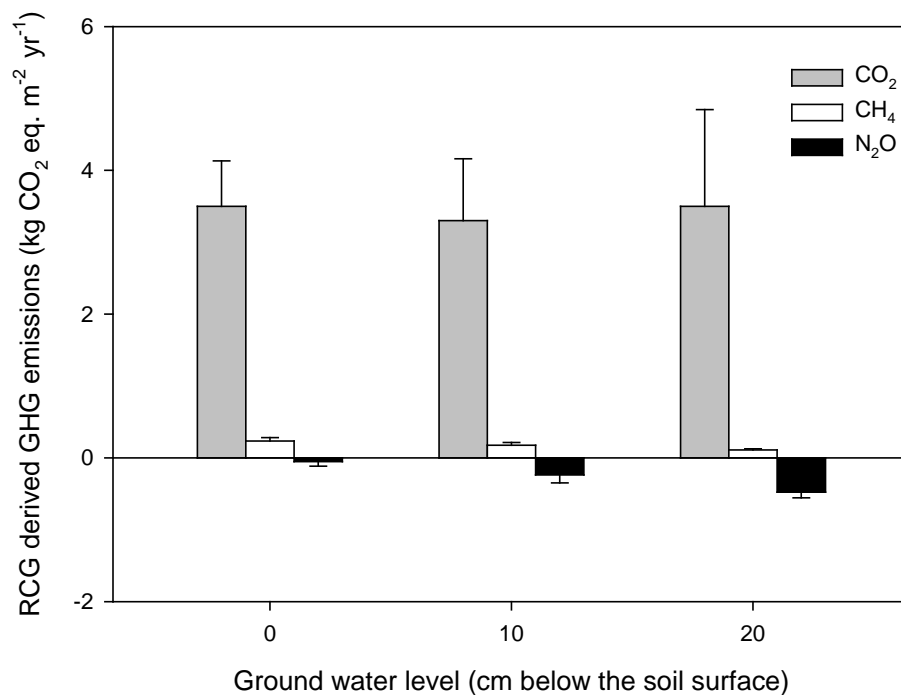


Figure 7. Plant-derived CO₂, CH₄ and N₂O emissions for RCG treatments at different ground water levels as compared in terms of CO₂ equivalents (CO₂ eq.).

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[◀](#)

[▶](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)

