

Agricultural Research Initiative

Final Report

**The impacts of agricultural drainage on greenhouse gas emissions and carbon
balance of boreal peatlands in western Newfoundland**

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Section 1: Executive Summary

The demand to develop peatlands for agriculture has been continuously increasing in Newfoundland and Labrador (NL) and throughout certain parts of the rest of Canada. This land-use pattern causes changes in vegetation communities and hydrological and biogeochemical processes in boreal peatlands. We designed a study to examine the impacts of drainage and agricultural activities on GHG emissions in northern peatlands in western Newfoundland. Our measurement was conducted during the growing season of 2013 from May to October 2013.

The following conclusion can be made based on our measurement during the growing season of 2013. (1) In terms of CH₄ emissions, the natural peatlands are higher than the pasture that is higher than the drained peatlands. (2) During the growing season, all the vegetated areas show a strong CO₂ sink for the three land use types. In terms of NEE, the pasture is significantly higher than the drained peatlands, which is higher than the natural peatlands. (5) There is a similar ER between the natural and drained peatlands, but the pasture has a significantly higher ER. The significantly higher ER along with a significantly higher NEE in the pasture indicate that the vegetation in the pasture presents a significantly higher photosynthesis. It is highly recommended that multi-year measurements be supported to better understand the hydrological, biogeochemical and biological controls of these changes in greenhouse gas emissions caused by drainage and agricultural development in northern peatlands, which will be the critical entry point for sustainable usage and development of northern peatlands.

Section 2: Background and Rationale for Investigation

Peatland ecosystems have been carbon (C) sinks for the past 5,000-10,000 years due to the positive balance between net primary production (NPP) and peat decomposition under consistently anoxic conditions [1,2]. On a global basis, peatlands uptake an average of $\sim 20\text{-}30 \text{ g CO}_2\text{-C m}^{-2} \text{ year}^{-1}$ [1,2], and approximately 550 G t of C ($1 \text{ G t C} = 10^{15} \text{ g C}$) is stored in boreal peatlands [1]. Therefore, boreal peatlands represent a globally important reservoir of soil carbon [1]. Peatlands have provided important ecosystem services of carbon and greenhouse gas (GHG) sequestration for thousands of years [2]. Despite this, there is a global concern that boreal peatlands represent a potential source of GHG due to enhanced mineralization of soil organic matter resulting from drainage, agriculture, and other anthropogenic disturbances, leading to climate change [3-6]. Climate change, with increases in temperature and reductions in soil water storage, is predicted to further elevate the risk of GHG emissions from boreal peatlands [7]. **Therefore, understanding of how human disturbances and climate change affect trace gas exchange and carbon balance in boreal peatlands is of critical importance to land-use planning and management of boreal peatlands and development of sound policy on mitigating climate change in NL and Canada.** In fact, supplemental guidance for greenhouse gas accounting in managed wetlands is currently under development and will include peatland drainage as activities that must be reported in national greenhouse gas inventories [8].

Peatlands may produce and emit methane (CH_4) [2], a potent GHG that is 25 times more effective than CO_2 in absorbing long-wave radiation in the atmosphere with a 100-year time horizon [9]. This is due to their high soil water content subjecting peat to anaerobic decomposition [10]. Wetlands are the largest natural CH_4 source, of which boreal peatlands contribute $\sim 10\%$ [11]. CH_4 flux is an important component of the total C balance for a fen, although it is only as low as $1 \text{ g C m}^{-2} \text{ yr}^{-1}$ for a dry bog [12].

Another important component in the total C balance of boreal peatlands is the waterborne C export, dominated by dissolved organic carbon (DOC) components [13-15]. Peat pore water normally

shows a high DOC concentration, since consistently anoxic conditions enhance DOC production, and acidity and low nutrient availability restrict the degradation of DOC [16]. This waterborne C efflux can consume up to 30% of net ecosystem production (NEP) [14]. Further, peatland ecosystems are linked with other ecosystems within a catchment through lateral linkage of hydrology and their waterborne C flux [17]. Both composition and magnitude of DOC efflux from terrestrial ecosystems will significantly affect the biogeochemical and ecological functions of downstream aquatic ecosystems [18]. Therefore, there is a pressing need to measure all three constituents of C flux, i.e. CO₂, CH₄ and DOC, from peatlands to fully understand the C cycling of boreal peatlands.

Studies have shown that trace gas exchange and carbon balance in boreal peatlands are susceptible to climate change [7,10,19-21], and human disturbance through changes in hydrology [4,22]. A strong feedback exists between peatland C cycling and climate change [10]. Further, boreal peatlands have been subject to significant human disturbance through drainage [4,23], causing changes in soil hydrological and physical properties. This will potentially affect each component of the carbon balance (i.e. CO₂, CH₄, and DOC), and N₂O flux of boreal peatlands. Moreover, changes in soil hydrological and thermal regimes in boreal peatlands due to drainage will alter the magnitude and composition of DOC and particulate organic carbon (POC) export to the downstream aquatic systems [17,24]. This will further affect the ecological function of aquatic systems.

Most of the unmanaged boreal peatlands have negligible emission of N₂O and they can even act as a small sink for N₂O [4], though some arctic peatlands may emit significant amount of N₂O [25]. Therefore, studies on GHG exchange of unmanaged peatlands have focused on the CO₂ and CH₄ exchanges [13,14,26]. N₂O flux is well correlated with soil nitrogen quantities and their availability [5], which is regulated by the water table depth in peatlands [4]. Peatland drainage increases the availability of oxygen and mineral nitrogen, and alters the soil carbon to nitrogen ratio (C:N ratio) [27]. This process may stimulate N₂O production in peatland soils [4], resulting in a much higher emission rate of N₂O [3],

even without N fertilization from managed peatlands [4]. Thus, to fully capture the characteristics of GHG emission from drained peatlands, it is essential to examine the N₂O fluxes and their environmental controls, because N₂O, a much stronger greenhouse gas, is 298 times more effective than CO₂ in absorbing long-wave radiation in the atmosphere with a 100-year time horizon [9].

Greenhouse gas (GHG) emission from drained and cultivated peat soils represents a great deal of uncertainty due to limited measurements and insufficient spatial coverage of measurements [3,4,27]. Moreover, there is large spatial variability associated with peatland ecosystems. Furthermore, data on complete GHG emission from peatlands drained for agriculture in NL and Canada are very limited. Therefore, more examination is needed to reduce this uncertainty and improve our understandings on GHG emission from drained and cultivated peatlands. Further, the knowledge gained from existing studies, focusing on croplands with peat soils [4], cannot directly be transferred to agriculture peatlands used for pastures in NL. **Therefore, there is urgent need to examine how agricultural activities, in particular, affect GHG emission from peatlands in NL and Canada. Such knowledge is vital for assessing and reporting accurate annual GHG inventory to assist in mitigating climate change** [28,29]. Moreover, to assess the GHG benefits for management of peat soils, it is essential to consider a full picture of GHG fluxes (i.e., CO₂, CH₄, and N₂O) from managed peatlands [30].

Peatlands drained for agriculture (hereafter called agriculture peatlands) may have a very different profile of GHG emission and DOC efflux than natural peatlands. Agriculture peatlands have normally shown a net loss of CO₂ due to a high decomposition rate of peat soil. They may function as a neutral or even small sink of CH₄ if not considering emissions from drainage ditches, where the hotspots of methane emission were found to contribute >84% of the ecosystem-scale methane emission [3]. Agriculture peatlands may significantly increase N₂O emission even without N-fertilization [3,4,6]. Moreover, agricultural drainage may reduce DOC concentration in soil water due to (1) a higher rate of biodegradation resulting from drainage and (2) increased DOC efflux because of increased runoff from

drained peatlands [17]. Here I propose a study in western Newfoundland, where there is increasing agricultural activity occurring on peatlands, to examine how agricultural activities alter the hydrological and biogeochemical functions of boreal peatlands. Each constituent of GHG (such as CO₂, CH₄ and N₂O) and carbon balance (such as CO₂, CH₄ and DOC) from agriculture peatlands will be examined.

Significant anthropogenic drainage has occurred on boreal peatlands for agricultural development. The demand to convert peatlands for agriculture has been increasing in Newfoundland, and throughout certain parts of the rest of Canada. This land-use pattern causes an alteration of vegetation communities and hydrological and biogeochemical processes in peatlands. We examined the consequences of these shifts in western Newfoundland. The peatlands of Newfoundland are not unique but they represent a significant fraction of the land cover, as they do in all of the boreal and subarctic regions in Canada. The overarching objective of this project **was to examine the impacts of agricultural drainage on greenhouse gas (GHG) emissions (i.e., CO₂, CH₄ and N₂O) in boreal peatlands in western Newfoundland. The specific objectives of this proposed study were to determine: (1) how agricultural drainage changes the physical and hydrological properties of boreal peatlands; (2) how these hydrological and physical changes influence trace gas exchange of CO₂, CH₄ and N₂O between peatlands and the atmosphere and the magnitude and composition of waterborne carbon export as dissolved organic carbon (DOC); and (3) whether the same or different relationships exist between environmental controlling variables and trace gas exchange and DOC export in agricultural peatlands as in natural or pristine peatlands.**

To our best knowledge, this study was the first project specifically designed to examine the greenhouse gas exchanges and carbon balance, and environmental controls on them in peatland ecosystems in NL. The proposed study directly made a significant contribution to fulfill one of the objectives of the Agricultural Research Initiative (ARI) Program, i.e. “**enhance environmental sustainability**”. This proposed study fitted in the following strategic area: “**soil, land and water**”.

resource management. It made a contribution to “**improving the competitiveness, sustainability and productivity of the sector**” and “**changing attitudes within the sector about R&D and innovation**”.

Section 3: Funding and Partnerships

Although the funding from the ARI project was only for one year, i.e., 2013-2014, this project was designed for a multi-year study. In this final report, I presented the funding supports from the ARI, as well as other partnerships. The funding support from the ARI and its use will be presented first, and followed by the contribution from other sources.

I only presented the approximate use of the funding from the ARI, and the details can be found from our financial claim. The awarded funding from the ARI was \$176,912. One post-doctoral researcher, Dr. Junwei Luan, has been supported by this funding from April 1, 2013 to March 31, 2014. He has been involved in forming our research design, establishing the experimental site, installing the field instruments, conducting the field observation and sampling, processing and analyzing the collected samples in the laboratory, examining the data and preparing the research manuscripts. One undergraduate research technician and assistant was hired to assist in collecting field samples and processing the samples in the laboratory from June 2013 to December 2013.

The majority of this funding from the ARI was used to establish our research infrastructure for this project. All the research instruments acquired by the ARI funding will continue to make a key contribution to the success of this proposed multi-year project. The ARI funding supported to purchase one complete eddy covariance (EC) systems along with other automatic data collection systems, such as data loggers, collars, chambers, vials, and other sensors, and one carbon dioxide isotope analyzer, which can help us identify the carbon allocation to each component of the ecosystem after the carbon has been absorbed by the vegetation from the atmosphere and examine the contribution of each component of the ecosystem to the total carbon balance. In addition, a portable hyperspectral field spectroradiometer was purchased by the ARI funding. This field spectroradiometer will be used to examine the relationship between hyperspectral remote sensing data and photosynthetic parameters, and to establish the relationships between remote sensing vegetation index (VI) and vegetation biophysical properties (e.g.

biomass and canopy height), in boreal peatlands with different disturbance regimes. This field spectroradiometer was only purchased in early January 2014. Therefore, we were not able to employ this instrument for our research yet during the growing season of 2013. No results from the spectroradiometer measurement were presented in this report.

This multi-year project cannot be succeeded without the funding support from other sources. We have received the funding from Canada Foundation for Innovation (CFI), Research & Development Corporation (RDC), NL, and Institute for Biodiversity, Ecosystem Science and Sustainability (IBES), NL. We have received \$225,000 from CFI and the Leverage R&D of RDC to establish the core research infrastructure of this proposed study. The research infrastructure that was acquired by this funding source included the other EC system, total organic carbon/total nitrogen (TOC/TN) analyzer, and greenhouse gas chromatography (GC) for CO₂, CH₄ and N₂O analysis. We have received \$100,000 from the Ignite R&D program of RDC. The Ignite R&D funding was used to purchase an ultraportable greenhouse gas analyzer for CO₂ and CH₄ analysis in the field. Starting from April 1, 2014, this funding, along with the funding from Regional Collaboration Research Fund (RCRF) of RDC (\$30,000) and Humber River Basin Project (\$120,000), will be used to continue to support two post-doctoral research fellows to carry out this project. With the complimentary support (\$8,000 per graduate student per year) from the School of Graduate Studies (SGS) of MUN, the graduate stipend funding (\$22,500 per year) from IBES is able to support two Ph.D. students who will continue to carry out this project after 2014. One Ph.D. student (Ms. Mei Wang) was recruited in September 2013. She will continue to make a significant contribution to this project while carrying out her Ph.D. thesis research under the support of all the funding sources, including the ARI. The second Ph.D. student will be recruited in September 2014 to be involved in this project as well.

All the research instruments purchased using the ARI funding will continue to make a significant contribution to the success of this proposed multi-year projects. They will be used by the Ph.D. students,

post-doctoral researchers and Dr. Jianghua Wu after 2014 to achieve the overarching objective of this project, i.e., understanding and examining the impacts of agricultural drainage on greenhouse gas emission in boreal peatlands, and continue to make their due contribution to **improving the competitiveness, sustainability and productivity of the agricultural sector in the province of Newfoundland and Labrador**

Section 4: Methods and Implementation

4.1 Site description and experimental design

Our research sites are located in Robinsons pasture, 100 km southeast of Corner Brook, Newfoundland and Labrador (NL) (48° 15.842'N, 58° 39.913' W). It is an oceanic temperate climate with an annual rainfall of 1340 mm and maximum and minimum yearly temperatures of 9°C and 1°C respectively (1981-2010). Our site is a peatland complex, comprising of discontinued pasture, drained peatlands, and natural peatlands. The discontinued pasture was converted from drained peatland 35 years ago, and was abandoned after 10 years of active pasture. It was composed of patches of different dominant species, including reed canary grass (*Phalaris arundinacea*) dominated patches, various lower herbaceous and graminoid species (*Carex* spp., *Ranunculus acris*, *Ranunculus repens*, *Hieracium* sp.) dominated patches, and clumps of low shrubs overtopped by the tall grass, including sweet gale (*Myrica gale*), labrador tea (*Rhododendron groenlandicum*), mountain fly honeysuckle (*Lonicera villosa*), rhodora (*Rhododendron canadense*), and chokeberry (*Photinia* sp.). The drained peatlands were with a substrate mostly of a brown bog moss (*Sphagnum* sp.) covered partly with several species of grey reindeer lichens (*Cladina* spp.). Patches of low ericaceous shrubs, such as huckleberries (*Gaylussacia* spp.), were interspersed with a variety of other shrubs (*Rhododendron groenlandicum*) and herbs (*Trichophorum cespitosum*) typical of this type of peatland on the island of Newfoundland. The natural peatlands are wetter than drained peatland and include some wet depressions and peatland pools. The same brown *Sphagnum* moss occurs on the drier hummocks and many of the same ericaceous shrubs and herbs occur, but with more lush and more vigorous growth. Microtopography, comprising of hummocks and hollows, exists in the natural peatlands and drained peatlands, but it disappeared in the discontinued pasture peatlands.

In the discontinued pasture, three plots were established, and in each plot four subplots were established to cover four communities, each of which has its dominated species, such as reed canary grass dominated, lower herbaceous and graminoid dominated, sweet gale dominated, labrador tea dominated, and drainage ditches. Three plots were also established in drained peatlands, and in each plot three subplots were established to cover one hummock with shrubs and mosses as dominant vegetation, hollow with sedges and mosses as dominant vegetation, and drainage ditch. In natural peatlands, three plots were set up, and in each plot three subplots were set up to cover one hummock with shrubs and mosses as dominant vegetation, hollow with sedges and mosses as dominant vegetation, and pool. In total, 33 collars were installed.

4.2 Measurement of dissolved organic carbon (DOC) concentration in the soil water and the exchange of CO₂, CH₄ and N₂O between peatlands and the atmosphere

Common approaches to measuring greenhouse gas (GHG) flux include static chamber, which measure GHG flux at micro-scale units covering only $\sim 0.05 \text{ m}^2$ and facilitate identification of within-ecosystem variability, and eddy covariance (EC), which provides an integrated ecosystem-scale GHG flux over the entire footprint. EC is a direct measure of the turbulent exchanges of CO₂ and CH₄ between the biosphere and the atmosphere [31] and has become a standard technique for continuous measurements of trace gas flux. In combination with the chamber measurements, EC provides information on the net exchange of CO₂ and CH₄ and the processes responsible for it. Moreover, EC can provide the flux measurement year round while most of the chamber measurements only focus on the snow-free period. In evaluating the net effects of a land use and land cover change, the annual carbon (C) budget, driven by the local meteorological conditions, is determined in part by the length of the C uptake period [32,33]. The rapid transition between CO₂ source and sink present in the spring and fall can be captured using EC. Continuous measurements of net CO₂ and CH₄ flux will thus provide a rigorous data

set to evaluate the net effect of drainage and land cover change and validate the peatland ecosystem models.

Paired EC towers, equipped with a 3-D sonic anemometer, enclosed path CO₂/H₂O (LI-7200, LiCor, USA) and open-path CH₄ analyzers (LI-7700, LiCor, USA), were installed for this study. The first EC system was purchased using the award from CFI and RDC's Leverage R&D, which was installed at the natural peatland site. The second EC system was purchased using the ARI funding, which was installed at the pasture site. Both of them were installed at the same time in September 2013. Data are measured at 10Hz, stored on flash cards and processed using EddyPro software freely offered by LiCor, USA. Post-processing and gap-filling followed the standard Fluxnet procedures [13]. A standard suite of environmental variables, including air temperature, relative humidity, radiation, precipitation, water table depth, soil temperature and soil moisture, were also be measured by the micrometeorological sensors. The paired EC towers will be continuously operated at the research sites for at least 3 years after 2014, since the data from the EC towers will be used to validate the peatland ecosystem models (i.e., MWM and Wetland-DNDC) that we will further develop with the inclusion of drainage and land-use change based on our further understanding of the biogeochemical processes in the managed peatlands from this study.

Due to the failure of the LI-7700 from the pasture site, we were not able to obtain a complete measurement data from the pasture site since the beginning. We requested a replacement for this defect LI-7700, and the new LI-7700 was shipped to me in early March 2014. No main power was available at our research sites. Therefore, we installed the solar power system to supply the power for the EC system. Due to the extreme cold weather this winter, the batteries of the solar power system were drained completely and finally failed to work in early January 2014. The batteries had to be shipped back to the factory for restoration. The restored batteries were shipped to us in late March 2014. They would be shipped back to the research sites in early April 2014 and new protective measures would be installed in

the solar power system to protect the power supply. The EC systems would be back to work normally from then on and continue to provide us with a continuous measurement of the exchange of water, CO₂, and CH₄ between peatlands and the atmosphere. One of my Ph.D. students will continue to work on these two EC systems to examine how agricultural drainage affects the biogeochemical and hydrological processes of northern peatlands. Due to the power outage and instrument failure, the results presented in this report did not include the measurement from the EC systems. Our results were primarily derived from the static chamber measurements.

Boardwalks were constructed to prevent any disturbance to peat gas storage and emission during our measurements and to prevent any damage to the vegetation when regularly visiting the site. The PVC collars (26 cm in inner diameter) were permanently inserted into the peat to a depth of 10-15 cm of each subplot one month before the start of our measurements. The upper part of the collars had a groove for the water seal needed for the chamber measurements. Adjacent to each of the collars, perforated ABS pipes with sealed bottoms were inserted into the peat to measure water table depth. Peat temperatures at the depth of 5 cm and 20 cm were also measured regularly near the collars when the gas samples were taken. Our measurements were conducted biweekly or monthly from May to October in 2013, and we will continue to make the similar measurements to better capture the annual and seasonal variation and their environmental controls for the next three years.

CH₄ emissions and CO₂ exchange rates of each subplot were measured by an Ultra-Portable Greenhouse Gas Analyzer (Los Gatos Research, CA, USA, funded by RDC's Ignite R&D) connected to a transparent chamber (made by clear acrylic tube, which allows 92% light transmission) or an opaque chamber (made by PVC tube). Both chambers were 50 cm in height and 26.3 cm in diameter. Air from the chamber passed through 4 m of tubing with an internal diameter of 3 mm to the analytical box; after the non-destructive analysis, it went back to the chamber. There was a battery-operated fan in the

chamber to help mix the air and cool the chamber while doing the measurement. The chamber was equipped with a capillary tube to retain atmospheric pressure inside the chamber when sampling.

The gas concentration data were collected at 1 Hz rate and the data acquisition lasted for three minutes for both chambers. Opaque chamber measurements were carried out shortly after the transparent chamber measurement was made. All fluxes were adjusted for field sampling temperature, headspace volume, and chamber area, and calculated by linear regression using all time points sampled. The net ecosystem CO₂ exchange (NEE) and methane emission rate with light were obtained by the transparent chamber measurements, and the total release of CO₂ (i.e., ecosystem respiration, R_{ECO}) and methane emission rate without light were obtained by the opaque chamber measurements. During the measurements, soil temperatures were measured near the collars with a temperature probe at the depths of 5 cm and 20 cm. The water table depth (WTD) was measured from the perforated pipes with a ruler. Soil moisture at 0-5 cm was measured with a GS3 probe connected to a ProCheck reader (Decagon Devices).

To obtain N₂O flux, air samples were extracted from the opaque static chambers using 30 ml syringes equipped with a three-way stopcock. The samples were taken at a 10 minutes interval for 30 minutes period. For each plot, we collected four air samples at 0, 10, 20 and 30 minutes after the chamber was covered by a head-space cover. For each sampling date, a total of 132 air samples were collected. Air samples were transferred to the 12 ml Labco exetainer® vials (Labco, UK). Air samples were analyzed using Bruker GHG gas chromatography (GC) equipped with thermal conductivity detector (TCD), flame ionization detector (FID) and electron capture detector (ECD) (funded by CFI and RDC's Leverage R&D), to measure CO₂, CH₄ and N₂O concentration. For each sequence of gas samples from a chamber, the flux (F , in mg m⁻² h⁻¹) was calculated as:

$$F = dC/dt \times \rho V/A \quad (1)$$

where dC/dt is the rate of change in concentration with time (t); ρ is the density of air in mol m^{-3} ; V is the volume of air within the chamber in m^3 , and A is the surface area within the chamber in m^2 . dC/dt was derived from the linear regression of the four gas samples against time over 30 minutes of measurement period. Data were excluded if the regression coefficient was less than 90%. The result for N_2O flux was not included in this report because we have not finished our analysis yet.

Soil water samples were taken from a depth of 10-15 cm, representing the rhizospheric zone, and 40-45 cm, representing the anoxic zone, besides the installed collars using 60 ml syringes with a three-way stopcock. MacroRhizons (Rhizosphere Research Products, the Netherlands), with a porous part with an outer diameter of 4.5 mm and a pore size of $0.15 \mu\text{m}$, were installed besides each collar to extract the soil water at the 10-15 cm depth. A 1/8" PVC pipe with the bottom 15 cm perforated, the bottom permanently sealed and the top covered by a cap was inserted into 45 cm depth of the soil. Every time when gas samples were taken a soil water sample was extracted from the PVC pipe using a 60 ml syringe, and then the extra water was removed to empty the PVC pipe. Water samples were first infiltrated through a Cole-Parmer nylon syringe filter of 25 mm diameter with a pore size of $0.45 \mu\text{m}$ and then transferred to a 20 ml vial. The soil water samples were analyzed for DOC and TN concentration using the Shimadzu TOC/TN analyzer (funded by CFI and RDC's Leverage R&D). The results for DOC and TN concentration were not presented in this report, because we have not completed our analysis yet.

Section 5: Results and Discussion

5.1 Abbreviations and flux computation

We used the following abbreviations to represent our sampling plots and present our results.

NU: Hummock of natural peatlands

NO: Hollow of natural peatlands

NP: Pool of natural peatlands

DD: Drainage ditch of drained peatlands

DO: Hollow of drained peatlands

DU: Hummock of drained peatlands

PD: Drainage ditch of pasture

PG: lower herbaceous and graminoid dominated in pasture

PGG: reed canary grass dominated in pasture

PGS: labrador tea dominated in pasture

PRS: sweet gale dominated in pasture

We employed the equation (2) to calculate the ecosystem-scale flux using a spatially area weighted average for natural peatlands, drained peatlands and pasture.

$$\text{Flux} = \sum_{i=1}^n W_i \times F_i \quad (2)$$

Where W_i is area percentage of each representative plot at each ecosystem; F_i is the flux calculated at each representative plot ($\text{mg C m}^{-2} \text{s}^{-1}$).

F_i was computed by (3):

$$F_i = \frac{\sum_{j=1}^N f_j}{N} \quad (3)$$

Where f_j is the flux measured at each representative plot during each measurement ($\text{mg C m}^{-2} \text{ s}^{-1}$); N is the number of measurements during the whole measurement period.

In this report, we used a negative flux value to represent a C emission to the atmosphere, and a positive value a C sequestration from the atmosphere.

Area percentage (W_i) of each microtopography and dominant vegetation types used in the equation (2) was presented in Table 1:

Table 1: Area percentage for each representative plot used in the equation (2).

Types	area percentage (W)
NP	0.3
NO	0.35
NU	0.35
DD	0.05
DO	0.475
DU	0.475
PD	0.05
PG	0.2375
PGG	0.2375
PGS	0.2375
PRS	0.2375

Table 2: Flux data for Fig.1-6.

The unit for all fluxes, including CH₄ fluxes, NEE, ER, and Weighted was mg m⁻² s⁻¹. SD represented the standard deviation of the flux measured at each plot during the whole measurement period. Weighted represented the area weighted flux of CH₄, NEE, and ER for each ecosystem.

	CH ₄	SD	Weighted-CH ₄	SD	NEE	SD	Weighted-NEE	SD	ER	SD	Weighted-ER	SD
NP	0.00005	0.00003	0.00015	0.00018	-0.00426	0.00227	-0.03210	0.02149	-0.00138	0.00161	1.21016	0.02118
NO	0.00036	0.00044			-0.06335	0.02708			0.09686	0.01110		
NU	0.00002	0.00003			-0.02471	0.04227			0.11469	0.05790		
DD	0.00024	0.00033	0.00006	0.00006	0.00715	0.00386	-0.04927	0.00762	0.01043	0.00160	1.16009	0.00558
DO	0.00011	0.00008			-0.05233	0.00813			0.06048	0.00620		
DU	0.00000	0.00001			-0.05215	0.01342			0.08919	0.01079		
PD	0.00065	0.00064	0.00009	0.00009	-0.11300	0.05065	-0.19513	0.09883	0.09690	0.02376	2.11784	0.11774
PG	0.00005	0.00003			-0.19446	0.08044			0.23817	0.04594		
PGG	0.00003	0.00002			-0.19503	0.03894			0.18944	0.01933		
PGS	0.00013	0.00013			-0.15438	0.02583			0.21838	0.06386		
PRS	0.00003	0.00004			-0.25395	0.13356			0.37496	0.23957		

5.2 Methane emissions

During the growing season (May 27 - October 11, 2013), the natural peatlands, drained peatlands, and abandoned pasture were net sources of CH₄ (Fig. 1). The drainage ditches were the ‘hotspots’ of CH₄ emission. They accounted for 20% and 36% of CH₄ emissions of drained peatlands and abandoned pasture respectively in spite of less than 5% of the land area.

The highest CH₄ emission rate occurred in the hollows (0.00036 ± 0.00044 mg CH₄ m⁻²s⁻¹) rather than ponds in the natural peatlands (Fig.1, Table 2). The hummocks in the drained peatlands acted as a weak sink of CH₄ (-0.002 ± 0.006 mg CH₄ m⁻²s⁻¹) as a result of a significantly lower water table (Table 2).

Spatially weighted extrapolations of static flux chamber measurements showed that drainage caused a decrease of CH₄ emission by 59% as compared with the natural peatlands (Fig.2). Abandoned pasture also showed a decrease of CH₄ emission by 41% as compared with the natural peatlands. However, this abandoned pasture showed 45% higher CH₄ emission than that of drained peatlands. This

higher rate of CH₄ emission might be attributed to the increased substrate supply in the pasture due to the altered vegetation composition.

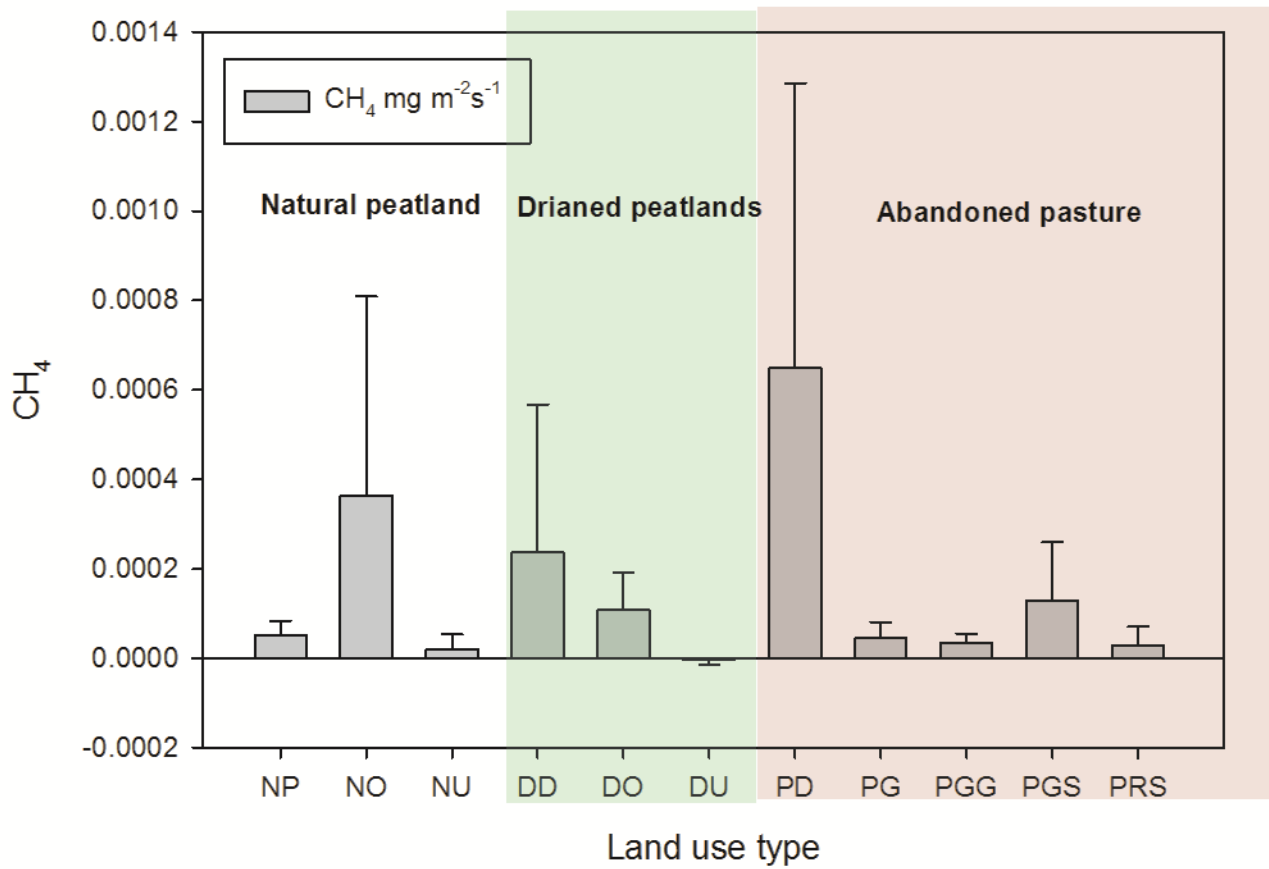


Fig. 1. The mean CH₄ emission rates during the growing season for different land use types (i.e., with different microtopography, and dominant vegetation)

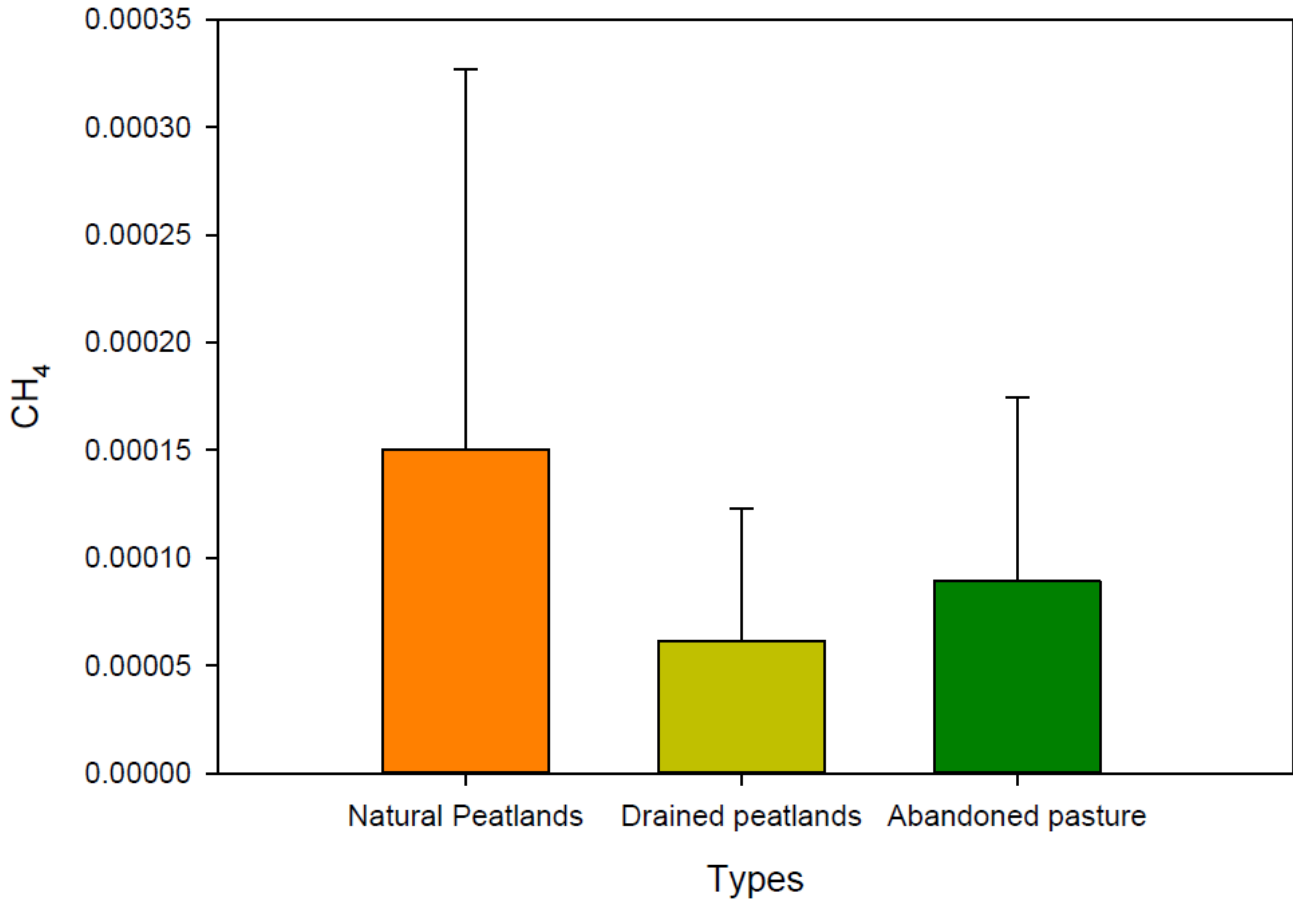


Fig. 2. The wighted mean CH₄ emission rates for different land use types after accounting for the area percentage of the microtopgraphy and dominant vegetation.

5.3 Net ecosystem exchange (NEE)

During the growing season, all the vegetated areas showed a strong CO₂ sink for the three land use types (Fig.3, Table 2). Vegetation in the abandoned pasture showed an especially stronger CO₂ sink capacity as compared with the natural and drained peatlands (Fig.3). Only the ditches in the drained peatlands showed a weak source of CO₂ ($0.00715 \pm 0.00386 \text{ mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$). This carbon souce was simply caused by the absence of vegetation in the ditches. A lower CO₂ uptake capacity in the ditches of the abandoned pasture was attributed to their fewer vegetation cover. Interstingly, the hollows in the natural peatlands showed a lower NEE than the hummocks, while the same pattern was not found in the

drained peatlands. This difference suggested that the water table drawdown in the drained peatlands might stimulate the photosynthesis capacity of the vegetation in the hollows.

Spatially weighted extrapolations of static flux chamber measurements showed that drainage increased NEE by only 5% as compared with the natural peatlands. The abandoned pasture, however, showed a 4.5 times higher NEE as compared with the drained peatlands (Fig. 4, Table 2). The significant higher NEE at the pasture is mainly attributed to the change in vegetation composition because the pasture and the drained peatland experienced a comparable water table depth.

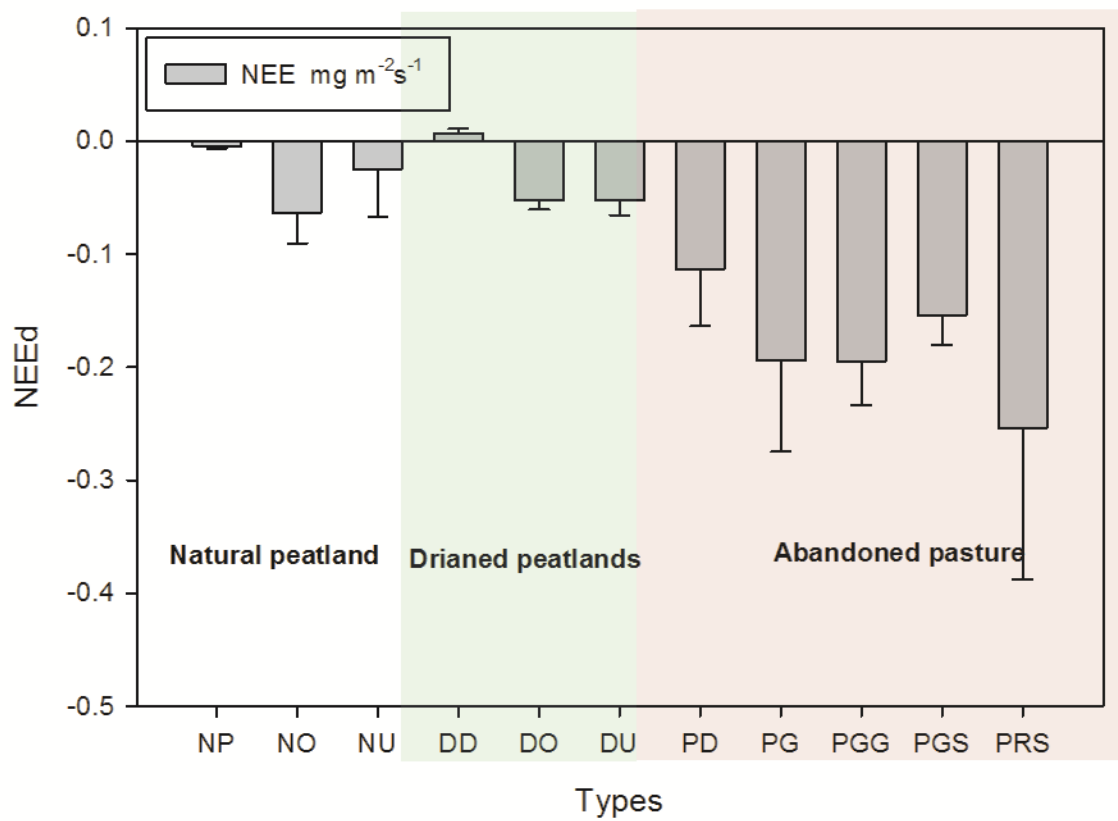


Fig. 3. The mean net ecosystem exchange (CO_2) during the growing season for different land use types (i.e., with different microtopography, and dominant vegetation).

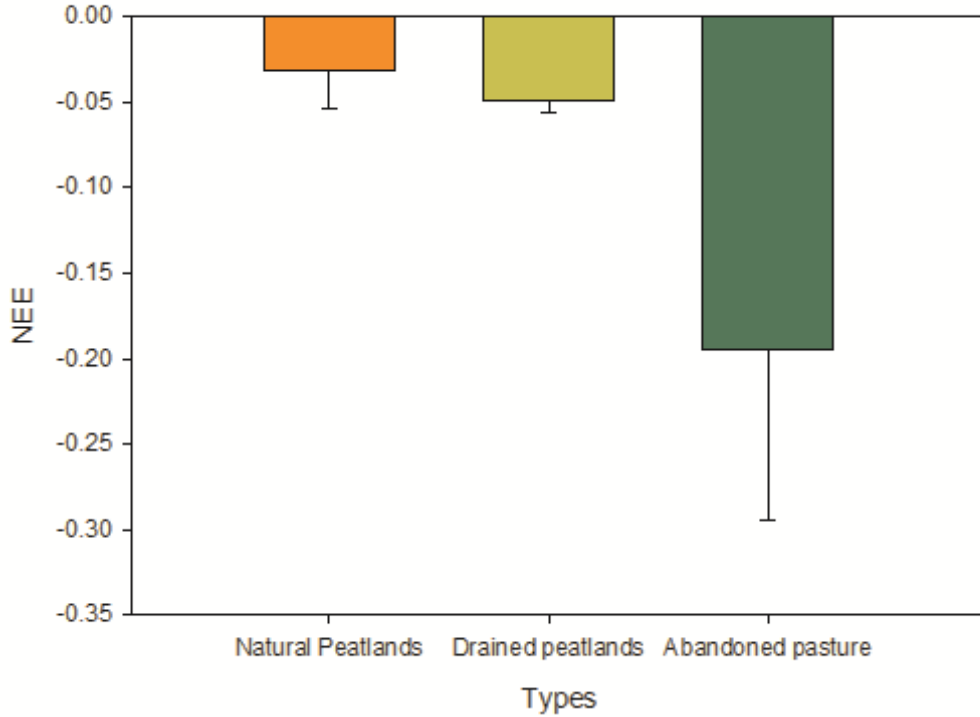


Fig. 4. The wighted mean NEE for different land use types after accounting for the area percentage of the microtopography and dominant vegetation.

5.4 Ecosystem respiration (ER)

The mean ER during the growing season of 2013 showed a similar pattern with NEE among the landforms (Fig. 5, Table 2). However, a similar ER was found between hummocks and hollows in the natural peatlands. A similar ER along with a lower NEE at the hummocks in the natural peatlands may suggest that there is a higher total photosynthesis capacity at the hollows. This higher photosynthesis capacity can be explained by the larger coverage of sedge at the hollows, while the hummocks have a larger coverage of shrubs. ER at the hummocks and hollows in the drained peatlands was lower than that of natural peatlands (Fig. 5, Table 2).

Spatially weighted extrapolations of static flux chamber measurements indicated that there was a similar ER between the natural and drained peatlands, while a 85% higher ER was found in the abandoned pasture than in the drained peatlands (Fig.6). This phenomana may suggest that water table

drawdown alone did not impact the ecosystem respiration significantly, while it was the alteration of vegetation composition that significantly affected the ecosystem respiration.

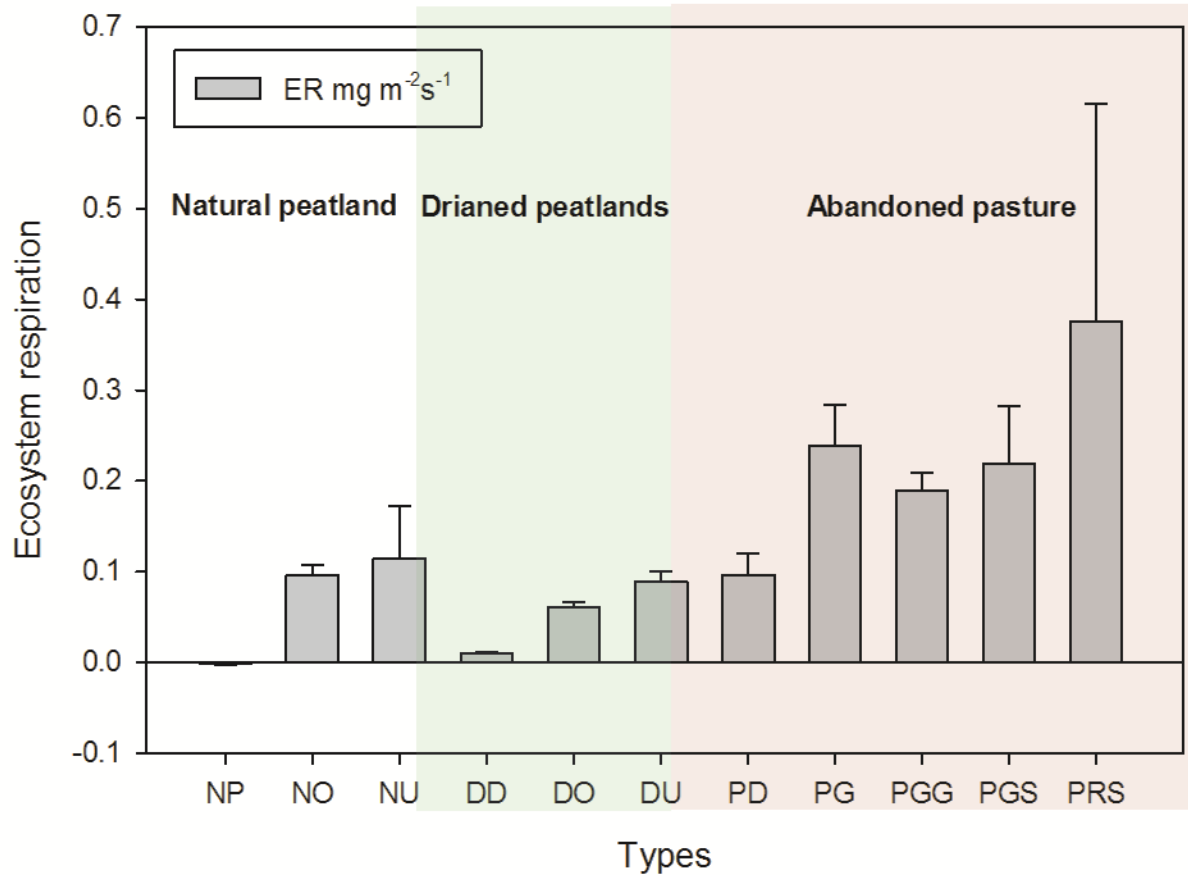


Fig. 5. The mean ecosystem respiration (CO₂, ER) during the growing season for different land use types (i.e., with different microtopography, and dominant vegetation).

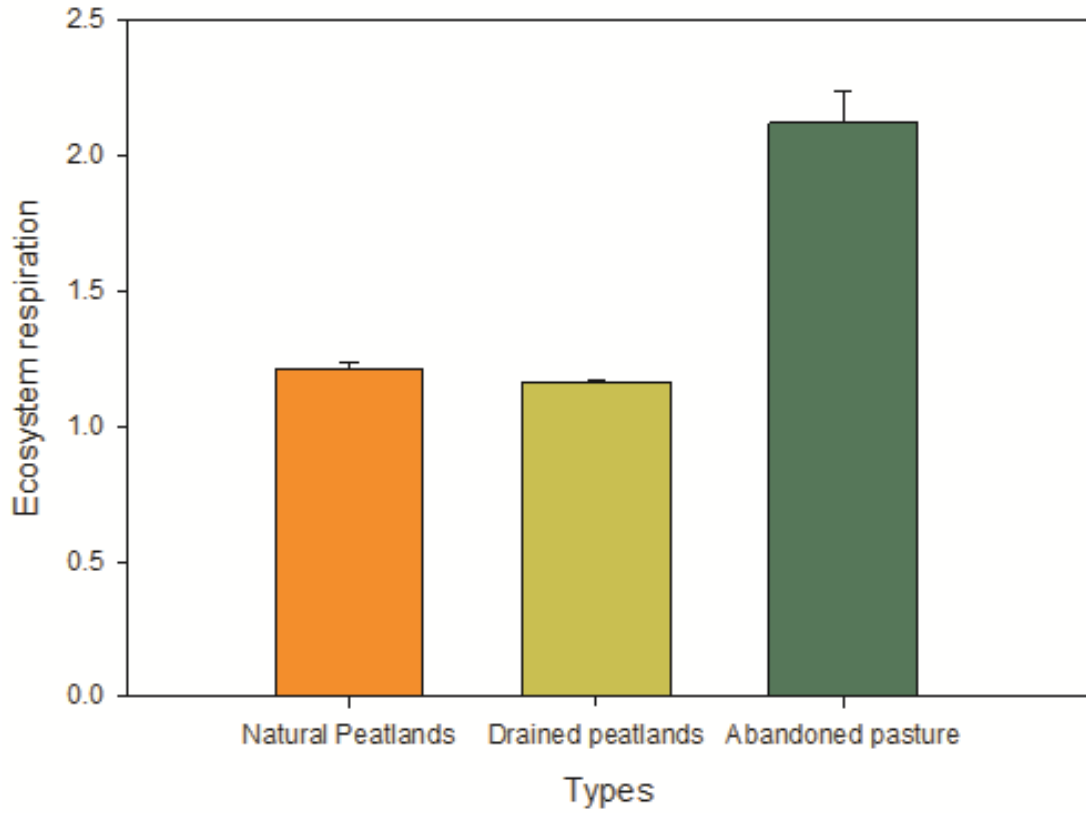


Fig. 6. The wighted mean ecosystem respiration (ER) for different land use types after accounting for the area percentage of the microtopgraphy and dominant vegetation.

Section 6: Communication and Outreach

The goal of this study was to facilitate the NL agricultural industry to maintain an environmentally responsible and sustainable practice. The following communication and outreach plan was made to ensure that the results of this project were effectively communicated to the industry and the local community.

- (1) We are still in the process of analyzing our collected data. All the scientific data, including the weather data that are collected using the eddy covariance system, soil nutrient data and hydrological data, which the local communities have shown most interests in, were and will be freely shared with the local communities.
- (2) The research sites have been remained open to the public for regular visits upon request. The availability of accessing our research sites helped address that the local communities and stakeholders are aware of this study and learn the importance of peatland in the climate system and potential economic benefits of maintaining the healthy ecosystem functions that peatlands can provide. The local news correspondent from CBC News (NL) visited our research sites on June 25, 2013, and Dr. Wu introduced and discussed our study with the correspondent on the CBC News (NL) on June 25, 2013. In addition, CBC (Radio) Corner Brook introduced our study on the CBC (Radio) morning show on June 25, 2013. A delegate composed of one member from RDC and one member from the Research Office of Grenfell Campus, MUN visited this site on November 1, 2013 and Dr. Wu presented our research instrument and research plan to this delegate.
- (3) We made every opportunity to present our study at local workshops held in Corner Brook, NL. Dr. Wu presented our study, entitled “Impacts of agricultural drainage and climate change on greenhouse gas emissions in northern peatlands”, at the Agricultural Research Symposium, in Corner Brook, NL, on November 23, 2012 (with ~150 participants). Dr. Wu was invited to

discuss our study, entitled “Impacts of agricultural drainage and climate change on greenhouse gas emissions in NL peatlands”, at the Green Economy Symposium, in Corner Brook, NL, on March 22, 2013 (with ~100 participants). Dr. Wu also presented our study, entitled “Drainage and agricultural development on boreal peatlands: for the better or worse?”, at the Grenfell Campus Research Gong Show, MUN, in Corner Brook, NL, on February 10, 2014.

- (4) Four research papers have been in preparation, and they will be submitted for consideration to be published in the peer-reviewed journals.

Junwei Luan, Jianghua Wu. Opaque chambers overestimate methane fluxes at the hummocks in boreal peat bogs. In preparation. To be submitted to *Environmental Monitoring and Assessment*.

Jianghua Wu, Junwei Luan. The effects of agricultural development on the net production of dissolved organic carbon in the rhizospheric and deep peat in boreal peatlands. In preparation. To be submitted to *Environmental Science and Technology*.

Junwei Luan, Jianghua Wu. Agricultural development stimulates methane emissions in boreal peatlands through increased the substrate availability. In preparation. To be submitted to *Agricultural and Forest Meteorology*.

Junwei Luan, Jianghua Wu. Greenhouse gas (CO₂, CH₄ and N₂O) fluxes from natural, drained and agriculturally developed peatlands. In preparation. To be submitted to *Atmospheric Environment*.

Section 7: Conclusion and Future Recommendation

Our studies show that changes in hydrology through drainage and changes in vegetation composition may impose a significant impact on greenhouse gas emissions from northern peatlands. However, drainage alone, through changes in hydrology, does not necessarily make a fundamental shift of ecosystem functions in terms of greenhouse gas emissions in boreal peatlands. It is the changes in vegetation composition that may shift the ecosystem functions of greenhouse gas emissions in northern peatlands.

The following conclusion can be made based on our measurement during the growing season of 2013. (1) The natural peatlands, drained peatlands, and abandoned pasture all show a net source of CH_4 . The drainage ditches are the ‘hotspots’ of CH_4 emission. The highest CH_4 emission rate occurs in the hollows of natural peatlands. (2) In terms of CH_4 emissions, the natural peatlands are higher than the pasture that is higher than the drained peatlands. Pastures may have a higher methane production because the vegetation in the pastures may produce a higher quality and greater amount of substrate supply for methane production. (3) During the growing season, all the vegetated areas show a strong CO_2 sink for the three land use types. Vegetation in the abandoned pasture shows an especially stronger CO_2 sink capacity as compared with the natural and drained peatlands. The ditches in the drained peatlands present a weak CO_2 source. (4) In terms of NEE, the pasture is significantly higher than the drained peatlands, which is higher than the natural peatlands. (5) There is a similar ER between the natural and drained peatlands, but the pasture has a significantly higher ER. The significantly higher ER along with a significantly higher NEE in the pasture indicate that the vegetation in the pasture presents a significantly higher photosynthesis.

Our data, generated from the measurement of one growing season, cannot present us a definitive conclusion on how the ecosystem function of greenhouse gas emissions may be affected by drainage and agricultural development in northern peatlands. To answer this question, the measurement during the

non-growing season is needed to calculate the annual GHG balance. Moreover, our measurements were only conducted during the day time. To obtain a complete picture of NEE for one ecosystem, the measurements of NEE during the night time are also required. Our continuous measurements from the paired EC towers, installed in the natural peatlands and the abandoned pasture, will be able to fill this data gap. Further, multi-year measurements are required to better understand the hydrological, biogeochemical and biological controls of these changes in greenhouse gas emissions caused by drainage and agricultural development in northern peatlands. The relationship between GHG emissions and hydrological, biogeochemical and biological variables, which can only be established based on a long-term measurement, will be a critical entry point to guide our decision making on sustainable usage and development of northern peatlands in the province of Newfoundland and Labrador. Therefore, we highly recommend that a multi-year study be supported to continue this project.

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