MS – thesis March 2015

Carbon budget of a drained peatland in Western Iceland and initial effects of rewetting

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60 ECTS thesis submitted in partial fulfilment of a *Magister Scientiarum* degree in Environmental Sciences

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Clarification of contribution

Rannveig Ólafsdóttir contributed to the design and establishment of the study, was responsible for both the preparation-for and the carrying-out of field work, contributed to the establishment of the automatic hydroclimatic stations, carried out post-field work analysis of CH_4 samples, oversaw all data management and analysis and wrote the thesis and the published paper. Hlynur Óskarsson designed the study, took part in the establishment of hydroclimatic stations, contributed to field work, data analysing and modelling and the writing of the published paper. Stefanía Lára Bjarnadóttir and Guðrún Óskarsdóttir contributed to field work. Jón Guðmundsson gave valuable information regarding the running of field equipment (Licor) and converting data from equipment to figures. Davíð Ólafsson oversaw the filling in of the ditch for the initiation of peat rewetting.

Abstract

Northern peatlands store vast amounts of organic carbon in their soils. They play an important role in the context of climate change, as they act as a valuable key source and sink for all the main greenhouse gases. In their natural stage, peatlands act as sinks of atmospheric CO_2 and sources of CH_4, but with drainage this is reversed. Icelandic peatlands have been intensely drained or disturbed since the 1940´s for agricultural use but large proportion has never been cultivated. In recent years peatland restoration has increased and since 2011 wetland rewetting is a possible method for reducing emissions within the Kyoto Protocol´s second commitment period. This study examined the carbon fluxes from an uncultivated drained peatland in Iceland and estimated the annual CO_2 budget. During the research period the site was rewetted and initial response in gas fluxes were estimated. Gas flux measurements were done regularly for a 17 months period, including two growing-seasons, using the chamber method.

The results showed that the drained site was a net annual source of CO_2 and a negligible sink of CH_4. Net annual emission was 4.1 ±0.9 t C ha^{-1} yr^{-1} with CO_2 contributing 91.9% of the emission of the pathways examined. Methane emission from ditches contributed approximately 3% and POC and DOC roughly 5%. First response after rewetting indicated an instant lowering of soil respiration and increased methane emission. These results verify the importance of water table on gas fluxes from soil, the effectiveness of the rewetting method and how immediate the response is.

Útdráttur

Víðáttumestu mýrlendi jarðar er að finna á norðlægum breiddargráðum og hafa þau að geyma gríðarlega mikinn forða af lífrænu kolefni. Mýrarjarðvegur gegnir mikilvægu hlutverki í kolefnishringrás jarðarinnar þar sem allar helstu gróðurhúsalofttegundirnar koma við sögu. Há jarðvatnsstaða mýra veldur því að loftfirrtar aðstæður eru ríkjandi í jarðveginum sem er forsenda fyrir bindingu CO_2 úr andrúmslofti og losun metans úr jarðvegi. Með framræslu mýra lækkar vatnsstaðan og upphefst loftað niðurbrot á lífrænu efni. Það leiðir til aukinnar losunar CO_2 út í andrúmsloftið en jafnframt dregur úr losun metans. Framræsla mýrlendis á Íslandi hefst um og upp úr 1940 með tilkomu stórtækra vinnuvéla í skurðagreftri samhliða auknum umsvifum í landbúnaði. Auk þess var framræsla að stórum hluta styrkt með opinberu fé allt til ársins 1987 og því skorti ekki fé til framkvæmda. Nú er svo komið að stærstum hluta náttúrulegs mýrlendis hér á landi hefur verið raskað en aftur á móti hefur aðeins lítill hluti þess verið ræktaður eftir framræslu. Á síðustu árum hefur endurheimt votlendis aukist verulega og nú nýlega var endurheimt votlendis viðurkennd sem aðgerð til að mæta skuldbindingum þjóðarinnar gagnvart Kyoto-bókuninni. Í þessari rannsókn var flæði gróðurhúsalofttegunda mælt á framræstum óræktuðum mýrarjarðvegi og mat lagt á árlegan kolefnisbúskap svæðisins. Á meðan á rannsókninni stóð var hluti svæðisins endurheimtur með því að fylla í skurði og fyrstu viðbrögð lofttegundabúskaps eftir hækkunar vatnsstöðu mæld og metin. Rannsóknin í heild stóð yfir í 17 mánuði, þar með talið tvö sumur, og voru mælingar á gróðurhúsalofttegundum gerðar með reglulegu millibili.

Niðurstöður gasmælinga á framræsta svæðinu sýndu fram á árlega losun CO_2 úr jarðvegi en litla sem enga bindingu á metani. Heildarlosun kolefnis mældist 4.1 ±0.9 tonn á hektara á ári og reyndist þáttur CO_2 leggja til tæp 92% af þeirri losun. Metanlosun frá skurðum átti um 3% þátt í heildarlosuninni og ríflega 5% með uppleystu og óuppleystu lífrænu kolefni með útskolun. Endurheimt skilaði skjótum árangri þar sem jarðvegsöndun minnkaði verulega og metan losun hækkaði á örskömmum tíma. Þessar niðurstöður sýna fram á mikilvægi jarðvatnsstöðu gagnvart flæði gróðurhúsalofttegunda frá jarðvegi sem og skjótan og áhrifaríkan árangur endurheimtaraðgerðar.

Acknowledgements

The present study was carried out at the Faculty of Environmental Science at the Agricultural University of Iceland in Keldnaholt and Hvanneyri. First and foremost I would like to thank my supervisor Dr. Hlynur Óskarsson for the guidance and help throughout the project. I thank the Agricultural University of Iceland for accepting me into this project, access to their facilities and for their excellent academic colleagues.

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1. Introduction

1.1 Climate change

Climate change and global warming have become one of the most pressing environmental concerns and the greatest global challenges in society today. Global concentrations of greenhouse gases in the atmosphere have increased significantly as a result of human activities and now far exceed pre-industrial values determined from ice cores spanning many thousands of years (IPCC, 2007a). The global increase in concentrations has primarily been related to anthropogenic sources and activities such as burning of fossil fuel, land use change, industrial activities, agricultural practices and waste generation (IPCC, 2007a).

The three primary greenhouse gases are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Of the three gases, carbon dioxide contributes most strongly, or 63%, to the atmospheric warming associated with the increased concentration of these gases. Methane and nitrous oxide contribute less to anthropogenic global warming, 18% and 6% respectively, although the climate effect of the latter two gas species is largely a result of their much higher global warming potential (GWP), compared to CO_2 (Augustin *et al.*, 2011). Global average surface temperatures are predicted to increase in the range of 1.1 to 6.4 °C by the end of this century, as compared with 1980-1999 temperatures, and northern latitudes are expected to experience the greatest change in temperature (IPCC, 2007a). Many concerns are raised regarding impacts of climate change on ecosystems, temperature and other climate phenomena but one major uncertainty factor in global climate models concerns the climate-carbon cycle feedback. One example of such a feedback effect involves increased CO_2 concentrations resulting in higher temperatures, which may intensify soil decomposition rates and further increase the CO_2 emissions to the atmosphere. This feedback effect by the biosphere is often found to be positive indicating that the terrestrial biosphere will take up less atmospheric CO_2 in the future (IPCC, 2007a, 2007b), which will further strengthen the effect of climate change.

Peatlands are one of the more important natural ecosystems, particularly at northern latitudes, in the context of climate change, as they act as a valuable key source and sink for all three main greenhouse gases, CO_2, CH_4 and N_2O. Peatlands store vast amounts of organic carbon in their soils (Gorham, 1991) and can thus potentially influence the climate strongly were the carbon stores to be disturbed. Small changes in soil hydrology can lead to big changes in greenhouse gas emissions due to its influence on peatland biogeochemistry. In Europe, up to 90% of peatlands have been cleared, drained or degraded which has led to a massive increase in net emissions of greenhouse gases, even comparable to global industrial emissions (Parish *et al.,* 2008). Thus the response of northern peatlands in terms of greenhouse gas exchange requires detailed and process-based knowledge, gathered from both descriptive studies of the greenhouse gas exchange as well as manipulation experiments.

Iceland is a party to The United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol. Like other parties, Iceland is required to report annually on their greenhouse gas emissions by sources and removals by sinks and work on a climate change strategy to slow down the release of greenhouse gases to the atmosphere (Birna S. Hallsdóttir *et al.,* 2010). Peatland degradation is becoming one of the most important global sources of CO_2 emissions from the Land Use, Land Use Change and Forestry (LULUCF) sector (Parish *et al.,* 2008) and in Iceland, wetlands converted to grasslands are a key source of CO_2 equivalents in the LULUCF sector according to the National Inventory Report (Birna S. Hallsdóttir *et al.*, 2010).

It is estimated that within Iceland peatland rewetting can decrease greenhouse gas emissions by 50-100 Gg by 2020 (Birna S. Hallsdóttir *et al.,* 2010), as well as being one of the most cost-effective ways of avoiding anthropogenic greenhouse gas emissions (Brynhildur Davíðsdóttir *et al*., 2009). Until recently, peatland restoration had not been approved within LULUCF as a possible method for reducing greenhouse gas emissions. However, at the UNFCCC´s conference meeting in Durban in 2011 it was agreed to introduce wetland rewetting as a possible method for reducing emissions within the Kyoto Protocol´s second commitment period (UNFCCC, 2011). In order to fulfil the requirements of the Kyoto´s Protocol there is increasing need for information on both peatland carbon storage and greenhouse gas emissions and to gather more detailed data on how these parameters respond to land use change, both draining and rewetting.

1.2 Northern peatlands

Peatlands are wetland ecosystems that are characterised by the accumulation of organic matter, i.e. peat, which derives from dead and decaying plant material under conditions of permanent water saturation (Parish *et al.*, 2008). Because of high water table level anoxic conditions prevail in the soil, which slows down microbial activity and decomposition of organic matter. Over thousands of years peatlands have accumulated and stored this organic matter and hence have played an important role in the overall global carbon balance.

Globally peatlands are one of the most important carbon stores comprising at least 550 Gt of carbon in their peat which equals to 30% of all global soil organic carbon or 75% of all atmospheric carbon (Gorham, 1991). This number is substantial given that peatlands cover only approximately 3% of the world´s land area. Peat formation is primarily a function of climate; high rainfall, humidity and low temperatures, although water-logging is the single most important factor enabling peat accumulation. Peat accumulates at a rate of about 0.5-1 mm per year (or 5-10 m over 10,000 years) with strong local variations. Peatlands are found in almost every country, but their distribution is greatest at high northern latitudes (Parish *et al.,* 2008), as figure 1 presents.

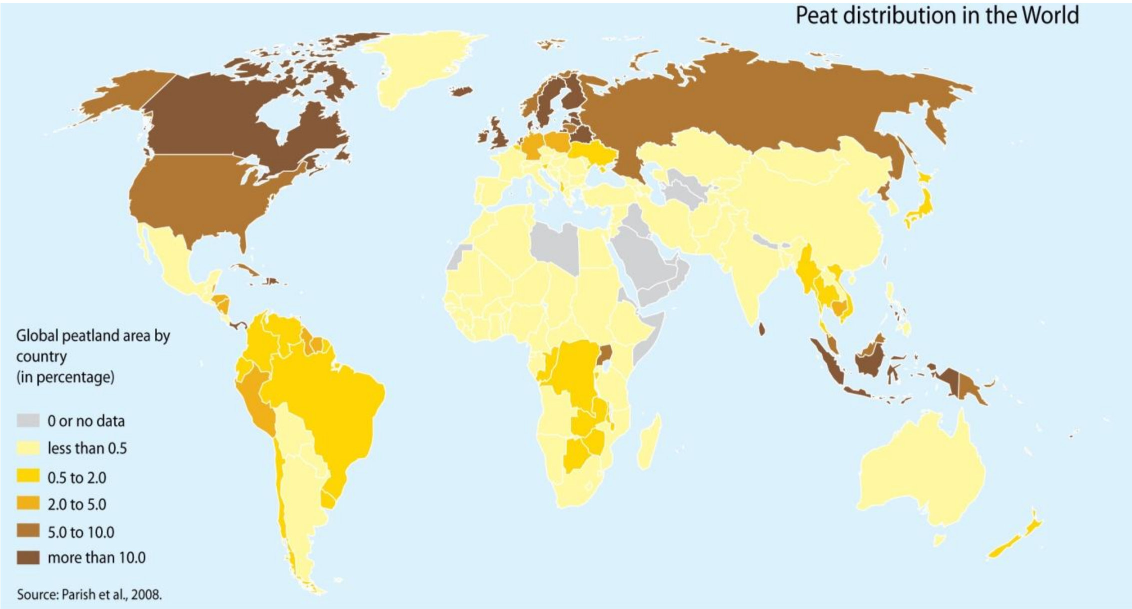

Figure 1. Global peatland distribution. Peatlands are found in every continent in the world but the most extensive areas are in the north. (Parish *et al*., 2008).

Peatlands have often been considered as wastelands of no use unless drained, logged or excavated. In addition to their important role in the regulation of global climate change through sequestering and releasing of greenhouse gases (Millennium Ecosystem Assessment, 2005), peatlands are of considerable value to human societies due to wide range of goods and services they provide (Parish *et al.,* 2008). Among beneficial functions of peatlands are water purification, water regulation, erosion protection, providing fibre and fuel, food and fresh water for domestic animals, recreational, aesthetic and educational functions and last but not least are peatlands important habitat for many species and biodiversity in general (Millennium Ecosystem Assessment, 2005; Joosten & Clarke, 2002).

In peatlands, water, peat and plants are strongly interconnected. It is obvious that if any one of these components is altered, the nature of the peatland will change (fig. 2). Unsustainable use of peatlands can have significant environmental and socio-economical side effects, such as habitat destruction and significant implications for biodiversity, productivity and ecosystem services, and even un-foreseen feedback mechanisms such as climate change (Parish *et al.*, 2008).

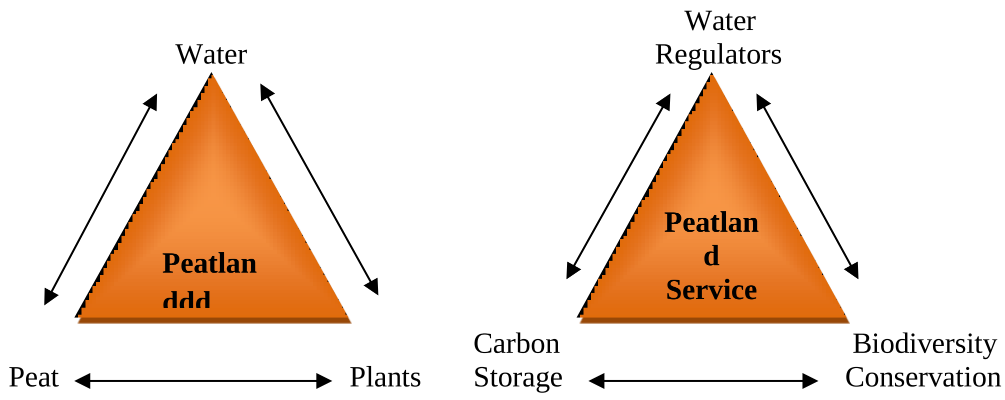

Figure 2. The interrelations between plants, water and peat in a peatland and important services of peatlands. Modified from Parish *et al.*, 2008.

1.3 Carbon dynamics of peatlands

Like in most other ecosystems, the carbon cycle of peatlands is driven by photosynthesis. During photosynthesis plants capture CO_2 from the atmosphere and reduce it into carbohydrates for use as a source of energy. This process is referred to as gross primary production (GPP). The carbohydrates are distributed over the entire plant and a large fraction of the carbon fixed in photosynthesis is used for sustaining the plant and returned to the atmosphere as CO_2, termed autotrophic respiration or plant respiration (R_p). The difference between gross photosynthesis and plant respiration is termed net primary production (NPP) (Eq. 1) (Augustin *et al.*, 2011).

$$GPP - R_p = NPP \qquad \text{(Eq. 1)}$$

In the aerated upper most part of the peat soil, root exudates and plant remains are subsequently decomposed by soil animals and microbes, leading to the release of CO_2 to the atmosphere. This microbial activity is referred to as heterotrophic respiration and the two respiration processes are collectively referred to as ecosystem respiration (R_{eco}). The net balance of CO_2 fluxes in a peatland is expressed as the difference between gross primary production (GPP) and ecosystem respiration (R_{eco}), referred to as net ecosystem exchange (NEE) (Eq.2) (Augustin *et al.*, 2011).

$$NEE = GPP - R_{eco} \qquad \text{(Eq. 2)}$$

In natural, unmanaged peatlands where waterlogged and anaerobic conditions prevail, significant amount of methane is released to the atmosphere. Methane (CH_4) is formed within the anoxic layer of the soil by a group of microorganisms termed methanogens (Augustin *et al.*, 2011). CH_4 follows various pathways to reach the atmosphere, involving diffusion, plant-mediated transport and ebullition (Whalen, 2005). In addition to the gaseous exchange of CO_2 and CH_4, carbon export as dissolved organic carbon (DOC) may contribute significantly to the carbon cycling of a peatland (Roulet *et al.*, 2007). Figure 3 summarizes the biochemical processes discussed in this section.

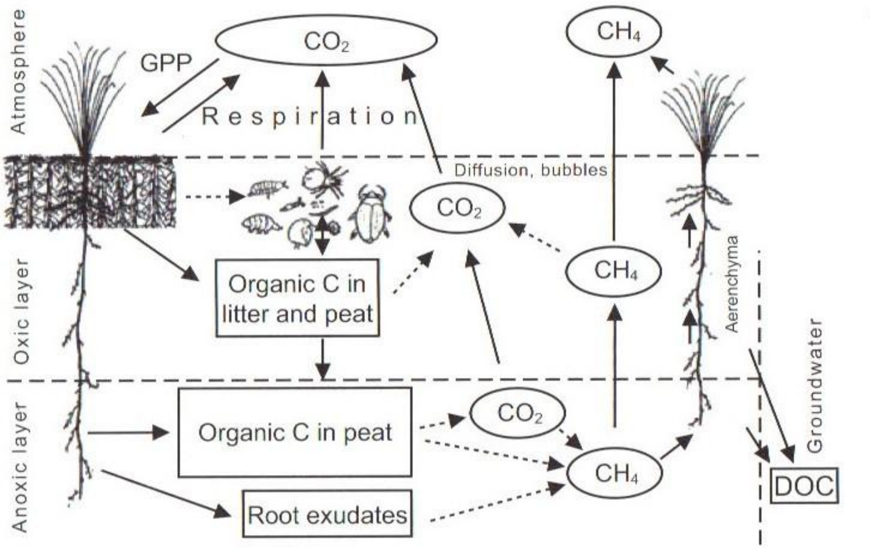

Figure 3. Simplified carbon cycling between the atmosphere and a peatland with an oxic upper part and an-anoxic layer beneath. Encircled symbols represent gases and dashed arrows show microbial processes. (Rydin & Jeglum, 2006; *Parish et al*., 2008).

The best single explanatory variable controlling peatland annual gas exchange rates is the mean water table depth (Couwenberger *et al.,* 2011) but other factors have significant impact, such as temperature, pH, vegetation type and substrate availability and quality (Whalen, 2005; Augustin *et al.,* 2011). Draining organic soils lowers the water table level which increases the oxygen content of the soil. Oxygenation of the peat primarily causes a drastic increase in net CO_2 emissions through ecosystem respiration and DOC losses (Gorham, 1991; Augustin *et al.*, 2011) while CH_4 emissions are reduced and generally become negligible (Maljanen *et al.*, 2012). According to Couwenberger *et al.* (2011), deeply drained peatlands in agricultural use show high emissions of CO_2, or over 20 t CO_2 $ha^{-1}year^{-1}$. When water levels are above -50 cm there is a marked decrease in emissions reaching near zero (or uptake) at mean water levels close to the surface. Methane emissions on the other hand have proven to be negligible (<2 kg ha^{-1} $year^{-1}$) at low mean water levels (<-20 cm), while values rise steeply with mean water levels above -20 cm (Couwenberger *et al.*, 2011). Methane emissions from deeply drained areas, however, are driven by „hotspots" of biological activity, namely the drainage ditches. Despite the fact that drainage ditches account for only a small percent of the land area, they have proved to contribute more than 84% of CH_4 emissions of a given site (Teh, 2011).

1.4 Carbon inputs and outputs

A carbon budget involves a quantified description of inputs and outputs from a peatland catchment. A carbon budget can provide information on ecosystem functions and determine the sink-source relationship along with chemical transformations within the peatland (Mitsch & Gosseling, 2007). Very few studies have measured all the possible carbon release pathways for one given site. Rowson *et al*. (2010) presented the first carbon budget for a drained peatland site including all the major carbon release pathways and found out that the catchment was a net source of all forms of carbon at between +63.8 and +106.8 Mg C km^{-2} yr^{-1}.

Figure 4 presents a schematic model of carbon budget as frequently considered in peatland carbon studies (Rowson *et al.,* 2010; Worrall *et al*., 2003). The arrows represent possible pathways where carbon is sequestrated or released from the peat. These pathways are gaseous CO_2 exchange, dissolved organic carbon (DOC) with precipitation, gaseous CH_4, dissolved CO_2, dissolved organic carbon (DOC), particulate organic carbon (POC) and dissolved inorganic carbon (DIC). The figure does not indicate transformations between compartments occurring within the peat or in peat stream water.

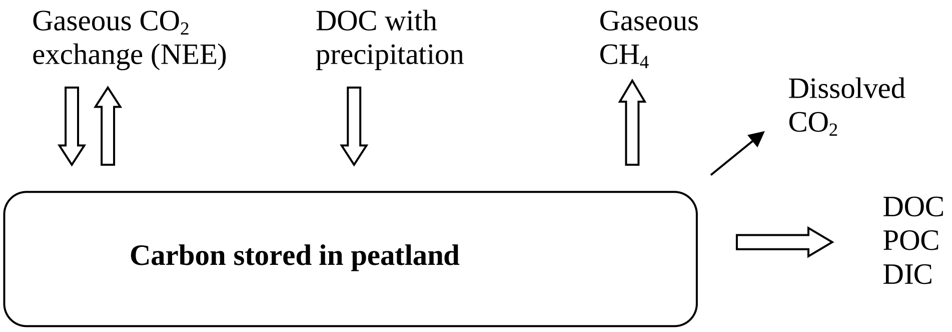

Figure 4. Schematic diagram of peatland carbon fluxes. Modified from Worrall *et al*., 2003.

1.5 Icelandic peatlands land-use history

Peatlands are a prominent landscape feature in Iceland and cover approximately 10% of the land area or 30-40% of fully vegetated land (Ingvi Þorsteinsson & Gunnar Ólafsson, 1975). Since early 1940´s a large proportion of Icelandic peatlands have been drained. At that time, heavy machinery were being introduced in agriculture and areas were drained for the purpose of converting wetlands into hay-fields. During the 1960-1970´s draining became more extensive as livestock populations in the country were at all-time high and there was a greater demand for hay-fields and grazing land than ever before. Due to over-grazing in the highlands, vulnerable vegetation in the highland commons had become degraded, and in order to disperse the grazing load of the highlands, intense draining efforts were initiated in the lowlands for the purpose of creating rangeland (Óttar Geirson, 1998). At the same time, peatland draining was financially supported by governmental subsidies. Since 1941, around 32.000 km of ditches have been excavated and the total area of fully drained wetlands in Iceland is over 4000 km^2 (Hlynur Óskarsson, 1998). Figure 5 shows the annual extent of wetland drainage in Iceland during the period 1940-2000. Research has shown that 97% of wetlands in South Iceland and 82% in West Iceland have been disturbed as a result of the drainage effort (Þóra Ellen *et al*., 1998; Hlynur Óskarsson, 1998).

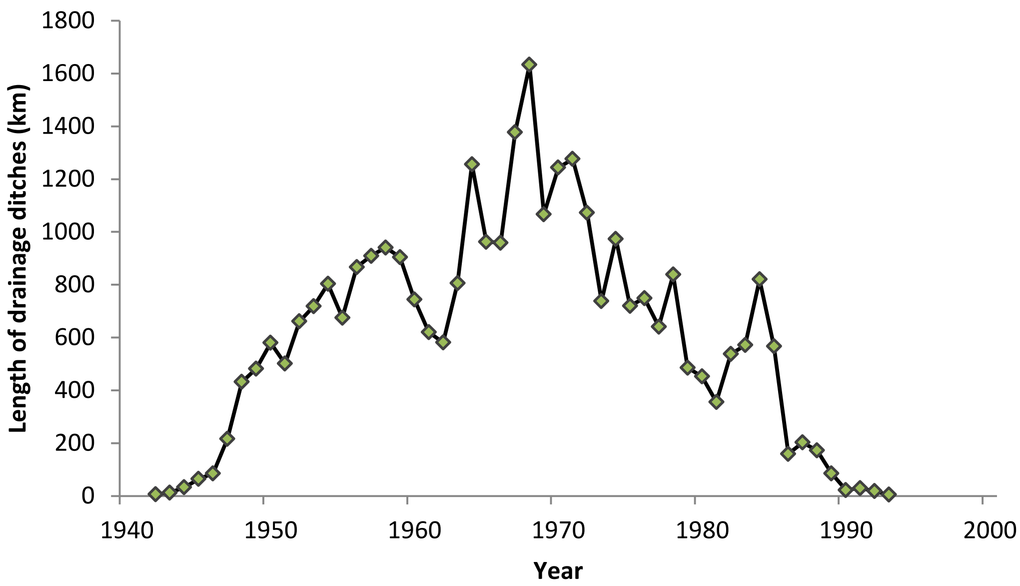

Figure 5. Length of drainage ditches excavated annually in Iceland during the period 1940-2000 (based on data from the Farmers Association of Iceland).

Peatland restoration has increased in recent years with increased research on that topic. Conditions for peatland rewetting in Iceland are in general good as large part of the drained areas have never been cultivated and seed bank of wetland vegetation still exists in the soil. Utilization of peatland is less intense in Iceland than in the neighbouring countries where cultivation is the dominant form of land-use and natural wetland vegetation has disappeared. Therefore restoration in Iceland is more cost-effective than in many other countries, as the natural stage is usually not far away (Arnþór Garðarsson *et al*., 2006).

1.6 Study aims

According to global climate model predictions northern peatlands are expected to experience drastic change in the next century as global warming progresses (IPCC, 2007a). Small changes to the peatland environment can alter the hydrology and the occurring biochemical processes, leading to significant loss of long stored carbon to the atmosphere. Peatlands rewetting is in focus to be a new option for reducing GHG emission set by the Kyoto Protocol as well as being a valued source for carbon credits (UNFCCC, 2011).

In 2010 the Wetland Centre of the Agricultural University of Iceland and the private company Alcan made a collaborative agreement to initiate a project concerning wetland rewetting in order to reduce greenhouse gas emissions. The aim of the project was twofold; firstly to aid landowners wanting to rewet drained peatlands, and on secondly to conduct research on GHG dynamics of a drained and rewetted peatlands with the aim of supplying sound data and to develop methods for evaluating the successfulness of rewetting efforts in relation to emission of greenhouse gases.

This study was initiated as a part of this collaboration project and hence funded by Alcan in Iceland. Prior to this day no study within Iceland has performed such detailed measurements on that topic. The aim of the study was to estimate greenhouse gas fluxes from an uncultivated drained peatland site in Iceland before, during and after rewetting. The study explores soil respiration of CO_2 and CH_4, primary production and CH_4 release from ditches. Another study that took place within the same field explored the hydrological input and output of the site, including dissolved organic carbon (DOC) and particulate organic carbon (POC) in drainage ditches (Stefanía L. Bjarnadóttir, 2012). Together these two studies allowed for estimation of all the major carbon uptake and release pathways of a drained peat site in Iceland. Other objectives were to:

I. Estimate the annual uptake and emissions of the two main greenhouse gases, CO_2 and $CH_{4,}$ of the drained peatland site
II. Estimate the overall carbon storage and carbon budget of the drained site
III. Estimate the initial response in greenhouse gas fluxes following peatland rewetting
IV. Explore the feasibility of using variables such as NDVI and PAR in estimating in-between-measurement gross primary production.

2. Materials and methods

2.1 Site description

The Mávahlíð site is a 2.85 hectare drained peatland located within the Hestur experimental farm complex in Borgarfjörður region, West Iceland (64°34´21.99´´N; 21°35´8.44´´W) (Fig. 6). The site, originally a gently sloping peatland, was drained in 1977 for the purpose of creating rangeland for domestic animals. Except for the drainage and intermediate sheep grazing, no other activities such as fertilization or ploughing have been carried out at the site. Dominant plant species are *Deschampsia cespitosa*, *Eriophorum angustifolium* and *Festuca rubra*. Mean annual rainfall of the area is 936 mm, and mean annual temperature 3.3°C (30-year averages (1964-1994), Icelandic Meteorological Office, 2014). The soil is Histic Andosol averaging 2.45 m in depth. More characteristics of the site are summarized in table 1.

Table 1. Average values for selected environmental variables of the Mávahlíð site. Data gathered in 2011 and 2012 unless otherwise indicated.

Site characteristics	
Size area (ha)	2.85
Location	64°34´21.99´´N;21°35´8.44´´W
Elevation (m.a.s.l)	55
Annual Rainfall (mm $year^{-1}$)	936 (average, 1964-1994)
Annual Temperature (°C)	3.3 (average, 1964-1994)
Soil water level winter (cm)	-0.10 (October-April)
Soil water level summer (cm)	-0.84 (May-September)
pH*	5.1
Soil (FAO)	Histic Andosol
Peat thickness (m)	2.45
Organic carbon (%)**	31.35
C/N ratio**	17.33
Bulk density (g cm^3)**	0.24

*(Elisabeth Jansen, 2008), **(Snorri Þorsteinsson, 2011)

Prior to drainage, water from numerous natural springs located further uphill from the site, maintained waterlogged conditions within the soil resulting in peat accumulation over time. In 1977 a drainage ditch was excavated above the site in order to divert the spring water flow away from the site (upper drainage ditch). Another ditch was excavated below the site for road construction (lower drainage ditch). The third ditch was excavated at the west side of the area connecting the upper ditch to the lower, and leading the water to a nearby river Grímsá (Fig. 7).

2.2 Experimental setup

Twenty plots were randomly chosen for replicate measurements of net ecosystem CO_2 exchange (NEE), methane (CH_4) flux, vegetation greenness (NDVI), soil water table depth (WTD) and soil temperature at 10 cm (Fig. 7). The study was initiated in May 2011 and measurements were carried out weekly during the growing season (June – September) and bi-weekly and monthly during the non-growing season (September – May). At each plot, aluminium frames were installed in the soil for measurements of CO_2 and CH_4. Pipe wells for measuring WTD were established 1.0 m to the left of each frame, and boardwalks were constructed to ensure a minimum disturbance to the vegetation while measuring. Two automatic hydroclimatic stations were put up in the site, each one centrally located in relation to plots 1-10 and 11-20, respectively. The stations recorded hourly values for various environmental parameters (see chapter 2.3.4).

Since one of the aims of the study was to look at the effect of rewetting the twenty measurement plots were set up in two separate sets of ten plots, termed section A and section B. In July 2012, section B was rewetted and measurements continued on all twenty plots (sections A and B), two times per week the first month after rewetting, weekly until the end of the growing season, and biweekly until the end of this study in October 2012.

It should be noted, for the purpose of describing the overall study setup, that an additional study was conducted at the same time at the site, investigating carbon and nitrogen runoff export from the same drained peatland and the first effect of rewetting (Stefanía L. Bjarnadóttir, 2012). Therefore six water sampling points were placed in the drainage ditches, three in the upper ditch and three in the lower ditch (Fig. 7). Timber dams were constructed at two sampling points where water was collected in a small reservoir above the dams and flows through a V-shaped overflow forming a water gush. At other sampling points metal pipes were installed in the ditch which caught all the water flow.

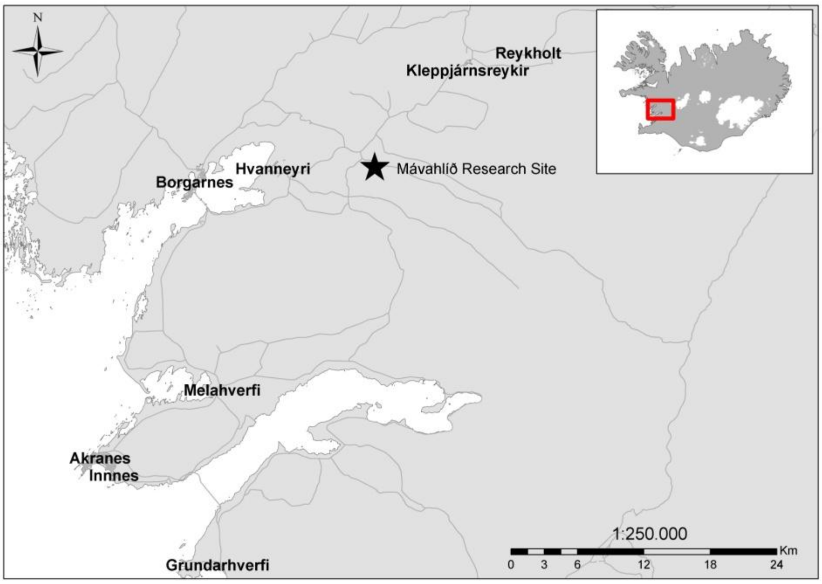

Figure 6. Location of Mávahlíð peatland study site in Borgarfjörður region, West Iceland.

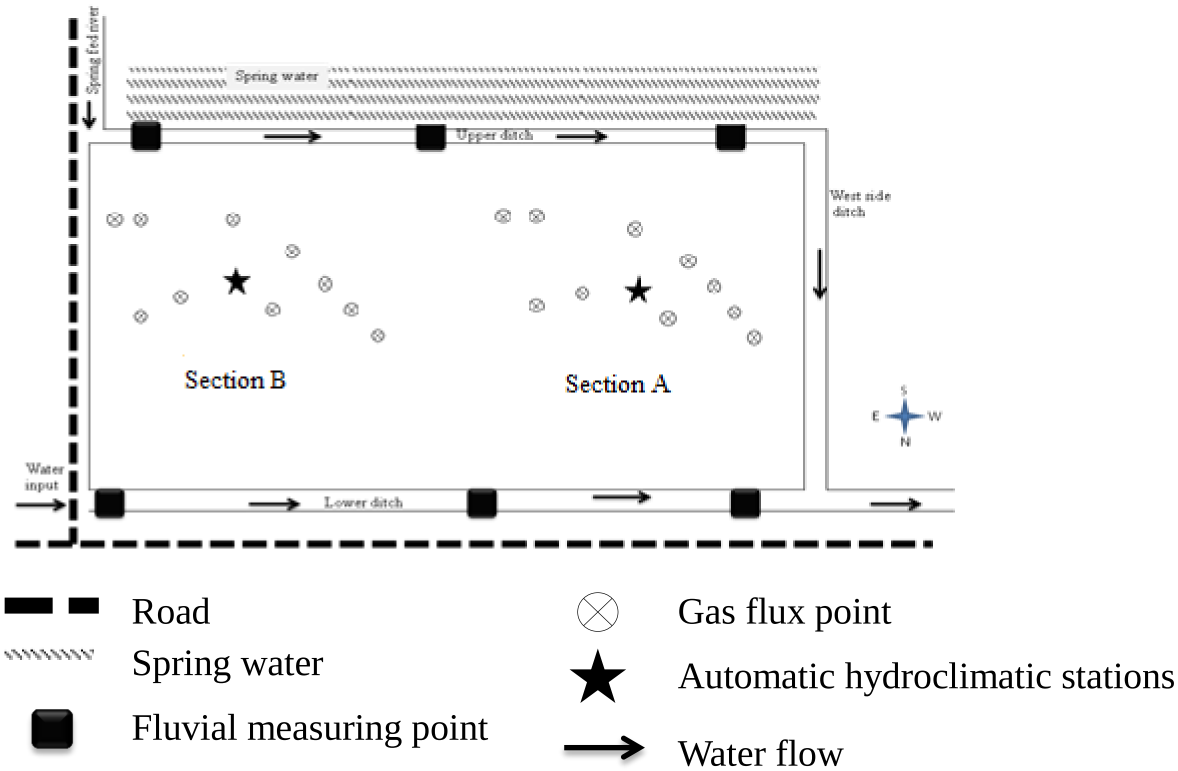

Figure 7. A simple diagram of the Mávahlíð peatland site depicting the study setup.

2.3 Measurements

2.3.1 CO_2 flux

Net ecosystem CO_2 exchange was measured with the closed chamber method using a transparent acrylic chamber (35x35x25 cm, volume 30,6 litres) with a fan inside to ensure well-mixed air. During measurements the chamber was placed over a grooved aluminium frame permanently fixed in the ground, and water poured into the groove to obtain good seal between chamber and frame. The change in the CO_2 concentration in the chamber was measured with an attached portable infrared gas analyzer (Li 6200, LiCor, Lincoln, NE, USA). At each plot, CO_2 concentration readings were recorded at one minute intervals during an incubation period of four minutes. The chamber was subsequently covered for measurement of ecosystem respiration using the same method. Net ecosystem exchange (NEE) is calculated as the difference between gross primary production (GPP) and ecosystem respiration (ER). Solar radiation was monitored constantly during the incubation period using point quantum sensor installed in one corner of the chamber, measuring the photosynthetically active radiation (PAR).

2.3.2 Methane flux

Methane (CH_4) flux was measured with an opaque, static closed chamber placed over the same grooved aluminium frames as those used for CO_2 measurement. Air samples of 2 ml were taken from the headspace of the chamber with a needle and syringe and pumped into a glass vial fitted with a gas-tight septum. The syringe was pumped twice in the chamber to ensure that the gases within the chamber were mixed, and then the gas sample was injected into the evacuated glass vial. From each chamber, four sample series were extracted over 45 min with a 15 min interval. Gas fluxes were derived from concentration changes in the sample series. Gas concentration of the samples were determined in the laboratory using a gas chromatograph (CP – 3800, Varian Inc., Walnut Creek, CA, USA). Additionally, CH_4 samples were taken from 2-3 plots situated in the ditches, six times during the time of measurements using the same method.

2.3.3 NDVI

Normalized difference vegetation index (NDVI) is based on the difference of the leaf absorbance in the red spectrum due to chlorophyll pigments and the reflectance in the infrared spectrum caused by leaf cellular structure, using the following equation:

$$\mathrm{NDVI} = \frac{R_{nir} - R_{red}}{R_{nir} + R_{red}} \qquad (3)$$

Where R_{nir} and R_{red} is reflectance in the near-infrared (800-2500 nm) and red (620-750 nm) spectral bands respectively.

NDVI was measured using hand held SKR 1800 Two Channel Light Sensor (Skye Instruments, Llandrindod Wells, UK) 2.0 m above ground level with a spectral footprint of 0.62 m^2. The two sensors had the centre wavelengths of 657 nm and 840 nm and bandwidths of 40 nm and 124 nm for the red and near-infrared spectral bands, respectively. At each plot at midday (10.00-15.00) NDVI readings were taken of the same spot on the ground, one meter away from flux measurement frames to ensure no reflection from the frames. All sky conditions, clear and cloudy, were included in the results. NDVI measurements were conducted from the boardwalks to prevent disturbance of the vegetation.

2.3.4 Environmental variables

Two automatic hydroclimatic stations were located in both the to-be restored and drained part of the site (Fig 7.) for continuous measurement of precipitation, temperature, peat moisture, water table level and photosynthetically active radiation (PAR). Precipitation was measured using a tipping bucket rain gauge, air temperature was measured using a thermocouple and peat temperatures were obtained using a series of thermocouples installed in the peat at various depths (10, 25 and 40 cm). Peat volumetric moisture content (VMC) was measured with moisture probes at 10, 25, 40 and 55 cm depths and water table level was monitored using pressure sensors installed in the peat layer in addition to manual measurements. PAR was measured with a point quantum sensor (LI-190, Li-COR Inc, Lincoln, Nebraska) attached to the site’s meteorological station, 2.0 m above the surface. The stations were equipped with

data loggers (CR1000, Campbell Scientific, Logan, UT, USA) and collected hourly data year around.
In addition, instantaneous measurements of peat temperature at 10 cm, water table level and PAR were made at the time of chamber sampling. Peat temperature was measured using a hand held temperature probe and water table level was measured from wells located at each twenty study plots, by blowing air through a plastic tube with measuring scale down at the well until you reach the water level. PAR was also measured using a quantum sensor attached to the chamber of the portable photosynthesis system.

2.4 Rewetting

Rewetting of section B took place on the 4th of July 2012, following thirteen months of regular gas flux measurements under drained conditions. A common method of drainage blocking was used, where the drainage ditches were filled up with the original excavated soil, resulting in increased water level. Half of the upper ditch, above section B, was blocked and totally filled in with soil; meanwhile the other half of the ditch, above section A, was left untouched and hence maintained drained state of that section. Heavy machinery was used to fill the ditch with the same soil that had been dug up initially when the site was drained, and lay next to the ditch. Water pipe was led from the small spring stream and above the whole rewetted site to ensure that water would enter the site. Regular holes on the pipe made sure water was dripping constantly across the whole rewetted site.

Figure 8. Rewetting of section B of the Mávahlíð peatland in July 2012. The site was originally drained in 1977.

2.5 Extrapolation of carbon fluxes

For calculating annual CO_2 fluxes of the site there is a need for methodology for estimating fluxes in-between the regular field measurements. The common approach to the estimation of CO_2 flux is to use an extrapolation method or gap-filling based upon calibrating equations for ecosystem respiration and primary productivity against climatic controls, in this case soil temperature at 10 cm depth and photosynthetically active radiation (PAR), respectively.

With methane there is no clear extrapolation method available in the literature, however, a common approach is to seek a relationship with water table depth (e.g. Rowson *et al.*, 2010). In this study mean water table depth was chosen as the primary variable concerning peatland greenhouse gas emissions.

2.6 Carbon budget calculations

The carbon budget of the study site is viewed as a summation of the following carbon input and output pathways:

Inputs:

- CO_2 sequestration from the atmosphere through primary production
- DOC and inorganic carbon as part of rainwater (Stefanía L. Bjarnadóttir, 2012)
- CH_4 fixation by methanotrophic bacteria

Outputs:

- CO_2 emission to the atmosphere through ecosystem respiration
- CH_4 emission to the atmosphere from soil surface

- CH_4 emissions to the atmosphere from drainage ditches
- Runoff outputs: DOC, POC, DIC and dissolved gases (Stefanía L. Bjarnadóttir, 2012)

Each uptake and release pathway was estimated for the calendar year 2012. In making the budget calculations it is assumed that no water leaves the catchment as groundwater. Site runoff measurements were a part of a larger study on carbon and nitrogen export from a drained peatland, as previously noted (Stefanía L. Bjarnadóttir, 2012).

3. Results

In this study atmosphere is chosen as reference, where net release of gases into the atmosphere are expressed as positive and net uptake of gases into soil and vegetation as negative values.

This chapter presents the measurement results from Mávahlíð study site for the entire measuring period (May 2011-October 2012). This includes measurements of CO_2 and CH_4 fluxes from drained peat, CH_4 fluxes from ditches, carbon stock estimates and environmental variables. Furthermore the carbon fluxes will be estimated on an annual basis for the year 2012 and lastly results of the initial effect of rewetting on gas fluxes will be presented.

3.1 Measured data

3.1.1 Fluxes of carbon dioxide

Midday chamber measurements of gross primary production (GPP) and ecosystem respiration (ER) indicated strong seasonal trends in CO_2 fluxes, largely driven by changes in plant activity. Figure 9 presents the average hourly midday CO_2 fluxes from the drained peat in g CO_2 m^{-2} hr^{-1} during the measurement period (May 2011 – October 2012) and covers two growing seasons. Both GPP and ER followed similar seasonal pattern, i.e. peaking during growing-season and near cessation during winter. Maximum average midday respiration recorded during the growing season was 1.09 ±0.05 g CO_2 m^{-2} hr^{-1} in August 2011 and 1.47 ±0.08 g CO_2 m^{-2} hr^{-1} in July 2012, whereas during winter respiration rates were low or usually below 0.1 g CO_2 m^{-2} hr^{-1}. Maximum average midday GPP recorded was -1.52 ±0.10 g CO_2 m^{-2} hr^{-1} in August 2011 and -1.58 ±0.10 g CO_2 m^{-2} hr^{-1} in July 2012, but neglectable plant C uptake was recorded during winter as vegetation was seasonally inactive and often covered in snow. More short-term variability was measured in GPP than ER due to rapid changes in cloud conditions affecting the GPP, compared to the relatively more stable soil parameters (temperature and moisture) affecting respiration.

Net ecosystem exchange (NEE) was determined directly from the closed chamber CO_2 flux measurements and was considered to be the sum of GPP and ER (the sum of heterotrophic and autotrophic respiration). During the growing season, midday measurements of net ecosystem exchange showed a net uptake of C as would be expected when night time measurements are left out.

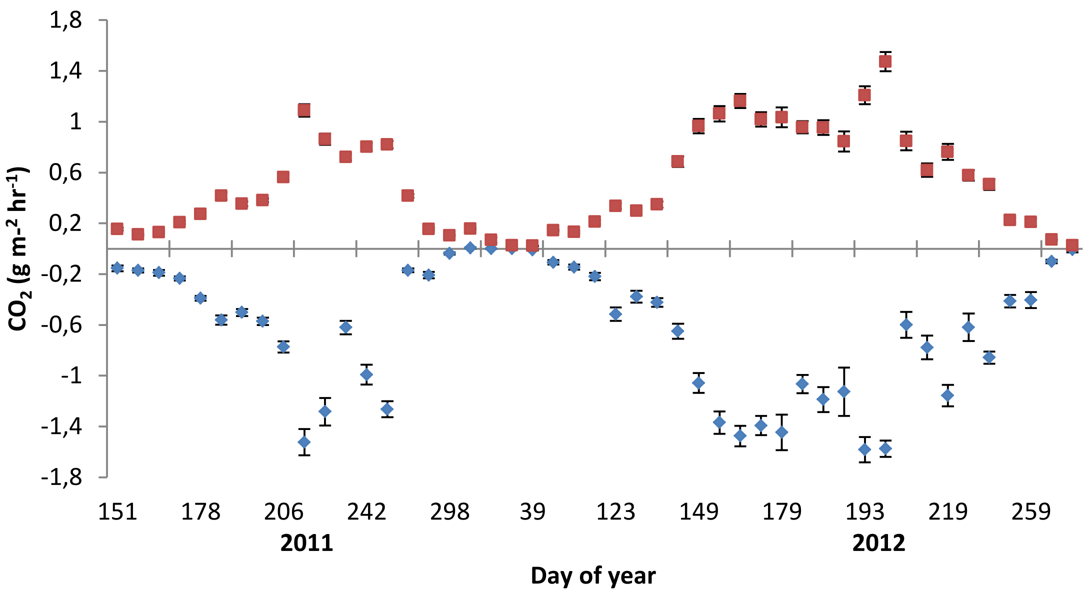

Figure 9. Chamber measurements of hourly midday CO_2 fluxes from the drained site during the measurement period. The graph shows ecosystem respiration (red) and gross primary production (blue) including standard error of the mean.

The growing seasons of 2011 and 2012 showed different overall pattern, characterized by an earlier start in productivity, a longer growing season and a greater number of high GPP and ER values in 2012 than 2011. The two growing seasons were tested and proved significantly different. In the early growing season (end of May-July), both GPP and ER fluxes were significantly higher in 2012 than 2011 ($p=0.000002$ and $p=0.00000005$ respectively). Less difference was measured between the late growing seasons (August-September), with weak significant difference in ER and non-significant difference in GPP between 2011 and 2012. The two growing seasons varied greatly in environmental conditions, especially temperature and humidity, which is presented in table 2. Annual precipitation was 1163.9 mm in 2011 but 899.1 mm in 2012 and 0.3°C higher temperature in 2012 than in 2011. Although both GPP and ER were significantly different between the two growing seasons, NEE turned out not to be significantly different ($p=0.244$).

Table 2. Hvanneyri weather station climatic data for 2011-2012.

	Annual precipitation (mm)	Mean annual temperature (°C)	Early summer mean temperature (May-June)
2011	1163.9	4.5	6.8
2012	889.1	4.8	8.4

3.1.2 Fluxes of methane

Figure 10 presents the measured hourly midday CH_4 fluxes from the drained peat over the measurement period. Overall the fluxes proved quite low and showed no clear seasonal trend, neither in emissions nor uptake. Throughout the measurement period CH_4 fluxes varied around zero with the highest average midday uptake recorded being -0.14 ±0.05 mg CH_4 m^{-2} hr^{-1} in June 2011 and -0.07 ±0.05 mg CH_4 m^{-2} hr^{-1} in August 2012. The highest average midday emission measured was 0.44 ±0.4 mg CH_4 m^{-2} hr^{-1} in September 2011 and 0.04 ±0.04 mg CH_4 m^{-2} hr^{-1} in September 2012. The very large error bars of the measurements in the fall of 2011 indicate the high variability in CH_4 fluxes during a wet period when some of the measurement points showed increased emission while other points remained closed to being inactive. No significant difference was measured between the CH_4 fluxes of 2011 and 2012 ($p=0.3$).

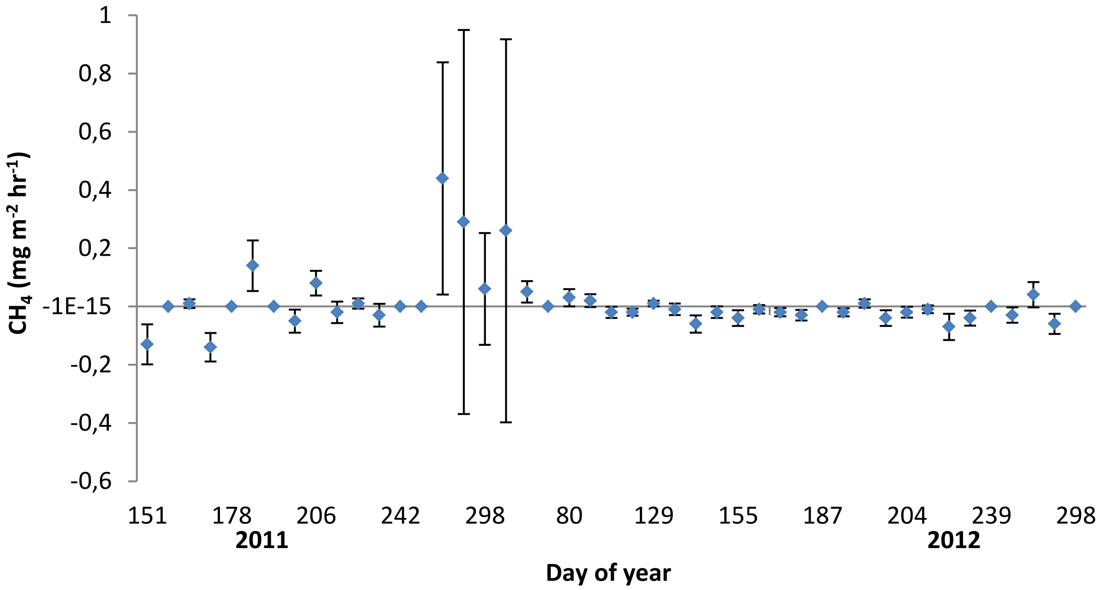

Figure 10. Hourly midday CH_4 fluxes measured at the Mávahlíð drained peat over the measurement period. Bars represent standard error of the mean.

Significantly more CH_4 emissions ($p=0.001$) were measured from ditches than the drained peat. Average CH_4 flux from ditches varied between -0.12 ±0.1 mg CH_4 m^{-2} hr^{-1} and 6.47

±2.45 mg CH_4 m^{-2} hr^{-1} and thus greatly exceeded the emissions recorded from the surface of the drained site. CH_4 fluxes from ditches varied significantly, both in time and space. Figure 11 presents the results of the chamber measurements of CH_4 flux from ditch water surface.

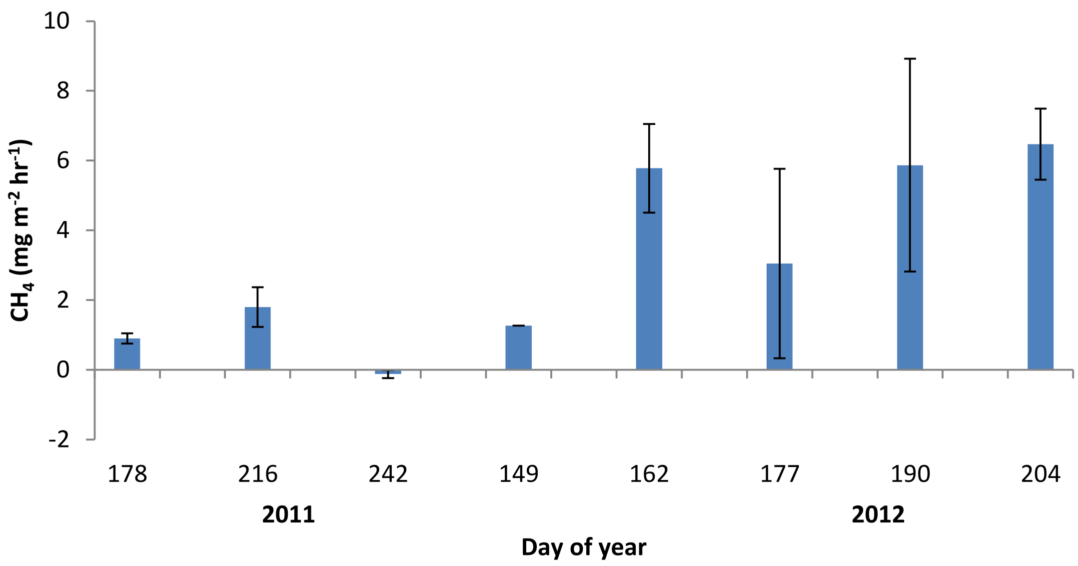

Figure 11. Hourly average midday CH_4 fluxes from ditches in Mávahlíð. Bars represent standard error of the mean.

No clear seasonal trend was seen in CH_4 fluxes from ditches, although significantly higher ($p=0.0028$) emissions were measured in 2012 than 2011. Ditches had standing water at all times of measurement, but CH_4 fluxes could not be measured during winter because ditches were covered with snow and/or ice.

3.1.3 Carbon stock

In order to put the gaseous carbon export into context, the total amount of carbon stored in the peat of Mávahlíð site was calculated. Average depth of organic layer of the site was 245 ± 4.9 cm (n=20). Carbon stock is estimated using the organic layer depth, bulk density (0.24 g cm^3) and proportion of carbon in soil (31.35%), by the following calculations:

$$2{,}450{,}000\ cm^3 * 0.24\ g\ cm^3 = 588{,}000\ g$$

$$588{,}000\ g * 0.3135\ \% = 184{,}338\ g\ C\ m^2$$

The result is 1,843 tons of C per hectare or 5,253 tons of carbon in the whole 2.85 ha site.

3.1.4 Environmental variables

Two automatic hydroclimatic stations were put up in Mávahlíð study site, one in each section A and B, on the 19th of August 2011, conducting hourly measurements of key environmental variables as previously described.

Figure 12 presents soil temperatures at three depths, 10 cm, 25 cm and 40 cm, along with outside air temperature. Air temperature ranged from -16.4°C in December 2011 and 20.5 °C in June 2012, with the annual average temperature of 4.6 °C in 2012. The soil profile shows clear seasonal trend in temperature, contingent up on air temperature. The top 10 cm of the soil is in closest contact with ambient temperature and therefore fluctuates most, both seasonally and daily. This layer is coldest in the winter time and warmest during summer, ranging from 0.3°C to 13.8 °C with an average of 5.5 °C. The deepest layer (40 cm) shows the least fluctuations in temperature, it does not respond to daily fluctuations in air temperature but shows clear annual fluctuations. The deepest layer is warmer than the other soil layers during winter and colder than the other layers during summer (fig. 12).

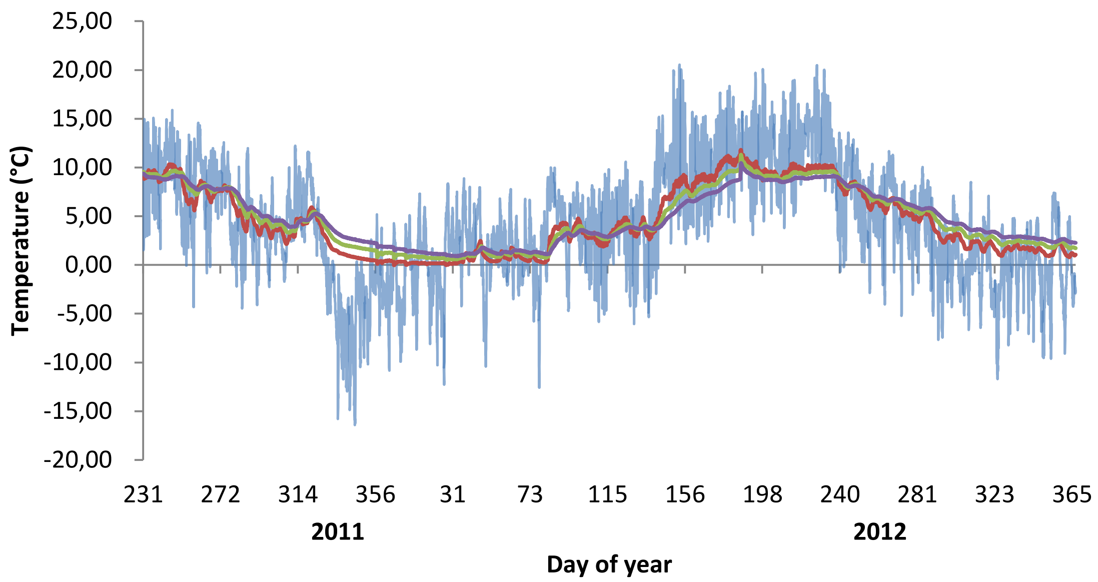

Figure 12. Air temperature (blue) and soil temperature at three depths, 10 cm (red), 25 cm (green) and 40 cm (violet) measured with automatic hydroclimatic stations from August 2011 – October 2012.

The soil water table level at both sections A and B were recorded hourly by an automatic sensor. The capability to measure cumulative rainfall was added to the station in March 2012. Figure 13 presents the results of measurements of water table level and cumulative rainfall.

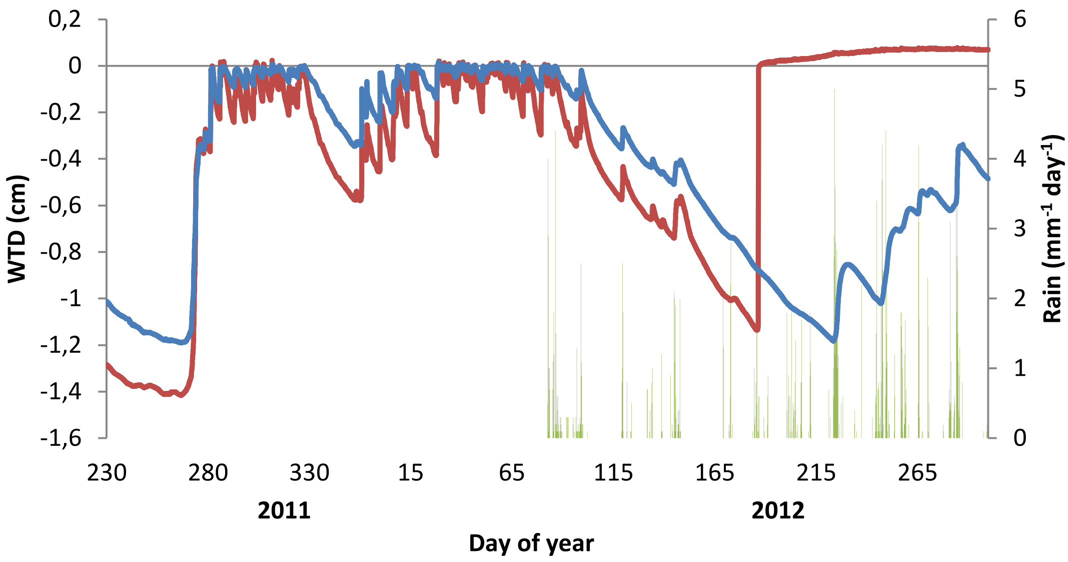

Figure 13. Daily cumulative rain (green) and water table depth (WTD) in section A (blue) and B (red) measured with automatic hydroclimatic stations. WTD was measured from August 2011 till end of study and rain gauge was installed in March 2012. (Day 185 in 2012: section B was rewetted and the water table reached the surface).

Initial water table level was -1.0 m and -1.2 m in section A and B respectively at the beginning of measurements in August 2011 and continued to drop until mid-September 2011 when water table level rose almost to the surface. The winter of 2011-2012 was unusually rainy, with monthly average 239.7 mm in September-March, compared to 129 mm same period the year before (Icelandic Meteorological Office, Andakílsárvirkjun). Therefore the study site stayed relatively wet the whole winter, until March 2012 when the water table level started to lower until it reached down to -1.0 m in July 2012 before the rewetting. At the time of rewetting, 4th of July, water table level of section B (red) rose immediately up to the surface, while water table level of section A continued to drop until heavy rainfall events in the autumn raised it again. Water level in section B was significantly lower throughout the measuring period, from the beginning of measurements until the rewetting event, after that water level in section B was significantly much higher than the drained section A.

Photosynthetically active radiation (PAR) was measured both hourly with an automatic sensor and manually at each plot during carbon flux measurements. Figure 14 presents the hourly results of the PAR from the automatic sensor. Seasonal midday fluxes in PAR ranged from near zero mmol m^{-2} sec^{-1} during winter to 1444.8 mmol m^{-2} sec^{-1} during growing season.

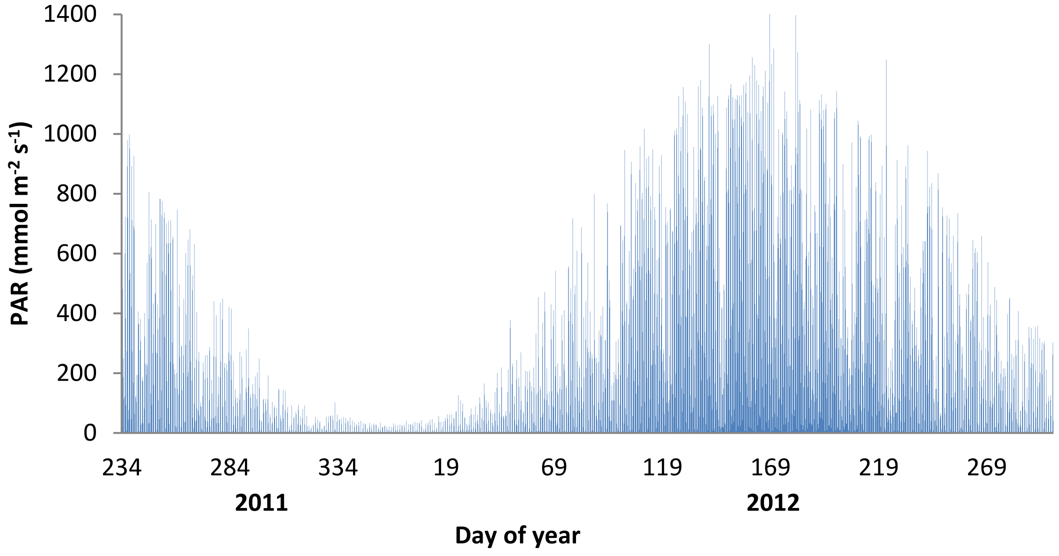

Figure 14. Photosynthetically active radiation (PAR) at the study site.

Instantaneous measurements of PAR show only midday values, taken from the chamber measurements of carbon fluxes, and are thus not shown on graph. Normalized difference vegetation index (NDVI) was measured each time of flux measurements and is presented in figure 15.

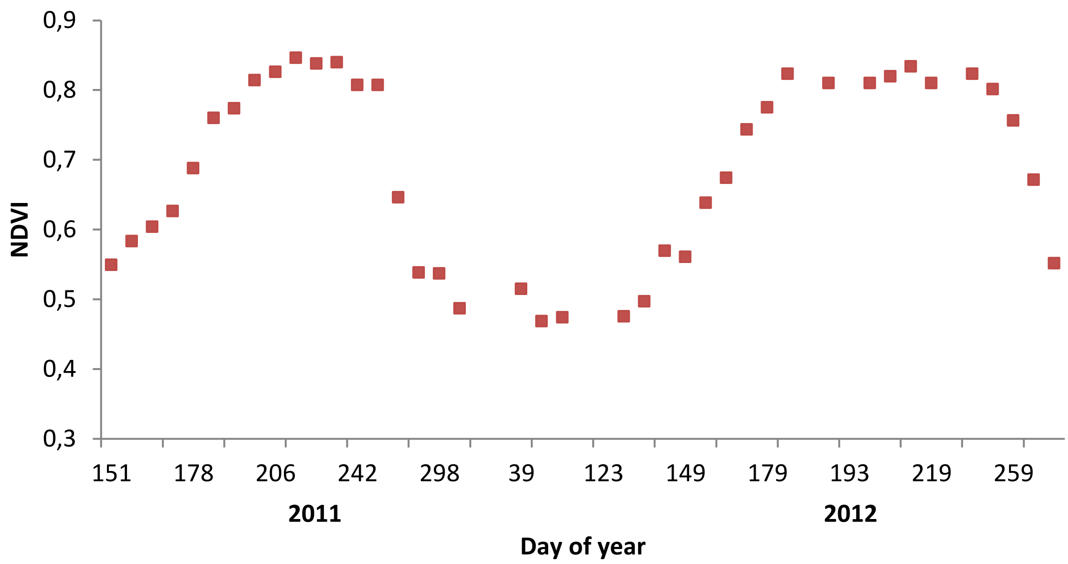

Figure 15. Instantaneous NDVI measurements 2011-2012.

The highest NDVI values measured 0.85 in early August 2011 (day 215) and 0.83 in end of July 2012 (day 207). The lowest NDVI was 0.47 in end of March (day 87).

3.2 Annual carbon fluxes of the drained peat

For estimating annual carbon fluxes of the site from the intermittent field measurements, an extrapolation or gap-filling method was needed. This chapter explains the methodology used for estimating carbon fluxes in-between the regular field measurements.

3.2.1 Annual CO_2 flux

Research has shown that ecosystem respiration is strongly correlated with soil temperature (Lloyd & Taylor, 1994; Hendriks *et al.*, 2007). Thus all instantaneous flux measurements of CO_2 from the drained peat in 2012 were correlated with soil temperature at 10 cm depth measured at the same time. The correlation gave the following exponential relation (fig. 16).

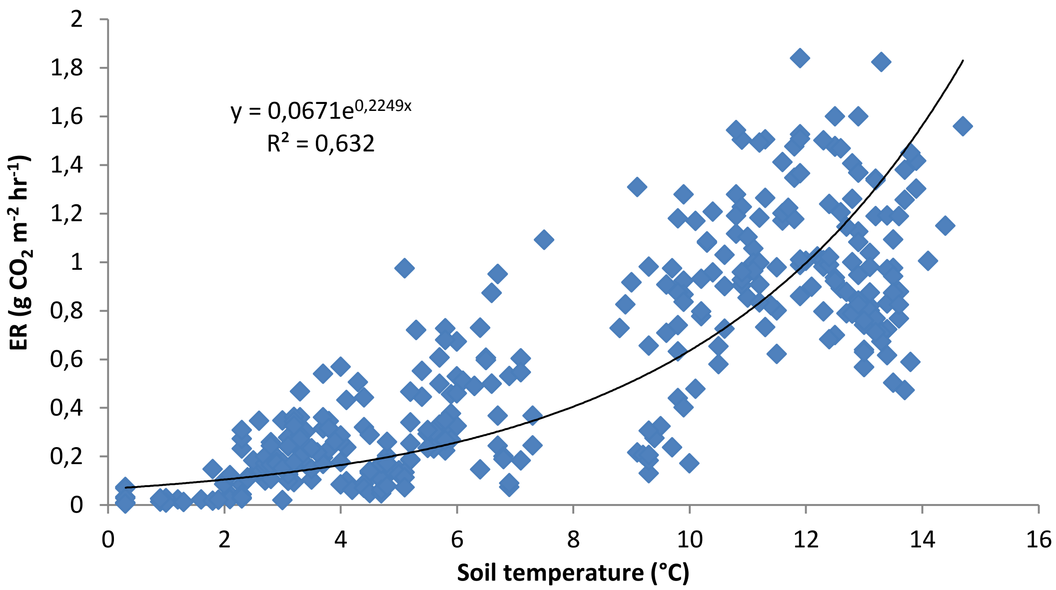

Figure 16. Best-fit line and its regression equations for ecosystem respiration as a function of soil temperature at 10 cm depth.

The relationship between instantaneous data of respiration and soil temperature was good (r^2=0.632) and gave the regression equation used to estimate the annual respiration of the site. As soil temperature was measured every hour throughout the year, the regression equation was used to extrapolate the respiration onto the days in-between measurements. Figure 17 presents the agreement of the modelled data from the time of flux measurements fitted with the mean measured data of ecosystem respiration.

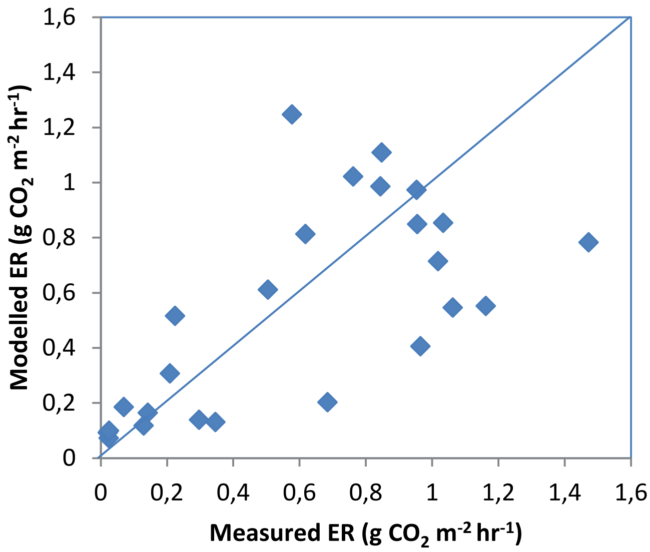

Figure 17. Comparison of measured and modelled daytime ecosystem respiration (ER). The line is indicating 1:1 agreement.

For ecosystem GPP there are two main drivers (given that moisture and nutrients are not overly lacking); on one hand there is the amount of energy available for photosynthesis, here quantified as photosynthetically active radiation (PAR), and on the other hand the amount of green plant mass able to catch the available energy, here quantified using the normalized difference vegetation index (NDVI). Hourly PAR values and intermittent measurements of NDVI and GPP for 2012 are shown in Figure 18. The early growing season increase in GPP corresponds to an increase in the vegetation´s greenness (NDVI), which again is dependent on the available light for photosynthesis (PAR). In the late growing season GPP was more sensitive to the availability of light (figure 18).

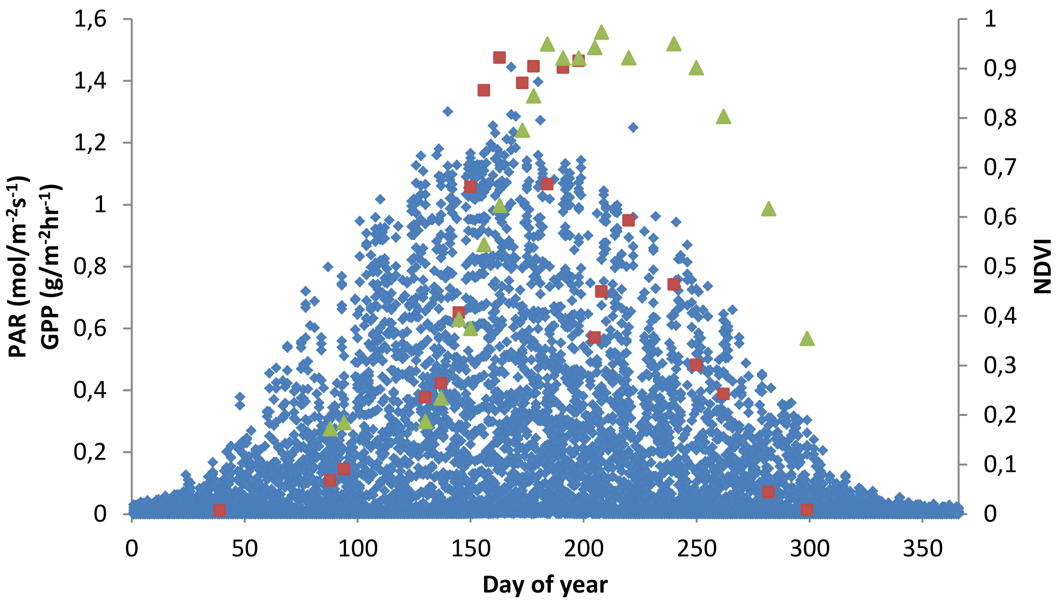

Figure 18. Annual fluctuations in hourly PAR (blue), measured GPP (red) and NDVI (green) at Mávahlíð in 2012 (see also Rannveig Ólafsdóttir & Hlynur Óskarsson, 2014).

As GPP is strongly dependent on PAR, GPP was expressed by its logarithmic relation with incoming PAR over two month period during the peak in vegetation greenness (July-August) (Fig. 19).

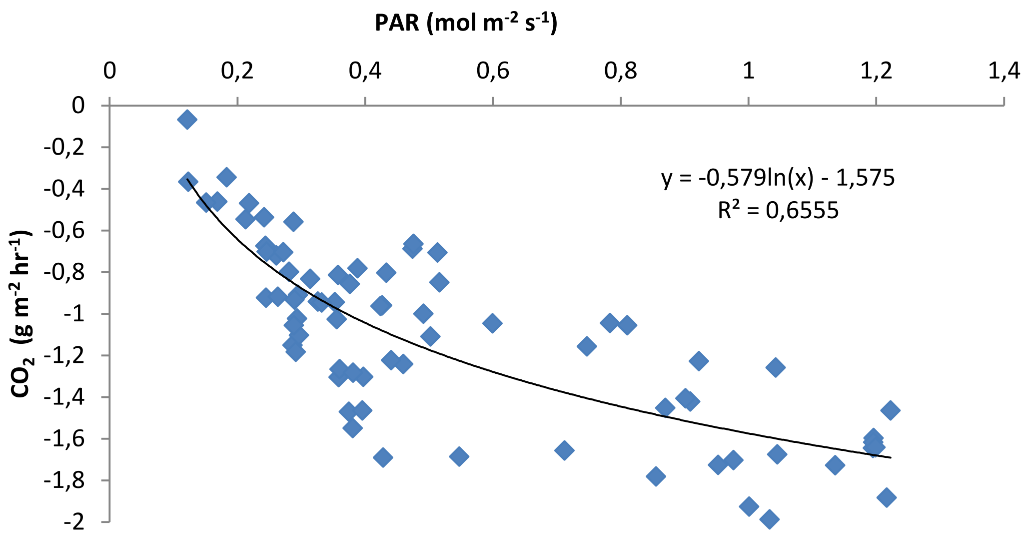

Figure 19. Best-fit line and its regression equations for GPP as a function of PAR in July-August 2012.

Because PAR was measured every hour throughout the year, the best-fit line and its regression equations were used to estimate the annual GPP of the drained peatland. Figure 20 presents the modelled data fitted with the measured data of GPP.

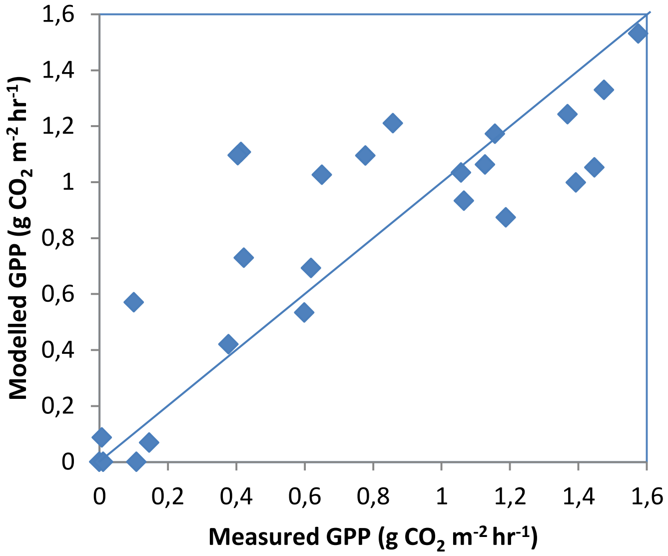

Figure 20. Comparison of measured and modelled daytime gross primary production (GPP). The line is indicating 1:1 agreement. GPP are shown as positive values.

Because of the late spring/early summer discrepancy between PAR and GPP (fig. 18), PAR alone is not a good predictor of GPP during that period. Using just PAR would result in a gross overestimation of GPP as the relatively small amount of plant green-mass of that period can only utilize a fraction of the available energy. PAR values were thus adjusted with scaled NDVI values, where the annual lowest NDVI value equalled zero and the annual highest value equalled one. Scaling NDVI was necessary since NDVI is not an incremental number but an index that varies between 0 and 1.0. Each modelled GPP value was then multiplied by its climatic end-product NDVI-adjusted PAR (Rannveig Ólafsdóttir & Hlynur Óskarsson, 2014).

In order to evaluate the usefulness of NDVI-adjusted PAR for predicting grassland GPP, correlations were run between measured GPP and measured PAR, measured GPP and measured NDVI, and measured GPP and NDVI-adjusted PAR. The results of these correlations are depicted in figure 21. NDVI-adjusted PAR proved significantly superior (R^2=0.695, p<0.01) to PAR alone (R^2=0.353, p<0.01) in terms of correlating with measured GPP. Correlation of NDVI and GPP proved worst (R^2=0.2943), p<0.01) and is thus not shown on the graph (Rannveig Ólafsdóttir & Hlynur Óskarsson, 2014)

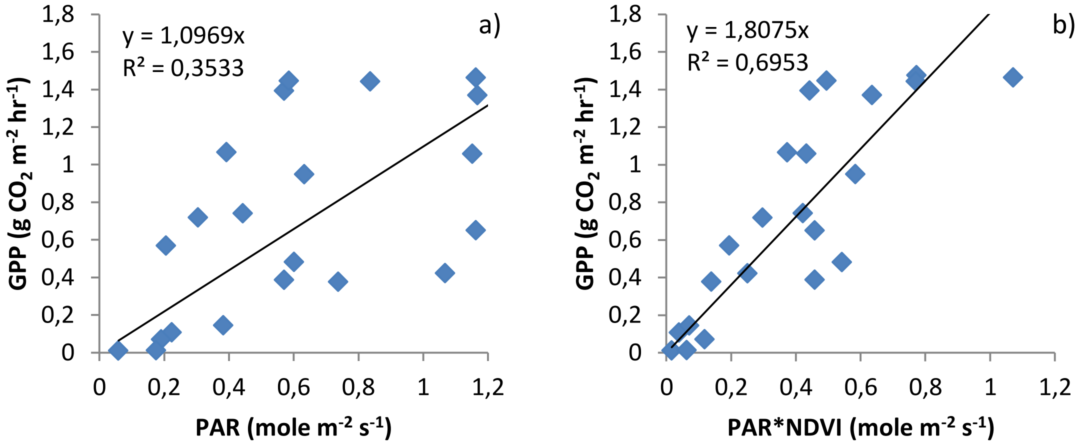

Figure 21. Linear regression between a) measured GPP and PAR, and b) measured GPP and NDVI-adjusted PAR, in 2012 (Rannveig Ólafsdóttir & Hlynur Óskarsson, 2014).

The two functions, for ER (fig. 16) and for GPP (fig. 21.b), were run with hourly values throughout the year and figure 22 presents the daily CO_2 exchange in ER, GPP and NEE for the year 2012. Net ecosystem exchange values were generally positive (net CO_2 emission), except for early summer when vegetation was growing rapidly. With increasing sunlight and greener vegetation daily fluxes become greater with net CO_2 uptake during daytime and respiration during night time.

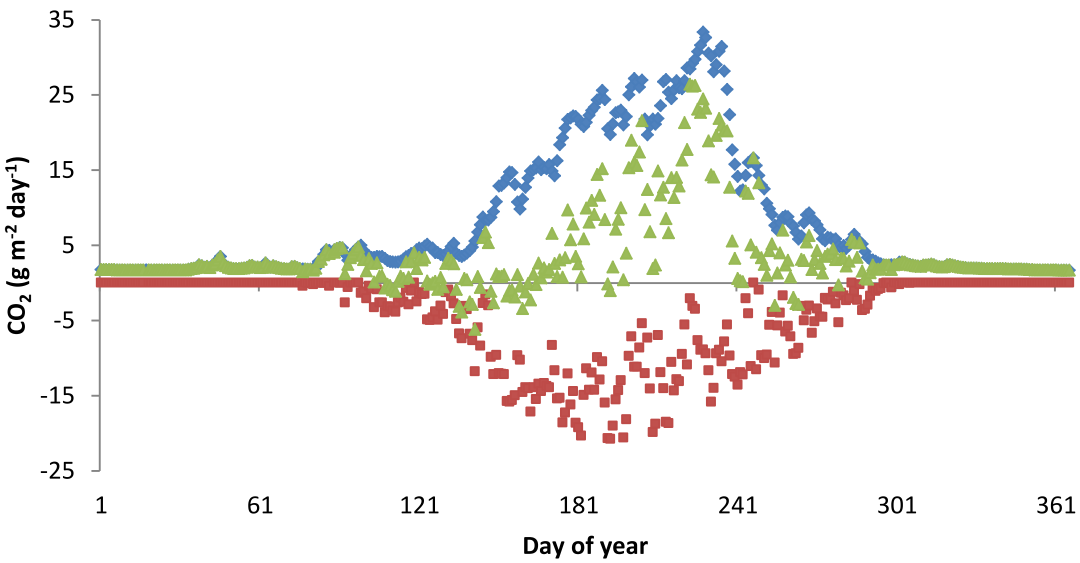

Figure 22. Daily NEE (green), GPP (red) and ER (blue) in Mávahlíð, over the year 2012.

The net exchange of CO_2 as estimated for the site in 2012 is shown in table 3, and indicates that the site was a net source of 14.1 t CO_2 ha^{-1} yr^{-1} or 3.8 t C ha^{-1} yr^{-1}.

Table 3. Annual ecosystem respiration (ER), gross primary production (GPP) and net ecosystem exchange (NEE) in Mávahlíð in 2012.

	ER	GPP	NEE
t CO_2 ha^{-1} yr^{-1}	30.8 ±2.59	-16.1 ±1.42	14.1 ±2.43
t C ha^{-1} yr^{-1}	8.15 ±0.68	-4.35 ±0.38	3.8 ±0.65

3.2.2 Annual CH_4 flux

Previous studies have shown a relationship between CH_4 flux and soil temperature and between CH_4 and soil water table level (Hendriks *et al.*, 2007; Rowson *et al.*, 2010). All instantaneous flux measurements of CH_4 from the drained peat in 2012 were correlated with both soil temperature at 10 cm depth and soil water table level measured at the same time. The correlation gave the following exponential relations with soil temperature and soil water level, R^2=0.025 and R^2=0.027 respectively. Thus no statistically significant correlation was found between CH_4 fluxes and the hydroclimatic variables, i.e. soil temperature and soil water level.

Because measured methane flux did not correlate with the climatic controls tested, and fluxes were generally low and variable, annual fluxes were estimated through extrapolation of field measurement averages. Average flux of CH_4 in the growing season (May-September) was -0.019 mg CH_4 m^{-2} hr^{-1} and -0.005 mg m^{-2} hr^{-1} in the winter (October-April). Two measurements were done in December and January while soil was covered in snow/ice and fluxes were negligible and therefore assumed no fluxes. The average hourly flux for each season (growing season and winter) was extrapolated on to the days without measurements, or in total 152 days for each season and the rest of the year (61 days) was assumed no fluxes. Based on this extrapolation there was a small total annual uptake of -0.88 kg CH_4 ha^{-1} $year^{-1}$ or -0.66 kg C ha^{-1} $year^{-1}$.

Significantly different CH_4 fluxes were found in 2012 for the drained peat surface on one hand and the peat ditches on the other, as previously mentioned for the whole measuring period in chapter 3.1.2. CH_4 fluxes from ditches were only measured during growing season (152 days) and varied between -0.23 mg CH_4 m^{-2} hr^{-1} and 8.92 mg CH_4 m^{-2} hr^{-1}, with an average of 4.48 mg CH_4 m^{-2} hr^{-1}. CH_4 flux from ditches during winter were assumed zero as ditches were often covered with snow and/or ice. Therefore the days outside growing season were estimated to have no flux. Annual fluxes of CH_4 from ditches were determined in the same way as for the drained land by extrapolating the average hourly flux onto the days without measurement. Total annual export of carbon with methane from the area ditches of Mávahlíð was 164.8 kg CH_4 ha^{-1} $year^{-1}$ or 123.6 kg C ha^{-1} $year^{-1}$.

3.2.3 Carbon stocks and fluxes

The overall carbon budget for the site in 2012 is summarized in table 4 and shows the site as a net source of 4,135 kg C ha^{-1}. Gaseous CO_2 emissions are by far the largest export factor of carbon from the drained peatland site, accountable for 91.9% of the overall total carbon exported.

Table 4. Summary of carbon budget from the drained study site in 2012.

Carbon species	**Flux (kg C ha^{-1} yr^{-1})**	**% of total**
Gaseous CO_2 (NEE)	3,800 ±650	91.90%
Soil CH_4	-0.7 ±1.3	-0.02%
Ditch CH_4	123.6 ±87.3	2.99%
POC*	95.7 ±62.1	2.31%
DOC*	116.5 ±19.8	2.82%
Total	**4,135 ±821**	

*Stefanía L. Bjarnadóttir, 2012

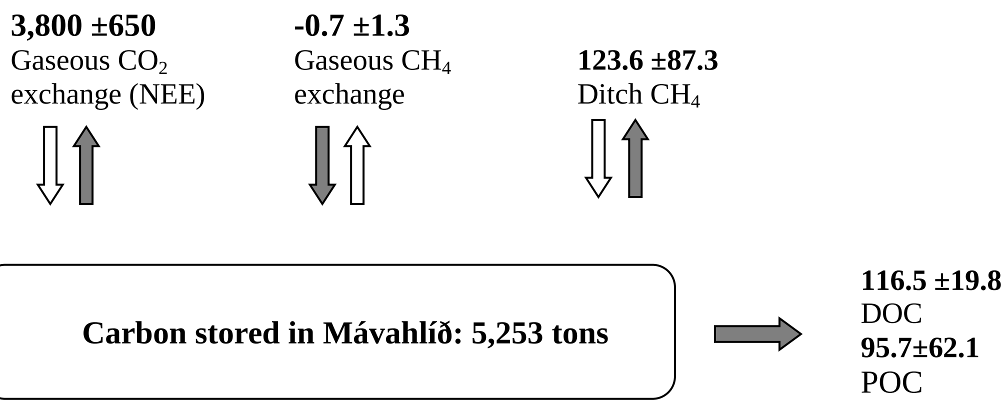

Figure 23. Schematic diagram of peatland annual carbon fluxes (kg C ha^{-1} yr^{-1}).

3.3 Initial effects of peatland rewetting

This chapter presents the results of a study of the initial effects of rewetting on peat carbon fluxes, carried out during the four months following ditch filling.

3.3.1 Hydrological response to ditch filling

Prior to rewetting, water entered the site primarily in the form of precipitation. Losses consisted mainly of runoff and evapotranspiration as well as potentially some infiltration of soil water to the underlying bedrock layers. Following the filling in of the upper ditch, water that previously was directed away from the site, now entered the site either free-flowing from the further-uphill springs or through a pipe network bringing water from a major uphill spring, which had the purpose of facilitating the rewetting of the site.

The upper ditch was filled in on July 4th 2012. Water table depth was measured before rewetting on July 2, and initially after the rewetting on July 9. Only 5 days after the rewetting event water level in section B (rewetted) had significantly risen 72 cm, from a depth of -105 cm below surface before rewetting up to -33 cm on July 9th. Meanwhile the water level in section A (drained) remained the same. Figure 24 presents the average water table depth for section A and B during two months around the rewetting event.

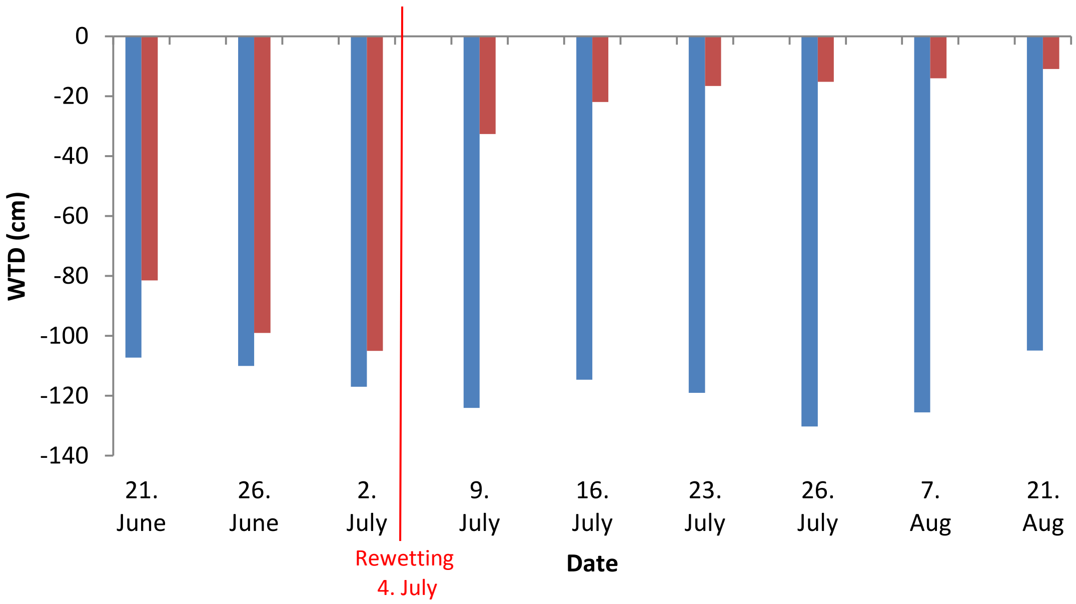

Figure 24. Mean water table depth of drained section A (blue) and rewetted section B (red) during three measurements before rewetting and six measurements after rewetting. Rewetting took place on July 4th.

Water table levels of both sections of the site were also recorded hourly by an automatic sensor, situated in the middle of the sections. According to the automatic sensors the rewetting of that specific given point occurred in only few hours. Figure 25 presents the average water level over 48 hours during the day of rewetting and the day after.

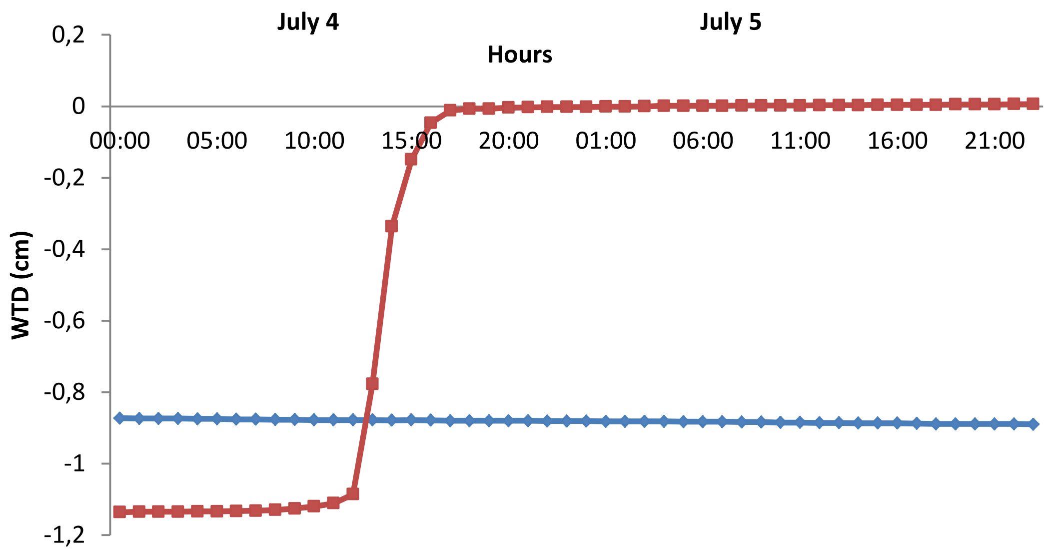

Figure 25. Soil water table level at the rewetted site (red) and drained site (blue) over 48 hours during rewetting.

Within 5 hours the water level of the rewetted section increased from -110 cm depth to 0 cm or at surface in the middle of the section where the automatic sensor was placed. Three plots that were situated on the margins of the rewetted site did not show significantly higher water table level until 12 days after rewetting. The drained section A showed no significant change in water level following the rewetting, except for normal increase in response to heavy rainfall.

3.3.2 Initial CO_2 fluxes following rewetting

Two days after the ditch was filled, carbon fluxes were measured both on the rewetted and still drained section of the study site. By then water level was at, above or near surface in the plots situated in the middle of the rewetted section. From the time of rewetting, July 4th, and until end of study October 25th, ecosystem respiration rates of the rewetted section were in the range of 0.013 to 1.06 g CO_2 m^{-2} hr^{-1} with an average of 0.5 g CO_2 m^{-2} hr^{-1}. In comparison respiration on the drained section ranged between 0.026 and 1.47 g CO_2 m^{-2} hr^{-1} with an average of 0.64 g CO_2 m^{-2} hr^{-1} during the same period. Figure 26 presents measurements of ecosystem respiration of the drained and rewetted sections in 2012, before and after the rewetting. Before the rewetting no significant difference was found between respiration of sections A and B, despite small variations. After the filling in of the ditch, significantly lower respiration was measured on the rewetted section B, in comparison with the still drained section A, on 9 out of 13 days of measurements.

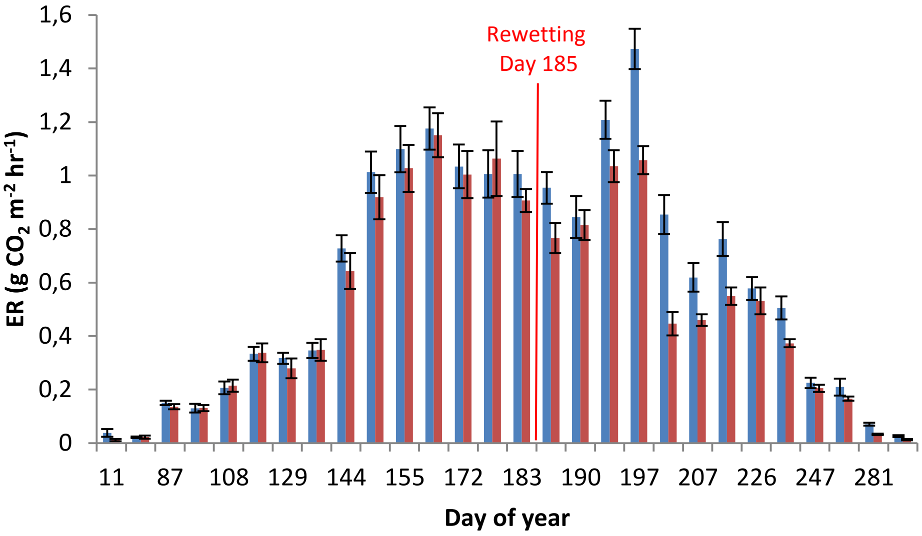

Figure 26. Ecosystem respiration of the drained section (blue) and rewetted section (red). Rewetting took place on the 4th of July (day 185).

Figure 27 presents the results from measurements of gross primary productions on section A and section B prior to and following the rewetting event. Before rewetting GPP was significantly higher on section A on 5 out of 14 measurement occasions. After rewetting GPP was, on the other hand, significantly higher on the rewetted section on three measurement dates, July 9, August 14 and September 6.

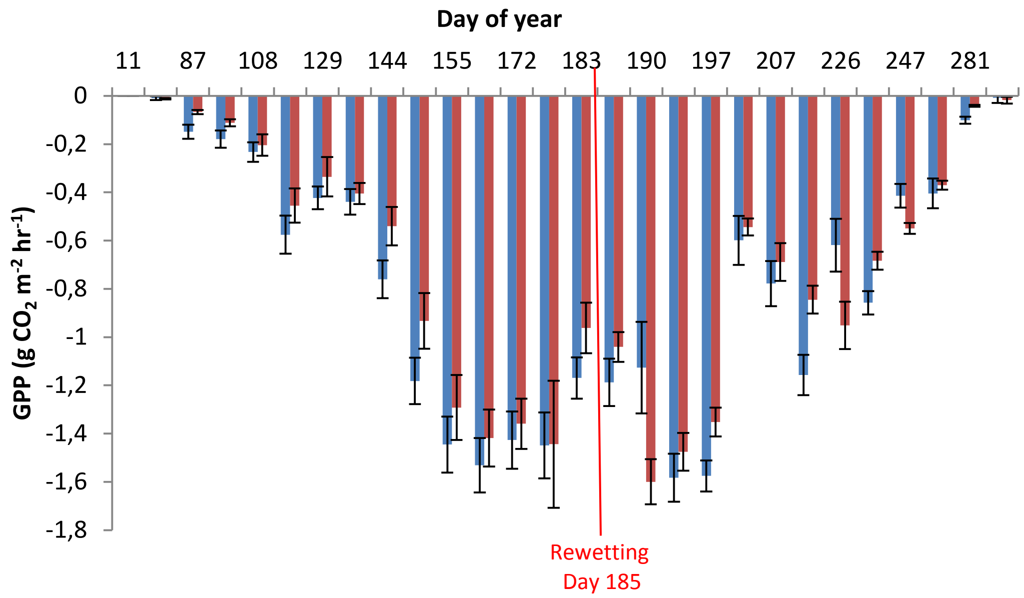

Figure 27. GPP from the drained section (blue) and rewetted section (red). Red line shows the time of rewetting 4th of July (day 185).

Correlation of section B ecosystem respiration following rewetting with soil temperature and water table depth was explored, shown in figures 28a and 28b. Soil temperature and water table level were measured in only 8 out of 13 times of flux measurements after the rewetting event. Clear relationship was between respiration and both variables although slightly better correlation with soil temperature (R^2=0.7603). Emissions are very low (less than 0.2 g CO_2 m^{-2} hr^{-1}) at high water levels (higher than -10 cm below surface), and show a linear response as the water level lowers (Fig. 28).

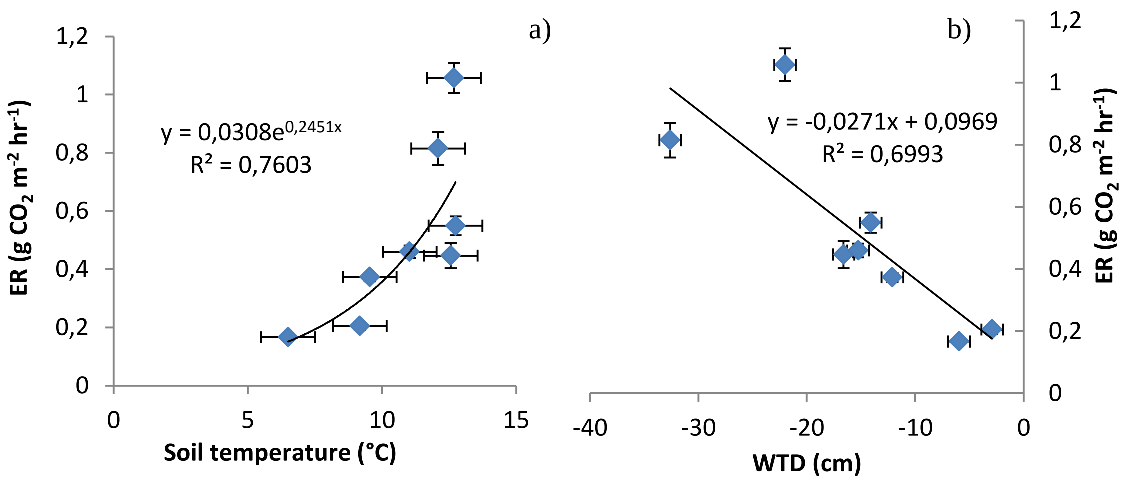

Figure 28. Average respiration from the rewetted section in relation to a) soil temperature at 10 cm and b) the mean water level.

3.3.3 Initial CH_4 fluxes following rewetting

Like CO_2 fluxes, methane fluxes were measured 13 times on regular basis after rewetting until the end of study in October. Before rewetting no statistical difference ($p=0.09$) was found between overall measured CH_4 fluxes on section A and section B, although significant difference was found between the sections on single measurements days (fig 29). After rewetting, fluxes on the rewetted section were significantly higher with a range of -0.06 to 0.2 mg CH_4 m^{-2} hr^{-1} and an average of 0.06 mg CH_4 m^{-2} hr^{-1} compared to a range of -0.07 to 0.04 mg CH_4 m^{-2} hr^{-1} and an average of -0.02 mg CH_4 m^{-2} hr^{-1} on the drained section. Figure 29 presents the measured CH_4 fluxes of the two sections, showing clearly higher emissions of CH_4 from section B following rewetting although variation in measured fluxes is high and fluxes in general low.

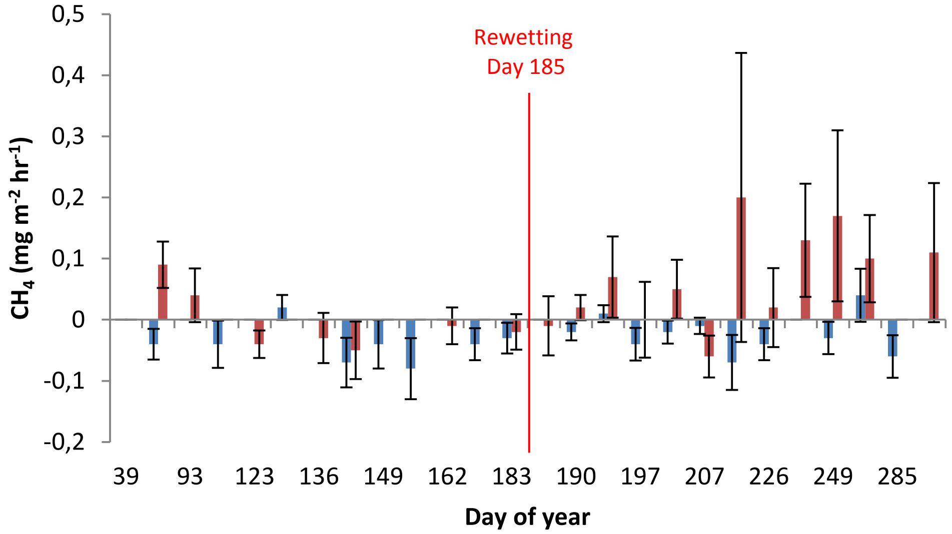

Figure 29. CH_4 flux from the drained section (blue) and rewetted section (red) in 2012.

Methane flux of the rewetted site was correlated with the same hydroclimatic variables as the drained site, i.e. soil temperature and water table depth. No statistically significant relation was found between CH_4 fluxes and soil temperature ($R^2=0.0727$) although much better relation was between methane fluxes from rewetted site and water table depth ($R^2=0.3098$) (fig 30).

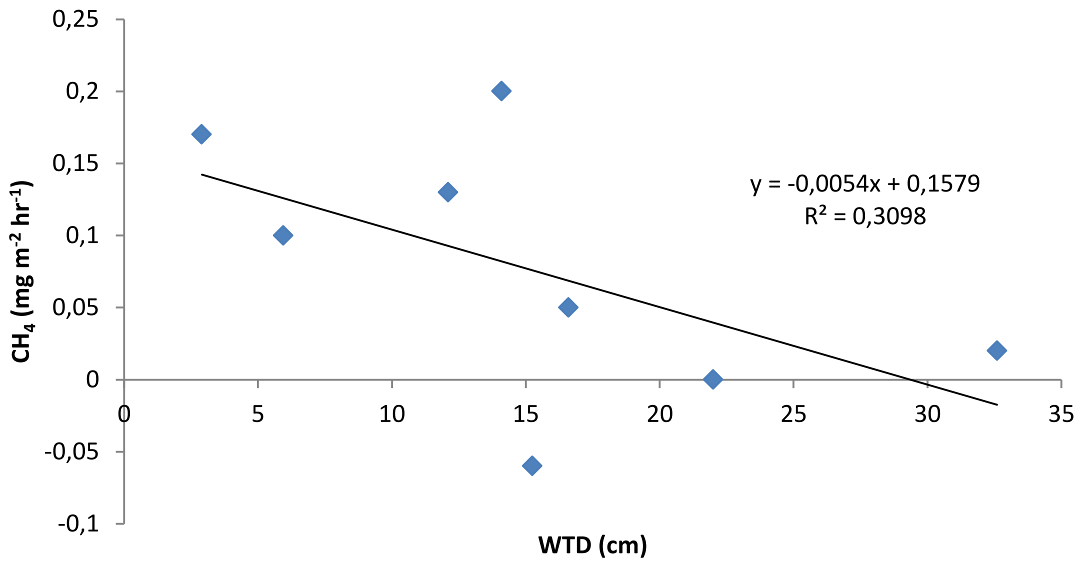

Figure 30. Relationship between methane emission and water table depth in the rewetted section of Mávahlíð.

4. Discussions

4.1 Carbon dynamics of drained peat

The carbon flux measurements campaign at the drained peat site in Mávahlíð covered 17 months including two growing seasons, 2011 and 2012. This study therefore represents one of the most extensive research undertaken of greenhouse gas fluxes from a drained peatland in Iceland, and together with Stefanía L. Bjarnadóttir (2012) presents the first C budget for peatland that includes all the major C uptake and release pathways on a drained peat site.

The campaigns' results showed a significant difference in carbon dioxide fluxes between the two growing seasons. The spring of 2011 was cold and wet in comparison to the warm spring of 2012. The spring associated rise in both ecosystem respiration and primary production occurred significantly earlier in 2012 than the year before, and growing season lasted longer, well portrayed in the NDVI measurements of vegetation green mass. Despite the difference in climate between years the net ecosystem exchange was non-significantly different.

Methane fluxes however showed greater spatial, rather than temporal heterogeneity. No statistically significant difference was found between seasons but each plot could be significantly different from the next each time of measuring, indicated with the big error bars. Bulk of the sites overall CH_4 emissions was clearly driven by release from the drainage ditches, similar to what other results have shown (e.g. Teh *et al*., 2011). Despite the almost negligible and fluctuating emissions from the drained soil the amount of methane emissions from ditches in Iceland must be significant with a present-day ditch network revealing 29,700 km (Fanney Ósk Gísladóttir *et al*., 2010). CH_4 emissions from the ditches are a result of methanogenesis within the anaerobic parts of the soil which supplies CH_4 statured water to the ditches and hence bypasses CH_4 oxidation in the aerated parts of the soil. From these observations we assumed a relationship between methane fluxes and water table depth and suggest higher CH_4 emission from the soil following peat rewetting.

Due to land inclination the water table level of section B was lower than section A from the beginning of measurements until the rewetting (fig 13). Despite the difference in initial water table level no statistical difference was found in gas fluxes between the sections before the rewetting. Most likely the site was so successfully drained in the first place that this difference in land inclination was not relevant to the carbon fluxes.

4.2 Carbon storage and annual carbon budget of the drained peat

This study showed that the carbon storage of the Mávahlíð peatland was 5,253 tons of C or 1,843 tons of C per hectare. Overall the site was a net source of 4.1 ±0.9 t of C ha^{-1} yr^{-1} for 2012. Of the carbon pathways examined in this study, CO_2 fluxes represented by far the greatest portion of the overall carbon emissions, or a net source of 14.1 t CO_2 ha^{-1} yr^{-1} (3.8 t C ha^{-1} yr^{-1}). This constitutes 91.9% of carbon exported from the site, and methane from ditches, POC and DOC contribute to the 8.1% exported. The CO_2 emission from Mávahlíð is comparable to what has been previously presented for drained organic soils in Iceland, none of which has been ploughed, harrowed or afforested since drainage, with a net annual emissions ranging from 3.97 to 8.25 t C ha^{-1} yr^{-1} (14.6 to 30.3 t CO_2 ha^{-1} yr^{-1}) (Jón Guðmundsson & Hlynur Óskarsson, 2014).

About 100 published articles or manuscripts are found in the literature reporting GHG fluxes from differently managed peatlands in the Nordic countries. Most of these studies describe peatlands drained for agriculture, forestry or peat extraction (e.g. Maljanen *et al.*, 2010), but very few studies report sites that have been drained but never ploughed or cultivated (Jón Guðmundsson & Hlynur Óskarsson, 2014), like Mávahlíð. In fact over 80% of drained organic soils in Iceland are abandoned (as uncultivated) or used only for livestock grazing, or in total 3,440 km^2, whereas the majority of drained peat in other Nordic countries is being used for forestry and agriculture. However comparing annual CO_2 emissions from Mávahlíð to drained peatlands in other Nordic countries the values are not much higher or 18 ±11 t CO_2 ha^{-1} for perennial crops, 25 ±10 t CO_2 ha^{-1} in fallow soils and 13 ±11 to CO_2 ha^{-1} for abandoned croplands (Maljanen *et al*., 2010).

For other European countries (Finland, Sweden, Netherland) Kasimir-Klemedtsson *et al*. (1997) reported farmed organic soils as large emitters of CO_2 with an estimated net flux range from 8 to 115 t CO_2 ha^{-1} yr^{-1} and negligible sources and/or sink of CH_4. Although farmed organic soils in most European countries represent a minor part of the total agricultural area, these soils contribute significantly to national greenhouse gas budgets. According to a study on drained peatlands in temperate Europe by Couwenberger *et al*. (2011) deeply drained agriculturally used peatlands show high emissions, up to 20 t CO_2 ha^{-1} yr^{-1} (5.4 t C ha^{-1} yr^{-1}).

These emissions reported from other European countries are somewhat higher than recorded in Mávahlíð which can possibly be explained by the long time since the drainage in Mávahlíð took place and that it has never been agriculturally used since the drainage. Both ploughing and fertilization are known to enhance the rate of microbiological processes in peat (Maljanen *et al*., 2010) so it could be expected that cultivated lands are emitting more CO_2 than uncultivated or abandoned.

Discounting emission from ditches, Mávahlíð was an annual negligible sink of CH_4 (-0.7 ±1.3 kg C ha^{-1} yr^{-1}) compared to a negligible source from drained (abandoned and unfertilized) organic peat soil cores from Iceland under laboratory conditions (Elisabeth Jansen, Jón Guðmundsson & Hlynur Óskarsson, 2008). In the same study undisturbed peatland showed an emission of about 620 mg CH_4 m^{-2} day^{-1}. From temperate European peatlands annual methane fluxes show a clear relationship with mean annual water level. Emissions are negligible (<2 kg ha^{-1} yr^{-1}) at low mean water levels (<-20 cm) while values rise steeply with mean water levels above -20 cm (Couwenberger *et al.*, 2011).

Natural wetlands are recognized as a source of CH_4 and sink of CO_2 while draining reduces the CH_4 emissions but increases the CO_2 emissions. This study shows that a considerable amount of CO_2 is emitted to the atmosphere from drained peatlands in Iceland and gives a more precise estimate of the annual budget of these drained areas than before. Although the study was mainly based on the carbon transfer between the atmosphere and land surface it was necessary to include the fluvial export of carbon in order to propose a total carbon budget for the peatland (Stefanía L. Bjarnadóttir, 2012).

4.3 Initial effects of peatland rewetting

Peatland rewetting is a term used for the concept to reconstruct a water saturated peatland from a drained site. With rewetting, the aim is to reverse the biochemical processes occurring in a drained peatland into the biochemical processes prevalent within water saturated peatland. Little is known about the initial response to the rewetting but this study shows a significant change in fluxes almost instantly after raising the water table level. Within 48 hours after the rewetting soil respiration had lowered and CH_4 emissions increased significantly. This sudden shift is likely the result of the physical alteration the raised water level has on the peat, causing anoxic conditions within the soil, and hence slowing down aerated microbial decomposition rates and enhancing anoxic methanogenic decomposition of the peat layer.

Many studies have shown that water table depth is the most relevant factor concerning greenhouse gas emissions from peatlands (Moore and Knowles, 1989; Hendriks *et al*., 2007; Couwenberger *et al*., 2011; Maljanen *et al*., 2012). According to Maljanens´ *et al*. (2012) research on abandoned boreal agricultural soils in Finland, the lowest net (CO_2 + CH_4) emissions occurred during a wet year with a high water table level. Therefore high GHG emissions from these soils can be best avoided if the water table is maintained close to the surface (less than 30 cm from the soil surface) when photosynthesis is favoured over respiration. Couwenberger *et al*. (2011) found out that when water levels reach above -50 cm there is a marked decrease in emissions of CO_2, reaching near zero (or net uptake) at mean water levels close to the surface, and marked increase in emissions of CH_4 with water levels above -20 cm. His suggestion was that the range of -20 and -50 cm water table depth is optimal for the least release of gases. The results of Mávahlíð peatland indicate however an even more narrow range of -15 to -20 cm water table depth to limit the release of carbon gases from soil. Therefore it may be suggested that by bringing the water table level, e.g. by blocking the drainage ditches after agricultural use has ended, close to the soil surface, high GHG emissions can be avoided. However, if the water table is very high and the peat is totally water saturated, there is a risk of CH_4 emissions similar to the fluxes from drainage ditches.

4.4 The feasibility of using variables such as NDVI and PAR in estimating in-between-measurement gross primary production.

Numerous studies have suggested a new remote technique to estimate GPP with a product of NDVI and PAR, termed NDVI-adjusted PAR (Wu *et al.*, 2009; Gitelson *et al*,. 2006; Peng *et al.*, 2013). As a side project, this thesis was tested at the ground level in Mávahlíð peatland (Rannveig Ólafsdóttir & Hlynur Óskarsson, 2014). The use of incoming radiation alone for predicting GPP is difficult in terrestrial ecosystems at high latitudes. The early-season discrepancy between available light and plant greening at higher latitudes makes measurements of incoming radiation a poor predictor of GPP, as evidenced by the poor correlation depicted in Figure 21a. Hence, if measurements of PAR are to be used for predicting GPP there is a need for adjusting PAR values in accordance with development of photosynthetic tissue through the use of some indicator of plant green mass. The results shown in Figure 18 clearly indicate that NDVI is a good indicator of early-season plant greening and development and therefore could be useful in adjusting PAR for the purpose of predicting GPP. This is confirmed by the relatively good correlation shown in Figure 21b. Also notable in Figure 18 is that despite relatively high plant green mass, as indicated by NDVI, grassland GPP is reduced with diminishing light in late summer - early autumn.

There are pressing reasons for acquiring good estimates of ecosystem GPP, whether it is for a better understanding of the world's carbon cycle; for deciphering ecosystem response to global warming; or for a better estimation of ecosystem production. Acquiring a good estimate of an ecosystem's annual GPP is, on the other hand, challenging because of large seasonal and diurnal fluctuations. Presently there are methods available for continuous measurements of ecosystem carbon fluxes, such as the eddy covariance method, but these are both costly and time consuming in maintenance and hence limited in their applicability. Interspersed field measurements of GPP, such as the static chamber method, fall short because extrapolating results over the in-between-measurements period is problematic due to the high diurnal and seasonal variation in GPP. What is needed are environmental variables that are useful in predicting GPP for intervals between regular field measurements, particularly in areas where applying other methods, such as eddy covariance methods, is difficult or next to impossible. Both PAR and NDVI can be monitored continuously in a reliable and inexpensive fashion and our results indicate that GPP can, in conjunction with regular field measurements, be sufficiently estimated from the product of these two variables. Additionally, since NDVI can be sensed remotely at various scales it holds promise as a tool for extrapolating measured GPP onto a larger scale.

4.5 Project limitations

This study examined the GHG fluxes, CO_2 and CH_4, from an Icelandic peatland based on 17 months measuring period, 2011-2012. The third main greenhouse gas species, N_2O, was not included in this study because of lack of both funding and analytical capability. The study period is more extensive than any other Icelandic study on the same topic and provides a complete annual estimate of carbon fluxes and a comparison between two growing seasons. Furthermore, the study period involved a rewetting of the peatland which provides an important comparison of fluxes before, during and after the process of rewetting. Since the end of this study, measurements are still ongoing to provide long term data of carbon fluxes from the rewetted peatland.

GHG fluxes are dependent on a wide spectrum of site parameters that vary strongly over the year and between years, including temperature, water level, plant growth and land use. Therefore, assessing annual GHG balances required highly frequent and prolonged observations to cover daily, seasonal and inter-annual variability. Moreover, a sufficiently dense net of observations was necessary for the chamber method to cover the often fine-scale spatial patterns that are typical for degraded and rewetted peatlands. Closed chambers are ideal for small scale studies such as this one, can be applied in nearly any terrain, offer low cost and portability, and allow for studying different site types in parallel. On the downside, closed chambers do not provide continuous time records. In order to achieve total annual flux estimates, models were applied to extrapolate the punctuated measurements. Although gas flux measurements from the site were measured highly frequently, more data of both fluvial fluxes and methane from ditches were lacking.

Finally, as peatlands are natural ecosystems where internal variability is large, comparing it with reported literature values often presents several issues. Peatland catchments are of many different types e.g. bogs, fens, mires and wetlands, draining techniques are different and draining intensity varies e.g. drained site, extensively drained site, eroded site or natural site. Also soil types and vegetation are different from one place to another and external environmental conditions like soil temperature and moisture, drought and rain events and frost-thaw mechanisms differ from one day to another. All these internal characteristics affect the gas fluxes and make any two studies hard to fully compare.

5. Conclusions

The study shows that drained uncultivated organic soils in Iceland emit annually significant amount of carbon to the atmosphere. Of the carbon fluxes examined, CO_2 emissions account for the majority of carbon emitted. In the light of how vast the area of drained organic soils in Iceland is, which have never been cultivated, the total emission from these areas raises concerns.

The main purpose of rewetting is to restore the natural state of a peatland and reduce soil respiration. Many different rewetting methods can be used depending on site conditions but the main objective is to reverse the draining effects of the ditches and to raise the water level towards the peatland surface. Most important is that rewetting works as a method for reducing GHG emission, as confirmed by this study in which case there was a relatively rapid change in the proportions of GHGs. In only few hours the water table level had risen and carbon fluxes had markedly changed within two days. For the four months measured after rewetting, there was on average 23% less respiration on the rewetted site as compared to the drained. On the other hand methane fluxes changed from being a net sink to a net source, or on average 0.06 mg CH_4 m^{-2} hr^{-1}.

Peatland rewetting has now become a possible mitigation strategy for reducing greenhouse gas emissions within the protocol succeeding Kyoto. This study shows that the effects of the rewetting appear relatively fast, which is positive because it is important for mitigating actions to take effect directly towards reduction in atmospheric concentration of GHGs. Given that rewetting is a cost-effective method, it can be applied through working with landowners willing to reduce greenhouse gases from their non-utilized drained land.

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Appendix I

Use of NDVI-adjusted PAR for predicting gross primary production in a temperate grassland in Iceland

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