EFFECT OF CONTROLLED DRAINAGE ON THE CARBON BALANCE OF A CULTIVATED PEAT SOIL

Md Rezaul Karim

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Tekijä/Författare – Author
Md Rezaul Karim

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Tiivistelmä/Referat – Abstract

Peat lands are net sinks of carbon (C) and a net source of carbon dioxide (CO_2) emissions owing to drainage during the growing season. The surface peat layer can be lost because of aerobic decomposition (oxidation) after drainage resulting in emissions of CO_2. One way to reduce these emissions is to keep the water table at a high level as much as possible. The resulting anoxic conditions reduce the decomposition of organic matter and hence CO_2 emissions. In the current Finnish agri-environmental scheme, the farmers may receive subsidies for controlled drainage on peatlands, and a raised ground water level through controlled drainage could be used as a greenhouse gas mitigation measure.

This study reports the carbon balance of drained peatland under controlled drainage during the growing season in Mouhijärvi, Southwestern Finland. The CO_2 fluxes measured with a transparent chamber method were divided into gross primary productivity (GPP) and ecosystem respiration (ER) for modelling based on environmental factors (light and temperature) and canopy reflectance (leaf area index, LAI). The GPP model estimates the effect of light and vegetation status, whereas the ER model captures the share of foliar biomass-dependent respiration and the ground water table. The sum of the study period (June–August 2016) GPP varied from -1301 to -670 g C m^{-2}, ER from 632 to 1029 g C m^{-2} and net ecosystem exchange (NEE) from -322 to 68.5 g C m^{-2}. NEE indicated a net sink of C in all plots except one with poor crop growth. The net ecosystem carbon balance (as the sum of NEE and carbon export as grains), indicated a net source of carbon in both plots with controlled drainage and a net sink in conventionally drained plots during the cultivation period. The greatest sink reported either as NEE or with the harvest included was the wettest plot, indicating that cereal production is possible in wetter than normal conditions.

Avainsanat – Nyckelord – Keywords
Peatland, CO_2 flux modelling, ecosystem respiration, gross primary productivity, net ecosystem exchange, controlled drainage, groundwater table.

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Abbreviations

CAOS	Climate-Smart Cultivation of Organic Soils
ER	Ecosystem Respiration
GHG	Greenhouse gases
GPP	Gross Primary Productivity
GWL	Ground Water Level
IMCG	International Mire Conservation Group
IPCC	Intergovernmental Panel on Climate Change
LAI	Leaf Area Index
Luke	Natural Resources Institute Finland
LULUCF	Land use, land-use change and forestry
NEE	Net Ecosystem Exchange
PAR	Photosynthetically Active Radiation

1 Introduction

Many facets of natural arrangements and human populations are under threat (Patz et al. 2005, Costello 2009, IPCC 2014.) from the continuous climb in global temperatures caused by anthropogenic greenhouse gas emissions (Ballester et al. 2009, IPCC 2013). Since there are numerous effects of climate change, scientists have mostly classified them into three areas: threats to human health and society, changed ecosystems and habitats, unpredictable climate and weather extremes (EDF 2017).

In the year of 1996, the European Union suggested the 2°C target as the maximum tolerable global temperature rise by 2100 (IPCC 2014). It was in the 1960s and 1970s, when doubling carbon dioxide (CO_2) concentration situations projected an approximate of 2°C as a long—term global goal warming (IPCC 2001). Regardless of differing views, limiting the temperature rise to 2 degrees has been set as the goal in the climate policy after 2020 in the implementation of the Paris Agreement (2016).

There are about 7 billion people now on our planet (World meter 2017). There were about 1500 million-hectare (1,417,153 ha) world arable land in 2014 followed by 34 million (3,315,542 ha) permanent meadow and pastures (FAO 2017). In 2008, a White Paper on agricultural policy has issued by the Norwegian government, in which it reveals that food production should upturn by 20% by 2030, proportionate to the inhabitant progress (Nordic Council of Ministers 2014). The percentage of peatland used for agriculture is 15%, which makes up 0.3% of the world's land cover, but emit almost 6% of global CO_2 emissions (Couwenberg et al. 2010).

Peat is formed when the input of dead organic material exceeds the mineralization of soil. Peat formation is favored by waterlogged conditions near the soil surface. Anaerobic soil condition retards the decomposition of organic material due to lack of oxygen. Physical conditions and microbial processes are largely determined by water content in peat soils (FAO 2014a). Peat soils are one of the net sink of carbon (C) and a net source (owing to drainage in the period of the growing season) of CO_2 emissions (Van de Riet et al. 2013). Drainage is the prerequisite of growing most agricultural crops. However, the peat layer above the drainage can be lost because of aerobic decomposition after drainage (Kechavarzi et al. 2010). In Finland, one of the biggest individual sources of CO_2 among emissions is the cultivation of organic soils reported in the land use, land-use change and forestry sector (LULUCF) in Finland (Statistics Finland 2013).

Cultivated peat soils are one of the most potential targets of mitigation measures in agriculture and land use (Smith et al. 2014). One way to reduce these emissions is to keep the water table as high as possible (Ellis et al. 2009). The anoxic condition will reduce the decomposition of organic matter and hence the CO_2 emissions (Regina et al. 2014). The farmer can raise the water table e.g. by controlled drainage that enables regulation of the water table using a control well connected to the drainage system (Regina et al. 2014).

The aim of this research work was to elucidate if the carbon balance of the soil and crop grown on a peat field with controlled drainage facility is affected by ground water level. The work was done in a project of 'Effect of controlled drainage on the carbon balance of a cultivated peat soil' carried out by Natural Resource Institute Finland (Luke) and University of Helsinki. The project was funded by Drainage Foundation sr.

2 Literature review

This literature review is intended to clarify the source of CO_2 emissions in peatland. The mitigation of CO_2 emissions from peatland is also clarified based on the effect of ground water level on the CO_2 emissions.

2.1 Peatlands as a source of greenhouse gases

Peatlands cover around 4 million square kilometers and can be found at least 175 countries of the world (IUCN 2011). In Europe, peatland is spread to about 515,000 km^2. Most of peat of the world is in South America, northern Europe and some part of Asia (Fig. 1). Peat deposits found in North America are principally in Canada and Northern United States. In the Southern Hemisphere, there is less peat since there is less land (Wikipedia 2017).

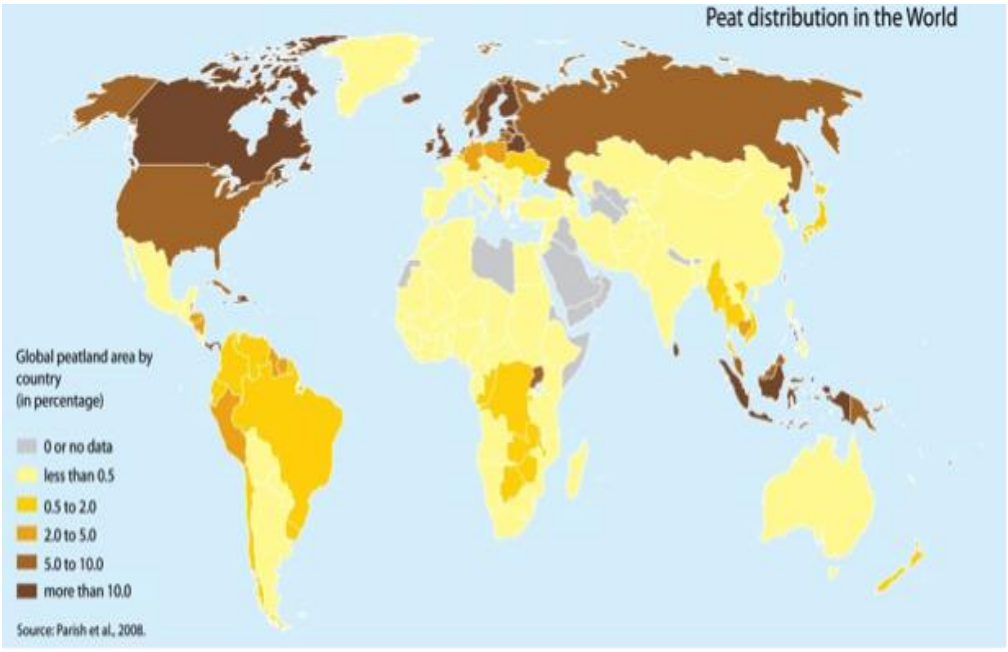


Figure 1. Peatland area (%) by country in the world. Dark ash color denotes >10% peat, light ash color denotes 5−10% peat, dark yellow color denotes 2−5% peat, bright yellow color denotes 0.5−2%, peat, hazy white color denotes <0.5% peat and darkish white color denotes 0 or no data (Parish et al. 2008).

Soil containing at least 30 percent (by dry mass) organic material is known as peat (Joosten and Clarke 2002). Some other definitions include the mineral contents which is determined by the ash content left after burning (e.g. less than 55 percent; Wüst 2009). There is no formal definition of "peatland" from the Intergovernmental Panel on Climate Change (IPCC) but it does include the idea of peatland in the "land with organic soil" category (IPCC 2013). International Peat Society (IPS) and International Mire Conservation Group (IMCG) use the terminology "peatland" for a naturally accumulated peat layer at its surface (IPS 2017). In addition, peatland does cover the former peatlands with mineral soil layer on its surface (IPS 2017).

The soil classification relevant to Peatland landscape are- "histosols", "organic soil" and "peat" (FAO 2014a). Histosols are classified as soils formed from organic material (plant and soil science eLibrary 2017). Organic soils are classified as based on either 1 and 2 or 1 and 3 listed below (IPCC 2013):

1. Width of organic horizon is either more than or equal to 10 centimeters. A horizon of less than 20 centimeters must have 12% or more organic carbon if it is mixed to a depth of 20 centimeters.

2. If soils are never saturated with water for more than a few days, then it must contain more than 20% organic carbon by weight (35% organic matter).
3. If soils are under the period of water saturation, and have either
   a) Minimum 12 % organic carbon by weight (20% organic matter) when the soil has no clay; or
   b) Minimum 18% organic carbon by weight (30% organic matter) when the soil has 60% or more clay; or
   c) An intermediate quantity of organic carbon for intermediate amount of clay.

In Finland, organic soils contain 20—40% organic matter and for peat the organic matter is >40% (Aaltonen 1949). Peat deposits are found all over Finland, with a greater density in the west and north region of the country (Fig. 2). Total area of peatland (Finland) is about 89000 km^2 and about half of that is used in forestry, agriculture and peat production (Ministry of agriculture and forestry Finland 2007). Slightly more that 40% are in a natural state and some of that area is protected for nature conservation (Ministry of agriculture and forestry Finland 2007). The main source of cultivated peat soils in Finland originates from *Carex* peat (nutrient-rich peat) but there is also nutrient poor peat from *Sphagnum* mosses (Myllys 1996).

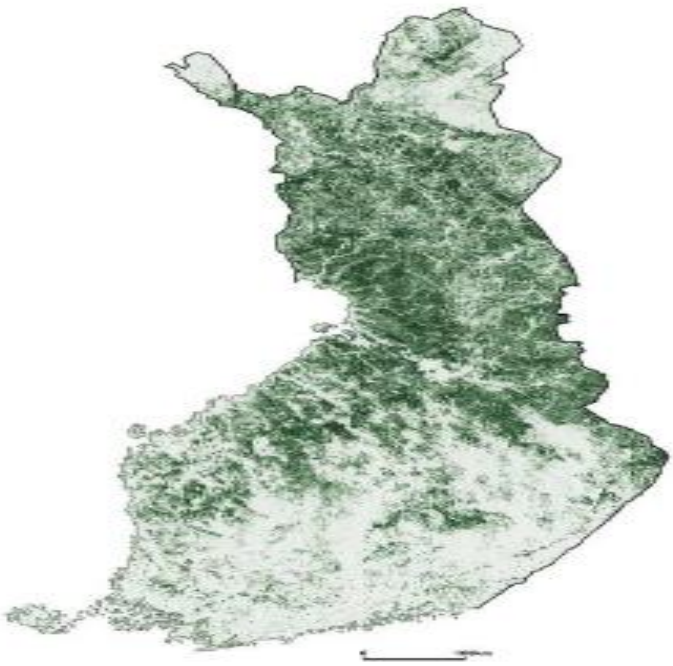


Figure 2. Map of peatland in Finland (Ministry of agriculture and forestry Finland 2007).

Carbon-dioxide is one of the notorious greenhouse gases (GHG) that contribute to the global temperature rise and both its sources and sinks demand to be quantified (Freeman et al. 1993). Peatlands are a significant sink and source of carbon in the atmosphere (Blodau et al. 2004). In waterlogged peat soil, plant remains accumulate organic matter because of low decomposition and thus peat soils are a large storage of carbon and nitrogen worldwide (Yu 2011). Although it comprises only 3% of land area globally, it contains 30% of the total soil carbon (FAO 2012). The country with highest GHG emissions from peat soils is Indonesia followed by Russia and China as per International Mire Conservation Group (Table 1). However, even a small country like The Netherlands can have a significant impact on atmospheric concentrations: the total yearly GHG emission from peatland is about 225 Mt CO_2 equivalents, which equates to an increase in global atmospheric CO_2 of 0.03 ppm (UNFCCC 2012). The emissions from organic soil cultivation amounted to 50 Tg in EU, which was 1.3 % of total emissions apart from LULUCF in 2010 (UNFCCC 2012). Germany is the top most position in this group among the EU with the total of its CO_2 equivalent emissions from agricultural peatlands being 30 Tg (3.4 % of the national total). The proportions of GHG emissions from cultivated peatland in Sweden and Finland are 3.9% and 9.5% of the national total, respectively (UNFCCC 2012).

Table 1. Annual CO_2 emissions from cultivated peat soils in the three most emitting countries.

Country	CO_2 emissions (Tg)
Indonesia	500
Russia	87
China	67

Source: Joosten (2009).

The CO_2 emissions (Fig. 3) from draining peatlands (together with emissions from peat fires) are globally total two gigatons per year (Joosten 2009) and signify almost 25% of the CO_2 emissions from the entire land use, land use change and forestry sector (LULUCF) (Canadell 2011). LULUCF is defined by the United Nations Climate Change Secretariat as the emissions and removals of greenhouse gases consequential from the direct human induced land use, land -use change and forestry activities. Conserving, restoring and refining the management of organic soils and peatlands are effective options to lessen the atmospheric GHG concentration (FAO 2012).

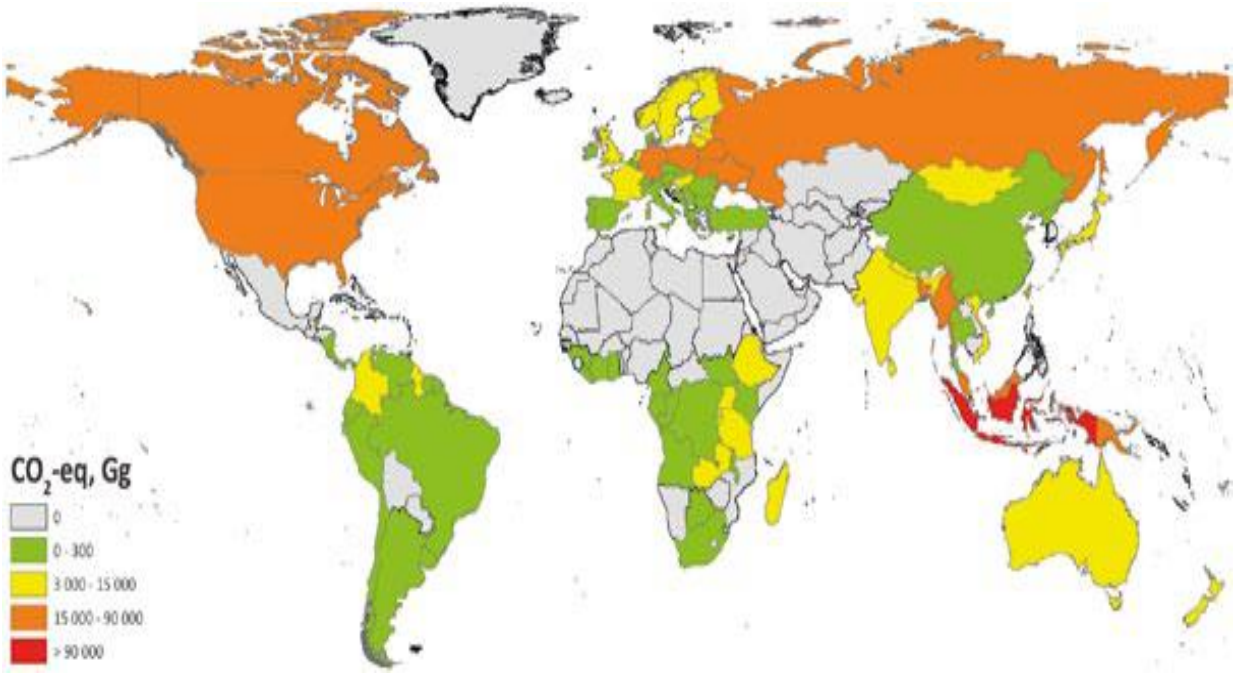


Figure 3. Global distribution of GHG emissions from drained organic soils (FAO 2014b). The unit is in gigagram (CO_2 equivalent). The red color (>90000 Gg), orange color (15000 −90000 Gg), yellow color (3000 −15000 Gg), green color (0 −300 Gg) represent the corresponding CO_2 emission in different parts of the world.

The CO_2 emissions globally increased by 20% in the period of 1990—2008 from draining peatland (Joosten 2009) and peatland emissions have increased in 45 countries (1990—2008). This indicates the pressure to take areas into farming owing to the production of agricultural or bioenergy crops (Smeets et al. 2007, Sheil et al. 2009). Clearance of peat soils for agriculture is not limited to developing countries. In Finland, approximately 30,000 ha of new organic soils has been brought into cultivation since 2000 (Regina et al. 2014). This relates to the goals of growing farm size and productivity; peat soils are easy and economical to clear and in many regions, there are no other soil types accessible. This has increased the yearly emissions of CO_2 and N_2O by 0.64 Tg CO_2 equivalents (Regina et al. 2014).

2.2 Ground water level as a regulator of CO_2 emission

A substantial lowering of the water table is required for agricultural practice (ranging from 0.4 meters for grasslands to 1.2 meters for crop production) that leads to decrease the soil moisture content (greater infiltration of precipitation) and the contraction of peat volume, which is further compounded by oxidation and finally more CO_2 emissions (Pfadenhauer and Klötzli 1996). Chemically carbon of the organic material will combine with oxygen leading to formation of CO_2. Drained peatland (grassland) is a net sink of CO_2, but can be a net source of CO_2 owing to

agricultural practice (Fig. 4). The conversion of net sink to net source can be fortified by many factors (Fleischer et al. 2015): land use change, climate change, agricultural intensification and socioeconomic changes.

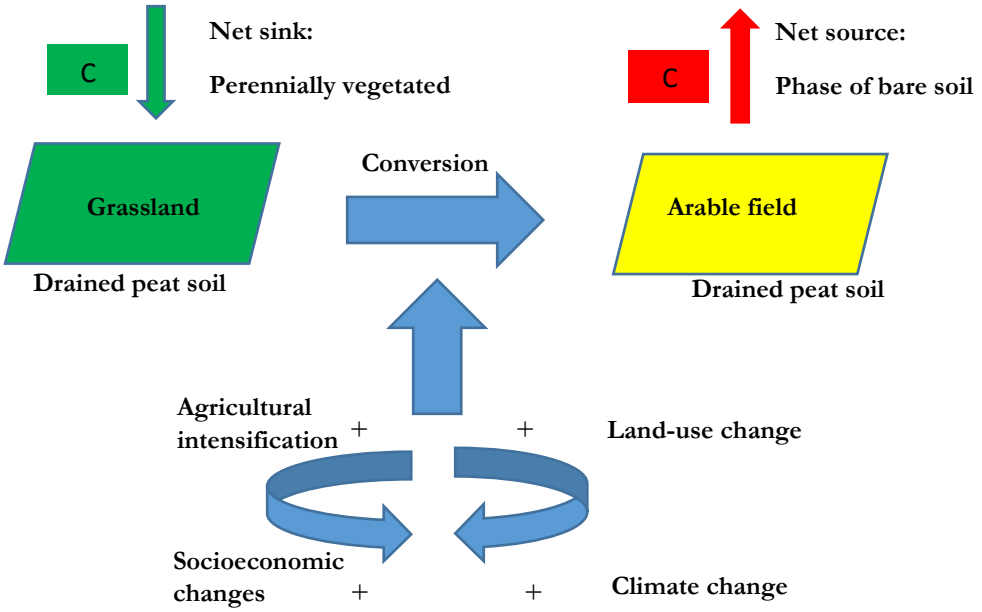


Figure 4. Schematic figure of drained peat soil. The additive (+) sign indicates the additive nature of the factors that leads to the net C source. Adapted from Fleischer et al. (2015).

There is a distinct relation between CO_2 emissions and the water table depth below the peat surface in all climate zones and land cover types (Couwenberg and Joosten 2010). The linear relation between lowering the water table and rising the CO_2 emission also illustrates the potential of water table rise as a mitigation measure (Hooijer et al. 2012).

Subsidence which consequences from peat oxidation, shrinkage, and compaction is one of the central topics related to peatland degradation (Schothorst, 1977, Andriesse, 1988, Dradjad, 2003, Couwenberg et al. 2010, Hooijer et al. 2012). Initial subsidence can be more than 50 cm per year, depending on the drainage level, type and depth of the peat in a newly drained area (Hooijer et al. 2012). After a few years, oxidation turns out to be the principal component, having up to 90 percent of the subsidence (Stephens et al. 1984). Certainly, undrained peatlands offer many appreciating ecosystem services both to individual customers and to society (Joosten and Clarke 2002). Conservation of undrained peatland is one of the effective approaches as it keeps ecosystems intact and avoids further expensive investment.

2.3 Mitigation options

Mitigating GHG emissions from soils has been projected as one of the most effective ways to shrink agricultural emissions (Smith et al. 2007). Conserving, restoration and adaptive management of organic soils have been suggested as mitigation actions (FAO 2012). Emissions of CO_2 from cultivated peat soils have not been under any binding targets of mitigation yet but under the Paris Agreement and the LULUCF framework of the EU they will be accounted as part of the LULUCF sector which has the general aim that sinks should counteract all emissions within the sector. Mitigating agricultural emissions has been assessed unmanageable without mitigating emissions from organic soils (Regina et al. 2009).

There are mostly two mechanisms in peat soils to mitigate GHG emissions: avoiding new drainage and decreasing emissions in the currently drained area (FAO 2012). The latter one can be attained for instance by endorsing perennial crops, decreasing the intensity of tillage and raising the groundwater table. Changing the peatland hydrology is the best means to mitigate emissions from drained areas since the GHG emissions from peatlands are powerfully controlled by groundwater levels (Renger et al. 2002). In Sebangau catchment area of Indonesia, rewetting methods was studied by dam construction as a part of the tactic for the peat soils (Jaenicke et al. 2010). Based on the assumption of the mitigation of 0.8−0.9 t $CO_2^{-1}ha^{-1}yr^{-1}$ per centimeter groundwater level rise (Couwenberg et al. 2010), the authors calculated that over 1.4 Tg of CO_2 emissions would be alleviated per annum due to the rewetting of the catchment area (Jaenicke et al. 2010).

Higher water table reduces the decay of organic matter and in consequence less CO_2 (>1-ton reduction in C loss per hectare annually) is emitted to the atmosphere and less nutrients leached to watercourses (Regina et al. 2014). One problem related to higher Water table (WT) is the production (23 g C m^{-2} yr^{-1}) of CH_4 (Kandel et al. 2017) and more importantly, that is 23 times as effective a GHG than CO_2 (IPCC 2001). The nearly rise in CH_4 emissions (4 t CO_2 equivalent) is anticipated with an emission element of 96 kg^{-1} CH_4 $ha^{-1}yr^{-1}$ for boreal soil (IPCC 2013). However, the net effect of rising water tables on the carbon emissions in peatland is unidentified and needs to be computed.

There are measures in the Rural Development Program for 2014–2020 to inspire farmers to alteration from cultivation of annual crops to long-term grass cultivation of organic soils in Finland and to finance controlled drainage systems (Ministry of Agriculture and Forestry 2013). Both measures have the aim of decreasing emissions from cultivated peat soils.

Controlled drainage is a method of manipulating the ground water level primarily for adapting to dry periods in crop production (Fig. 5). The GWL control is done by an adjustable pipe in a control well (Busman and Sands 2002). Thus, GWL can be optimized for crop production through manipulating the amount of stored water. As the topography (surface shape) and the amount of rainfall are critical to maintaining the desired level, applicability of the system is limited to some extent (Busman and Sands 2002). For instance, accurate control of the water level per the root growth requires an even ground (<1% slope). The short term related water stress can be reduced through controlled drainage, thus making inefficient system for very dry areas. Controlled drainage can also be used to reduce peat decomposition e.g. by raising the water table moderately during the growing season and thoroughly after harvest.

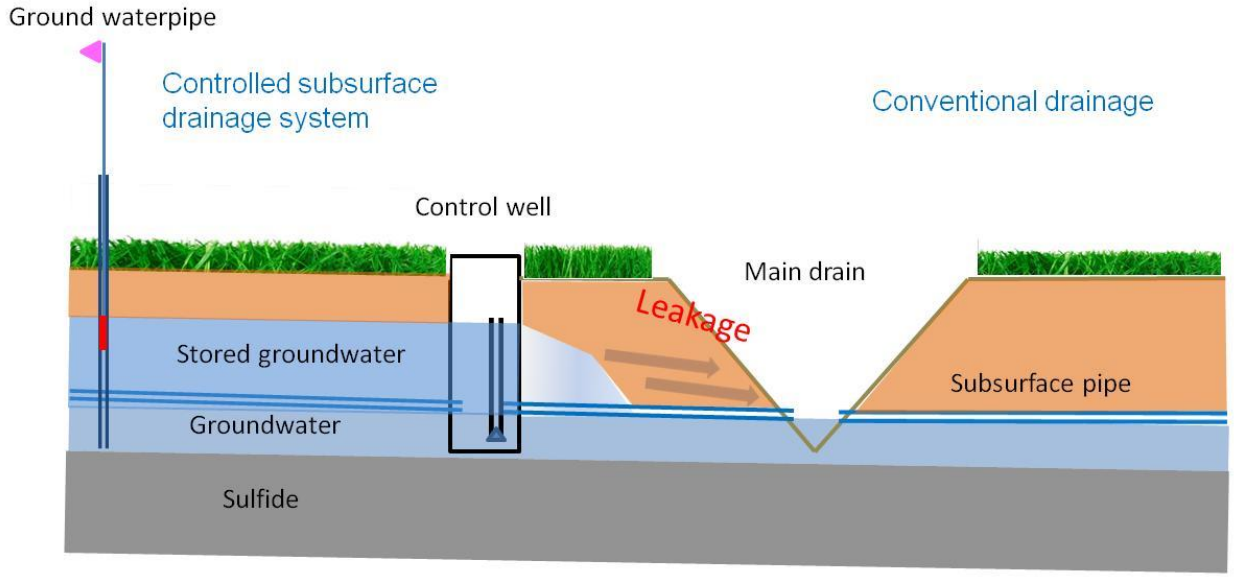


Figure 5. Design of a controlled drainage (Rainer Rosendahl). The controlling pipe can be manipulated to define the height of outflow and thus the ground water.

In Finland 120 cm is the initial drain depth (the depth of pipe drains below the soil surface) for cultivating the organic soil, but for mineral soil, it is about 1m, and ultimately the water table comes to the soil surface as drain depth drops with time. Hence the age of drainage and hydraulic properties of land are the two critical factors determining the stage of the water table (Regina et al. 2014). Soil water table typically varies (in Finland) from 40—110 cm in the growing season (Maljanen et al. 2003, Regina et al. 2004).

The subsequently increased aeration in the upper stratum of peat increases mineralization of organic matter and emissions of CO_2 and N_2O, but the methane (CH_4) emissions are lowered (Oleszczuk et al. 2008). Both in natural peatlands (Regina et al. 1999) and on cultivated grassland

or arable soils (Best and Jacobs 1997, Beetz et al. 2013) the effect of water table on greenhouse gas has been studied. The mineralization of peat could be reduced to 30% to 40% and total GHG by 50—60% if WT can be maintained at 30 cm depth (Renger et al. 2002).

The CO_2 flux was subdivided into light-dependent Gross Primary Productivity (GPP) and light-independent ecosystem respiration (ER). GPP can be defined as the total rate at which the ecosystem capture and stock carbon as plant biomass, for a specific time (Amthor and Baldocchi 2001). In other words, Gross Primary productivity is the rate at which photosynthesis or chemosynthesis occurs. GPP was calculated as GPP = NEE—ER, i.e., ensuing the atmospheric sign convention, where ER is constantly positive, GPP is always negative and a net flux of CO_2 to the atmosphere denotes a positive NEE. Since 2012 the experimental site (Mouhijärvi) has gone with measuring greenhouse gas emission. There were two levels of controlled drainage in Mouhijärvi differing in soil, water status: water table from the surface at 30 cm and the other one had 25 cm on an average. The greenhouse gas measurement was done every second week during the growing season (June–August 2016).

3 Objectives

Arable peatland soils are one of the highest sources of greenhouse gas emission in Finland and measures are required to mitigate emissions (TEM 2017). There is a current absence of information on how a change from elevated ground water tables in peatlands affects the net ecosystem exchange (the difference between ecosystem respiration and CO_2 uptake by plants is known as the net ecosystem CO_2 exchange, NEE) of CO_2 which in turn denotes the first step in valuations of more comprehensive carbon balances (Jacobs et al. 2007). To fill this gap, CO_2 fluxes were measured with an advanced transparent chamber method throughout the growing period of a peatland (Mouhijärvi) in a field scale plot experiment.

My specific goal was to ascertain an answer to one specific question: how does elevated water table affect the discharge and fixing of carbon on a cultivated field during the growing season. The hypothesis is that flying the water table from 35 to 21 cm lessens the net flux of CO_2 to the atmosphere.

4 Materials and methods

The study was conducted in the Southwestern part of Finland (Mouhijärvi) from June–August 2016. All necessary Materials were taken from the Natural Resources Institute (Luke), Jokionen, Finland.

4.1 Study site

The experimental site (Fig. 6) was located 23.1^0 East and 61.5^0 North in Finland (Mouhijärvi). The peat soil has been taken into cultivation since 1996, and has been used to grow spring sown wheat (*Triticum aestivum*), barley (*Hordeum vulgare*) and oats (*Avena sativa*) for the last three years. In 2016, oat was cultivated. The reduced tillage method (10 cm deep) was used for the cereal (oat) cultivation.

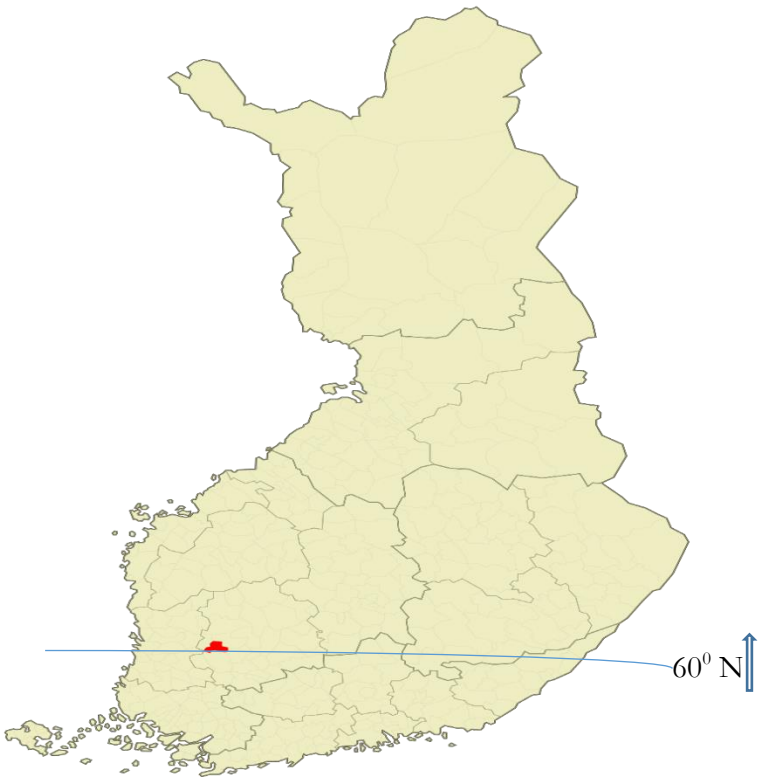


Figure 6. Location of the study site (Mouhijärvi, Finland).

Source: Wikipedia 2017.

The depth of peat layer is more than one meter (>120cm) with moderately humified sedge peat soil (Regina et al. 2014). The mean monthly air temperature (^{0}C) during the study period (June–August, 2016) and in the long period (1981—2010) was similar (Fig. 7) but in August the study period had 1.2 (^{0}C) lower air temperature than the long-term average temperature.

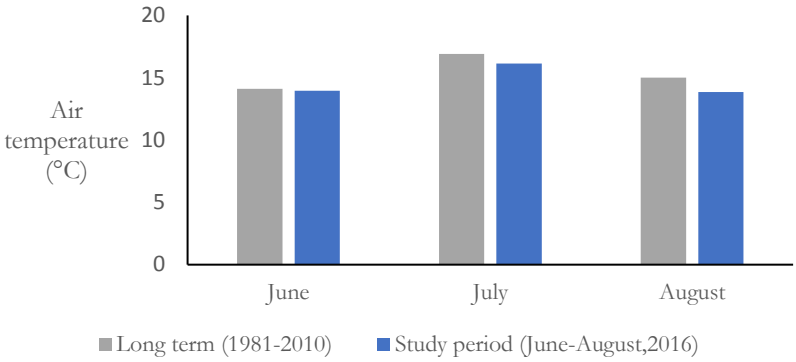


Figure 7. Average (a) air temperature (^{0}C) during the study period (June–August 2016) and during 1981—2010.

The total precipitation was also similar in June and July (Fig. 8) but the largest anomaly was in August where the study period received 33.8 mm more precipitation than during the long term. The mean GWT for the study period was 20−35 cm below the surface during the growing period (Table 2).

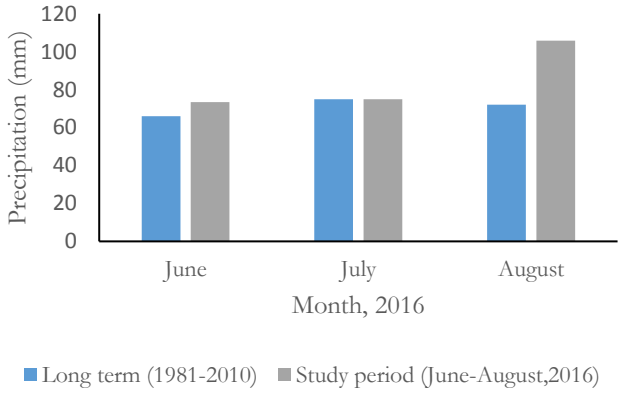


Figure 8. Total precipitation (mm) during the study period (June–August 2016) and during 1981—2010.

In the early summer, 2016 soil samples (0−20, 20−40, 40−60, 60−80 cm) were taken from the study area (four sample per plot thus altogether sixteen sample) for the analysis (Table 2). The content of total carbon (C) and nitrogen (N) was measured with a CN analyzer (CN-2000, Leco Corp., St. Joseph, Mich., USA) from air-dried samples. Bulk density was measured by drying samples at 105 °C over night of known volume (Blake and Hartge 1986). The mean GWT for the study period was 20−35cm below the surface during the growing period (Table 3).

Table 2. Soil properties (mean± standard deviation, n= 16)

Depth (cm)	Total N%	Total C%	Dry bulk density g/cm^3
0−20	1.11 ± 0.08	24.3 ± 1.9	0.47 ± 0.05
20−40	1.50 ± 0.15	40.3 ± 2.1	0.28 ± 0.13
40−60	1.64 ± 0.18	48.5 ± 2.3	0.14 ± 0.01
60−80	1.54 ± 0.10	46.6 ± 4.6	

4.2 Experimental layout

The study was initiated in 2012 with four plots (Fig. 9 and 10). Two of these plots were in naturally wet (Plot 1) and dry condition (Plot 4) and the other two had controlled wet (Plot 2) and dry condition (Plot 3). Each plot had four measurement points (60×60×60 cm) and thus there were altogether 16 measurement points in the study area. The gas chamber measurement was done twice in a month (June–August 2016) along with leaf area index (LAI meter), soil moisture (TDR method) and soil temperature (thermometer) measurements. The field was free of shading from adjacent crops and trees.

Figure 9. The aerial photo from google maps of the study area (Mouhijärvi). The brown area is a field and the lines denote the slope of 5 m.

The ground water pipes were used to measure the water table in the soil. The leveling of the head of the pipes, water level in controlled well and in soil surface were done twice in a month. The experimental site started with two pipes for each plot, but later, six additional pipes were mounted. The open bottom pipes were distributed - four in close contact with the drains and the remaining two in the middle of drains.

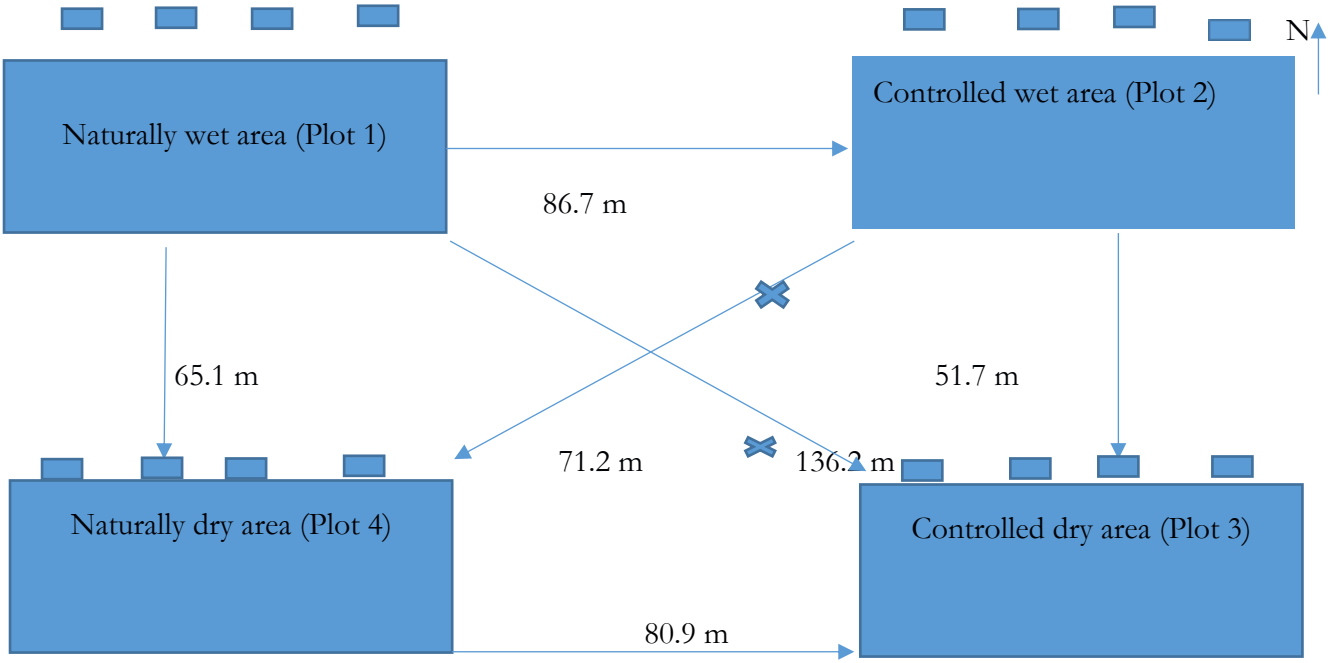


Figure 10. Layout of the field experiment. Four plots and each plot with four measurement points (60×60×60 cm) as shown by small rectangular. The multiplication sign (×) in controlled wet and dry area represents the controlling well.

Table 3. Overview of the mean ground water level (cm) and drainage condition during the growing season (June–August, 2016).

Plot	Ground water level (cm)	Drainage condition
1	21±7	Naturally wet
2	30±10	Controlled wet
3	25±11	Controlled dry
4	35±5	Naturally dry

The control well (Fig. 11) was regulating the water table in plots 2 and 3. The aim was to keep WT at 60 cm or 30 cm and to lower it in the wet area only at the time of sowing, harvest and ploughing. However, in practice the WT (Table 2) varied between 20 cm and 35 cm during the cultivation period.

a b

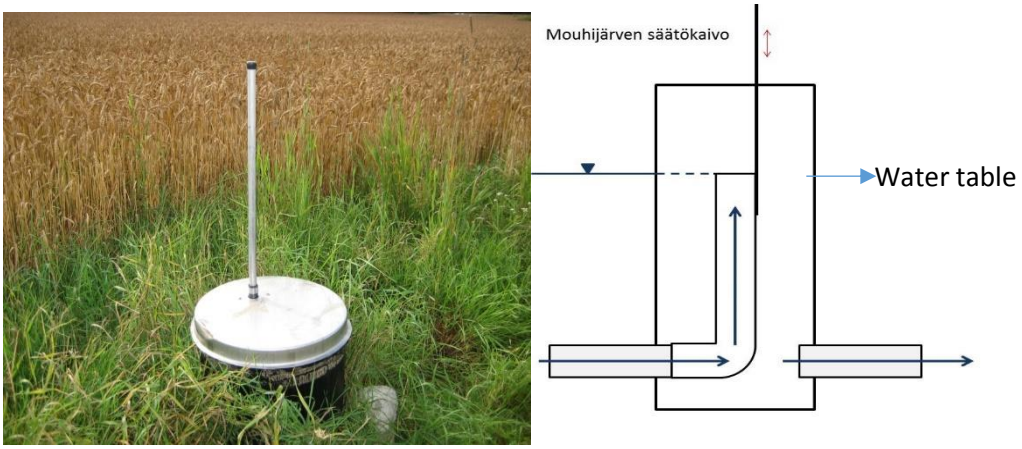


Figure 11. Overview of a control well (a). Inside the well (b) water table was regulated by adjusting the height of the flexible tube.

4.3 Environmental variables

Photosynthetically Active Radiation (PAR) was measured for every second with a Li-Cor quantum sensor (attached outside the chamber) simultaneously with gas chamber measurement and every hour average PAR was recorded. An Arduino pro-mini (SparFun Electronics, Boulder, CO. USA) based data logger was used to log the PAR values. Continuous measurements of soil temperature (20 cm depth), air temperature, air humidity, precipitation, wind direction, wind speed, global radiation was logged continuously every hour at a weather station (Mouhijärvi) next to the experimental site.

The GWL was measured by inserting the plastic tube (125 cm long and 4.5 cm inner diameter) in the ground so that the bottom of the tube was about 1 m below the ground. There was a plug at the bottom of the tube with small holes (for the water to rise). The water table was measured with a measuring scale (tape, 4916IM, 6.6×4.2×1.4 inches, China) that had a bottle cork at the end of it. The sound of the cork hitting the water surface in the tube gave us the distance to the surface of the top end of the plastic tube. The GWL was then calculated with the known length of the tube that was above the ground.

Leaf area index (LAI) was determined by LAI meter (SunScan type ss1; Peak Design Ltd.; Derbyshire, U.K.) simultaneously with the net ecosystem exchange (June–August 2016). Ten measurements from each plot were taken preferably on a sunny day. LAI was measured six times

(two times per month) during the growing season. The calibration was done before each measurement and within a measurement if cloudiness happened. The hourly LAI data interpolation (linear) from six measurement days were done in MATLAB (MathWorks Inc., Natick, MA, USA) for the whole growing season.

4.4 Measurement of CO_2 fluxes

Fluxes of CO_2 were measured at each plot by a transparent chamber technique from 28 June 2016 to 24 August 2016. In general, during the growing season (June–August) CO_2 flux were measured at 2-week interval. At each of the 16 measurement points one steel collar with a basal area of (60×60) was placed after sowing the oats. The height of the chamber was 60 cm (+40 cm extra collar when vegetation was high). The collar was about 10 cm above the ground level (height was measured regularly).

The transparent acrylic chamber (60×60×60 cm) as described in detail by Elsgaard et al. (2012) was used for CO_2 measurements. Briefly, to record the PAR a quantum sensor (190-SA; Li-Cor Inc., Lincoln, NE, USA) was positioned inside the chamber. The concentration of CO_2 and relative humidity were measured with a gas analyzer (GMP-343; Vaisala Oy, Finland). A data logger (MI70; Vaisala Oy, Finland) with temperature sensor (HMP75; Vaisala Oy, Finland) was recording the temperature inside the chamber. In addition, four ice blocks were used inside the chamber during the flux measurements to ensure not more than 1.5 ^{0}C difference in temperature between inside and outside the chamber. A thin rope was used to tie up the leaves when the vegetation extended out from the chamber area during the growing season.

At first the CO_2 flux was measured for 1 minute with the transparent chamber (100% PAR) and the readings were recorded for every 5 second (CO_2 emission, relative humidity, PAR and temperature). After that, to return the ambient CO_2 concentration (380—390 ppm) and to discard vapor condensed on the chamber wall, the chamber was lifted and vented to air. After that, the chamber was covered with a shroud (75% PAR) followed by repositioning on the collar and 1 minute measurement procedure. Similarly, the same process was followed that blocked 50% (two shroud) and dark (0% PAR) incident PAR for each plot. Thus, at each collar, four CO_2 fluxes at different level of PAR intensity (i.e. including darkness) were measured for subsequent modelling of light response of GPP (e.g. Burrows et al. 2005). Generally, to characterize the light response of GPP for a large range of PAR the flux measurements were done on a bright sunny day.

4.5 Calculations and modelling of CO_2 fluxes

The CO_2 concentration, PAR, temperature and vegetation parameters were processed with the MATLAB (MathWorks Inc., Natick, MA, USA) script (Kutzbach et al. 2007). Fluxes of CO_2 were calculated by means of linear regression and Akaike's Information Criterion (AIC) was used to fit best models (Burnham and Anderson 2004). The raw data from the measurements days were processed as per Kutzbach et al. (2007) script and ran with the MATLAB to get the respective emissions (μg CO_2 m^{-2} s^{-1}). Some measurement points showed a strange fluctuation of CO_2 concentration in the beginning of measuring time (most likely CO_2 probe did not reach the ambient CO_2 concentration before the start of the measurement) and it was solved by discarding 10 second from the beginning (as there is a discard time and end option in the MATLAB script) time. The GPP, ER were modelled (nonlinear) in MATLAB using the equation 1 and 2 with one hour interval from the sowing date (18.5.2016) to the harvesting date (24.9.2016).

4.5.1 GPP modelling

GPP was calculated for each collar with different PAR (100%, 75%, 50% light) from its respective dark measurements (0%). GPP was then modelled (hourly) using a rectangular hyperbolic saturation curve (Thorney and Johnson, 1990, equation 1) for every plot starting from sowing date (18.5.2016) to harvesting time (24.9.2016).

$$\mathrm{GPP} = \frac{(\alpha \times GPP_{max} \times \mathrm{PAR} \times \mathrm{LAI})}{(\alpha \times \mathrm{PAR}) + (\mathrm{PAR} \times \mathrm{LAI})} \qquad (1)$$

Where α (μg CO_2 μmol $^{-1}$ photon) is the initial slope of the photosynthetic light response and GPP_{max} (μg CO_2 m^{-2} s^{-1}) is the theoretical maximum rate of photosynthesis at infinite PAR.

Above equation with modelled parameters (α, GPP_{max}) were used to interpolate hourly GPP during study period using continuous PAR (hourly) measurements obtained from the nearby weather station and linearly interpolated LAI (hourly) measurements.

4.5.2 ER modelling

A temperature modifier function used in RothC and ECOSSE soil respiration models (Jenkinson et al. 1987, equation 2) was applied for ER modelling. In addition, the model was stretched with LAI and GWL to model the impact of biomass and ground water table on ER (Kandel et al. 2013d). Thus, a three-parameter ER model depicting basal soil respiration, biomass respiration and ground water table was applied:

$$\mathrm{ER} = (R_b \times \mathrm{GWL} + \beta \times \mathrm{LAI}) \times \frac{47.9}{(1+\exp(\frac{106}{T_{air}+18.3}))} \qquad (2)$$

Where R_b is the parameter relates to basal soil respiration, β is the scaling parameter for LAI, T_{ai} is the air temperature (^{0}C) during the chamber enclosure. The other numerals follow the RothC respiration model (Jenkinson et al. 1987). Total study period ER was calculated similarly as for GPP using the hourly air temperatures and linearly interpolated LAI and ground water level.

4.5.3 Statistics, uncertainties and model evaluation

The results from different plots were averaged for statistical analysis and the standard error (SE) of LAI, CO_2 flux denote the spatial variation of the plot scale. As the temporal effects were noticeable no ANOVA was done for the raw data. The dynamic fit curve function ("fitnlm" for nonlinear model) available in MATLAB 2012 were used to fit the GPP and ER model. The goodness- of- fit (Zar 1996) was measured by R^2 value. NEE (overall flux from or to the atmosphere) was calculated for each plot (NEE = GPP+ER). The cumulative C balance (g C m^{-2} during the growing season) was calculated as the sum of NEE and carbon export as grains during the harvest period for each plot (Table 3).

The fitted GPP and ER model parameters were derived connected with SE signifying the degree of uncertainty associated with modelling. However, no consensus exists on how to proceed from parameters-uncertainty into a modelling uncertainty for annual estimates (Kandel et al. 2013d).

5 Results

5.1 Leaf Area Index (LAI)

LAI measurements (from sowing time to harvest time) for oats (*Avena sativa*) in different plots for the study period are shown in Figure 12 (hourly interpolated). LAI (mean) was higher in naturally dry area (2.9) and controlled wet area (3.3) than the naturally wet and controlled dry area during the growing season (June–August 2016). In Mid of July (week between 9 and 10 at the start of booting stage), a sharp increase in LAI was observed in all plots. However, when the LAI peaked during the vegetative growth it was 80% higher in plot 4 (naturally dry area) than the plot 1 (naturally wet area) (Fig. 12). LAI did not sharply increase or decrease in controlled dry area compared to the other plots which reflected its dwarf and poor growth.

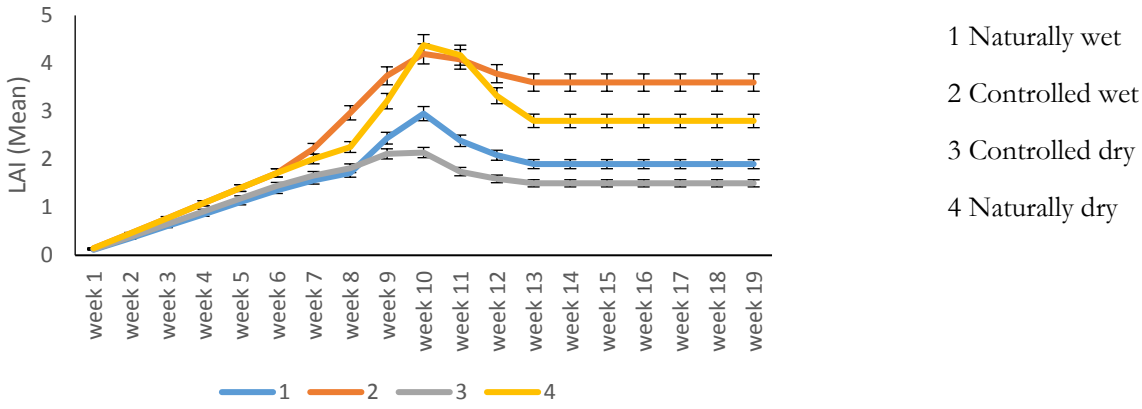


Figure 12: Interpolted leaf area index (LAI) during the study period (sowing date to harvest date). Week 1 starts with the sowing date (18.5.2016) and ends with harvest date (24.92016) on week 19. The error bar represent 95% confidence interval (mean ± 2SE).

5.2 Measured CO_2 flux

Measured CO_2 (µg m^{-2} s^{-1}) flux followed the expected seasonal pattern with highest uptake of carbon during the time of vigorous growing period and decrease towards the harvest (Fig. 13). The maximum (809 CO_2 µg m^{-2} s^{-1}) in plot 4 and minimum flux (-870 CO_2 µg m^{-2} s^{-1}) was observed in plot 2 (Fig. 13d).

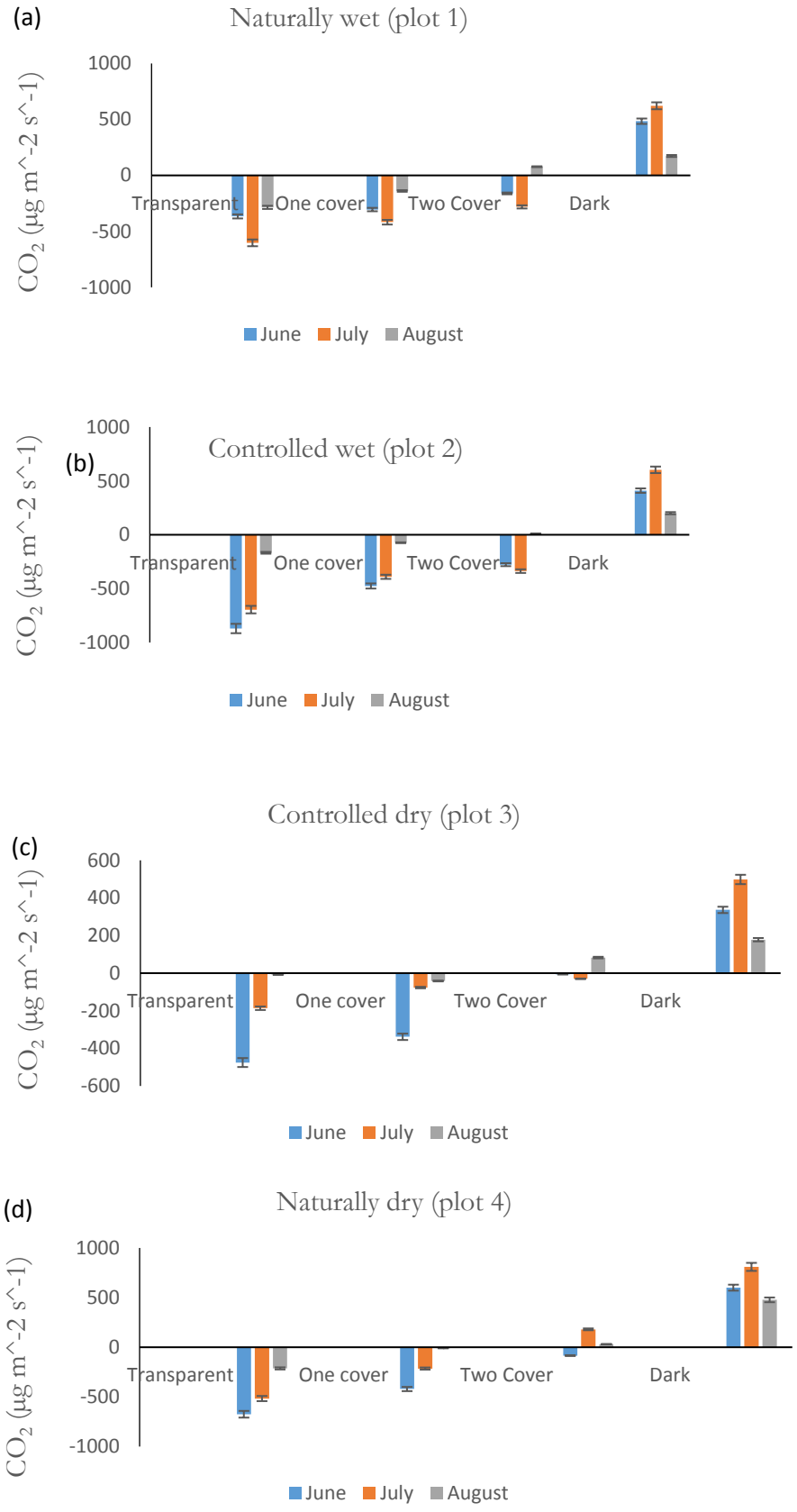


Figure 13. Measured CO_2 flux (a, b, c, d) in different light intensities for the different plots. The wet area was in plot 1 (GWL=21 cm), 2 (GWL=30 cm) and dry area was in

plot 3 (GWL=25 cm) and 4 (GWL=35 cm). Transparent measurement represents 100% incoming light, one cover measurement represents 75% light, two cover measurement denotes 50% incoming light and dark measurement represents 0% incoming light. The error bars represent the spatial variation at plot scale (95% confidence interval).

The GPP (difference between light and dark measurements) were negatively correlated (r= -0.642 to -0.668) with the air temperature (^{0}C) (Appendix 1). In contrast, dark measurements (ER) were positively correlated (r = 0.769 to 0.941) with the air temperature (^{0}C) (Appendix 2).

5.3 Modelled GPP, ER and NEE

The mean modelled CO_2 fluxes (GPP, ER, NEE) during the study period (June–August 2016) for different plots with the water table is showing the figure 14.

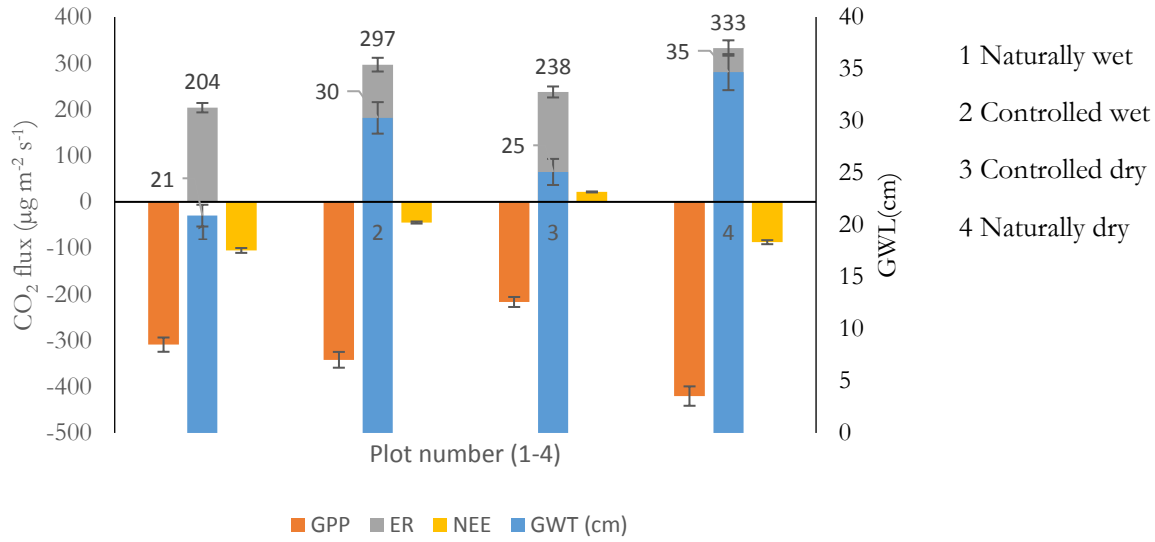


Figure 14. Study period (June–August 2016) modelled fluxes of gross primary productivity (GPP), ecosystem respiration (ER), net ecosystem exchange (NEE) and mean ground water table (GWT). Error bar represent the spatial variation at plot scale (95% confidence interval).

5.3.1 GPP

The highest value of mean GPP (-420 ± 8 CO_2 µg m^{-2} s^{-1}) was in the naturally dry area (Fig. 14) and the lowest (-217 ± 4 CO_2 µg m^{-2} s^{-1}) was in the controlled dry area. Controlled wet area with 30 cm GWT and naturally wet area with 21 cm GWT had close GPP values (341 ± 7 and 309 ± 6 CO_2 µg m^{-2} s^{-1}). At the first measurement campaign, after 3 weeks of sowing (oat) date, the GPP increases up and again reached the highest level (-665 µg m^{-2} s^{-1}) at the end of July (Fig.

15b) for naturally dry area. The leaves of oats (*Avena sativa*) started to turn yellow at the middle of July, which instigated a decline in the GPP rate for all plots. The cumulative GPP C (Table 3) showed a similar result as the naturally dry area had the highest GPP (-1301 g C m^{-2}) among the different drainage area.

5.3.2 ER

Highest mean ER (333 ± 3 CO_2 μg m^{-2} s^{-1}) was observed in naturally dry area whereas the lowest ER (204 ± 2 CO_2 μg m^{-2} s^{-1}) was measured in naturally wet area (Fig. 14). Controlled wet area had slightly higher mean ER than controlled dry area (297 ± 3, 238 ±3 CO_2 μg m^{-2} s^{-1}). In contrast, the cumulative C for naturally dry area was 1029 g C m^{-2} during the growing season, which was higher compared to other areas (Table 3). The ecosystem respiration also followed a strong seasonal pattern (Fig. 15c). At the first measurement, and during the entire farming season, ER was similar in controlled wet and naturally dry area. Overall, ER decreased continuously during the harvesting month almost reaching 100 CO_2 μg m^{-2} s^{-1}in the end of September (week 19, senescence growth stage). Unlike GPP, ER was not fluctuating abruptly with different area although the difference was observed (Fig. 14) between naturally wet (GWT 21 cm) and controlled dry area (GWT 35 cm). A steady state increase of ER was observed for all plots until the end of July (week 10 and 11, booting and ear emergence growth stage) which coincided with higher temperature and the growth of foliar biomass. After the peak growth, period the ER decreased for all plots probably because of lower respiration from the older crops compare to the green parts of the crops (Fig. 15c). Hourly modeled GPP and ER were negatively correlated ($r = -0.441^{**}$to -0.659^{**}) each other in this ecosystem during the measurement period (Appendix 6).

5.3.3 NEE

Controlled wet area with 30 cm GWT had (-45 ± 6 CO_2 μg m^{-2} s^{-1}) NEE representing a net uptake of CO_2 (Fig. 14). However, a net source of CO_2 (21 ± 4 CO_2 μg m^{-2} s^{-1}) was observed in controlled dry area with 25 cm of GWT (Fig. 14). The modelled NEE of CO_2 was negative during the most part of the growing season indicating a net CO_2 uptake for all the areas (Fig. 15a).

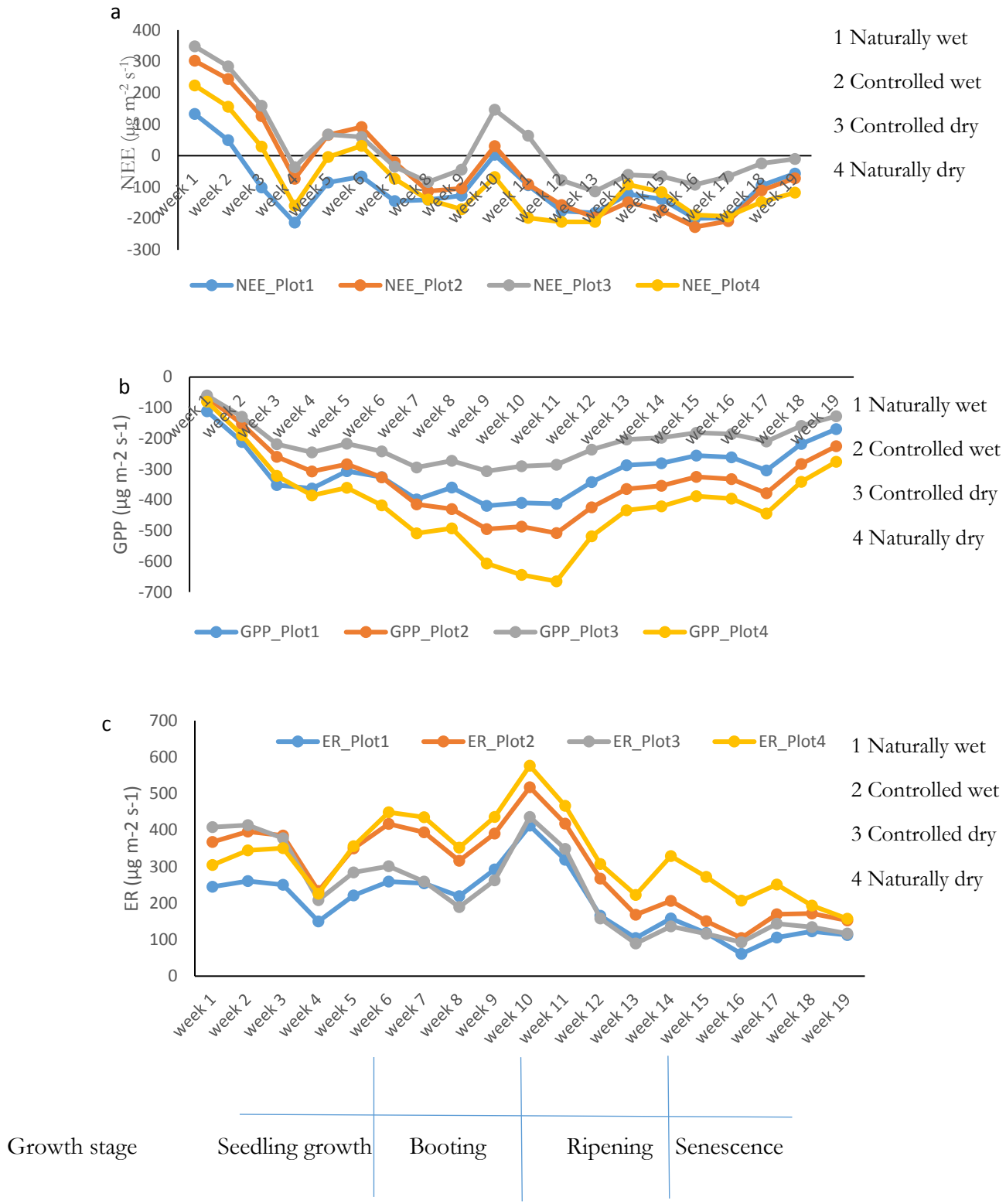


Figure 15. Weekly modelled net ecosystem exchange (NEE), gross primary productivity (GPP), ecosystem respiration (ER) and. The growth stage of oats crop is: Seedling growth, tillering, stem elongation, ear formations (week 1−5, from sowing time), booting, ear emergence (week 5 −10), flowering, milk

development, dough development, ripening (week 10 −15), senescence (week 15 −19).

The naturally dry area had the highest value (Table 3) of C (248 g C m^{-2}) at the harvesting period (C taken off from the field as grain) followed by naturally wet (235 g C m^{-2}), controlled wet (179 g C m^{-2}) and controlled dry area (170 g C m^{-2}). The naturally wet (-87.1 g C m^{-2}) and naturally dry area (-24.8 g C m^{-2}) showed a net sink of C balance while the controlled wet (40.7 g C m^{-2}) and controlled dry area (239 g C m^{-2}) showed a net source of C balance.

Table 4. Modelled cumulative C balance of the field (g C m^{-2} during the growing season)

Plot	GPP	ER	NEE	Harvest	Total (NEE+Harvest)
1 (Naturally wet)	-954	632	-322	235	-87
2 (controlled wet)	-1058	920	-138	179	41
3 (controlled dry)	-670	738	68.5	170	239
4 (naturally dry)	-1301	1029	-272	248	-25

5.3.4 Model performance and sensitivity analysis

The R-squared value for GPP models varied between 0.53-0.67 that means the model did not explain nearly 50% of the variation (Appendix 3b). However, the model coefficient, α and GPP_{max} was highly significant with P-value lower than 0.001 (Appendix 3a). In case of ER modelling, the model coefficient R_b was highly significant at 0.001 level (Appendix 4) indicating that ground water level is one of the main drivers for CO_2 emissions from cultivated peatlands.

Overall the curve showed a strong dependency of GPP to PAR (Fig. 16) throughout the study period and a significantly higher (1880 μg CO_2 m^{-2} s^{-1}) light response (GPP_{max}) was observed in naturally wet plot (Appendix 5). Naturally wet area showed a sharp increase (at LAI =1) of GPP (lowest GPP = -1094 CO_2 μg m^{-2} s^{-1}) with the increase of PAR. In addition, not much variation (lines are close to each other) was observed in controlled wet (GWL = 30 cm) and controlled dry area (GWL = 25 cm) compare to naturally wet (GWL = 21 cm) and naturally dry area (GWL = 35 cm). In contrast, at LAI = 3, controlled wet and controlled dry area the GPP variation (lines are separate to each other) were obvious (Fig. 16). However, naturally wet area at LAI = 3 showed even lower GPP (-1789 CO_2 μg m^{-2} s^{-1}) in comparison to LAI at 1.

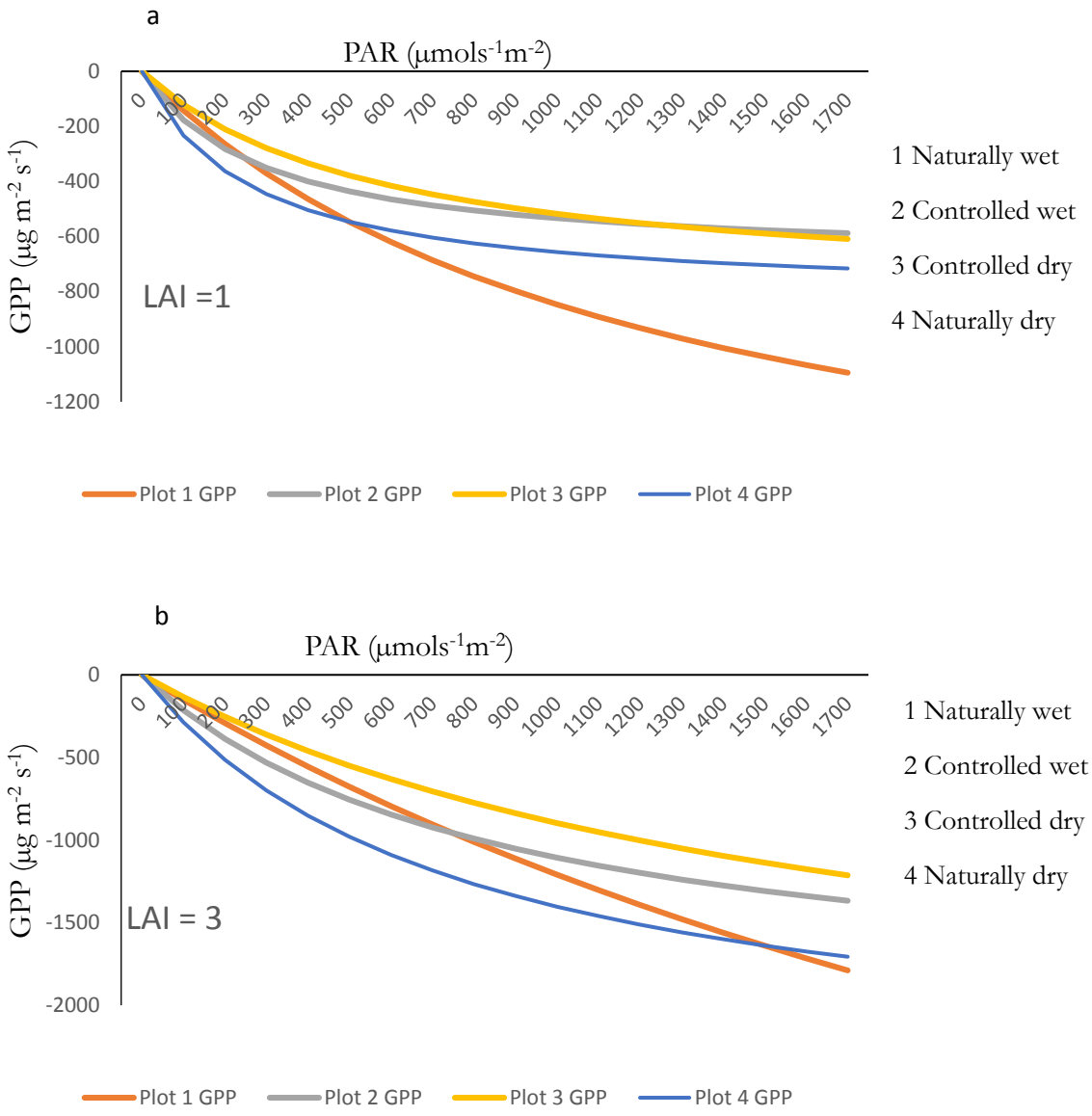


Figure 16. Responses of modelled gross primary productivity (GPP) to incident photosynthetically active radiation (PAR) in relation to different LAI (a, b).

The monthly measured and modelled ER (Fig. 17) were positively correlated (r = 0.863**). The measured and modelled ER were close to each other as shown in figure 17. The measured and modelled GPP (Fig. 18) in scatter plot were not far apart from each other (correlation coefficients varied between 0.569** to 0.825**).

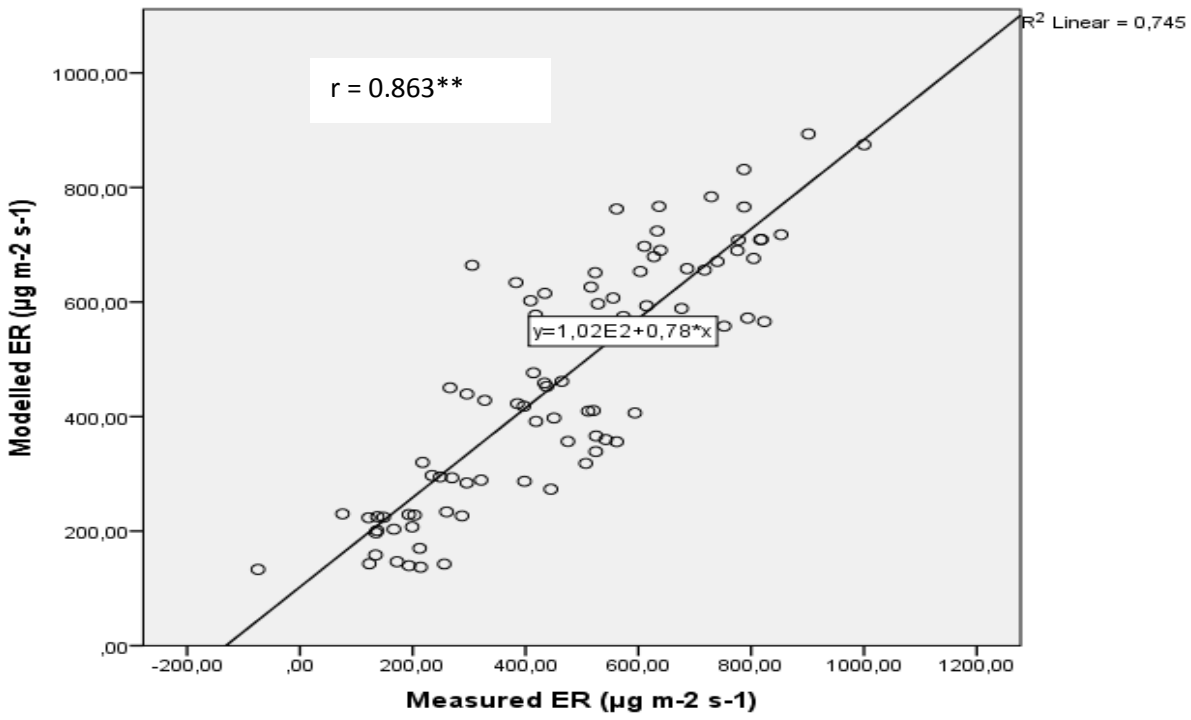
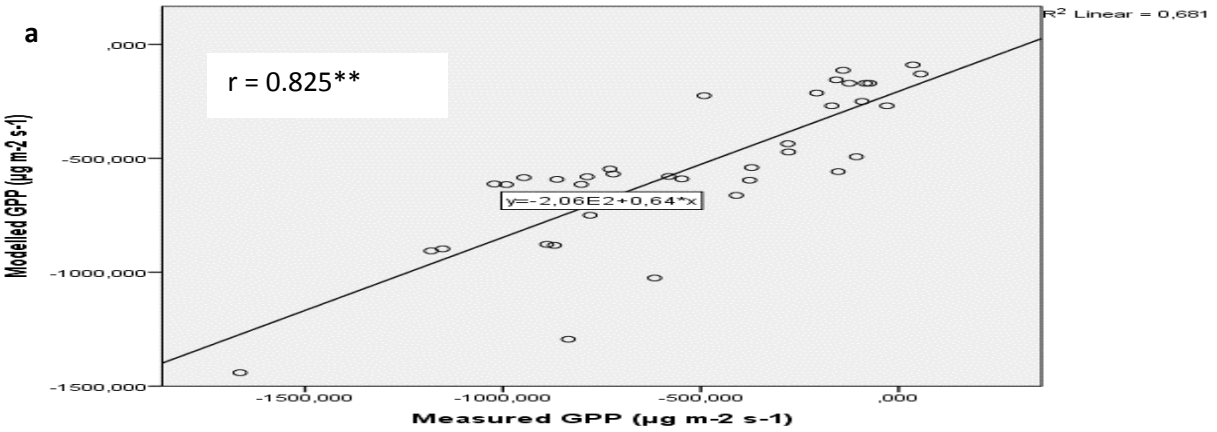
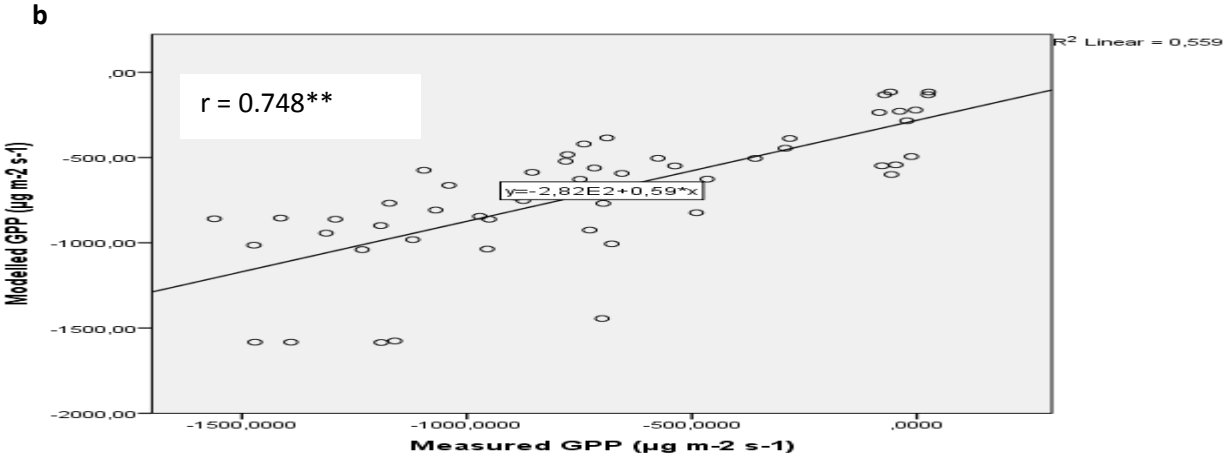
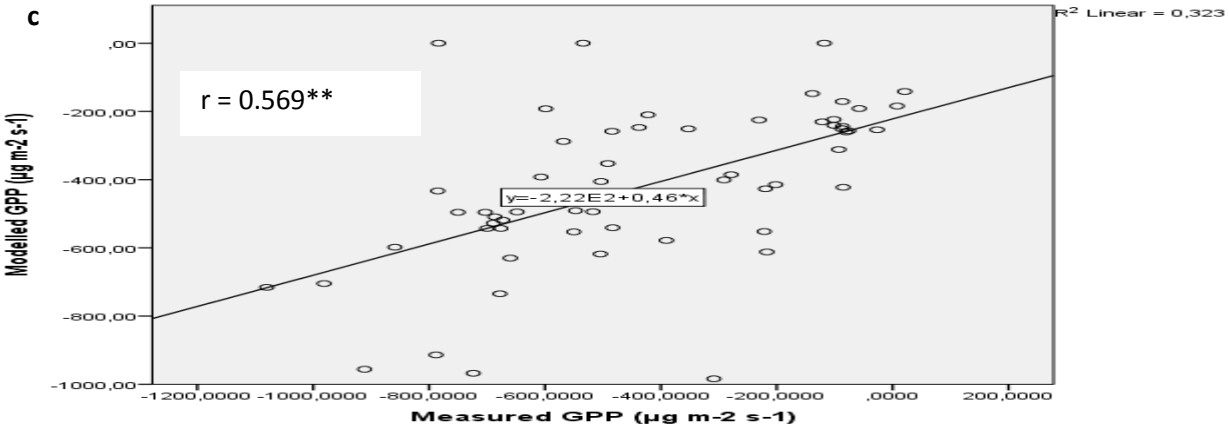


Figure 17. Comparison of modelled and measured ecosystem respiration (June–August 2016) using an integrated model (model 2) including leaf area index, temperature and ground water level as variables. The correlation coefficient (r) denotes the relationship between measured and modelled ER for all plots.


a
r = 0.825**
R² Linear = 0,681
y=-2,06E2+0,64*x
Modelled GPP (µg m-2 s-1)
Measured GPP (µg m-2 s-1)


b
r = 0.748**
R² Linear = 0,559
y=-2,82E2+0,59*x
Modelled GPP (µg m-2 s-1)
Measured GPP (µg m-2 s-1)


c
r = 0.569**
R² Linear = 0,323
y=-2,22E2+0,46*x
Modelled GPP (µg m-2 s-1)
Measured GPP (µg m-2 s-1)

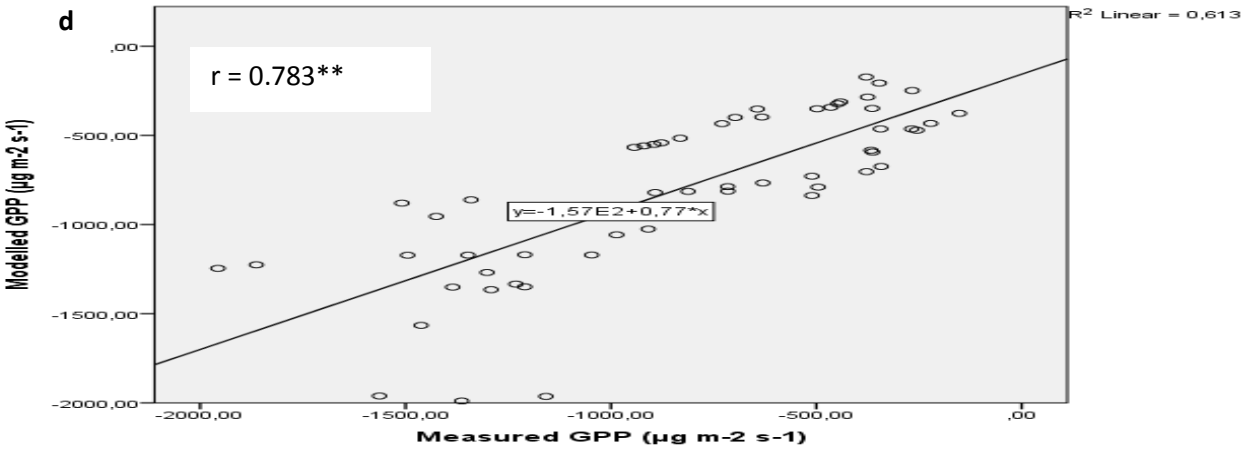

d
r = 0.783**
R² Linear = 0,613
y=-1,57E2+0,77*x
Modelled GPP (µg m-2 s-1)
Measured GPP (µg m-2 s-1)

Figure 18. Comparison of modelled and measured gross primary productivity (June–August 2016) for naturally wet (a) controlled wet (b), controlled dry (c) and naturally dry areas (d). The correlation coefficient (r) denotes the relationship between measured and modelled GPP.

The ER level was not affected (Fig. 19a) significantly with ground water level in different LAI value at constant temperature (10 °C). In contrast, there was significant variation with constant LAI value in different temperature (Fig. 19b). In each plot, the ER was increasing with increasing the temperature. As the temperature effect is obvious some researchers further developed the GPP model based on plot scale vegetation data and air temperature (Kandel et al. 2013a, Mahadevan et al. 2008). They developed temperature sensitivity (T_{scale}) of photosynthesis defined by Raich et al. (1991) as the optimum temperature is 20 ^{0}C. However, no such model was developed since the current research was focused on the growing season only not the whole year including the winter season.

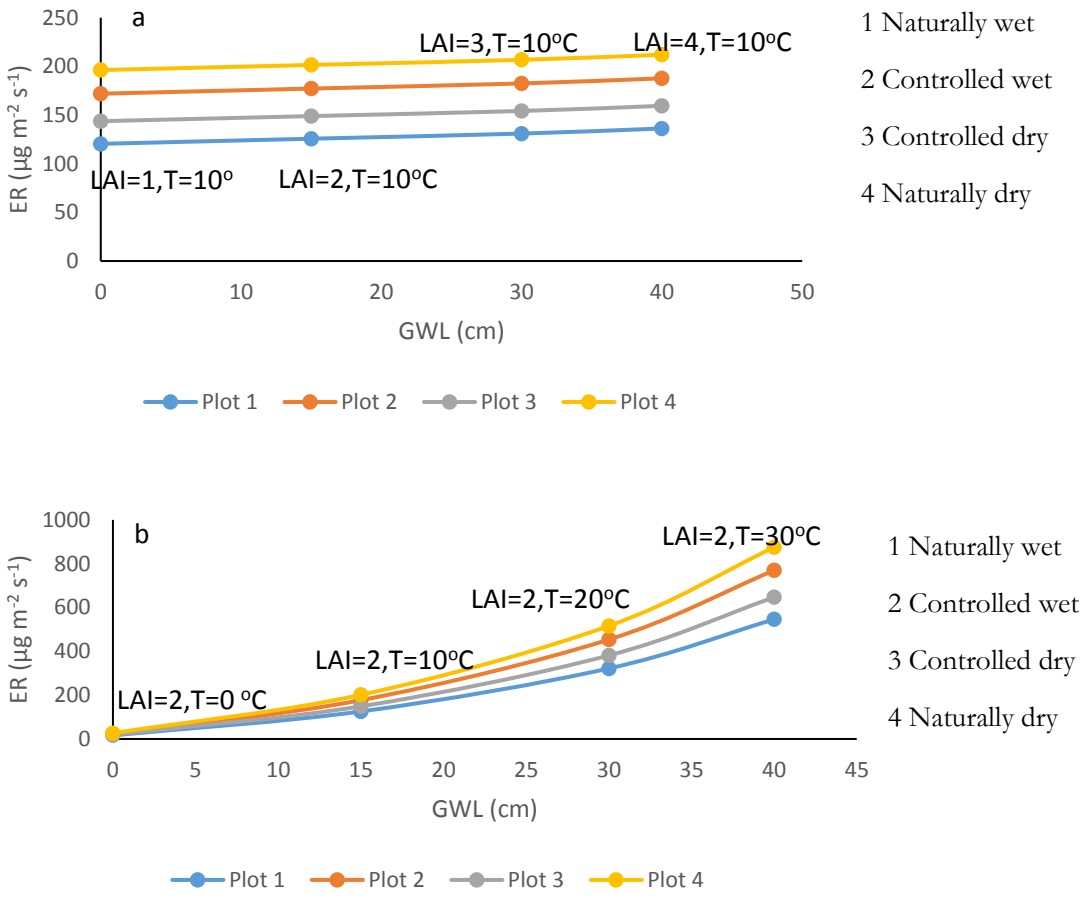


Figure 19. Sensitivity analysis of ER (a) at constant temperature (10°C) with different LAI (1, 2, 3 and 4), (b) at constant LAI (2) with different temperature (0 °C, 10 °C, 20 °C and 30 °C).

6 Discussion

6.1 Carbon balance of the study area

To our knowledge, this was the first attempt to measure the effect of controlled drainage on CO_2 flux with a transparent chamber in Finland. The results can be compared with summertime C exchange rates from barley on organic soil types in Finland. In Southern Finland, Lohila et al. (2004) reported a net CO_2 loss of 23 μg CO_2 m^{-2} s^{-1} for barley on an organic soil during the growing season by using the eddy covariance method and Maljanen et al. (2001) reported NEE of -80 μg CO_2 m^{-2} s^{-1} based on a chamber technique. The NEE values of this study were nearly in the range of these observations.

In the current study, the difference in GWL between plots was smaller than expected and consequently there were minor differences between the CO_2 fluxes. Plot 1 with the highest WT did not seem to suffer from the high-water table as the biomass production and yield were at normal level. Based on the proper biomass yield and moderate ER, the climatic impact of plot 1 was the smallest with the most negative NEE. Plot 3 with the 25 cm WT from the surface, on the other hand, had similar ER as plot 1 but the poor biomass growth turned it to a net source of carbon. The driest plot 4 had the highest ER and highest GPP that yielded a NEE value not significantly different from the wettest site. WT rise is expected to lower the soil respiration and thus ER (Best and Jacobs 1997, Beetz et al. 2013) but based on our results if the biomass growth is lowered, the NEE of the field may not be improved.

In the case of an agricultural field, the harvest that is taken away forms an important part of the climatic impact and it should be accounted as a carbon loss as well. In this study, the grain harvest was of the magnitude of 170 − 250 g C m^{-2} which negates the C sink measured as NEE in most cases. The lateral losses of dissolved organic carbon (DOC) to ditches with draining water, were not considered here. For instance, in European grassland the DOC (to ditches) loss has varied from 7 to 21 g C m^{-2} yr^{-1} (Schulze et al. 2009, Hendriks et al. 2007, Worrall and Evans 2009). These numbers suggest that the dissolved carbon loss is not significantly high compared to the CO_2 flux although the losses through water are presumably higher from a cereal growing peatland. A more detailed climate impact including nitrous oxide and methane to the atmosphere could be considered but it was not included in this study. However, they form a smaller portion of the total impact. For instance, Karki et al. (2015) calculated 12.5% as the proportion of the total global warming potential for nitrous oxide and methane from barley plots on drained peat soil in Denmark.

The CO_2 exchange (Fig.13) showed a similar trend (high flux during the growing period and decreased towards at the harvest time) with other studies where alike methods were used (Alm et al. 1997, Bubier et al. 1999). The air temperature was a critical factor (Fig. 19b) for ecosystem respiration and there was a distinct seasonal variation as stated earlier for peatlands and agricultural soils (Silvola et al. 1996). The higher ER in the naturally dry area (1029 g C m^{-2}) compared to naturally wet area (632 g C m^{-2}) might resulting from the effect of depth of the GWL (Alm et al. 2007). With a 10 cm difference in GWL there was a 10cm layer more of peat that is prone to aerobic decomposition.

6.2 Modelling of the fluxes

The modelled fluxes uncertainties were estimated for both spatial variation and uncertainties in terms of modelling (Laine et al. 2009). The fluxes both in measured (Fig. 13) and modelled (Fig. 14) uncertainties were small (error bar at plot scale). The relative modelled uncertainty of NEE is more important than measured flux uncertainty (Kandel et al. 2013a). The calculation of flux uncertainty based on chamber measurements follow several methods. The typical methods include Taylor series approximations of response function (Bubier et al. 1999), derivation of standard error of mean (SE) from models (± SE), and parameter estimation by boot-strapping technique (Laine et al. 2009). However, it is difficult to evaluate modelled flux uncertainty since there is no consensus for ideal approach (Kandel et al. 2013a). A comprehensive analysis of different approaches is beyond the scope of this research but we considered SE and spatial variation for the data interpretation.

The rectangular hyperbola function (model 1) fitted for all individual responses with R^2 (0.53-0.68). Controlled wet plot showed a slightly higher (2.4 μg CO_2 μmol $^{-1}$ photon) initial slope (α) than controlled dry plot (1.4 μg CO_2 μmol $^{-1}$ photon). The shaded leaves in the lower canopy of tall and dense vegetation could not get enough PAR to reach saturation that results in higher GPP_{max} than normal PAR range (Appendix 5). The results of GPP_{max} and α in this study are in contrast with Kandel et al. (2013a) study. The whole year study including the winter time possibly makes the difference from current study to Kandel's study.

Temperature was identified as a critical component of ER but GWL was also used in the model to visualize the effect of GWL on ER. The R^2 (0.77) value showed a good performance (model explained more than 70% variation of ER real data points) of for all plots (Appendix 4). However, the lack of model fit to seasonal data often resulted from the dependency of temperature in ER model. The possible reason can be the confounding contributions from

biomass dynamics and therefore, some studies considered the cluster-wise ER modelling for distinct plant phenological stages to nullify such confounding effects (Beetz et al. 2013, Poyda et al. 2016).

This current study considered simple yet useful GPP and ER models that introduce LAI as an active vegetation proxy. The models confirmed that temperature was the major driver of both GPP and ER at cultivated peatlands (Lohila et al. 2004, Maljanen et al. 2004). The integrated GPP model with minimal number of parameters can be a robust method to capture diurnal seasonal variation of CO_2 flux during the cultivation period. Thus, the GPP model includes temperature and vegetation index (LAI) as critical drivers of photosynthesis. Kandel et al. 2013a proposed a scaling factor (T_{scale}) for capturing the temperature variation throughout the year in GPP model. However, no such temperature scale was considered in this study as only the growing period CO_2 flux was the point of interest. The GPP (this study) model was presented by Kandel et al. (2013a) was successfully adopted by other studies (Järveoja et al. 2016; Karki et al. 2016). In the current study, the ER model was extended from Kandel et al. (2013a) with a ground water table depth parameter in analogy to describe the water table effect on ER and NEE. The model parameters were highly significant ($p<0.001$) for both GPP and ER model (Appendix 3a, b, 4). However, greenness indices such as LAI can be a useful parameter for ER modelling, but canopy reflectance or other crop development parameters were not included in the current protocols.

The extrapolation of fluxes can be crucial in chamber measurements when there is a large data gaps resulting from low sampling frequency compared to long period (often annual) of interest (Kandel et al. 2017). Thus, for the validity of fluxes extrapolated from chamber measurements demand a robust model and significant parameter for the gap filling. In the current study, LAI, GWL and temperature explained most of the variations in ER fluxes. The robust ER and GPP model parameters (Appendix 3a, 4) were obtained but it may be more important to capture the complete amplitude of driving variables rather than acquiring a high frequency of measurements (Kandel et al. 2017).

A large variety of apparent temperature sensitivities of ER on seasonal scales were shown by the previous studies (Curiel Yuste et al. 2004, Reichstein et al. 2005), which may be related to the combined effects of temperature and other variables co-varying with the temperature. This current study showed the temperature sensitivity over the ER, but it did not show with the LAI (Fig. 19a). This means ER is sensitive for the temperature fluctuation but not with the LAI. In addition, at a lower temperature higher sensitivity of ER has also been reported by Kirschbaum

(1996), Rayment and Jarvis (2000). Moreover, GPP has been hypothesized to be one of the factors driving the ecosystem respiration (ER) (Janssens et al. 2002).

6.3 Practical considerations for controlled drainage

In Finland, controlled drainage of peat soil is increasing because there are subsidies for it (LULUCF 2013). Thus, it could be used as a mitigation measure and the subsidy is designed to ease both the investment and the work load resulting from GWL adjustments. A German study disclosed that growers were in contradiction of management changes, mostly in areas where agricultural production on peatland is profitable (Schaller et al. 2011). The mitigation with controlled drainage is supposed to endanger the farm income less than more profound wetting of the soil and thus controlled drainage could be a way to slow down peat decomposition also in soils in actively cultivated regions. To report the resulting GHG mitigation, there should be a way to estimate the mean GWL and the resulting GHG fluxes. As the water table and the flux are not static a modelling approach could be a solution forward. The practical consideration for controlling drainage listed above are based on the results from this study during the growing period but the effect for the rest of the year demand further study.

7 Conclusion

This study suggests that the controlled dry area served as the highest net source of carbon and that by keeping the ground water level higher than normally, part of the negative climatic impacts of cultivated organic soils could be mitigated. As the emissions of CO_2 from peat mineralization are reduced, but crop cultivation still possible, controlled drainage is a promising mitigation measure. In this study, the GWL of all plots was higher than in average farming and thus the mitigation effect could be even higher than reported here. In conventional drainage practice the GWL is maintained at 60−70 cm and thus change to 25−30 cm is a more drastic change than the differences in this study. The practical constraints of keeping the ground water table at a desired level certainly deserve further studies.

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References

Alm, J., Shurpali, NJ. & Minkkinen, K. 2007. Emission factors and their uncertainty for the exchange of CO_2, CH_4 and N_2O in Finnish managed peatlands. Boreal Environmental Research 12: 191–209.

Aaltonen, V.T. 1949. Maaperäsanaston ja maalajien luokituksen tarkistus v.1949. Summary: A critical review of soil terminology and soil classification in Finland in the year 1949. Agricultural Society of Finland 21: 37-66.

Andriesse, JP. 1988. Nature and Management of tropical peat soils. In FAO Soils Bulletin 59. Rome FAO. 179 pp. Bain, C.G., Bonn, A., Stoneman, R., Chapman, S., Coupar, A., Evans, M., Gearey, B., Howat, M., Joosten, H., Keenleyside, C., Labadz, J., Lindsay, R., Littlewood, N., Lunt, P., Miller, C.J., Moxey, A., Orr, H., Reed, M., Smith, P., Swales, V., Thompson, D.B.A., Thompson, P.S., Van de Noort, R., Wilson, J.D. & Worrall, F. 2011. IUCN UK Commission of Inquiry on Peatlands. Edinburgh, IUCN UK Peatland Programme. (available at: www.iucn-uk-peatlandprogramme.org/resources/188).

Amthor, J.S. & Baldocchi, D.D. 2001. Terrestrial Higher Plant Respiration and Net Primary Production. In: Roy, J., Saugier, B. & Mooney, H. (eds.). Terrestrial Global Productivity. Academic Press s. 33-59.

Ballester, J., Douville, H. & Chauvin, F. 2009. Present-day climatology and projected changes of warm and cold days in the CNRM-CM3 global climate model. Climate Dynamics 32: 35-54.

Beetz, S., Liebersbach, H., Glatzel, S., Jurasinski, G., Buczko, U. & Hoper, H. 2013. Effects of land use intensity on the full greenhouse gas balance in an Atlantic peat bog. Bio geosciences 10: 1067–1082.

Best, EPH. & Jacobs, FHH. 1997. The influence of raised water table levels on carbon dioxide and methane production in ditch-dissected peat grasslands in the Netherlands. Ecological Engineering 8: 129–144.

Blake, GR. & Hartge, KH. 1986. Bulk density. In: Klute, A. (eds.). Methods of soil analysis, Part 1, Physical and mineralogical methods, 2nd eds. Soil Science Society of America, Madison, s. 363–375.

Blodau, C., Basiliko, N. & Moore, TR. 2004. Carbon turnover in peatland mesocosms exposed to different water table levels. Biogeochemistry 67:331–351.

Bubier, JL., Frolking, S., Crill, PM. & Linder, E. 1999. Net ecosystem productivity and its uncertainty in a diverse boreal peatland. Journal of Geophysical Research 104: 27683–27692.

Burnham, K. & Anderson, D. 2004. Multi model inference. Sociological Methods and Research 33: 261–304.

Burrows, EH., Bubier, JL., Mosedale, A., Cobb, GW. & Crill, PM. 2005. Net ecosystem exchange of carbon dioxide in a temperate poor fen: A comparison of automated and manual chamber techniques. Biogeochemistry 76: 21–45.

Busman, L. & Sands, G. 2002. Agricultural Drainage Issues and Answers. St. Paul University of Minnesota. URL [Accessed: 03.06.2017].

Canadell, P. 2011. The Global Carbon Budget and the Role of Forests and Peatlands. Presentation Workshop on Tropical Wetland Ecosystems of Indonesia, Bali, April 11–14, 2011. (available at: http://www.forestsclimatechange.org/fileadmin/tropicalworkshop/Overview_Session/1P_CanadellP_GCP.pdf).

IPCC 2016. https://www.ipcc.ch/report/ar4/(30.12.2016).

Costello, A. 2009. Managing the health effects of climate change. Lancet 373: 1693-1733.

Couwenberg, J., Dommain, R. & Joosten, H. 2010. Greenhouse gas fluxes from tropical peatlands in South-East Asia. Global Change Biology 16: 1715–1732.

Curiel Yuste, J., Janssens, IA., Carrara, A. & Ceulemans, R. 2004. Annual Q10 of soil respiration reflects plant phenological patterns as well as temperature sensitivity. Global Change Biology 10: 161–169.

Dradjad, M., Soekodarmodjo, S., Shodiq Hidayat, M. & Nitisapto, M. 2003. Subsidence of peat soils in the tidal swamp lands of Barambai, South Kalimantan. Jurnal Ilmu Tanah dan Lingkungan 4: 32–40.

Drainage foundation Sr. 2017. http://www.tukisaatio.fi/en. Retrieved date 9.8.2017.

Ellis, T., Hill, PW., Fenner, N., William, GG., Godbold, D. & Freeman, C. 2009. The interactive effects of elevated carbon dioxide and water table draw-down on carbon cycling in a Welsh ombrotrophic bog. Ecological Engineering 35:978–986.

Elsgaard, L., Schafer, C-M., Hoffmann, CC., Blicher-Mathiesen, G., Schelde, K. & Petersen, SO. 2012. Net ecosystem exchange of CO_2 and carbon balance for eight temperate organic soils under agricultural management. Agriculture, Ecosystems and Environment 162: 52–67.

EDF 2016. https://www.edf.org/climate/climate-changes-effects-plunder-planet (26.12.2016).

FAO 2012. Peatlands—guidance for climate change mitigation by conservation, rehabilitation and sustainable use. In: Joosten, H., Tapio-Biström, ML. & Tol, S. (eds.). Available at: http://www.fao.org/docrep/015/an762e/an762e00.htm.

FAO 2014a. Agriculture, forestry and other land use emissions by sources and removals by sinks 1990 – 2011 analysis. In: Tubiello, F.N., Salvatore, M., Cóndor R.D., Golec, A., Ferrara, S., Rossi, R., Biancalani, S., Federici, H., Jacobs, A. & Flammini, ESS. Working Paper 2, Rome. 87 pp.

FAO 2014b. FAOstat (available at http://faostat3.fao.org/faostatgateway/go/to/home).

FAO 2017. FAOstat. http://www.fao.org/faostat/en/#data/RL/visualize Retrieved date 24.5.2017.

Fleischer, E., Khashimov, I., Hölzel, N. & Klemma, O. 2015. Carbon exchange fluxes over peatlands in Western Siberia: Possible feedback between land-use change and climate change. Science of the Total Environment 545–546 (2016): 424–433.

Freeman, C., Lock, MA. & Reynolds, B. 1993. Fluxes of CO_2, CH_4 and N_2O from a welsh peatland following simulation of water-table draw-down—potential feedback to climatic-change. Biogeochemistry 19:51–60.

Hendriks, D. M. D., van Huissteden, J., Dolman, A. J. & van der Molen, M. K. 2007. The full greenhouse gas balance of an abandoned peat meadow. Bio geosciences 4: 411–424.

Hooijer, A., Page, S., Jauhiainen, J., Lee, W.A., Lu, X.X., Idris, A. & Anshari, G. 2012. Subsidence and carbon loss in drained tropical peatlands. Bio geosciences 9: 1053–1071.

IPCC. Climate Change 2001. Impacts, Adaptation and Vulnerability (Cambridge University Press, 2001).

IPCC. 2001. Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). In: Houghton, J., Ding, T., Y., Griggs, D. J., Noguer, M., Van der Linden, P. J. & Xiaosu, D. (eds.). Cambridge University Press (Cambridge) s. 944.

IPCC. Climate Change, 2013. The Physical Science Basis (Cambridge University Press, 2013).

IPCC. 2013. Supplement to the 2006 IPCC guidelines for national greenhouse gas inventories: Wetlands. Geneva: Intergovernmental Panel on Climate Change. Retrieved from http://www.ipcc-nggip.iges.or.jp/home/wetlands.html.

IPCC. Climate Change 2014. Impacts, Adaptation, and Vulnerability (Cambridge University Press, 2014).

IPS. 2017. http://www.peatsociety.org/peatlands-and-peat/what-peat. Retrieved date 9.8.2017.

IUCN. UK. Commission of Inquiry on Peatlands Full Report, IUCN UK Peatland Program October 2011.

Jacobs, CMJ., Jacobs, AFG. & Bosveld, FC. 2007. Variability of annul CO_2 exchange from Dutch grasslands. Bio geosciences 4: 803–816.

Jaenicke, J., Wosten, H., Budiman, A. & Siegert, F. 2010. Planning hydrological restoration of peatlands in Indonesia to mitigate carbon dioxide emissions. Mitigation and Adaptation Strategies for Global Change 15: 223–239.

Janssens, IA., Lankreijer, H. & Matteucci, G. 2002. Productivity overshadows temperature in determining soil and ecosystem respiration across European forests. Global Change Biology 7: 269–278.

Järveoja, J., Peichl, M., Maddison, M., Teemusk, A. & Mander, U. 2016. Full carbon and greenhouse gas balances of fertilized and non-fertilized reed canary grass cultivations on an abandoned peat extraction area in a dry year. Global Change Biology Bioenergy 8: 952–968.

Jenkinson, DS., Hart, PBS., Rayner, JH. & Parry, LC. 1987. Modelling the turnover of organic matter in long-term experiments at Rothamsted. INTECOL Bulletin. 15: 1–8.

Joosten, H. & Clarke, D. 2002. Wise use of mires and peatlands – Background and principles including a framework for decision-making. Saarijärvi, International Mire Conservation Group and International Peat Society.

Joosten, H. 2009. The global peatland CO_2 picture. Peatland status and emissions in all countries of the world. Ede: Wetlands International. Retrieved from http://tinyurl.com/yaqn5ya.

Kandel, TP., Elsgaard, L., Karki, S. & Lærke, PE. 2013a. Biomass yield and greenhouse gas emissions from a drained fen peatland cultivated with reed canary grass under different harvest and fertilizer regimes. Bio Energy Research 6: 883–895.

Kandel, TP., Elsgaard, L. & Lærke, PE. 2013d. Measurement and modelling of CO_2 flux from a drained fen peatland cultivated with reed canary grass and spring barley. Global Change Biology Bioenergy 5: 548–561.

Kandel, T. P., Elsgaard, L. & Lærke, P. E. 2017. Annual balances and extended seasonal modelling of carbon fluxes from a temperate fen cropped to festulolium and tall fescue under two-cut and three-cut harvesting regimes. GCB Bioenergy.

Karki, S., Elsgaard, L., Kandel, TP. & Lærke, PE. 2016. Carbon balance of rewetted and drained peat soils used for biomass production: a mesocosm study. Global Change Biology Bioenergy 8: 969–980.

Kechavarzi, C., Dawson, Q. & Bartlett, M. 2010. The role of soil moisture, temperature and nutrient amendment on CO_2 efflux from agricultural peat soil microcosms. Geoderma 154:203–210.

Kirschbaum, MUF. 1996. The temperature dependence of soil organic matter decomposition, and the effect of global warming on soil organic C storage. Soil Biology and Biochemistry 27: 753–760.

Kutzbach, L., Schneider, J. & Sachs, T. 2007. CO_2 flux determination by closed chamber methods can be seriously biased by inappropriate application of linear regression. Bio geosciences 4: 1005–1025.

Laine, A., Riutta, T., Juutinen, S., Valiranta, M. & Tuittila, ES. 2009. Acknowledging the spatial heterogeneity in modelling/reconstructing carbon dioxide exchange in a northern mire. Ecological Modelling 220: 2646–2655.

Lohila, A., Aurela, M., Tuovinen, JP. & Laurila, T. 2004. Annual CO_2 exchange of a peat field growing spring barleys or perennial forage grass. Journal of Geophysical Research, 109: D18116.

Mahadevan, P., Wofsy, SC. & Matross, DM. 2008. A satellite-based biosphere parameterization for net ecosystem CO_2 exchange: vegetation photosynthesis and respiration model (VPRM). Global Biogeochemical Cycles 22: GB2005.

Maljanen, M., Hytonen, J. & Martikainen, P. 2001. Fluxes of N_2O, CH_4 and CO_2 on afforested boreal agricultural soils. Plant and Soil 231: 113–121.

Maljanen, M., Liikanen, A., Silvola, J. & Martikainen, P. 2003. Nitrous oxide emissions from boreal organic soil under different land-use. Soil Biology and Biochemistry 35:689–700.

Ministry of Agriculture and Forestry 2013. Luonnos Manner-Suomen maatalouden kehittämisohjelmaksi. [In Finnish] Available at: http://www.maaseutu.fi/attachments/ohjelmakausi_2014-2020/6LmoiR08y/Luonnos_Manner. Suomen_maaseudun_kehittamisohjelmaksi_2014-2020_netti.pdf.

Ministry of agriculture and forestry, Finland, 2007. http://mmm.fi/documents/1410837/1724539/trm2011_1_Suostrategia.pdf/40955-9891-4192-9f0b-971258e021f1. Retrieved date: 26.5.2017.

Myllys, M., 1996. Agriculture on peatlands. Peatlands in Finland. Finnish Peatland Society, Helsinki, Finland.

Nordic Council of Ministers 2014. Nordic countries in figures 2014. Copenhagen: Nordisk Ministerraåd. Retrieved from http://dx.doi.org/10.6027/ANP2014-752.

Norwegian Government 2008. Climate challenges – agriculture as a part of the solution [Klimautfordringene – landbruketen del av løsningen]. Landbruks- og matdepartementet. Retrieved from- http://www.regjeringen.no/nb/dep/lmd/dok/regpubl/stmeld/2008-2009/stmeld-nr-39-2008-2009- .htmlid=563671.

Oleszczuk, R., Regina, K., Szajdak, L., Höper, H. & Maryganova, V. 2008. Impact of agricultural utilization of peat soils on the greenhouse gas balance. In: Strack, M. (eds.), Peatlands and climate change. International Peat Society.

Patz, J. A., Campbell-Lendrum, D., Holloway, T. & Foley, J. A 2005. Impact of regional climate change on human health. Nature 438: 310-317.

Parish, F., Sirin, A., Charman, D., Joosten, H., Minayeva, T., Silvius, M. & Stringer, L. (eds.) 2008. Assessment on Peatlands, Biodiversity and Climate Change: Main Report. Global Environment Centre, Kuala Lumpur and Wetlands International, Wageningen.

Paris Agreement 2016. Center for climate and energy solution. https://www.c2es.org/international/negotiations/cop21-paris/summary. Retrieved date 17.8.2017.

Plant & soil science eLibrary 2017. http://passel.unl.edu/pages/informationmodule.php?idinformationmodule=1130447032&topicorder=3&maxto=16. Retrieved date 9.8.2017.

Pfadenhauer, J. & Klözli, F. 1996. Restoration experiments in middle European wet terrestrial ecosystems: an overview. Vegetation 126:110-115.

Poyda, A., Reinsch, T., Klub, C., Loges, R. & Taube, F. 2016. Greenhouse gas emissions from fen soils used for forage production in northern Germany. Bio geosciences 13: 5221–5244.

Raich, JW., Rastetter, EB. & Melillo, JM. 1991. Potential net primary productivity in South America: application of a global model. Ecological Applications 1: 399–429.

Rayment, MB. & Jarvis, PG. 2000. Temporal and spatial variation of soil CO_2 efflux in a Canadian boreal forest. Soil Biology and Biochemistry 32: 35–45.

Regina, K., Lehtonen, H., Nousiainen, J. & Esala, M. 2009. Modelled impacts of mitigation measures on greenhouse gas emissions from Finnish agriculture up to 2020. Agricultural and Food Science 18:477–493.

Regina, K., Sheehy, J. & Myllys, M. 2014. Mitigating greenhouse gas fluxes from cultivated organic soils with raised water table. Mitigation and Adaptation Strategies for Global Change 20(8):1529–1544.

Regina, K., Silvola, J. & Martikainen, P. 1999. Short-term effects of changing water table on N_2O fluxes from peat monoliths from natural and drained boreal peatlands. Global Change Biology 5:183–189.

Regina, K., Syvasalo, E., Hannukkala, A. & Esala M. 2004. Fluxes of N_2O from farmed peat soils in Finland. European Journal of Soil Science 55:591–599.

Reichstein, M., Falge, E. & Baldocchi, D. 2005. On the separation of net ecosystem exchange into assimilation and ecosystem respiration: review and improved algorithm. Global Change Biology 11: 1424–1439.

Renger, M., Wessolek, G., Schwarzel, K., Sauerbrey, R. & Siewert, C. 2002. Aspects of peat conservation and water management. Plant Nutritional Soil Science 165:487–493.

Schaller, L., Kantelhardt, J. & Droesler, M. 2011. Cultivating the climate: socio-economic prospects and consequences of climate-friendly peat land management in Germany. Hydrobiologia 674:91–104.

Schothorst, LC. 1977. Subsidence of low moor peat in the Western Netherlands. Geoderma, 17: 265–271.

Schulze, E. D., Luyssaert, S., Ciais, P., Freibauer, A., Janssens, I.A., Soussana, J., Sheil, D., Casson, A., Meijaard, E., van Nordwijk, M., Gaskell, J., Sunderland-Groves, J. & Kanninen, M. 2009. The impacts and opportunities of oil palm in Southeast Asia: What do we know and what do we need to know? (Occasional Paper No. 51). Bogor: CIFOR.

Silvola, J., Alm, J., Ahlholm, U., Nykänen, H. & Martikainen, P.J. 1996. CO_2 fluxes from peat in boreal mires under varying temperature and moisture conditions. Journal of Ecology 84: 219–228.

Smeets, E. M. W., Faaij, A. P. C., Lewandowski, I. M. & Turkenburg, W. C. 2007. A bottom-up assessment and review of global bio-energy potentials to 2050. Progress in Energy and Combustion Science 33: 56–106.

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, B. & Sirotenko, O. 2007. Agriculture. In: Metz, B., Davidson, OR., Bosch, PR., Dave, R. & Meyer, LA. (eds.). Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

Statistics Finland 2013. Greenhouse gas emissions in Finland 1990–2011. National Inventory Report under the UNFCCC and the Kyoto Protocol, April 15th, 2013. Available at: www.stat.fi/greenhousegases.

Stephens, J.C., Allan, L. H. & Chen, E. 1984. Organic Soil Subsidence. Geological Society of America. Reviews in Engineering Geology 6: 107–122.

TEM. 2017. Government report on the National Energy and Climate Strategy for 2030.

UNFCCC. 2012. National inventory submissions. Bonn: UNFCCC Secretariat. Retrieved from http://unfccc.tnational_reports/annex_i_ghg_inventories/national_inventories_submissions/items/6598.php.

Vaisala Vantaa Finland. http://www.vaisala.com/en/industrialmeasurements/products/carbondioxide/Pages/GMP343.aspx. Retrieved date 30.11.2016.

Vaisala Vantaa Finland. https://store.vaisala.com/eu/productresources/large1/HM70A0A1A0AB.jpg. Retrieved date 30.11.2016.

Van de Riet, BP., Hefting, MM. & Verhoeven, JTA. 2013. Rewetting drained peat meadows: risks and benefits in terms of nutrient release and greenhouse gas exchange. Water Air Soil Pollution 224:1440.

Wikipedia 2017. https://fi.wikipedia.org/wiki/Mouhijärvi. Retrieved date 12.6.2017.

Wikipedia 2017. https://en.wikipedia.org/wiki/Peat. Retrieved date 27.8.2017.

World meters 2017. http://www.worldometers.info/world-population Retrieved date 27.12.2016.

Worrall, F. & Evans, M. G. 2009. The carbon budget of upland peat soils, In: Bonn, A., Allott, T., Hubacek, K. & Stewart, J. (eds.). Drivers of Environmental Change in Uplands, Routledge, Taylor & Francis Group, Abingdon 2: 93–112.

Wüst, H. 2009. The global peatland CO_2 picture. Peatland status and emissions in all countries of the world. Wetlands International(eds.). Retrieved from http://tinyurl.com/yaqn5ya.

Yu, Z. 2011. Holocene carbon flux histories of the world's peatlands: Global carbon-cycle implications. Holocene 21: 761–774.

Zar, JH. 1996. Bio statistical Analysis. Prentice-Hall, Englewood Cliffs, NJ.

Appendices

Appendix 1. Correlation matrix of modelled gross GPP and air temperature (inside the chamber).

Plot 1 = Naturally wet, Plot 2 = Controlled wet, Plot 3 = Controlled dry, Plot 4 = Naturally dry.

Correlations

	Temperature (^{0}C)	GPP_Plot1	GPP_Plot2	GPP_Plot3	GPP_Plot4
Temperature (^{0}C)	1	-.666**	-.642**	-.668**	-.651**
GPP_Plot1	-.666**	1	.968**	.992**	.965**
GPP_Plot2	-.642**	.968**	1	.979**	.996**
GPP_Plot3	-.668**	.992**	.979**	1	.978**
GPP_Plot4	-,651**	.965**	.996**	.978**	1

**. Correlation is significant at the 0.01 level (2-tailed).

Appendix 2. Correlation matrix of modelled ER and air temperature (inside the chamber).

Plot 1 = Naturally wet, Plot 2 = Controlled wet, Plot 3 = Controlled dry, Plot 4 = Naturally dry.

Correlations

	Temperature (^{0}C)	ER_Plot 1	ER_Plot 2	ER_Plot 3	ER_Plot 4
Temperature (^{0}C)	1	.842**	.866**	.769**	.941**
ER_Plot1	.842**	1	.985**	.935**	.957**

ER_Plot2	.866**	.985**	1	.951**	.951**
ER_Plot3	.769**	.935**	.951**	1	.855**
ER_Plot4	.941**	.957**	.951**	.855**	1

**. Correlation is significant at the 0.01 level (2-tailed).

Appendix 3 (a). Estimated coefficient for GPP.

Nonlinear regression model for GPP:

$$GPP = (\alpha * GPP_{max} * PAR * LAI) / ((\alpha * PAR) + (PAR * LAI))$$

Where, α ($\mu g\ CO_2\ \mu mol^{-1}$ photon) is the initial slope of the photosynthetic light response and GPP_{max} ($\mu g\ CO_2\ m^{-2}\ s^{-1}$) is the theoretical maximum rate of photosynthesis at infinite PAR.

Coefficients	Estimate	SE	T-Stat	P-value	Plots
α	-1.5405	0.24979	-6.1675	2.7483^{-07}	1
GPP_{max}	-1880.3	814.02	-2.3099	0.026136	1
α	-2.388	0.40179	-5.9435	3.2766^{-07}	2
GPP_{max}	-687.1	155.51	-4.4185	5.8214^{-05}	2
α	-1.4173	0.25343	-5.5923	7.2586^{-07}	3
GPP_{max}	-814.66	207.96	-3.9174	0.00024961	3
α	-3.2526	0.34108	-9.5362	5.2205^{-13}	4
GPP_{max}	-822.27	98.456	-8.3516	3.5556^{-11}	4

Appendix 3 (b): Modelled GPP statistics

Plot number	Number of observations	Error degrees of freedom	Root Mean Squared Error	R-Squared	Adjusted R-Squared	F-statistic vs. zero model	P-value
1	42	40	227	0.678	0.67	164	5.43^{-20}
2	49	47	263	0.67	0.663	216	1.93^{-24}
3	57	55	197	0.536	0.528	364	2.73^{-31}

4	54	52	230	0.674	0.667	163	8.18^{-24}

Appendix 4. Estimated coefficient for ER.

Nonlinear regression model for ER*:

$$ER = (R_b * GWL + \beta * LAI) * (47.9 / (1 + \exp(106 / (T_{air} + 18.3))$$

Where, R_b is the parameter relates to basal soil respiration, β is the scaling parameter for LAI, T_{ai} is the air temperature (^{0}c) during the chamber enclosure.

Coefficients	Estimate	SE	T-Stat	P-value
R_b	4.98	0.39	12.65	3.6456^{-21}
β	4.76	4.30	1.10	0.27

* Number of observations: 86, Error degrees of freedom: 84, Root Mean Squared Error: 112, R-Squared: 0.769, Adjusted R-Squared 0.767, F-statistic vs. zero model: 874, p-value = $5.94e^{-57}$.

Appendix 5. Fitted parameters for the rectangular hyperbola function (model).

GPP_{max} is the asymptote of the light response (μg CO_2 m^{-2} s^{-1}) and α is the initial slope (μg CO_2 μmol $^{-1}$ photon).

GPP-coefficient	Plot 1	Plot 2	Plot 3	Plot 4
α	1.54	2.38	1.41	3.25
GPP_{max}	1880.31	687.10	814.66	822.26

Appendix 6.

Plot 1 = Naturally wet, Plot 2 = Controlled wet, Plot 3 = Controlled dry, Plot 4 = Naturally dry.

Correlations

	GPP_Plot1	ER_lot1	GPP_lot2	ER_Plot2	GPP_Plot3	ER_Plot3	GPP_Plot4	ER_Plot 4
GPP_Plot1	1	-.571**	.968**	-.581**	.992**	-.467**	.965**	-.669**
ER_Plot1	-.571**	1	-.517**	.985**	-.567**	.935**	-.546**	.957**
GPP_Plot2	.968**	-.517**	1	-.507**	.979**	-.368**	.996**	-.637**
ER_Plot2	-.581**	.985**	-.507**	1	-.573**	.951**	-.532**	.951**
GPP_Plot3	.992**	-.567**	.979**	-.573**	1	-.441**	.978**	-.672**
ER_PLOT3	-.467**	.935**	-.368**	.951**	-.441**	1	-.394**	.855**
GPP_PLOT4	.965**	-.546**	.996**	-.532**	.978**	-.394**	1	-.659**
ER_PLOT4	-.669**	.957**	-.637**	.951**	-.672**	.855**	-.659**	1

**. Correlation is significant at the 0.01 level (2-tailed).