Greenhouse gas exchange of organic soils in Northwest Germany

Effects of organic soil cultivation, agricultural land use and restoration

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α	Lichtnutzungeffizienz (*light use efficiency*)
AFOLU	*Agriculture, Forestry and other Land Use*
C	Kohlenstoff (*carbon*)
$CaCO_3$	Kalziumkarbonat (*calcium carbonate*)
CCM	*Corn cob mix*
CH_4	Methan (*methane*)
CO_2	Kohlendioxid (*carbon dioxide*)
C_{org}	Organischer Kohlenstoff (*organic carbon*)
Cv	Koeffizient der Variabilität (*coefficient of variability*)
DIC	Ungelöster anorganischer Kohlenstoff (*dissolved inorganic Carbon*)
DOC	Ungelöster organischer Kohlenstoff (*dissolved organic Carbon*)
E_0	Aktivierungsenergie-Parameter (*Activation energy like parameter*)
EC	Eddy Kovarianz (*Eddy Covariance*)
ECD	Elektroneneinfangdetektor (*electron capture detector)*
EF	Emissionsfaktor (*emission factor*)
FID	Flammenionisationsdetektor (*flame ionization detector*)
GHG, THG	Treibhausgas (*greenhouse gas*)
GM	Anmoorgley (*histic gleysol*)
GP_{max}	Max. C-Aufn. bei unendlicher PAR (*max. rate of C fix. at PAR infinite*)
GPP	Brutto Primär Produktion (*gross primary production*)
GWP	Globales Erwärmungspotential (*global warming potential*)
HH	Hochmoor (*bog*)
HN	Niedermoor (*fen*)
LAI	Blattflächen-Index (*leaf area index*)
Lf	Elektrische Leitfähigkeit (*electrical conductivity*)
LULUCF	*Land use, land use change and forestry*
N	Stickstoff (*nitrogen*)
NECB	Netto Ökosystem Kohlenstoff Bilanz (*net ecosystem carbon balance*)
NEE	Netto Ökosystem Austausch (*net ecosystem exchange*)
NH_4^+	Ammonium (*ammonium*)
Nmin	Mineralisierter Stickstoff (*mineralized nitrogen*)
NO_3^-	Nitrat (*nitrate*)
N_2O	Lachgas (*nitrous oxide*)
p	Signifikanzwert (*p-value*)
PAR	Photosynthetisch aktive Strahlung (*photosynthetic active radiation*)
Ppb	Teile pro Milliarde (*parts per billion*)
Ppm	Teile pro Million (*parts per million*)
PV	Porenvolumen (*pore volume*)
RCG	Rohrglanzgras (*reed canary grass*)

R_{eco}	Ökosystem Respiration (*ecosystem respiration*)
R_{ref}	Respiration bei der Referenztemp. (*respiration at the reference temp.*)
SB	Sommergerste (*spring barley*)
SOC	Organischer C im Boden (*soil organic C*)
s_{yx}	Standardabweichung der Residuen (*standard deviation of the residuals*)
VGA	*vascular green area*
wl	Wasserpegel über Geländeoberfläche (*water level above ground surface = water table above ground surface*)
wfps	Wassergefülltes Porenvolumen (*water filled pore space*)

1 Einleitung

1.1 Klimarelevante Gase aus Mooren

Die globale Temperatur ist innerhalb eines Zeitraums von 100 Jahren (1906 bis 2005) um 0,74 °C angestiegen. Seit den siebziger Jahren ist eine noch stärkere Zunahme zu verzeichnen: Innerhalb von 30 Jahren ist die Temperatur um ca. 0,55 °C angestiegen (IPCC 2007). Auch Menge, Intensität, Häufigkeit und Art der Niederschläge ändern sich seither (IPCC 2007). Der Klimawandel steht im Zusammenhang mit der anthropogen verursachten Zunahme der Treibhausgas-Konzentrationen: Während der vergangenen 10.000 Jahre bis zur Industrialisierung (Mitte des 18. Jahrhunderts) lag die CO_2-Konzentration bei 280 +/- 20 ppm. Seitdem findet eine exponentielle Zunahme statt. Im Jahre 2005 wies die Atmosphäre eine CO_2-Konzentration von 379 ppm auf (IPCC 2007). Die Methan-Konzentration schwankte zwischen 400 und 700 ppb während der vergangenen 500.000 Jahre. Seit dem 19. Jahrhundert stieg die Konzentration an und lag 1998 bei 1.745 ppb und 2005 bei 1.774 ppb. Dieser Peak ist eindeutig anthropogen verursacht (IPCC 2007). Vor der Industrialisierung betrug die N_2O-Konzentration 180-260 ppb. Im Jahre 1998 wurde eine Konzentration in Höhe von 314 ppb und im Jahre 2005 von 319 ppb festgestellt (IPCC 2007). Der Anstieg der CO_2-Konzentration hat einen Anteil von ca. 70 % am anthropogen verstärkten Treibhauseffekt bis heute. Methan und Lachgas tragen ca. zu jeweils 24 % und 6 % bei (Houghton 2004).

Eine signifikante Rolle im globalen Kohlenstoff- und Stickstoff-Kreislauf spielen Moore. Moore bestehen aus Torflagern, die durch Kohlenstoffakkumulation aufgebaut werden und sind damit wichtige Kohlenstoffspeicher. Aufgrund der anaeroben Bedingungen findet eine verlangsamte Mineralisation statt, und die Stoffbilanz ist dauerhaft positiv (Göttlich 1990, Succow & Joosten 2001). Moore bedecken nur ca. 3 % der Landoberfläche, speichern aber schätzungsweise 20 bis 30 % der weltweiten terrestrischen Kohlenstoff- und Stickstoffvorkommen und sind damit der größte terrestrische organische Kohlenstoffspeicher (Augustin & Merbach 1996, Drösler et al. 2011). 202 bzw. 550 Pg C sind weltweit in Mooren gespeichert (Post et al. 1982, Drösler et al. 2011). Allein in borealen und subarktischen Mooren sind 270 bis 455 Pg C gespeichert (Gorham 1991, Turunen et al. 2002). In der Atmosphäre befinden sich 700 Pg C (Munk 2001). Da der Kohlenstoff in Form von Kohlendioxid der Atmosphäre entzogen wird, sind Moore bedeutende CO_2-Senken. Auf der anderen Seite wird ein sehr kleiner Teil als Methan an die Atmosphäre abgegeben. Methanogene Bakterien bilden Methan aus Kohlenstoffverbindungen unter anaeroben

Bedingungen. Im aeroben Milieu wird CH_4 durch methanotrophe Bakterien zu CO_2 oxidiert (Munk 2001). Da der Wasserpegel in natürlichen Mooren bis nahe der Geländeoberfläche ansteht, wird kaum oder kein CH_4 oxidiert und folglich an die Atmosphäre abgegeben.
Entwässerte Moore dagegen stellen große CO_2- und N_2O-Quellen dar. Unter aeroben Bedingungen werden die Kohlenstoffverbindungen verstärkt mineralisiert und es entstehen CO_2 und H_2O. N_2O bildet sich hauptsächlich als Nebenprodukt der Nitrifikation und als Zwischenprodukt der Denitrifikation (Firestone & Davison 1989, Schlesinger 1997, Maljanen et al. 2003, Höper 2007). Stickstoffdünger tragen ebenfalls zu N_2O-Emissionen bei (Chadwick et al. 2000, Flessa & Beese 2000, Couwenberg 2009, Couwenberg 2011, Jassal et al. 2011).
Die Treibhauswirkung ist je nach Treibhausgas unterschiedlich und kann im globalen Erwärmungspotential (*global warming potential* = GWP) relativ zum Referenzgas CO_2 in CO_2-Äquivalente (CO_2-Äq.) ausgedrückt werden (IPCC 2007). Da die Gase unterschiedliche Lebensdauer haben, wird das GWP für verschiedene Zeitfenster (20, 100 und 500 Jahre) berechnet (IPCC 2007).

In der Bundesrepublik Deutschland ist fast die gesamte Moorfläche (14.000 bis 18.000 km²) entwässert und wird landwirtschaftlich oder für den Torfabbau genutzt (Höper 2007, Drösler et al. 2011). Das hat zur Folge, dass große Mengen an Treibhausgasen aus Mooren freigesetzt werden. Drösler et al. (2011) schätzen die Emissionen klimarelevanter Gase der Moore auf 5,1 % der gesamten nationalen Treibhausgasemissionen. Die Bundesrepublik Deutschland ist mit 12 % der zweitgrößte Emittent klimarelevanter Gase aus Mooren in Europa, obwohl nur 3,2 % der europäischen Moore in der Bundesrepublik Deutschland liegen (Byrne et al. 2004, Drösler et al. 2008).
Seit den achtziger Jahren werden in der Bundesrepublik Deutschland zunehmend entwässerte Moorflächen zum Schutz von Biotopen, seltenen Arten und der Biodiversität sowie zur Verbesserung des regionalen Tourismus wiedervernässt; aktuell spielt vor allem der Klimaschutz eine bedeutende Rolle (Höper & Blankenburg 2000, Gorham & Rochefort 2003, Höper et al. 2008).
Niedersachsen gehört zu den moorreichen Bundesländern. Ca. 10 % (4.200 km²) sind von Mooren bedeckt. Die Menge des akkumulierten Kohlenstoffes entspricht dagegen etwa 50 % des gesamten in Böden gespeicherten Kohlenstoffes (Höper 2007).

1.2 Verbundprojekte

Diese Dissertation entstand im Rahmen des vTI-Projektes „Organische Böden“ und zum Teil im Rahmen des BMBF-Projektes „Klimaschutz-Moornutzungsstrategien“ im Landesamt für Bergbau, Energie und Geologie (LBEG), Hannover.

Das „Verbundvorhaben: Klimaberichterstattung ‚Organische Böden‘ – Ermittlung und Bereitstellung von Methoden, Aktivitätsdaten und Emissionsfaktoren für die Klimaberichterstattung LULUCF/AFOLU“ war ein vom Thünen-Institut (TI), Braunschweig, gefördertes bundesweites Verbundprojekt mit einer Projektlaufzeit von Januar 2009 bis Dezember 2012. Insgesamt sind zehn Testgebiete (TG) in Nord- und Süddeutschland eingerichtet worden, die von verschiedenen Projektpartnern bearbeitet wurden (Abb.1.1). Das Verbundvorhaben baut auf das Projekt „Klimaschutz-Moornutzungsstrategien“ auf. Das Ziel ist die Schaffung der fehlenden Grundlagen für die Klimaberichterstattung „Organische Böden“ in den Berichtskategorien Landwirtschaft (Sektor 4) und Landnutzung, Landnutzungsänderung und Forstwirtschaft (Sektor 5). Aus verwaltungstechnischen Gründen konnte beim LBEG in Hannover erst im September 2009 mit der Untersuchung begonnen werden. Im LBEG wurde im Modul 2 („Emissionsfaktoren“) das Teilprojekt „Erfassung des Spurengasaustauschs in den TG 7 (Leegmoor-Westermoor) und 2 (Dümmer) bearbeitet. Die Zielsetzung lag in der Ermittlung von Emissionsfaktoren der Treibhausgase Kohlendioxid, Methan und Lachgas für die in Nordwestdeutschland relevanten Moorflächen.

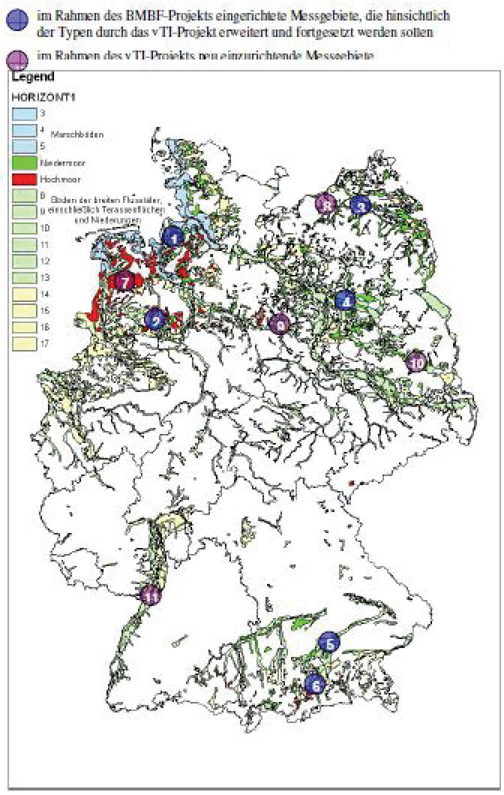

Fig. 1.1: Lage der Testgebiete. 1-6: BMBF-Projekt. 7-11: neu hinzugekommen im vTI-Projekt (Drösler 2008).

Das vom Bundesministerium für Bildung und Forschung gefördete bundesweite Verbund-Projekt „Klimaschutz-Moornutzungsstrategien“ war das Vorläuferprojekt und hatte eine Projektlaufzeit von Juli 2006 bis Juni 2010. Für die Dissertation wurden Daten aus dem TG 2 (Dümmer) verwendet.

1.3 Rahmenübereinkommen der Vereinten Nationen über Klimaänderungen

Die Bundesrepublik Deutschland hat sich als Unterzeichner des Rahmenübereinkommens der Vereinten Nationen über Klimaänderungen (englisch: *United Nations Framework Convention on Climate Change*, UNFCCC) im Jahre 1992 verpflichtet, regelmäßig über nationale Treibhausgasemissionen zu berichten. Mit der Unterzeichnung des Kyoto-Protokolls ist die Bundesrepublik gehalten, die nationalen Treibhausgasemissionen zu reduzieren. Das Kyoto-Protokoll ist ein internationales Abkommen in Verbindung mit dem Rahmenübereinkommen der Vereinten Nationen über Klimaänderungen, welches im Dezember 1997 verabschiedet wurde und im Februar 2005 in Kraft trat. Eine Nichtbeachtung der Verpflichtungen kann sanktioniert werden.

Treibhausgase aus organischen Böden werden in den Sektoren Landwirtschaft (Sektor 4) und Landnutzung, Landnutzungsänderung und Forstwirtschaft (Sektor 5) des nationalen Inventarberichts berichtet. Die entscheidenden Treibhausgase dieser Sektoren sind CO_2, N_2O sowie CH_4 (IPCC 2006). Die Landnutzungskategorien sind in den IPCC (2006) Leitlinien (*Guidelines*) festgeschrieben: Wälder, Ackerland, Grünland, „Feuchtgebiete“ (*wetland*), Siedlungen und sonstiges Land. Eine Differenzierung nach Bodentyp (innerhalb der organischen Böden) wurde nicht vorgenommen. Aber eine feinere Unterteilung der Kategorien wird als „gute Praxis“ (*good practice*) bezeichnet, falls die Kohlenstoffverluste signifikante Unterschiede zeigen. Des Weiteren ist es „gute Praxis“, landesspezifische Emissionsfaktoren zu verwenden (IPCC 2006). Entwässerte organische Böden stellen die größte nationale Einzelquelle für Treibhausgase außerhalb des Energiesektors dar. Damit gehören diese Kategorien zu den Hauptkategorien (*key categories*). Gleichzeitig stellen organische Böden die größte Unsicherheit im nationalen Treibhausgasinventar dar. Die Bundesrepublik Deutschland ist derzeit nicht in der Lage, für die Sektoren vier und fünf regelgerecht zu berichten, da sowohl Aktivitätsdaten als auch Emissionsfaktoren für die genannten Kategorien unvollständig sind. In diesem Zusammenhang ist es auch problematisch, dass die Definition von Moor nach der bodenkundlichen Kartieranleitung (AG Boden 2005) nicht mit der Definition von „organischen Böden“, die im Treibhausgasinventar verwendet wird, übereinstimmt (s. 1.6). Im aktuellen Treibhausgasinventar (UBA 2012) wird auf entsprechenden Verbesserungsbedarf hingewiesen (Tab.1.1).

Tab. 1.1: Zusammenfassung und Status der in den Quellgruppenkapiteln des Treibhausgasinventars (NIR) genannten geplanten Verbesserungen (UBA 2012). EF: Emissionsfaktor

Kategorie	Kategorie Bezeichnung	Einzelziel	Handlungsbedarf	STATUS	Quell-verweis
5.B, 5.C	Acker, Grünland *(cropland, Grassland)*	Organische Böden: Treibhausgasmessungen zur Verbesserung bzw. Validierung der nationalen Emissionsfaktoren: laufendes Forschungsprojekt.	Mit Hilfe von Treibhaus-gasmessungen sind die nationalen Emissionsfaktoren für organische Böden zu verbessern bzw. zu validieren.	offen	NIR Kap. 7.3.8
5.B; 5.C; 5.D	Acker, Grünland, Feuchtgeb.	Neue, nach Bodentyp und Nutzung differenzierte Emissionsfaktoren für organische Böden	Ermittlung differenzierter EF für organische Böden.	offen	NIR Kap. 7.3.8, 7.4.8, 19.5.2.6
5.D	Feucht-gebiete (*wetlands*)	Für die Kategorie Feuchtgebiete (*wetlands*) wird angestrebt landesspezifische Emissionsfaktoren für die THG CO_2, N_2O und CH_4 aus dem Torfabbau zu ermitteln. Diesbezüglich werden im Rahmen des Projektes „Organic Soils— Messungen vorgenommen, die alle Phasen dieser Wirtschaftsmethode umfassen (vergl. Kapitel 19.5.2.6). Die Ergebnisse werden zur Parametrisierung und Validierung mathematischer Modelle verwendet, bzw. zur Ermittlung landesspezifischer, regionaler Defaultfaktoren. Die Ergebnisse dieses Projektes sollen, sobald verfügbar, in die nationale Berichterstattung einfließen.	Die Ergebnisse aus dem Vorhaben (s. Einzelziel) sind in das Inventar einzuarbeiten.	offen	NIR Kap. 7.5.8

Als „Emissionslücke“ (*emissions gap*) wird die Differenz zwischen den Emissionen, die konsistent mit den Klimazielen sind, und den tatsächlichen Emissionen, wenn die Zusagen und Verpflichtungen der Staaten eingehalten werden (UNEP 2013), bezeichnet. Das festgelegte Ziel, dass der Temperaturanstieg nicht mehr als 2 °C im Vergleich zum vorindustriellen Niveau betragen soll, wird bei den bis zum Jahr 2020 beschlossenen Maßnahmen voraussichtlich nicht eingehalten werden; die „Emissionslücke“ in 2020 wird also nicht geschlossen sein. Somit besteht weiterer Handlungsbedarf. Wenn die „Emissionslücke“ bis 2020 nicht geschlossen wird, sind höhere Kosten zur Erreichung des 2 °C-Ziels zu erwarten (UNEP 2013).

1.4 Stand der Forschung / Forschungsbedarf

Die bisher veröffentlichten Zahlen über den Austausch von Kohlenstoff sowie der klimarelevanten Gase Kohlendioxid, Methan und Distickstoffoxid in organischen Böden variieren sehr stark. Belastbare Zahlen für die Emissionen sowohl aus entwässerten als auch aus natürlichen und wiedervernässten Mooren sind kaum vorhanden. Die Gründe hierfür können sowohl methodisch als auch standortspezifisch bedingt sein.

So gibt es beispielsweise nur wenige ganzjährige Messungen der CO_2-, CH_4- und N_2O-Austauschraten in Mooren. Viele Untersuchungen konzentrieren sich auf den Sommer. Für eine vollständige jährliche Bilanz sind jedoch auch die Flussraten in der kühleren Jahreszeit mitzurechnen.

Die Bilanzen der drei Gase Kohlendioxid, Methan und Lachgas können von Jahr zu Jahr stark schwanken, das trifft besonders auf den NEE zu. Nur wenige Untersuchungen wurden über mehrere Jahre durchgeführt. Es sind also Messungen über einen Zeitraum von mehreren Jahren notwendig, um repräsentative Bilanzen zu erhalten (Byrne et al. 2004, Drösler et al. 2008).
In den meisten Studien wurde nur der Austausch von ein oder zwei Gasen gemessen und keine vollständige Bilanz des globalen Erwärmungspotentials erstellt (Drösler et al. 2008). Um eine komplette GWP-Bilanz zu erstellen, müssten alle drei Gase (CO_2, CH_4, N_2O) berücksichtigt werden.
Hinzu kommt, dass unterschiedliche Methoden verwendet wurden. In vielen Untersuchungen wurde der Gasaustausch nicht direkt gemessen, sondern aus Höhenverlust- oder Torfakkumulationsraten ermittelt (Höper 2007, Höper & Blankenburg 2000).

Da sowohl die Bodentypen der organischen Böden als auch die Nutzungsvarianten (Ackerbau, Grünland, Abtorfung, Wiedervernässung, naturnaher Zustand) sehr unterschiedliche Emissionsfaktoren und damit stark abweichende GWP-Bilanzen aufweisen können, sind Messungen auf allen Kombinationen aus Moortypen und Nutzungsvarianten notwendig. Hier gibt es weltweit noch erhebliche Lücken.
Stabilste Emissionsfaktoren sind bisher für Grünland auf Niedermoor zu verzeichnen. Daten über den Gasaustausch von Hoch- und Niedermooren anderer Nutzungsvarianten, wie

Ackerland, Torfabbau, verlassene Torfabbauflächen und wiedervernässte Torfabbauflächen liegen kaum vor und sind daher notwendig (Byrne et al. 2004, Höper 2007).

Untersuchungen über den Gasaustausch in Mooren wurden bislang vor allem in borealen Gebieten vorgenommen (Alm et al. 1997, Nykänen et al. 1998. Joiner et al. 1999, Tuittila et al. 1999), zum Beispiel im Rahmen der „Boreal Ecosystem-Atmosphere Study“ (Sellers et al. 1995). Auch in Europa wurden die meisten Messungen in den skandinavischen Ländern durchgeführt und überwiegend nur während des Sommers. Für den nicht untersuchten Zeitraum sind die Flussraten geschätzt oder modelliert worden, um jährliche Flussraten zu erhalten (Byrne et al. 2004).

In der Bundesrepublik Deutschland wurden Gasflüsse in Niedermooren unter anderem von Flessa et al. (1998), Meyer (1999), Sommer & Fiedler (2002) und Augustin (2003) durchgeführt, während in Hochmooren Studien von Drösler (2005) und Glatzel et al. (2008) veröffentlicht wurden. Seit 2011 werden die Ergebnisse des BMBF-Projektes „Klimaschutz-Moornutzungsstrategien“ veröffentlicht (Drösler et al. 2011, Beetz et al. 2013). Dies führte zu einer Verbesserung der Datenlage in der Bundesrepublik Deutschland. Allerdings fehlen Daten zu Emissionsfaktoren für sämtliche Nutzungsvarianten auf Anmoor. Des Weiteren liegen nach wie vor keine Daten über ackerbaulich genutzte Hochmoore vor, weder über Schwarzkulturflächen noch über Sandmischkulturflächen. Auch über den nationalen Torfabbau sind dringend Erhebungen zu den Emissionsfaktoren erforderlich.

Seit den achtziger Jahren werden zunehmend entwässerte Moorflächen renaturiert. Hier sind langfristige Untersuchungen notwendig, um das Potential zur Klimaentlastung und für den Einsatz als biologische Senke zu klären. Es gibt nur wenige Studien und langfristige Daten fehlen völlig. Vermutlich stellen sich Gasflüsse, wie sie in natürlichen Mooren stattfinden, erst nach langer Zeit ein (Augustin & Joosten 2007). Drösler (2005) stellte fest, dass nach zwölf Jahren Wiedervernässung eines ehemaligen Torfabbaugebietes in Bayern weiterhin CO_2 emittiert wurde. Eine Renaturierung durch Überflutung führt zu höheren CH_4-Emissionen (Drösler et al. 2008).

In Norddeutschland werden derzeit entwässerte organische Böden als Testflächen für *Sphagnum*-Farming („Paludikultur“) genutzt. Für diese Nutzungsvariante wurden bisher keine Untersuchungen über den Austausch klimarelevanter Gase und die Klimarelevanz durchgeführt.

Zu berücksichtigen ist auch, dass klimatische Unterschiede innerhalb der Bundesrepublik vorhanden sind. Somit lassen sich Ergebnisse aus Süddeutschland und Nordostdeutschland nur bedingt für Niedersachsen verwenden. Das Gasaustauschverhalten nordwestdeutscher

Moore lässt sich vermutlich eher mit Untersuchungen aus den Niederlanden vergleichen. Die niederländischen organischen Böden liegen ebenso wie die niedersächsischen organischen Böden im „nordwestmitteleuropäischen Regenmoor-Bezirk“ (Succow & Joosten 2001). Im deutschen Raum dieser Moorprovinz wurden bisher nur von Meyer (1999) und Beetz et al. (2013) sowie im Rahmen der Projekte „Klimaschutz-Moornutzungsstrategien“ und „Organische Böden“ Haubenmessungen der drei Gase CO_2, CH_4 und N_2O durchgeführt (s.u.). In den Niederlanden wurden unter anderem Messungen von Velthof et al. (1996), Langeveld et al. (1997), Van den Pol-van Dasselaar et al. (1999) und Dirks et al. (2000) durchgeführt.
In Leegmoor/Westermoor sind bisher keine Messungen durchgeführt worden. Im Dümmermoor wurden bereits mit der Haubenmethode CO_2-Emissionen durch heterotrophe Respiration sowie CH_4- und N_2O-Flussraten auf vegetationsfreien Messplots ermittelt (Meyer 1999). Nettoökosystemaustauschraten (CO_2) sowie CH_4- und N_2O-Austauschraten, bei der das gesamte Ökosystem, also auch die Vegetation mit einbezogen wird, fehlen bisher für Moore in ganz Niedersachsen.

Für die nationale Berichterstattung gemäß Rahmenübereinkommen der Vereinten Nationen über Klimaänderungen steht nur ein unzureichender Datensatz zur Verfügung, aus dem Emissionsfaktoren gebildet werden. Damit ist die Bundesrepublik Deutschland derzeit nicht in der Lage, regelgerecht über Emissionen organischer Böden zu berichten. Es sind direkte Messungen des Austausches klimarelevanter Gase notwendig. Da die deutsche Definition von „Moor“ nicht mit der Definition in der nationalen Berichterstattung „organischer Böden“ übereinstimmt, wird ein Teil der organischen Böden nicht berücksichtigt, dies verstößt gegen die Regeln. Im Treibhausgasinventar (UBA 2012) werden innerhalb der organischen Böden nur Emissionsfaktoren in Abhängigkeit der Nutzung aufgeführt. Unklar ist, ob die Emissionsfaktoren im Treibhausgasinventar auch nach Klima, Hydrologie und Bodentyp (der organischen Böden) zu differenzieren sind.

1.5 Zielsetzung / Fragestellung

Ziel dieser Arbeit ist die Quantifizierung der Kohlendioxid-, Methan- und Lachgas-Flussraten in verschiedenen niedersächsischen Ökosystemen organischer Böden und die Bestimmung der entscheidenden Einflussfaktoren auf den Gasaustausch. Darauf aufbauend wird der Einfluss auf das Klima und die Kohlenstoffbilanz bestimmt. Dabei sollen alle für Nordwest-Deutschland relevanten Kombinationen aus organischem Bodentyp und Nutzungstyp abgedeckt werden. Darunter sind auch organische Bodentypen und Nutzungstypen, die bisher nicht auf den Austausch klimarelevanter Gase untersucht wurden. Die saisonalen und jährlichen Gasflussraten der Untersuchungsflächen werden verglichen, um die unterschiedlichen Boden- und Nutzungstypen hinsichtlich ihrer Klimarelevanz zu bewerten und um zu klären, welche Maßnahmen zur Verringerung von Treibhausgas-Emissionen und in Bezug auf die Kohlenstoffbilanz sinnvoll sind. Die Arbeit dient auch der Weiterentwicklung und Verbesserung einer zeitlich hochaufgelösten Gasflussberechnung und -modellierung.

Das übergeordnete Ziel ist die Bestimmung von Emissionsfaktoren in Abhängigkeit von Klima, Bodentyp, Nutzung und Nutzungsintensität, um die Sektoren Landwirtschaft (Sektor 4) und Landnutzung, Landnutzungsänderung und Forstwirtschaft (Sektor 5) des Nationalen Inventarberichts zum Deutschen Treibhausgasinventar mit Daten zu versorgen. Die Ergebnisse sollen Entscheidungshilfen für die Politik und für die Durchführung von klimafreundlichen Moorschutzmaßnahmen liefern.

Kapitel zwei bis fünf bilden das Kernstück der Dissertation und sind in einem kumulativen Ansatz verfasst. Die Kapitel sind nach Standorten differenziert und werden in gekürzter Form in internationalen Fachzeitschriften publiziert. Entsprechend sind diese vier Abschnitte in sich geschlossen und in englischer Sprache verfasst. Die bisher fertiggestellten Publikationen sind als Anlage angehängt. Als sechstes Kapitel folgt eine Synthese, in der eine Metadaten-Analyse erfolgt. Die Fragestellungen der fünf Kapitel lauten:

Kapitel 2 (*Four years of greenhouse gas flux measurements on a temperate fen soil used for cropland or grassland*):

- Wie hoch sind Treibhausgasemissionen aus Niedermooren, die als Acker oder Grünland genutzt werden?
- Welche Einflussfaktoren spielen hierbei eine Rolle?
- Welche Maßnahmen können empfohlen werden, um die Emissionen zu verringern?

Kapitel 3 (*Greenhouse gas emissions from agriculturally used organic soils in Lower Saxony*):

- Wie hoch sind Treibhausgasemissionen aus Hochmoor-Sanddeckkultur und Anmoorgley-Sanddeckkultur im Vergleich zu Hochmoor-Schwarzkultur?
- Wie hoch sind Treibhausgasemissionen aus Ackerland im Vergleich zu Grünland?
- Welche Einflussfaktoren bestimmen die Gasflussraten?
- Welche Maßnahmen können empfohlen werden, um die Emissionen aus landwirtschaftlich genutzten organischen Böden zu verringern?

Kapitel 4 (*Greenhouse gas emissions from restored bogs in North Germany*):

- Wie hoch ist der Treibhausgasaustausch 30 Jahre nach Wiedervernässung?
- Wie ist der Treibhausgasaustausch im Vergleich zu natürlichen Mooren zu bewerten?
- Wie ist das GWP von wiedervernässten Mooren für den Anbau von Sphagnum im Vergleich zu gewöhnlichen wiedervernässten Mooren?
- Welche Maßnahmen können empfohlen werden, um Emissionen zu verhindern bzw. die Aufnahme zu fördern und um Kohlenstoffakkumulation zu fördern?

Kapitel 5 (*Climate relevance of peat mining in Northern Germany*):

- Wie hoch sind die Treibhausgasemissionen aus Torfabbauflächen?
- Sind die Emissionen in den gemäßigten Breiten höher als in der borealen Zone?
- Wie hoch sind Emissionen von der Torfabbaufläche selbst im Vergleich zu den Gesamtemissionen durch Torfabbau?
- Welche Einflussfaktoren bestimmen die Gasflussraten?

Kapitel 6 (*Emission factors, carbon balances and global warming potentials of organic soils in Northern Germany, Synthesis*):

- Wie groß sind die Unterschiede zwischen den Emissionsfaktoren dieser Untersuchung und den Standardwerten des Nationalen Inventarberichts sowie des IPCC (2006)?
- Wie hoch ist der Emissionsfaktor deutscher Torabbauflächen?
- Sind die Gasaustauschraten der Bodentypen Hochmoor, Niedermoor und Anmoorgley ähnlich?
- Welchen Anteil haben die einzelnen Treibhausgase am GWP?
- Welches ist der Haupteinflussfaktor für das jährliche GWP organischer Böden?
- Stellen Paludi-Kulturen eine klimafreundliche Alternative zu konventionellen Landnutzungen dar?

1.6 Untersuchungsgebiete

Untersucht wurden zwei Moorgebiete im Westen Niedersachsens, die zum „nordwestmitteleuropäischen Regenmoor-Bezirk“ (Succow & Joosten 2001) gehören: Das Testgebiet zwei besteht aus einem Niedermoor am Dümmer, das Testgebiet sieben ist eines der größten Hochmoorkomplexe Deutschlands und befindet sich nahe der niederländischen Grenze (Abb.1.2). Das Klima ist gemäßigt und liegt im Übergangsbereich vom subozeanischen zum ozeanischen Klima (nach Troll & Paffen 1963: III. 1 b: Kühlgemäßigte Zone, Waldklima, Übergangsklimate; nach IPCC Klimazonen: *cool temperate moist* (IPCC 2006)). An der DWD-Klimastation Diepholz (2008) wurde im langjährigen Mittel (1961 bis 1990) eine mittlere Jahrestemperatur in Höhe von 8,9 °C und ein durchschnittlicher jährlicher Niederschlag in Höhe von 695 mm gemessen.

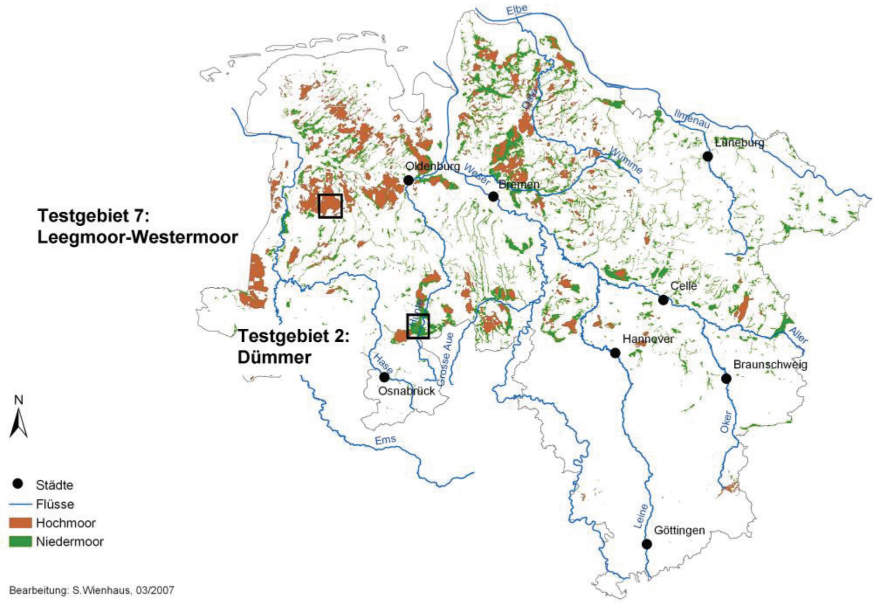

Fig. 1.2: Übersicht der in der Dissertation untersuchten Gebiete. (Karte: S. Wienhaus, LBEG 2007, verändert).

Das ca. 70 km^2 große Dümmermoor (Testgebiet 2, 52°30’N, 8°20’O), welches sich nördlich, südlich und südwestlich des Dümmers erstreckt und einen Teil der Dümmerniederung bildet, besteht zum größten Teil aus Niedermoor (Verlandungsmoore und Überflutungsmoore) und nur vereinzelt aus Hochmoor (Schneekloth & Schneider 1972, Dietrich et al. 2001). Die Torfarten sind meist stark zersetzte Erlen-, Bruchwald- und Seggentorfe, teilweise mit Schilfresten. Der 50 cm bis 2 m mächtige Niedermoortorf wird von Sand und (über dem

Sand) von einer bis zu einem Meter mächtigen meist kalkhaltigen Tonmudde und organogenen Mudde unterlagert (Schneekloth & Schneider 1972).

Das am Südrand des Niedermoorgebietes gelegene Ochsenmoor ist nach der bodenkundlichen Kartieranleitung (AG Boden 2005) nicht mehr als Moor anzusprechen, sondern als Anmoorgley (GM). In der ersten Hälfte des 20. Jahrhunderts sind großräumige Meliorationen durchgeführt worden, 1953 erfolgte die Eindeichung des Dümmers (Taux 1986). Heute wird fast das gesamte Gebiet als Grünland oder Acker landwirtschaftlich genutzt, natürliches Niedermoor und Forstflächen sind sekundär (Schneekloth & Schneider 1972). Seit den achtziger Jahren werden auf einigen Flächen Wiedervernässungsmaßnahmen durchgeführt.

Der 12,4 km^2 große und 37 m über NN gelegene Dümmer ist ein eutropher Flachwassersee und der zweitgrößte Binnensee Niedersachsens (Taux 1986, Meyer 1999, Liedtke & Marcinek 2002). Gespeist wird der Dümmer von der Hunte (Feibicke 2006). Die Vegetation besteht nach Taux (1986) in erster Linie aus Seggen, Röhrichten und Schwimmblattgesellschaften sowie Weidengebüsch und Erlenbruchwald an den Ufern.

Die Dümmerniederung entstand im Spätglazial infolge von Sackungen und Senkungen, die durch das „Austauen“ von Eislagen und -linsen ausgelöst wurden (Dahms 1977). Dadurch bildete sich ein flacher See. Nach Liedtke und Marcinek (2002) lösten spätglaziale Schwemmfächer in der Hunteniederung, die aus den Tälern der Dammer Berge aufgeschüttet wurden, ein Austreten des Grundwassers südlich der Aufschüttung aus, infolgedessen sich der See bildete (Abb.1.3).

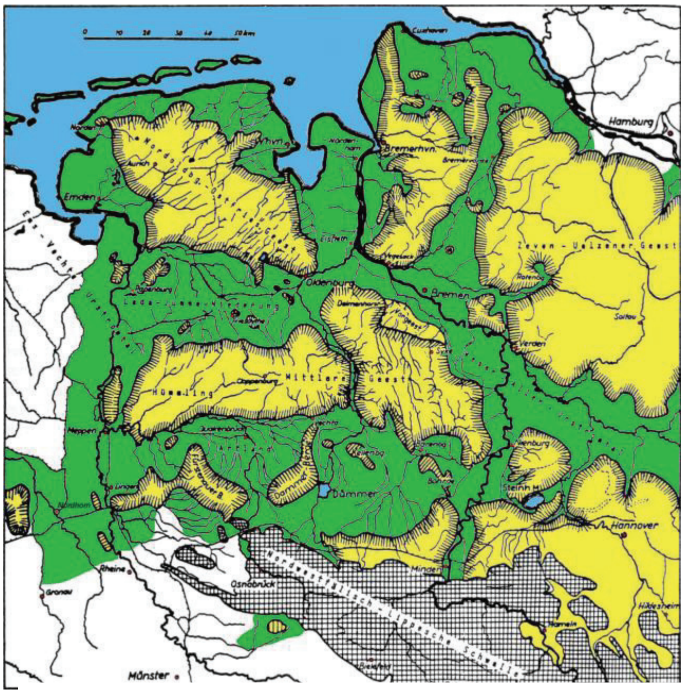

Fig. 1.3: Im Eiszeitalter geschaffene morphologische Einheiten in Nordwest-Niedersachsen (http://www.stadt-land-oldenburg.de/Karten/NW-Morphologie.JPG)

Im Spätglazial stieg der Wasserspiegel und die Fläche des Sees nahm zu. Durch Sedimentationsprozesse entstanden Ton- und Kalkmudden. Erst im Boreal erfolgte ein Zuwachsen des Sees durch Pflanzen und es entstanden die ersten Seggen- und Bruchwaldtorfe (Schneekloth & Schneider 1972, Dahms 1977). Im späten Boreal und frühen Atlantikum wurden Lebermudden abgelagert. Das

Atlantikum (ab ca. 5500 v. Chr.) ist durch starke Verlandung, Niedermoorbildung und Schrumpfung des Sees gekennzeichnet (Schneekloth & Schneider 1972, Dahms 1977). Seit ca. 2000 J. v. Chr. bilden sich Hochmoore (Schneekloth & Schneider 1972).

In Tabelle 1.2 sind die GPS-Koordinaten aller Untersuchungsflächen aufgelistet. Abbildung 1.4 zeigt Luftbilder der Untersuchungsflächen im Dümmermoor.

Tab. 1.2: GPS-Koordinaten der Untersuchungsflächen (GPS-Gerät: Garmin e Trex Legend)

Fläche	Links (O)	Hoch (N)
HN Acker	3451376	5820311
HN Grünland	3451378	5820299
GM Acker	3452766	5814216
GM Grünland	3452757	5814238
Leegmoor 1	3401786	5876082
Leegmoor 2	3401745	5876082
Leegmoor 3	3401743	5876082
Sanddeckkultur Acker	3402179	5874345
HH Acker	3402257	5874335
Torfabbau (neu)	3409439	5883068
Torfabbau (alt)	3409427	5882996
Sphagnum-Farming	3409434	5882999

Fig. 1.4: Untersuchungsflächen: a) HN Acker und HN Grünland, b) GM Acker und GM Grünland (Hintergrundkarte: http://www.bing.com/maps/)

Der Hochmoorkomplex Nordhümmlinger Moore (Testgebiet 7, 53°N, 7°32`O) liegt in der Hunte-Leda-Moorniederung, welches Teil des niedersächsischen Tieflandes ist. Dieses 111 km² große Areal ist eines der größten Hochmoorkomplexe Deutschlands. Die West-Ost-Erstreckung der Nordhümmlinger Moore beträgt 24 km, der Nord-Süd-Durchmesser 20 km. Im Süden wird das Gebiet durch den Hümmling (73 m ü NN) begrenzt, ein päriglaziales

Aufschotterungsgebiet, welches durch Solifluktion sowie Wasser- und Winderosion abgetragen und überformt wurde, so dass das Gebiet heute aus Geschiebedecksand, Flugsand und Dünen über glazifluviatilem Sand besteht (Jonas 1935, Eggelsmann & Blankenburg 1990).

Das Gebiet ist geprägt durch große Torfabbauflächen neben ehemaligen, inzwischen wiedervernässten Abbauflächen. Ein Teil des Areals wird landwirtschaftlich genutzt. Im südlichen Bereich, südlich des Küstenkanals, liegt das 449 ha große Leegmoor. Das Leegmoor liegt ca. 5 bis 10 m über NN und ist ein ehemaliges, anthropogen entstandenes Heidemoor (Jonas 1935, Eggelsmann & Blankenburg 1990). Ursprünglich war es vermutlich ein gewölbtes Hochmoor (Eggelsmann & Blankenburg 1990). Auf dem größten Teil der Fläche wurde Torf abgebaut. 1983 wurde das Leegmoor unter Naturschutz gestellt und abschnittsweise durch Anstauung der Gräben und Errichtung von Polderdämmen wiedervernässt (Eggelsmann & Blankenburg 1990). Da kaum Erfahrungswerte über die Wiedervernässung vorlagen, wurde das Erprobungs- und Entwicklungsvorhaben Leegmoor (E+E-Vorhaben) „Wiedervernässung abgebauter Schwarztorfflächen im Leegmoor“ gestartet. Im Nordteil des Leegmoores befindet sich ein wurzelechtes Hochmoor, während der südliche Bereich von Übergangs- und Niedermoortorfen unterlagert ist, hier begann die Moorbildung als Versumpfungsmoor.

Der Hochmoorkomplex entstand im Hunte-Leda-Urstromtal und am Nordrand des Hümmlings, einer überwiegend aus nährstoffarmen Quarzsanden aufgebauten Grundmoränenlandschaft der Saale-Eiszeit mit sehr geringem Gefälle (Abb.1.3). Die daraus resultierende mangelhafte Vorflut führte zu einer ausgedehnten Moorfläche. Ein Teil der Hochmoore entstand auf versumpftem Mineralboden (meist über Bruchwaldtorf) in Untergrundmulden im Grundwasserbereich. Wurzelechtes Hochmoor bildete sich über podsoliertem Feinsand auf Kuppen (Eggelsmann & Blankenburg 1990, Nick 1993). Vermutlich kam es zur Ausbildung älteren Hochmoortorfes (Schwarztorf) in der atlantischen Periode und jüngeren Hochmoortorfes (Weißtorf) während des Subatlantikums (Woldstedt 1950).

Erste menschliche Eingriffe fanden in der Form der Moorbrandkultur um 1710 statt. In der Folge breiteten sich *Calluna*- und *Erica*-Heiden auf den Flächen aus, die das Moor zu einem „Heidemoor“ konvertierten. Schafhaltung führte zu einer Düngung der Hochmoore. Der Schaftritt auf stark beweideten Flächen hatte eine Vermulmung und damit eine Deflation

(Erosion durch Wind) zur Folge. Auf einem Teil der Heidemoore wurden Heidesoden entnommen. Um 1950 begann die industrielle Abtorfung (Eggelsmann & Blankenburg 1990).

In Abbildung 1.5 sind Luftbilder der Untersuchungsflächen der Nordhümmlinger Moore zu sehen.

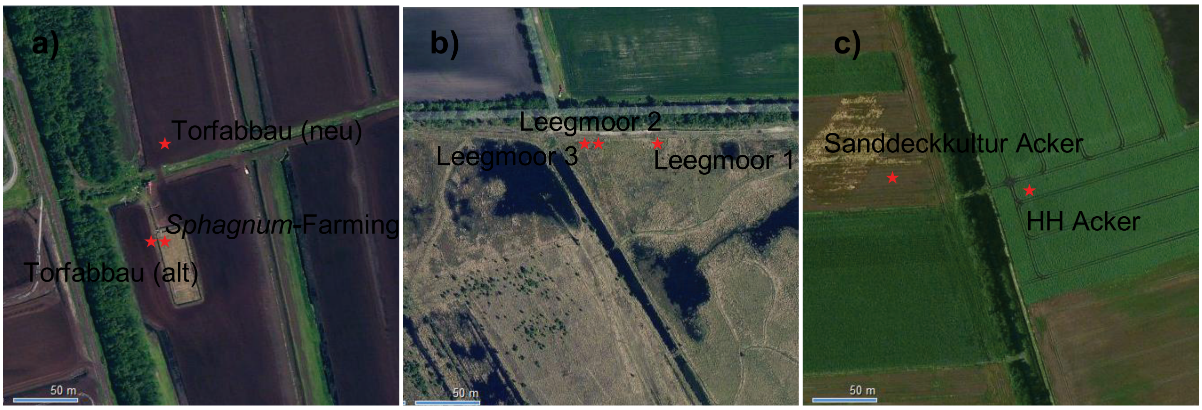

Fig. 1.5: Untersuchungsflächen: a) Torfabbau (neu), Torfabbau (alt) und *Sphagnum*-Farming, b) Leegmoor (wiedervernässte Flächen), c) Sanddeckkultur Acker und HH Acker (Hintergrundkarte: http://www.bing.com/maps/)

Im Anhang sind die Untersuchungsflächen photographisch festgehalten. Genauere Beschreibungen der einzelnen Untersuchungsflächen erfolgen in den nachfolgenden Kapiteln.

1.7 Wichtige Definitionen

Die folgenden Begriffe sind für das Verständnis dieser Arbeit entscheidend. Aufgrund der in der Literatur zum Teil nicht konsistent verwendeten Termini und um Konfusionen zu vermeiden, werden an dieser Stelle Definitionen aufgeführt, die für diese Arbeit gültig sind. Da die einzelnen Kapitel in englischer Sprache verfasst wurden, erfolgt die jeweilige englische Übersetzung in Klammern.

Anmoor (*peaty soil*): Als Anmoor werden Böden mit mind. 1 dm mächtigem Aa- (15 bis 30 Masse-% organischer Substanz) -Horizont bezeichnet (AG Boden 2005). Anmoore gehören teilweise zu den organischen Böden (*organic soils*). Anmoorgley (histic gleysol) ist ein Gleyboden mit hohem Anteil Rohhumus.

Brutto-Primär-Produktion (*gross primary production* = GPP): Die Brutto-Primär-Produktion ist die Kohlendioxidaufnahme durch Assimilation (Photosynthese) der Pflanzen und hat ein negatives Vorzeichen.

Emissionsfaktor (*emission factor*): Emissionsfaktoren sind repräsentative jährliche Gasaustauschraten zwischen organischen Boden und der Atmosphäre, differenziert nach Bodentyp und -management (Höper 2007).

Flussrate (*flux, exchange*): Hiermit ist die Gasaustauschrate zwischen Ökosystem (Pedosphäre und Biosphäre) und Atmosphäre gemeint. Bei einem positiven Vorzeichen ist die Flussrate eine Freisetzungsrate, bei einem negativen Vorzeichen handelt es sich um eine Aufnahmerate.

Globales Erwärmungspotential (= globales Treibhauspotential; *global warming potential* = GWP): Das globale Erwärmungspotential ist ein Index, mit dem angezeigt wird, wie viel ein Gas oder Gasgemisch relativ zu dem Gas Kohlendioxid zum Treibhauseffekt beiträgt, ausgedrückt in CO_2-Äquivalente (= CO_2-Äq.; *CO_2-equivalents* = *CO_2-eq.*). Da die Gase unterschiedliche „Lebenszeiten" haben, kann das GWP für verschiedene Zeiträume berechnet werden. GWP-Bilanz (*GWP balance*): Die Summe der gewichteten Gasflüsse werden in der GWP-Bilanz ausgedrückt.

Hochmoor (HH, *bog*): Als Hochmoore werden durch Regenwasser entstandene Moore bezeichnet (ombrogene bzw. ombrotrophe Moore bzw. Regenwassermoore).

Moor (*peatland*): Moore sind nach der bodenkundlichen Kartieranleitung (AG Boden 2005) „Böden aus Torfen (mindestens 30 Masse-% organische Substanz) von mindestens 3 dm Mächtigkeit (einschließlich zwischengelagerter mineralischer Schichten und Mudden mit einem Flächenanteil von weniger als 30 %)".

Natürliches Moor (*mire*): Mit einem natürlichen Moor ist ein Moor gemeint, das sich in einem Zustand befindet, der nicht (wesentlich) anthropogen modifiziert wurde oder wird, z.B. durch Änderung der Wasserstände sowie eine typische Vegetation aufweist. Ein naturnahes Moor bezeichnet ein Moor, welches in einem weitgehend natürlichen Zustand ist, aber anthropogen beeinflusst ist.

Netto-Ökosystem-Austausch (*net ecosystem exchange* = NEE): NEE = GPP + R_{eco}. Der NEE ergibt sich aus der Differenz zwischen CO_2-Aufnahme durch Assimilation und CO_2-Abgabe durch Dissimilation. Der NEE wird als jährliche oder monatliche Gasaustauschrate angegeben. In dieser Gasaustauschrate kann auch der jährliche Kohlenstoffexport durch Ernte und der jährliche Kohlenstoffinput durch Dünger enthalten sein (NEE inkl. importiertes/exportiertes C durch Dünger und Ernte).

Netto-Ökosystem-Kohlenstoff-Bilanz (*net ecosystem carbon balance* = NECB): Hierbei handelt es sich um die Nettorate des Kohlenstoffaustauschs zwischen Ökosystem und Atmosphäre. Es ist also die gesamte Kohlenstoffbilanz unter Berücksichtigung aller Quellen und Senken (physikalische, biologische und anthropogene) (Chapin et al. 2006). In dieser Arbeit sind neben dem NEE nur die kohlenstoffhaltigen Verbindungen Methan, gelöster anorganischer Kohlenstoff, gelöster organischer Kohlenstoff, Kohlenstoffexport durch Ernte und Kohlenstoffinput durch Dünger signifikant am Kohlenstoffaustausch beteiligt und werden deshalb berücksichtigt. Für den Austausch des gelösten anorganischen und gelösten organischen Kohlenstoffs wurden Literaturwerte herangezogen.

Niedermoor (HN, *fen*): Als Niedermoore werden durch Grundwasser entstandene Moore bezeichnet (topogene Moore bzw. minerotrophe Moore).

Ökosystem-Respiration (*ecosystem respiration* = R_{eco}): Die R_{eco} ist die Kohlendioxidabgabe durch Dissimilation (Atmung) und setzt sich aus autotropher Atmung durch Pflanzen (Wurzeln, Blätter, Holzgewebe) und heterotropher Atmung durch Bodenmikroorganismen zusammen (Lavigne et al. 1997). Flussraten durch Respiration werden mit einem positiven Vorzeichen versehen.

Organischer Boden (*organic soil*): Für organische Böden existieren zwei internationale Definitionen, die sehr ähnlich sind, aber nicht identisch. Beide Definitionen sind komplex:

a) Die Definition für organischen Boden bzw. *Histosol* der *World Reference Base for Soil Resources* (FAO 2006) umfasst Böden, die „organisches Material" (*organic material*) enthalten, entweder (a) in einer mind. 10 cm mächtigen Schicht zwischen Bodenoberfläche und Eis oder Gesteinsschicht (dessen Zwischenräume auch mit „organischem Material" gefüllt sind) oder (b) kumuliert innerhalb der oberen 100 cm des Bodens, entweder in einer mind. 60 cm mächtigen Schicht - wenn mind. 75 Volumen-% des Materials aus Moosfasern besteht - oder in einer mind. 40 cm mächtigen Schicht, die nicht mehr als 40 cm unterhalb der Bodenoberfläche ansteht.

„Organisches Material" entspricht dem deutschen Begriff „Torf", die Definitionen weichen aber voneinander ab. „Organisches Material" ist dadurch gekennzeichnet, dass es entweder (a) mind. 20 Masse-% organischen Kohlenstoff enthält oder (b) über einen Zeitraum von 30 Tagen in den meisten Jahren ununterbrochen wassergefüllt ist (außer im entwässerten Zustand) und entweder mind. 12 (+ Tonanteil der Mineralfraktion · 0,1) Masse-% organischen Kohlenstoff oder mind. 18 Masse-% organischen Kohlenstoff enthält.

b) Die Definition des *International Panel on Climate Change* (IPCC) ist angelehnt an die Definition des *World Reference Base for Soil Resources*, weicht aber leicht davon ab (IPCC 2006). Diese Definition wird im Treibhausgasinventar verwendet. Bei einem organischen Boden treffen entweder Kriterium 1 und 2, oder Kriterium 1 und 3 zu. Nach Kriterium 1 haben organische Böden einen „organischen Horizont" (*organic horizon*), der mind. 10 cm mächtig ist. Wenn der Horizont geringmächtiger als 20 cm und vermischt ist, müssen mind. 12 % organischer Kohlenstoff enthalten sein. Kriterium 2 besagt, dass Böden, die nicht mehr als für ein paar Tage wassergesättigt sind, mehr als 20 Gewichts-% organischen Kohlenstoff enthalten müssen (z.B. ca. 35 % organisches Material). Nach Kriterium 3 sind organische Böden zeitweise wassergefüllt und haben entweder (a) mind. 12 Gewichts-% organischen Kohlenstoff (z.B. ca. 20 % organisches Material), wenn der Boden keinen Ton enthält, oder (b) mind. 18 Gewichts-% organischen Kohlenstoff (z.B. ca. 30 % organisches Material), wenn der Boden mind. 60 % Ton enthält, oder (c) einen dazwischen liegenden Anteil an organischem Kohlenstoff bei dazwischen liegenden Tongehalten, proportional berechnet.

Quelle (*source*): Als Quelle wird ein Reservoir (Speicher) bezeichnet, welches einen Stoff an ein anderes Reservoir abgibt. Wenn der Boden eine Quelle ist, hat die jährliche Bilanz des entsprechenden Stoffes ein positives Vorzeichen.

Senke (*sink*): Eine Senke ist ein Reservoir (Speicher), welches einen Stoff aufnimmt, also ein Reservoir, welches an Zuwachs gewinnt.

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2 Four years of greenhouse gas flux measurements on a temperate fen soil used for cropland or grassland

Abstract

To date, there is still a lack of reliable data about fluxes of greenhouse gases and global warming potentials for drained fens to determine the climatic relevance and supply the National Inventory Report for the German Greenhouse Gas Inventory. In this study, flux rates of carbon dioxide, nitrous oxide and methane and global warming potentials for two drained agriculturally used fen ecosystems in Northern Germany (cropland and grassland) were achieved. The gas exchange was measured roughly monthly year-round with a closed chamber technique from June 2007 until December 2011. Transparent and opaque closed chambers were used, to separate ecosystem respiration and gross primary production, and to include the vegetation in the measurements, to factor the influence of the plants into the gas exchange. The CO_2 exchange was modelled at high resolution with site parameters with the measured and modelled values fitting very well together (R^2 = 95 at both sites). There is a strong correlation between model parameters and vegetation development. Net CO_2 emissions at the cropland and grassland site were similarly high, taking into account changes in management; net ecosystem exchange including carbon import and export amounted to 4,000 to 5,000 kg CO_2-C ha^{-1} a^{-1}. N_2O and CH_4 emissions were low at both sites. At the cropland site N_2O fluxes were observed after N-fertilizer application. The mean GWP100 balance amounted to about 16,000 to 19,000 kg CO_2-eq. ha^{-1} a^{-1}, taking into account changes in management. Gas fluxes were predominantly influenced by water level, water filled pore space and short-term changes in management. Because of inter-annual variation, measurements over several years are necessary.

2.1 Introduction

Peatland ecosystems (Histosols) are significant sinks for carbon and play an important role in the global carbon cycle. Worldwide peatlands cover about 3 % of the terrestrial landsurface, but store about 20 % of all terrestrial carbon (Post et al. 1982, Gorham 1991, Augustin & Merbach 1996, Turunen et al. 2002).

Peatlands in the temperate zone have been widely drained for agricultural use, e.g. as cropland or grassland (Couwenberg 2011), converting the sink into a source of CO_2: As soon as drainage takes place, the stored carbon is released through mineralisation and carbon dioxide is emitted into the atmosphere. But lowering the water level leads also to a decrease of methane emissions or even a small uptake of methane from the atmosphere, mainly because of accelerated oxidation of produced CH_4 by methanotrophic bacteria in the aerobic peat layer during transport (Christensen et al. 2003, Byrne et al. 2004, Drösler 2005).

Drainage may result in the release of high amounts of organically fixed nitrogen and nitrous oxide may emerge as a result of the nitrification and denitrification processes (Kasimir Klemedtsson et al. 2009). Production of nitrous oxide is especially favoured after fertilization, after thawing and under periodically wet conditions (Christensen & Christensen 1991, Paul et al. 1993, Flessa et al. 1998, Kaiser et al. 1998, Brumme et al. 1999, Meyer 1999, Chadwick et al. 2000, Flessa & Beese 2000, Kasimir Klemedtsson et al. 2009, Jassal et al. 2011). Thus, peatlands under agricultural use exhibit a disproportionate high percentage of the total agricultural nitrous oxide emissions, although the proportion of the total agricultural area is marginal (Flessa et al. 1998).

The flux rates of CO_2, CH_4 and N_2O are mainly driven by processes in the upper 25-30 cm of peat soil, thickness and composition of peat are less crucial (van den Bos & van de Plassche 2003a).

To determine the climatic relevance of the greenhouse gas exchange in a peatland, it is necessary to multiply the emission of each gas by the corresponding global warming potential (GWP), because each gas has an individual radiative forcing capability (IPCC 2007, Drösler et al. 2008).

In Germany, peatlands cover an area of approximately 13,648 km², about 75 % (10,434 km²) of which are fens (Höper 2007). Almost the entire fen area (95 %) is under agricultural use. For the last few centuries restoration programmes have been conducted, thus a small fraction

has been rewetted meanwhile (Höper & Blankenburg 2000). German fens and bogs contribute approximately 2-4.5 % to the national anthropogenic emissions of greenhouse gases, 80 % originating from fens. Agriculture is the main emitter with 75 % of total emissions from peatlands (Höper 2007, Drösler et al. 2008).
Germany is with 12 % the second largest emitter of greenhouse gases in Europe, although only 3.2 % of the European peatlands are located in Germany, because of intensive agricultural use (Byrne et al. 2004, Drösler et al. 2008).

Until today, data of GHG fluxes in German peatlands are not sufficient to determine both reliable annual balances as well as the climatic relevance of diverse peatland land use types (Byrne et al. 2004, Drösler et al. 2008, Couwenberg 2011).
To achieve the requirements for the sectors 4 (agriculture) and 5 (Land Use, Land Use Change and forestry) of the National Inventory Report for the German Greenhouse Gas Inventory these data are necessary.

The aim of this study is to compare the annual CO_2, CH_4 and N_2O balances of two drained agriculturally used fen ecosystems in Northern Germany (cropland and grassland) via flux measurements with closed chambers. It was hypothesized that both study sites emit high amounts of greenhouse gases, but that losses from the cropland site are higher because of more intensive use, involving N fertilization, tillage and cultivation of maize as a row crop.
The main questions of this research are: How high are GHG emissions from fens used as cropland and grassland? Which factors control the gas fluxes? Which measures can be recommended to reduce GHG emissions of agriculturally used fens?
This paper presents the results of continuous measurements over four and a half years resulting from two projects ("Klimaschutz-Moornutzungsstrategien" and "Organische Böden").

The chosen method to determine the gas flux rates, especially of CO_2, is frequently-used (Maljanen et al. 2010) and recently improved by Drösler (2005). The advantages are its ability to measure flux rates in a small scale environment, its suitability for field conditions and its low cost. The vegetation plays an important role in peat degradation processes and in soil-atmosphere gas exchange, but the function of the vegetation is not fully determined (Meyer 1999, van den Bos 2003, Drösler et al. 2008). The vegetation was included in the measurements and transparent and opaque chambers were used to yield the most appropriate estimates. To obtain annual balances modeling and interpolation were carried out. Additional field measurements were conducted to determine the driving parameters.

2.2 Methods

2.2.1 Site discription

The research area, Dümmer Peatland, is located in the southwest part of Lower Saxony in Germany (52.30°N latitude, 8.20° longitude, 37 m a.m.s.l.). In the approximately 70 km² minerotrophic fen area, situated basically west and southwest of Dümmer Lake, mainly 50 cm to 2 m thick strongly decomposed alder- and sedges-peats, partly with remnants of reed, emerged through siltation. Underneath resides calcareous clay gyttja and silt gyttja over sand. In a few places bogs developed on top of the fen. The 12.4 km² lake Dümmer is an eutrophic shallow lacustrine.

Today, almost the whole region is in agricultural use, since from the beginning of the 20th century large-scaled meliorations have been effected. In contrast, during the last 25 years in some areas of the fen rewetting has been carried out.

The Dümmer fen area developed during the last 7,500 to 8,500 years through siltation of the lake. Bogs began to emerge about 4,000 years ago (Schneekloth & Schneider 1972, Dahms 1977).

The area is situated in the temperate zone and has a 30-year (1961-1990) mean annual temperature of 8.9 °C and annual precipitation of 695 mm (DWD weather station Diepholz). The warmest month is July (16.9 °C) and the coldest month is January (0.9 °C). Total precipitation is quite evenly distributed among the twelve months of the year, with a maximum in June (70.7 mm) and a minimum in February (41.9 mm).

Measurements were carried out at two locations, west of Lake Dümmer. The two sites are classified as Eutric Histosols (German soil classification: Norm-Erdniedermoor (KVn), AG Boden 2005) and are in a degraded status. One site (cropland) has been under tillage to grow maize since 1969, previously it was used as grassland. Annual harrowing and ploughing, as well as occasional grubbing, takes place. The site was supplied with pig manure each year in spring. The number of maize plants per measurement collar varied between three and five.

Until 2006 silage maize was harvested; in 2007 the farmer switched to corn-cob-mix maize (CCM). Vegetation of the cropland site consists of *Echinichloa crus-galli* and *Chenopodium album* beside *Zea mays*. The other site (grassland) is located next to the cropland site and under low intensity grassland management with typical grassland-vegetation (*Lolium perenne, Festuca pratensis, Poa trivialis, Agrostis stolonifera and Rumex acetosa*). In spring 2008, the site was treated with a total herbicide and newly sowed. Until 2008 the grass was cut yearly, but left in the field. Since 2009, the grass has been harvested two to three times per year.

2.2.2 Measurements of site factors

Soil identification: The soil identification (peat substrate, soil horizon, substrate type), was conducted according to AG Boden (2005) in September 2010 in cooperation with the Humboldt-University Berlin. The decay degree was determined according to von Post-scale. Carbon and nitrogen was determined with an elemental analyser (Variomax C from Elementar) in the Humboldt-University Berlin. C and C_{org} was analysed according to DIN ISO 10694 (1994), N was analysed according to DIN ISO 13878 (1998).

True density (s): The soil samples for determination of true density (s) were taken in the depth of 0 to 10 and 10 to 20 cm, respectively in June 2011. True density was calculated according to Segeberg (1955) and Scheffer & Blankenburg (1992):

$$\text{True density (s) [g cm}^{-3}\text{]} = 0.00957 \cdot W_A + 1.44$$ **equation 1**

W_A = mineral content (ash) [%]

The mineral content was determined through heating to 550 °C in the drying oven (DIN 19684 1977, VDLUFA 1991).

Dry bulk density (ρt): Dry bulk density (ρt) was determined on intact soil cores (250 ml) for the surface horizon in June 2010 and March 2011 using this formula:

$$\rho t \text{ [g cm}^{-3}\text{]} = DM/V$$ **equation 2**

DM = dry mass [g]

V = volume of the sampling rings [250 cm^{-3}]

The soil samples were heated to 105 °C in the drying oven to determine the dry mass (VDLUFA 1991).

At the grassland site the dry bulk density determined in June 2010 was taken for the time period from April until September, and the value determined in March 2011 was taken for the time period from October until March.
At the cropland site a different procedure was chosen: From the date when soil cultivation took place until December, the value of the dry bulk density determined in June was taken, and from January until the date when soil cultivation took place, the value determined in March was used.

Dry bulk densities (ρt) for subsurface horizons were determined on tamped wet peat material in soil cores (VDLUFA 1991). For calculation of wet bulk densities (ρf) this formula was used:

$$\rho f\ [\mathrm{g\ ml^{-1}}] = E/V \qquad \textbf{equation 3}$$

E = weight (mass) of tamped soil [g]
V = volume of measuring vessel [250 ml]

Dry bulk densities (ρt) were calculated with this formula:

$$\rho t\ [\mathrm{g\ ml^{-1}}] = pf \cdot (DM/100) \qquad \textbf{equation 4}$$

DM = dry mass of soil [%]

Pore volume (PV): The pore volume (PV) was determined according to Kuntze et al. (1994):

$$PV\ [\mathrm{vol\%}] = (1 - (\rho t/s)) \cdot 100 \qquad \textbf{equation 5}$$

ρt = dry bulk density [g cm^{-3}]
s = true density [g cm^{-3}]

Nitrate and ammonium: With each CH_4 und N_2O flux measurement (September 2009 – December 2011) or every three months (July 2007 - August 2009), ten soil samples were taken with a boring rod for mineralised nitrogen (N_{min}-Bohrstock) in 0-20 cm depth and subsequently mixed. The analysis of nitrate and ammonium content was carried out in the laboratory of "Landwirtschaftliches Labor Dr. Janssen" with the continuous-flow-analyser. The compounds were extracted with a calcium chloride ($CaCl_2$) solution (VDLUFA 1991).

Gravimetric water content: To calculate the gravimetric water content of the same soil samples used for nitrate and ammonium analyses, the following equation was used:

$$gW\ [\%] = ((IW - OW) / OW) \cdot 100 \qquad \textbf{equation 6}$$

IW = initial weight of soil sample

OW = output weight of soil sample after drying in drying oven (105 °C)

Water filled pore space: The water filled pore space (wfps) is the relative fraction of water filled pores in the whole pore volume, and was calculated according to Teepe (1999):

$$wfps\ [\%] = 100 \cdot (gW \cdot \rho t) / PV \qquad \textbf{equation 7}$$

gW = gravimetric water content

ρt = dry bulk density

PV = pore volume

Meteorological parameters: Meteorological parameters (air and soil temperature at 2, 5 and 10 cm depth, photosynthetic active radiation (PAR), air pressure and precipitation) were recorded half hourly at a meteorological station on the grassland site. Soil temperatures for the cropland site were separately measured and saved half hourly with a datalogger (DN Messtechnik, Norderstedt) or corrected using temperature models. The temperature models are linear regressions between the data of the meteorological station and the measured values at the sites during the CO_2 gas flux measurements every four weeks.

Water level: Both sites were equipped with two meter tubes perforated in the peat body. Water level (wl) at the grassland site was measured during each gas measurement campaign with an electric contact gauge during the entire measurement period. At the cropland site the wl was measured with an electric contact gauge from March 2010 until October 2010 and continuously recorded every half hour using a Schlumberger MiniDiver from October 2010 until December 2011. Until February 2010 the data of the grassland site were also used for the cropland site.

Biomass: Sampling of aboveground biomass (cut by hand) was conducted during each CO_2 flux measurement campaign from three subplots.

In case of harvest, aboveground biomass was cut from the complete measurement collars: At the cropland site the biomass in the measurement collars were cut and collected shortly before harvest. Subsequently, the collars and boardwalks were removed to make way for the combine harvester. The samples were separated in harvested parts (cobs and corn) and the remaining plant (which was normally left in the field). At the grassland site the grass in the measurement collars was cut within few days before or after harvest. If the farmer left the grass in the field, we also left the grass inside the collars in a fairly homogenous way. In case of harvest, the cut grass in the collars was collected.

The samples were separated in green (living biomass) and brown (dead biomass) plantparts as well as green maize plants and brown maize plants. Dry matter was determined by drying the samples in a drying oven at a temperature of 105 °C for two days (until constant weight). Fresh and dry biomass was quantified using a laboratory balance.

Carbon import and export: In case of slurry application at the cropland site, the collars and boardwalks were removed to make sure that the slurry was distributed evenly through the fertilizer spreader. The amount of slurry applied was estimated by the farmer. A variation coefficient in spreading accuracy of less than 25 % was assumed (Frick 1999, Pöllinger 2006).

Carbon content of the dry biomass was assumed to be 45 % (KTBL 2005). C-export through harvest was calculated accordingly. C/N ratio and nitrogen content of slurry is 8 and 4 kg N t^{-1}, respectively (KTBL 2005). Thus, carbon content amounts to 32 kg C t^{-1} or 32 kg C m^{-3}.

2.2.3 Measurements and modeling of carbon dioxide exchange

For determination of CO_2 flux rates between the ecosystem (soil and vegetation) and the atmosphere a temperature controlled portable closed chamber technique was applied (Drösler 2005, Beetz et al. 2013). Net ecosystem exchange (NEE) was measured with transparent chambers (0.78 · 0.78 m, height: 0.5 m, 3 mm strong Plexiglas “XT type 20070”), ecosystem respiration (R_{eco}) with opaque chambers (PVC). NEE consists of gross primary production

(GPP) less R_{eco}. Fluxes from the soil-plant compartment to the atmosphere were provided with a positive sign (sign convention following IPCC 2007).

The bottom side has a closed cell rubber tube to ensure hermetic closure during the measurement. The chambers are equipped with a thermometer, a vent outlet with a rubber tube (length: 220 cm, inner diameter: 2 mm), a pair of turnable (3 V) fans, and is connected via a tube (length: 750 cm, inner diameter: 5 mm) with a portable CO_2 gas analyser (Licor LI-820; measures with non-dispersive infrared radiation; measurement of gas concentration every 5 sec.). In case of high solar radiation, thermal packs were placed on a bar inside the transparent chambers to avoid the increase of temperature of more than 1.5 °C during gas measurement within the chambers. If necessary, extensions were applied (max. 200 cm).

Each research plot was arranged with 3 collars (3 mm strong PVC, about 20 cm apart), on which the chambers were placed airtightly. To ensure minimal disturbance to the ecosystem, boardwalks were built.

Parallel to the gas exchange measurements, air temperature, soil temperature at 2, 5 and 10 cm depth (measured with inserting thermometers), PAR, wl and air pressure were measured. One gas flux measurement procedure lasted for one to four minutes. It was assured that the chamber was placed airtightly on the collar without disturbing or damaging the plants. At each site measurements started prior to sunrise and ended in the afternoon, in order to cover the entire daily range of PAR and temperatures. Per site and measurement campaign about 30 to 36 measurements with transparent and 15 to 18 measurements with opaque chambers were carried out. Generally, measurement campaigns were carried out every four weeks, starting July 2007 and ending December 2011. Additional measurements were conducted in case of management events (e.g. harvesting, tilling). The CO_2 gas analyser was calibrated in the laboratory before each measurement campaign with pure nitrogen (0 ppm CO_2) and synthetic air (390 ppm CO_2).

To calculate flux rates the change of gas concentration over time inside the chamber was determined and inserted in equation eight (according to Drösler 2005, Beetz et al. 2013). To ensure the quality and representativeness of the slope of gas concentration the following parameters were tested (only data from 9/2009 until 12/2011): 1) linearity of the slope, 2) difference of the slope from 0 (slopes not different from 0 were set to 0), 3) variability of the slopes, and 4) constancy of the PAR (coefficient of variation < 5 %).

$$F_{CO_2} = k_{CO_2} \cdot (273.15 \cdot T^{-1}) \cdot (V \cdot A^{-1}) \cdot (p1 \cdot p0^{-1}) \cdot (dc \cdot dt^{-1}) \cdot Mc^{-1}$$ **equation 8**

F_{CO_2} = flux rate of CO_2 (µmol CO_2-C m^{-2} s^{-1})

k_{CO_2} = gas-constant at 273.15 K (0.536 µg C μl^{-1})

T = instant air temperature during the measurement (K)

V = volume of the chamber (l)

A = surface area within the collar of the chamber (m²)

p1 = air pressure during the measurement (hPa)

p0 = 1013 (hPa)

$dc \cdot dt^{-1}$ = concentration change in the chamber atmosphere over time (CO_2: ml l^{-1} h^{-1})

M_C = molar mass of carbon (12 g mol^{-1})

To model the ecosystem respiration (R_{eco}), an exponential regression equation of CO_2 flux against temperature was applied (Lloyd & Taylor 1994, Drösler 2005, Reichstein et al. 2005, Veenendaal et al. 2007, Elsgaard et al. 2012, Beetz et al. 2013). In 2007 and 2008 the flux was modelled based on the soil-temperature at 5 cm depth. In 2009, 2010 and 2011 the flux model was based on the temperature with the best fit (air temp., soil temp. at 2 cm depth or soil temp. at 5 cm depth). R_{ref} and E_0 were determined by iteration.

$$R_{eco} = R_{ref} \cdot e^{E_0(1 / (T_{ref}-T_0) - 1 / (T-T_0))}$$ **equation 9**

R_{eco} = ecosystem respiration (µmol CO_2-C m^{-2} s^{-1})

R_{ref} = R_{eco} at the reference temperature (µmol CO_2-C m^{-2} s^{-1})

E_0 = Ecosystem sensitivity parameter (K)

T_{ref} = reference temperature: 283.15 (K)

T_0 = temperature constant for the start of biological processes: 227.13 (K)

T = temperature (K)

For the net ecosystem exchange a rectangular hyperbola against the photosynthetic active radiation (PAR) was implemented (Michaelis & Menten 1913, Bellisario et al. 1998, Bubier et al. 1998, Frolking et al. 1998, Drösler 2005, Veenendaal et al. 2007, Elsgaard et al. 2012, Beetz et al. 2013). NEE is calculated as the difference between gross primary production (GPP), which has a negative sign and R_{eco}, with a positive sign. GP_{max} and α were determined by iteration. The permeability of global radiation of the Plexiglas is ca. 95 % (Drösler 2005). Thus, the measured photosynthetic active radiation (PAR) used for modelling was reduced by 5 %.

$$NEE = \frac{GPmax \cdot \alpha \cdot PAR}{\alpha \cdot PAR + GPmax} +/- R_{eco} \quad \textbf{equation 10}$$

NEE = net ecosystem exchange (µmol CO_2-C m^{-2} s^{-1})

PAR = photon flux density of the photosynthetic active radiation (µmol m^{-2} s^{-1})

GP_{max} = maximum rate of carbon fixation at PAR infinite (µmol CO_2-C m^{-2} s^{-1})

α = initial slope of the curve; light use efficiency (µmol CO_2-C m^{-2} s^{-1}/µmol m^{-2} s^{-1})

R = model of R_{eco}

Fitting of the parameters E_0, R_{ref}, GP_{max} and α was done using Microsoft Excel® Solver. Half-hourly flux rates between two measurement campaigns were interpolated linearly using equation 11: R_{eco} and NEE were calculated using the model parameters of both measurement campaigns n and n+1, and the two flux rates for each half-hourly time step were weighted and added together.

$$F_i = \frac{t_i - t_n}{t_{n+1} - t_n} \cdot F_n + \frac{t_{n+1} - t_i}{t_{n+1} - t_n} \cdot F_{n+1} \quad \textbf{equation 11}$$

F_i, t_i = flux rate and time at time step i to be modelled,

t_n, t_{n+1} = time of the campaigns n and n+1.

F_n, F_{n+1}, = flux rates calculated with the model parameters of campaigns n and n+1

When harvesting or tillage occurred between measurement campaigns n and n+1, the parameters derived from campaign n were used to model fluxes up to the intervention and the parameters derived from campaign n+1 were used to model fluxes after the intervention. For the period between a grass cut and the first measurement after the grass cut at the grassland site, the parameters GP_{max} and α were set to -0.01 and -0.0001, respectively, at the moment of the grass cut, and interpolated between these values and the parameters of the first measurement after the grass cut. Finally, monthly and annual balances were calculated.

2.2.4 Measurements of nitrous oxide and methane exchange

The chambers used for N_2O and CH_4 flux rate determination are identical in construction with the opaque chambers applied for R_{eco} (CO_2), but not ventilated. A measuring procedure lasted one hour, every 20 minutes a gas sample (total: 4 samples) was transferred from the headspace of the chamber to evacuated glass bottles (until August 2009: 12 ml glass vials filled using a double-sided injection needle; from September 2009: 60 ml sample glass vials equipped with a PTFA valve, Hassa Laborbedarf, Lübeck, filled using a flexible tube). Gas-samples from June 2007 until June 2009 and from September 2009 until December 2011 were analysed in the laboratory using a gas-phase chromatograph "Finnigan Trace GC Ultra with Finnigan Valve Oven Trace GC Ultra" (Thermo Fisher Corp.) and a Perkin Elmer Auto System, respectively. An ECD-Detector was used to detect N_2O, while a FID-Detector identified CH_4.

In addition, manual measurements of air temperatures, soil temperatures at 2, 5 and 10 cm depth (measured with inserting thermometers) and wl were held. Generally, measurement campaigns were held in intervals every two weeks, beginning in June 2007 and ending in December 2011.

For calculation of flux rates equation twelve was used (according to Drösler 2005, Beetz et al. 2013). The slopes of gas concentration were tested for difference from 0. Slopes not different from 0 were set to 0.

$$F = k \cdot (273.15 \cdot T^{-1}) \cdot (V \cdot A^{-1}) \cdot (dc \cdot dt^{-1}) \qquad \textbf{equation 12}$$

F = flux rate of N_2O (mg N_2O-N m^{-2} h^{-1}) or CH_4 (mg CH_4-C m^{-2} h^{-1})
K = gas-constant at 273.15 K (1.25 µg N μl^{-1} for N_2O, 0.536 µg C μl^{-1} for CH_4)
T = instant air temperature during the measurement (K)
V = volume of the chamber (l)
A = surface area within the collar of the chamber (m²)
$dc*dt^{-1}$ = concentration change in the chamber atmosphere over the time (N_2O and CH_4: µl l^{-1} h^{-1})

Hourly flux rates over the whole research period were obtained by linear interpolation between the measurement campaigns and used to calculate annual balances.

2.2.5 Net ecosystem carbon balance and global warming potential

To obtain a complete carbon balance of a peatland, all fluxes of carbon must be considered. Beside CO_2 the flux rates of CH_4, dissolved organic carbon (DOC), dissolved inorganic carbon (DIC), carbon monoxide (CO) and volatile organic C (VOC) are factored in the net ecosystem carbon balance (NECB), which was calculated by using equation 13 (Chapin et al. 2006). DOC was estimated to 26 kg C $ha^{-1}a^{-1}$ according to Moore (1987). Values of DIC, CO and VOC are assumed to be negligible and not considered.

$$NECB = -NEE + F_{CO} + F_{CH_4} + F_{VOC} + F_{DOC} + F_{DIC} + F_{PC} \quad \textbf{equation 13}$$

NECB = $dC\ dt^{-1}$

NEE = net ecosystem exchange (g CO_2-C m^{-2} a^{-1})

F_{CO} = net carbon monoxide absorption [or -efflux (negative sign)](g CO-C m^{-2} a^{-1})

F_{CH_4} = net methane consumption [or -efflux (negative sign)] (g CH_4-C m^{-2} a^{-1})

F_{VOC} = net volatile organic C absorption [or -efflux (negative sign)] (g VOC-C m^{-2} a^{-1})

F_{DOC} = net dissolved org. C input to the ecosystem [or net DOC leaching loss (neg. sign)] (g DOC-C m^{-2} a^{-1})

F_{DIC} = net dissolved inorganic C input [or net DIC leaching loss (neg. sign)] (g DIC-C m^{-2} a^{-1})

F_{PC} = net lateral transfer of particulate (nondissolved, nongaseous) C into the ecosystem [or out of (negative sign)], e.g. harvest (g PC-C m^{-2} a^{-1})

A widely-used technique to establish the climatic relevance of the greenhouse gas exchange at each site, expressed as CO_2-equivalents, is the global warming potential (GWP) methodology (equation 14) (Drösler 2005, IPCC 2007, Beetz et al. 2013). In general, the global warming potential over a time span of 100 years is taken (Drösler 2005). Positive values represent efflux of CO_2-equivalents into the atmosphere.

$$\text{GWP balance } [\text{g } CO_2\text{-eq. } m^{-2}] = NEE \cdot GWP_{CO_2} + F_{CH_4} \cdot GWP_{CH_4} + F_{N_2O} \cdot GWP_{N_2O} \quad \textbf{equation 14}$$

GWP_{CO_2} = 1

GWP_{CH_4} = 72 (20 years), 25 (100 years), 7.6 (500 years)

GWP_{N_2O} = 289 (20 years), 298 (100 years), 153 (500 years)

2.2.6 Statistical analyses

Average values are arithmetic means +/- standard error.

Error analysis of CO_2 gas fluxes was conducted by calculating the standard error for each calibrated regression model. Analogous to the interpolation of the half-hourly gas fluxes, standard errors were interpolated. The monthly and annual standard errors were calculated using appropriate error propagation equation. The standard errors of the means of the exported carbon through harvest were included.

For CH_4 and N_2O the standard error of the replicate chamber measurements of each measurement campaign were calculated and interpolated between the measurement campaigns analogous to the interpolation of the fluxes. The annual standard errors were calculated using appropriate error propagation equations.

Correlation and regression analysis was conducted providing the coefficient of determination (quadrate of Pearson Correlation Coefficient = R^2) and tested for significance using a t-test.

Significant linearity of slope of the changes in gas concentration was tested following Huber (1984). To test if slopes are significantly different from 0, a t-test was performed (Neter et al. 1996).

The variability of the slopes was calculated as the standard deviation of the residuals (s_{yx}). For the variability in PAR the coefficient of variability (cv %) was calculated.

Significant ($p < 0.05$) differences between the study sites as well as between the study years were tested with the Permutation test “diffmean” (1000 permutations) using R script 0.97.237 (version 2.15.2; simba package).

2.3 Results

2.3.1 Land use and carbon import and export

The main differences between the study sites were the different land use and the different management practices, i.e. soil labour, slurry application and maize cultivation for corn-cob-mix on the arable land and permanent grassland, meadow use with two to three cuts per year and no fertilization on the grassland site. The cropland site was supplied with pig slurry each year in April or May (April 2007 and May 2008: 20, April 2009: 24, April 2010 and April 2011: 22 m^3 ha^{-1}). The carbon import was calculated to be 675 (2007 and 2008), 810 (2009) and 743 kg C ha^{-1} (2010 and 2011). Through harvest each year in October the carbon export amounted to 1,478 +/- 228 (2007), 2,052 +/- 784 (2008), 2,768 +/- 302 (2009), 3,557 +/- 769 (2010) and 2,396 +/- 139 kg C ha^{-1} (2011).

At the grassland site 2,094 +/- 171 (July 2009), 1,056 +/- 123 (Sept. 2009), 1,242 +/- 133 (June 2010), 1,291 +/- 116 (Aug. 2010), 447 +/- 27 (Oct. 2010), 1,255 +/- 187 (June 2011), 761 +/- 46 (Aug. 2011) and 463 +/- 53 kg C ha^{-1} (Sept. 2011) were exported through cutting.

2.3.2 Soil parameters and water table

The two study sites cropland and grassland did not differ much in their physical and chemical characteristics, because of their closeness (Tab.2.1). Bulk density and substance volume were only slightly higher at the cropland than at the grassland site in the upper horizon, organic substance, total carbon and total nitrogen were slightly lower in the upper horizon. The average of all mineralized nitrogen-measurements (0-20 cm depth) at the cropland and the grassland site amounted to 54.7 +/- 31.6 kg ha^{-1} and 41.1 +/- 10.9 kg ha^{-1}, respectively. The $pH_{(CaCl2)}$ of the cropland and the grassland site were 5.6 and 5.4, respectively. Also the wl was in the same range (Fig.2.1). Averaged over four years the annual mean wl was 28 and 26 cm below ground surface at the cropland site and the grassland site, respectively. During wintertime the wl remained at the ground surface level. Wfps was on average over the four years 88 +/- 16.4 and 78 +/- 23 % at the cropland site and the grassland site, respectively (Fig.2.2).

Tab. 2.1: Soil properties of the cropland and the grassland site.

a) cropland site

depth [cm]	soil horizon [a]	peat substrate [a]	bulk density [g/cm³]	substance volume [%]	decay degree [b]	org. substance [%]	C_{org} [%]	Nt [%]	St [%]	$CaCO_3$ [%]	pH_{CaCl2}
0-30	Hvp	Hn	0.49	26.2	z5	53.2	29.1	1.5	0.3	0	5.6
30-60	Hw	Hn	0.16	9.9	z2	85.2	48.6	2.2	0.3	0	5.6
60-100	Hr	Hn	0.11	7.1	z2	90.4	49.5	2.5	0.5	0	5.3
100-205	Hr	Hn	0.09	5.7	z4	87.7	48.9	2.4	0.4	0	5.2
205-275	Fr	Fmu	0.65	27.6		5.4	3.8	0.2	0.5	7.6	7.5
275-300	Gr	Su2	1.59			0.8	0.7	0.0	0.1	3.3	7.6

b) grassland site

depth [cm]	soil horizon [a]	peat substrate [a]	bulk density [g/cm³]	substance volume [%]	decay degree [b]	org. substance [%]	C_{org} [%]	Nt [%]	St [%]	$CaCO_3$ [%]	pH_{CaCl2}
0-20	Hvp	Hn	0.41	22.5	z5	58.1	30.9	1.7	0.3	0	5.4
20-60	Hw	Hn	0.16	10.1	z3	84.8	47.1	2.1	0.3	0	5.4
60-110	Hr	Hn	0.11	6.9	z2	90.2	49.7	2.5	0.4	0	5.1
110-205	Hr	Hn	0.09	5.7	z4	87.7	48.9	2.4	0.4	0	5.2
205-275	Fr	Fmu	0.65	27.6		5.4	3.8	0.2	0.5	7.6	7.5
275-300	Gr	Su2	1.59			0.8	0.7	0.0	0.1	3.3	7.6

[a] According to AG Boden (2005); [b] According to von Post-scale

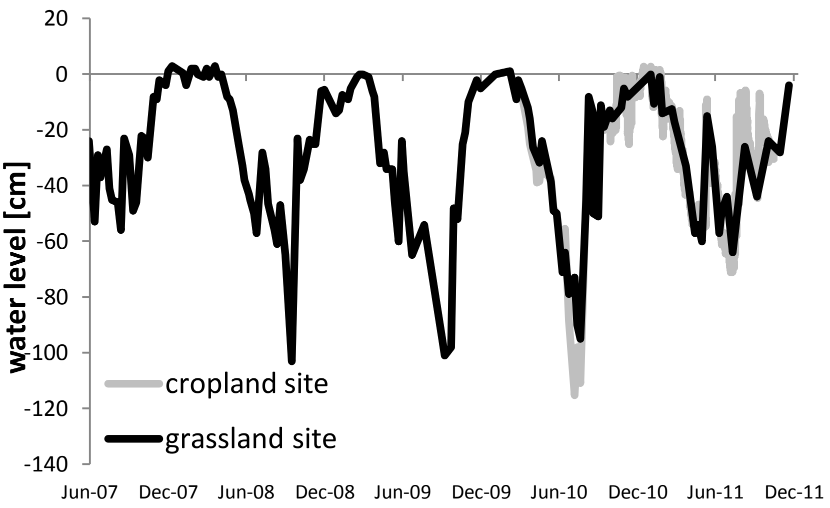

Fig. 2.1: Water level of the cropland (from March 2010 until Dec 2011) and the grassland site (from June 2007 until Dec 2011) in cm above ground surface.

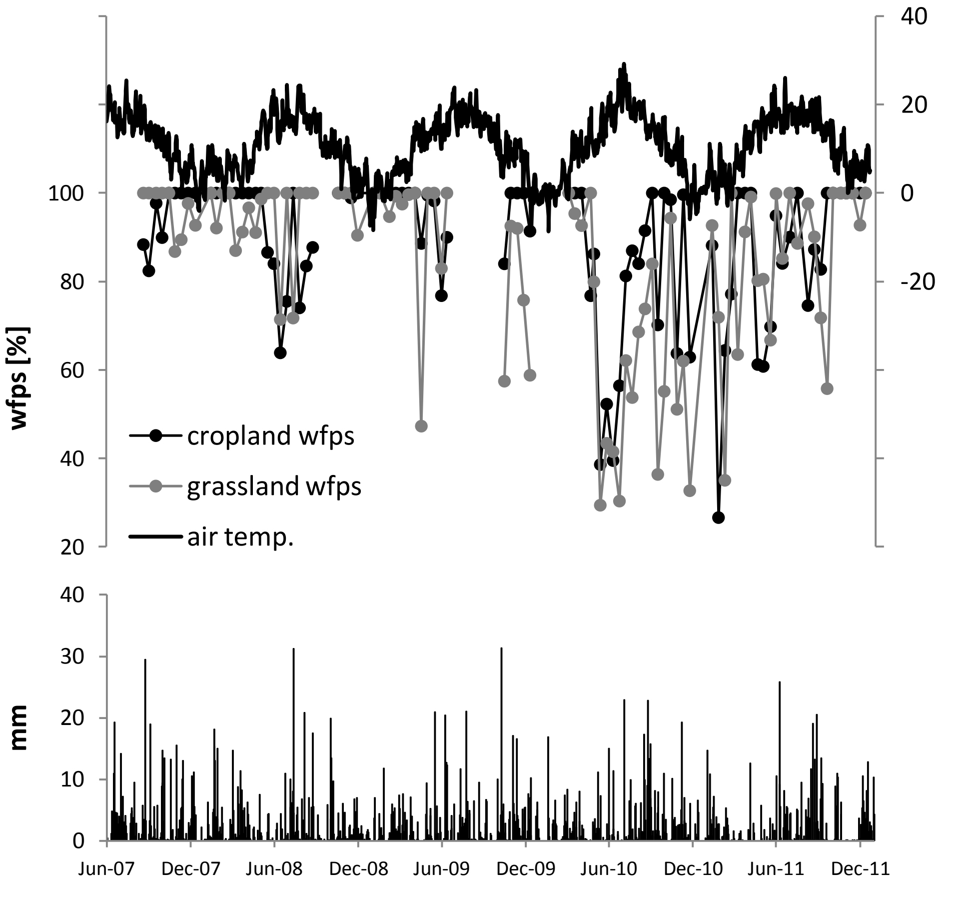

Fig. 2.2: Water filled pore space (wfps) of the cropland and the grassland site as well as air temperature and precipitation (daily values) at the weather station (from June 2007 until Dec 2011).

2.3.3 Biomass

The total biomass of the cropland site reached highest values in August and September, the green biomass achieved maximum values in August (Fig.2.3). In winter, the biomass was 0 or near 0. The greatest amount of total biomass and green biomass was assessed in September 2010 (20 +/- 1 t dry matter ha^{-1}) and in August 2010 (13 +/- 1 t dry matter ha^{-1}), respectively.

At the grassland site the values of biomass and green biomass were higher from 2007 until the first half of 2009 and lower from the second half of 2009 until 2011 (Fig.2.4). In other words, since harvesting took place, the values were lower. The maximum of biomass and green biomass was 13 +/- 1 t dry matter ha^{-1} and 10 +/- 1 t dry matter ha^{-1}, respectively, on 12.06.2009.

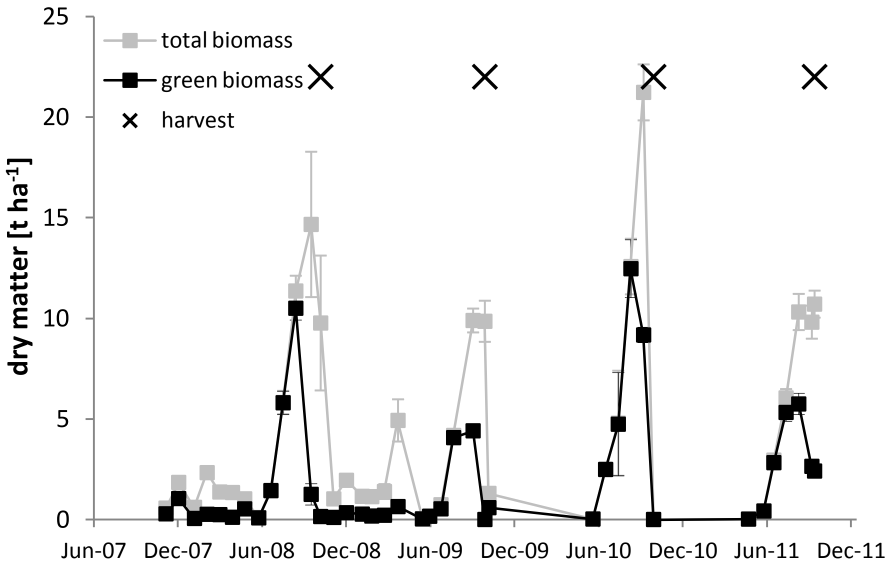

Fig. 2.3: Total and green above-ground biomass (dry matter) of the cropland site. X: Harvest

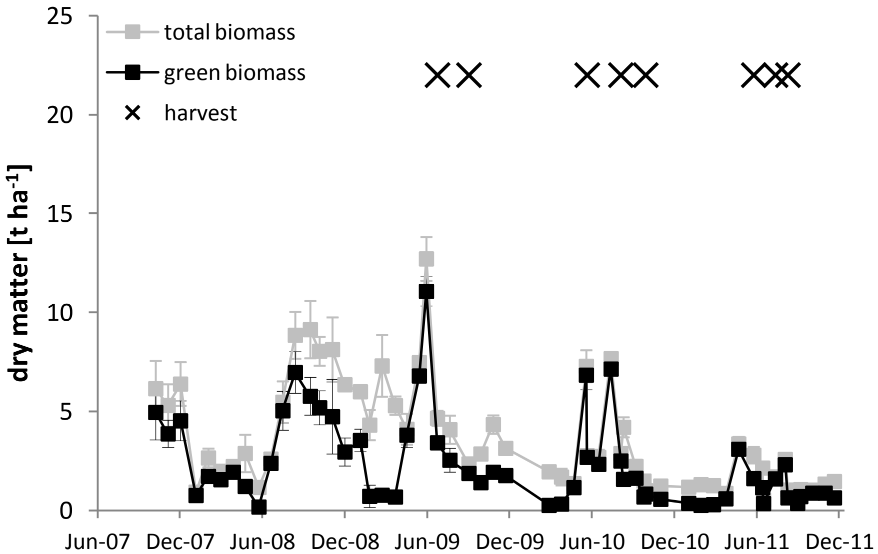

Fig. 2.4: Total and green above-ground biomass (dry matter) of the grassland site. X: Harvest

2.3.4 Weather

Average annual precipitation was 569 mm in 2008, 607 mm in 2009, 549 mm in 2010 and 559 mm in 2011. The 30 year average of Diepholz amounts to 695.4 mm per year. Average annual air temperature was 10.0 °C in 2008, 10.2 °C in 2009, 9.9 °C in 2010 and 11.1 °C in 2011. The 30 year average of Diepholz is 8.9 °C.

There was exceptionally high precipitation with almost 150 mm in August 2010, and autumn 2010 was notably wet (Fig.2.5). In contrast, spring 2011 was remarkably dry (in March precipitation was only 7.5 mm). August 2011 featured also comparatively high precipitation. The winters 2007/2008, 2008/2009 and 2011/2012 were quite mild, while 2009/2010 and 2010/2011 the monthly mean dropped below 0 °C. July 2010 was an extremely warm month.

The monthly mean values of the PAR were in general highest in May, June and July (Fig.2.5). In 2008, the PAR was very high in May and June, whereas in 2009 July until September revealed high values compared to the remaining years, and 2011 showed exceptionally low values in June and July.

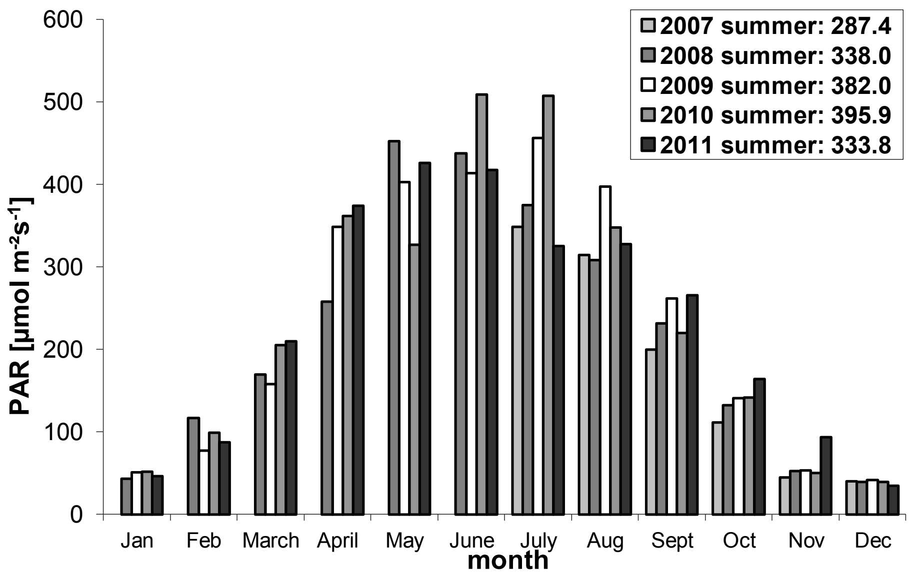

Fig. 2.5: Monthly mean of PAR (photosynthetic active radiation) calculated from the daily maximum of half-hourly values. Note: 2007 only from July to Dec. Upper right corner (summer-values): PAR during main growing period of the maize (June until September).

2.3.5 Carbon dioxide

2.3.5.1 Evaluation of methodology

The increase of the gas concentration inside the chamber with time was linear during (at least) the first minute (transparent chamber) or first few minutes (opaque chamber) of measurement. The time span of one to a few minutes was sufficient to determine the flux rate. The test of linearity revealed at almost all measurements significant linearity ($p < 0.05$). In 2011, about

99.5 % (n = 195) and 98.5 % (n = 201) of the measurements at the cropland site with opaque and transparent chambers, respectively, were significantly linear. At the grassland site 99.4 % (n = 170) of the opaque chamber measurements and all of the transparent chamber measurements (n = 474) were significantly linear (2011).

The coefficient of variability in the PAR during the CO_2 measurement was always less than 5 % with a very few exceptions. Thus, the driving forces of the models for the CO_2 gas exchange (temperature and PAR) were quite constant during measurement.

Model parameters for R_{eco} and NEE are listed in table 2.2 and 2.3. Regressions between measured and modelled flux rates for R_{eco} of each measurement campaign were in almost all cases significant ($p < 0.1$ for R_{eco}; $p < 0.05$ for NEE). In a few cases, mainly in winter (Nov. – March) due to the low gradient of temperatures and PAR, the results of two adjacent measurement campaigns needed to be pooled together. Pooling was necessary six times (R_{eco}) and twice (NEE) at the cropland site and four times at the grassland site (R_{eco}).

Tab. 2.2[next page]: Parameters for the R_{eco} and NEE models of the cropland site: Left: Date of measurement campaign. Middle: E_0: Activation energy like parameter [K], R_{ref}: Respiration at the reference temperature [µmol CO_2-C m^{-2} s^{-1}], R²: Coefficient of determination (Pearson) between modelled and measured values. S.e.: Standard error of the model [µmol CO_2-C m^{-2} s^{-1}], n: Number of samples, temp: Best fit temperature for R_{eco} model [air temp. or soil temp. in cm below ground surface]. Right: GP_{max}: Maximum rate of carbon fixation at PAR infinite [µmol CO_2-C m^{-2} s^{-1}], α: Light use efficiency [µmol CO_2-C m^{-2} s^{-1}/µmol m^{-2} s^{-1}], R²: Coefficient of determination (Pearson) between modelled and measured values. S.e.: Standard error of the model [µmol CO_2-C m^{-2} s^{-1}], n: Number of samples. Maximum and minimum values are printed in bold. Eventually measurement campaigns were pooled together. 09.01.2008, 06.02.2008, 24.09.2008, 26.10.2010: No significant correlation between measured and modelled values. E_0 was set to 0.

Tab. 2.3 [page after next]: Parameters for the R_{eco} and NEE models of the grassland site: Left: Date of measurement campaign. Middle: E_0: Activation energy like parameter [K], R_{ref}: Respiration at the reference temperature [µmol CO_2-C m^{-2} s^{-1}], R²: Coefficient of determination (Pearson) between modelled and measured values. S.e.: Standard error of the model [µmol CO_2-C m^{-2} s^{-1}], n: Number of samples, temp: Best fit temperature for R_{eco} model [air temp. or soil temp. in cm below ground surface]. Right: GP_{max}: Maximum rate of carbon fixation at PAR infinite [µmol CO_2-C m^{-2} s^{-1}], α: Light use efficiency [µmol CO_2-C m^{-2} s^{-1}/µmol m^{-2} s^{-1}], R²: Coefficient of determination (Pearson) between modelled and measured values. S.e.: Standard error of the model [µmol CO_2-C m^{-2} s^{-1}], n: Number of samples. Maximum and minimum values are printed in bold. Eventually measurement campaigns were pooled together.

date	E0	Rref	R²	s.e.	n	temp	GPmax	α	R²	s.e.	n
20.06.07	565.4	1.00	0.68****	0.90	17	soil5	-24.93	-0.0073	0.56****	0.93	28
17.07.07	328.8	2.42	0.18**	1.10	21	soil5	-42.78	-0.0358	0.80****	4.36	53
14.08.07	528.4	2.50	0.62****	1.37	21	soil5	-73.23	**-0.0801**	0.93****	4.17	54
12.09.07	322.5	3.30	0.47***	0.40	18	soil5	-73.34	-0.0604	0.97****	1.69	44
07.11.07	239.6	1.93	0.56***	0.09	15	soil5	-40.53	-0.0331	0.99****	0.34	27
05.12.07	**1152.2**	2.46	0.57****	0.03	21	soil5	-14.54	-0.0485	0.96****	0.40	30
09.01.08	0.0	**0.40**	0.01	0.01	30	soil5	-2.02	-0.0052	0.87****	0.14	34
06.02.08	0.0	**0.40**	0.01	0.01	30	soil5	-2.02	-0.0052	0.87****	0.14	34
05.03.08	254.6	1.13	0.16*	0.02	18	soil5	-8.33	-0.0015	0.74****	0.27	32
02.04.08	430.4	0.93	0.5***	0.07	15	soil5	-4.17	-0.0072	0.85****	0.21	27
29.04.08 05.05.08	450.8	1.74	0.49****	0.24	21	soil5	-10.85	-0.0177	0.89****	0.66	39
30.05.08	292.5	1.79	0.67****	0.59	18	soil5	-1.63	**-0.0013**	0.29****	0.47	48
26.06.08	310.7	4.01	0.72****	0.98	16	soil5	-44.16	-0.0564	0.98****	1.41	28
23.07.08	952.1	1.68	0.61****	0.87	21	soil5	-164.26	-0.0633	0.92****	3.56	39
20.08.08	469.7	3.11	0.20**	0.69	21	soil5	-144.86	-0.0505	0.93****	4.08	31
24.09.08	0.0	3.85	0.04	0.09	17	soil5	-18.66	-0.0121	0.80****	1.08	27
14.10.08	380.7	1.72	0.27*	0.16	14	soil5	-2.74	-0.0328	0.63****	0.26	30
12.11.08	587.3	1.15	0.70****	0.08	18	soil5	-4.51	-0.0153	0.98****	0.15	24
10.12.08							-4.35	-0.0144	0.98****	0.14	24
14.01.09 04.02.09	692.2	1.76	0.32****	0.03	36	soil5	-1.67	-0.0090	0.87****	0.10	24
04.03.09	524.9	1.76	0.89****	0.07	15	soil5	-6.46	-0.0107	0.96****	0.26	24
03.04.09	344.8	2.32	0.82****	0.33	15	soil5	-5.39	-0.0163	0.92****	0.34	29
29.04.09	171.2	4.43	0.14*	1.09	21	soil5					
27.05.09	154.8	2.79	0.17*	0.26	23	soil5	**-0.27**	-0.0118	0.16**	0.20	33
12.06.09	594.6	0.62	0.82****	0.15	26	soil5	-7.49	-0.0099	0.94****	0.38	33
07.07.09	**47.5**	7.31	0.17*	0.40	18	air	-18.23	-0.0336	0.89****	1.26	27
04.08.09	222.9	4.83	0.33*	0.82	19	soil2	-124.01	-0.0502	0.94****	4.06	37
16.09.09	298.7	2.34	0.75****	1.16	11	air	-98.36	-0.0532	0.89****	3.74	32
13.10.09	750.2	1.18	0.60**	0.26	9	soil5	-8.98	-0.0136	0.87****	0.63	36
23.10.09	130.6	4.05	0.02*	1.12	53	air					
10.11.09 08.12.09	582.7	1.72	0.15**	0.50	29	soil2					
16.03.10	210.5	0.42	0.41***	0.06	18	air					
13.04.10	235.8	1.37	0.34**	0.36	15	soil2					
30.04.10	139.5	2.39	0.04*	0.57	72	air					
11.05.10	185.3	1.81	0.17*	0.29	19	soil2					
08.06.10	160.2	2.74	0.16*	0.90	20	soil5	-5.37	-0.0036	0.73****	0.42	51
06.07.10	102.7	7.85	0.81****	0.64	21	air	-64.29	-0.0591	0.95****	2.81	42
03.08.10	172.0	**9.11**	0.60****	1.63	18	air	-142.18	-0.0736	0.93****	6.93	32
31.08.10	305.9	3.79	0.70***	1.36	9	air	**-217.90**	-0.0494	0.82****	9.88	30
28.09.10	849.7	1.43	0.40**	0.60	14	soil2	-27.35	-0.0696	0.74****	2.69	26
26.10.10	0.0	1.80	0.00	0.41	17	air					
23.11.10 25.01.11	967.3	1.42	0.73****	0.08	27	soil2					
22.02.11 22.03.11	103.1	1.57	0.41****	0.31	33	soil2					
19.04.11	48.8	9.09	0.14*	2.56	21	air					
18.05.11	75.6	2.21	0.19*	0.39	18	air	-0.98	-0.0026	0.17**	0.10	36
21.06.11	185.7	2.60	0.82****	0.31	15	air	-28.47	-0.0189	0.95****	1.08	33
13.07.11	95.1	6.32	0.44***	0.48	15	air	-190.80	-0.0336	0.91****	1.82	33
09.08.11	1117.2	0.91	0.65***	0.82	12	soil2	-69.26	-0.0660	0.89****	4.50	36
06.09.11	127.2	4.43	0.74****	0.31	12	air	-61.25	-0.0406	0.91****	2.50	36
05.10.11	418.3	2.36	0.38**	0.22	12	soil5	-29.93	-0.0185	0.96****	0.53	27
01.11.11 29.11.11	166.8	2.38	0.33***	0.73	33	soil2					
20.12.11	316.4	0.54	0.30*	0.04	12	soil2					

* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$; **** $p < 0.001$

date	E0	Rref	R²	s.e.	n	temp	GPmax	α	R²	s.e.	n
20.06.07	**1260.5**	1.24	0.55*	3.41	73	soil5	-27.19	**-0.2963**	0.73****	4.12	24
17.07.07	1091.2	**0.23**	0.75****	1.84	13	soil5	**-84.10**	-0.0147	0.83****	2.57	55
14.08.07	174.3	7.57	0.42***	0.56	18	soil5	-17.21	-0.1291	0.93****	1.13	34
12.09.07	520.4	3.97	0.50****	0.66	21	soil5	-76.23	-0.0686	0.97****	1.76	39
10.10.07	918.5	3.19	0.62****	0.51	60	soil5	-27.18	-0.0962	0.86****	2.13	60
07.11.07	534.8	3.18	0.22***	0.13	15	soil5	-43.37	-0.0466	0.95****	0.71	21
05.12.07	1241.2	5.28	0.47****	0.32	24	soil5	-61.66	-0.0335	0.96****	0.45	30
09.01.08	424.6	2.84	0.33**	0.10	15	soil5	-1.84	-0.1239	0.88****	0.23	12
06.02.08	480.7	3.86	0.27*	0.11	11	soil5	-15.06	-0.0532	0.94****	0.93	21
05.03.08	560.2	8.40	0.61****	0.32	18	soil5	-28.81	-0.0191	0.98****	0.72	36
02.04.08	884.7	5.62	0.86****	0.30	12	soil5	-41.32	-0.0427	0.98****	0.83	27
29.04.08	618.6	5.30	0.55****	0.65	21	soil5	-18.55	-0.0337	0.78****	1.37	33
30.05.08	181.5	6.06	0.53****	0.98	18	soil5	-6.74	-0.0487	0.43****	1.00	41
26.06.08	272.9	6.11	0.14*	0.63	24	soil5	-40.53	-0.0658	0.97****	1.53	41
23.07.08	645.9	3.33	0.44***	0.93	20	soil5	-55.48	-0.0607	0.95****	1.83	35
20.08.08	224.7	5.39	0.31****	0.68	39	soil5	-36.81	-0.0955	0.96****	1.72	27
24.09.08	224.7	5.39	0.31****	0.68	39	soil5	-59.09	-0.0457	0.96****	1.12	27
14.10.08	313.3	5.57	0.94****	0.31	14	soil5	-30.97	-0.1200	0.81****	2.23	30
12.11.08	362.7	2.65	0.55****	0.50	30	soil5	-24.62	-0.0426	0.95****	1.02	24
10.12.08	362.7	2.65	0.55****	0.50	30	soil5	-11.70	-0.0385	0.83****	0.97	24
14.01.09	179.6	1.74	0.08*	0.07	33	soil5	-26.86	**-0.0051**	0.61****	0.13	24
04.02.09							**-0.39**	-0.0504	0.25**	0.12	23
04.03.09	728.8	6.10	0.70****	0.24	15	soil5	-4.80	-0.0055	0.83****	0.27	21
03.04.09	363.5	3.44	0.83****	0.42	15	soil5	-8.67	-0.0246	0.87****	0.63	29
29.04.09	521.4	4.40	0.16*	0.64	20	soil5	-8.67	-0.0246	0.87****	0.63	29
27.05.09	160.2	5.83	0.15*	0.34	24	soil5	-36.61	-0.0755	0.96****	2.12	36
12.06.09	230.1	4.09	0.20**	0.73	25	air	-31.45	-0.0844	0.93****	2.35	30
07.07.09	47.5	7.31	0.20*	0.31	16	air	-18.23	-0.0336	0.89****	1.26	27
04.08.09	186.7	8.20	0.37**	0.60	12	soil2	-53.57	-0.0693	0.95****	2.39	36
16.09.09	292.0	2.75	0.56**	1.33	15	air	-64.74	-0.0226	0.74***	2.46	29
13.10.09	700.3	3.79	0.51***	0.73	15	soil2	-31.39	-0.0471	0.90****	1.67	36
10.11.09	486.6	3.21	0.79****	0.23	28	soil5	-33.14	-0.0552	0.88****	0.67	33
08.12.09							-6.34	-0.0956	0.82****	0.35	44
16.03.10	223.6	1.71	0.84****	0.10	18	air	-2.70	-0.0054	0.83****	0.16	52
13.04.10	237.4	3.65	0.67****	0.66	18	soil2	-11.11	-0.0276	0.85****	0.75	75
11.05.10	648.5	3.62	0.15*	0.73	24	soil2	-33.50	-0.0536	0.94****	1.26	72
08.06.10	**26.7**	11.08	0.14*	1.18	21	air	-52.08	-0.0681	0.96****	2.22	45
06.07.10	61.9	**11.27**	0.38****	1.38	21	air	-43.55	-0.0742	0.96****	1.77	40
03.08.10							-50.31	-0.0432	0.94****	2.41	33
31.08.10	598.6	1.75	0.88****	0.50	12	soil2	-10.48	-0.0358	0.84****	1.01	29
28.09.10	188.1	5.12	0.27*	0.46	14	air	-63.12	-0.0464	0.98****	0.65	30
26.10.10	137.2	2.50	0.63****	0.26	18	air	-6.53	-0.0210	0.90****	0.33	48
23.11.10	397.5	3.26	0.72****	0.09	15	air	-17.43	-0.0422	0.97****	0.34	39
25.01.11	853.7	5.55	0.41**	0.11	14	air	-7.96	-0.0409	0.77****	0.64	33
22.03.11	101.7	3.44	0.72****	0.63	18	air	-14.96	-0.0269	0.85****	0.79	54
19.04.11	103.2	7.51	0.85****	0.90	16	air	-31.31	-0.0715	0.92****	1.42	63
18.05.11	49.2	9.01	0.07*	1.65	33	air	-52.27	-0.0931	0.95****	2.41	33
21.06.11							-13.63	-0.0241	0.78****	1.61	36
13.07.11	594.1	2.31	0.24*	0.49	14	soil5	-9.32	-0.0076	0.61****	0.70	30
09.08.11	92.0	9.12	0.40*	0.86	9	air	-53.01	-0.0828	0.95****	2.30	35
06.09.11	242.2	4.98	0.64***	0.98	11	air	-23.55	-0.0415	0.88****	1.20	38
05.10.11	791.5	2.14	0.52***	0.78	12	soil2	-40.47	-0.0630	0.97****	1.03	27
01.11.11	97.8	4.32	0.77****	0.56	15	air	-32.24	-0.0486	0.91****	1.24	48
29.11.11	581.0	5.47	0.60***	0.26	12	soil2	-16.33	-0.0425	0.84****	0.89	42
20.12.11	95.3	1.10	0.60****	0.05	15	air	-14.70	-0.0321	0.93****	0.32	36

* p < 0.1; ** p < 0.05; *** p < 0.01; **** p < 0.001

At the cropland site no significant correlation between measured and modelled values for R_{eco} existed on four dates, and pooling was not possible, thus E_0 was set to 0, and R_{ref} was replaced by the mean value of the measured values. This is a conservative way to get an accurate result. R_{ref} was low during winter, while the rest of the year the values varied strongly. E_0 showed no seasonal trend. The parameters at the grassland site showed no seasonal trend at all.

Pooling was not necessary for NEE at the cropland site, with one exception (29.04.2008 and 05.05.2008). The parameters showed seasonal trends. GP_{max} revealed highest values before harvest, while α was in general highest in summer. At the grassland site, in general, values of GP_{max} and α were highest in summer and autumn, but this trend was very weak for α.

GP_{max} values were much more negative at the cropland than at the grassland site, whereas α was more negative at the grassland site, especially in the summer months. R_{ref} and E_0 were higher at the grassland than at the cropland site.

Regressions between all modelled and measured values (Fig.2.6) at the cropland and the grassland site showed both a coefficient of determination of $R^2 = 0.95$ ($p < 0.0001$). Standard errors were 2.81 and 1.64 µmol CO_2-C m^{-2} s^{-1}, respectively. The coefficient of determination of the regressions between all modelled and measured values of R_{eco} at the cropland and the grassland site were $R^2 = 0.89$ and 0.95 ($p < 0.0001$), respectively. The regressions were close to the 1:1 line.

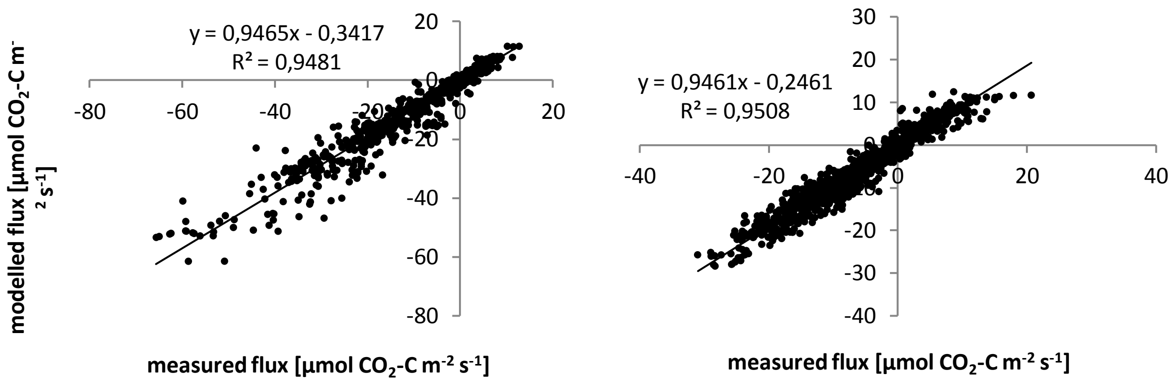

Fig. 2.6: Fit of modelled with measured CO_2-C flux data of NEE at the cropland site (left) and the grassland site (right).

2.3.5.2 Ecosystem respiration

At the cropland site highest monthly R_{eco} was determined in July and August (Fig.2.7), with highest values in July 2010 (> 4,000 kg CO_2-C ha^{-1}). January, February and December revealed lowest fluxes. On one hand, flux rates showed a relatively steep rise in July and decline in September reflecting the phenology of the maize crop and the management practice. On the other hand, values in April, May and October were also high, although no or almost no vegetation was abundant; these emissions are due to the heterotrophic respiration of the soil microorganisms. The variability between the years was high, especially regarding the months April to August, and reflected differences in weather conditions and crop growth.

At the grassland site the annual course of the monthly fluxes of R_{eco} showed a more regular sinusoidal curve (Fig.2.8). Highest emissions occurred in July of up to 4,500 kg CO_2-C ha^{-1} in 2010. The respiration in April, May and October was clearly higher at the grassland compared to the cropland site. This can be attributed to additional autotrophic respiration due to the dense grass sward as compared to the fallow cropland before and after the maize culture.

Generally, the monthly flux rates over the four and a half years differed significantly between the cropland and the grassland site. Only in August and September 2008 as well as in August and September 2010 the monthly flux rates were not significantly different.

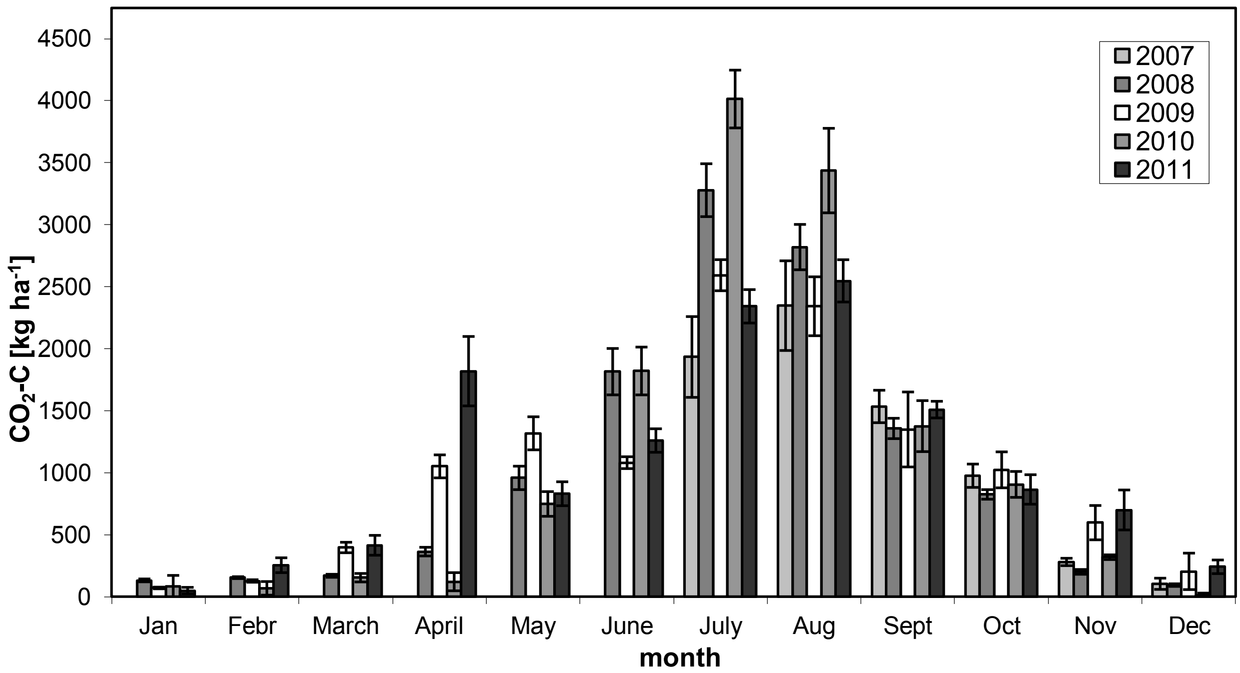

Fig. 2.7: Monthly cumulated ecosystem respiration (R_{eco}) of the cropland site. Note: 2007 only from July to Dec. Error bars are standard errors.

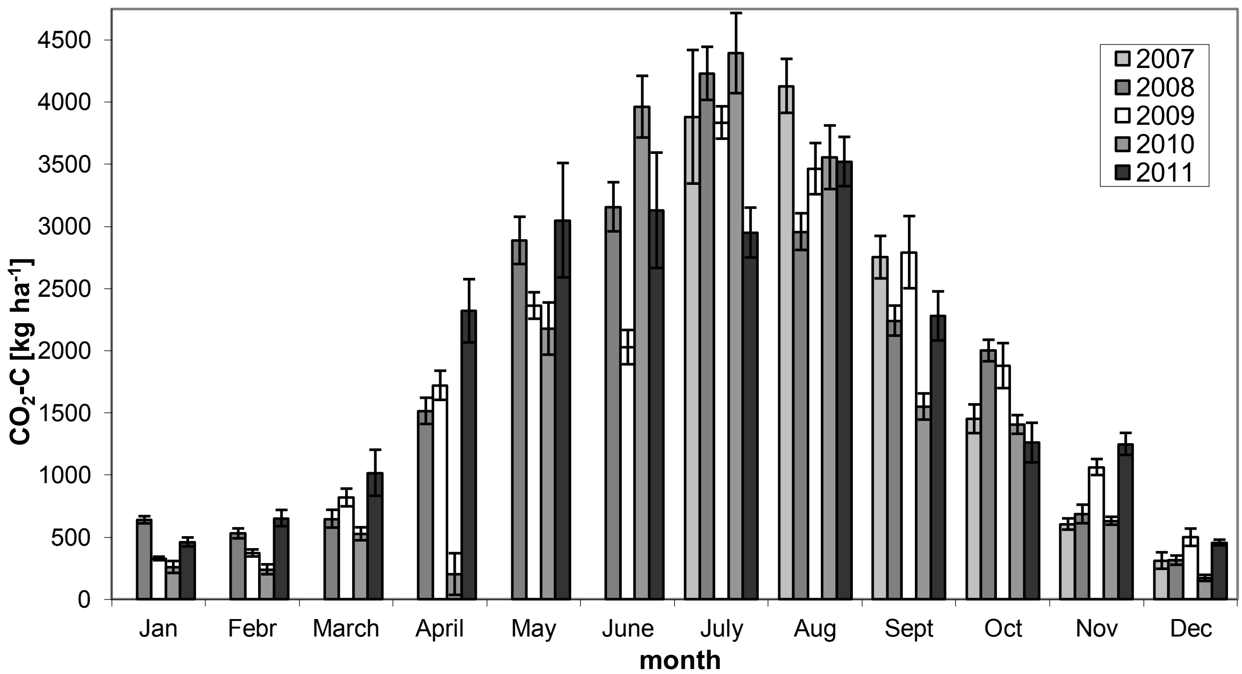

Fig. 2.8: Monthly cumulated ecosystem respiration (R_{eco}) of the grassland site. Note: 2007 only from July to Dec. Error bars are standard errors.

2.3.5.3 Net ecosystem exchange

At the cropland site GPP was higher than R_{eco} in the months June to September, resulting in negative NEE (net uptake of CO_2; Fig.2.9). The most negative NEE occurred in August 2009 (more than -2,000 kg CO_2-C ha^{-1}). In 2010, from drilling the maize in May until harvest in October, the ecosystem absorbed about -4,000 kg CO_2-C ha^{-1} from the atmosphere. Highest net emissions occurred in April 2011. From December to February the emissions were low, but still present. There was a weak trend from 2008 until 2011 (in 2007 no full year is available) to increasing emissions with time in spring.

The monthly NEE at the grassland site showed only a weak seasonal trend. A slightly higher uptake of CO_2 in early summer and a slightly higher release of CO_2 in late summer have been observed (Fig.2.10). From November until March monthly NEE varied between -500 and 500 kg CO_2-C ha^{-1}, but on average net emissions prevailed by far. During winter (Dec. - Feb.), net emissions from the grassland site were comparable to the cropland site. Variability between the years was high. November was the only month at the grassland site, in which all years showed a net release of CO_2. The highest net emissions occurred in July 2009 with almost 2,000 kg CO_2-C ha^{-1} per month, the highest uptake was in May 2011 with more than -1,000 kg CO_2-C ha^{-1} per month.

In general, the monthly flux rates over the study period differed significantly between the cropland and the grassland site. In January 2011, April 2008, October 2009, November 2010, December 2009 and December 2011 the monthly flux rates were not significantly different.

Maximum daily release and uptake per day at the examination sites are presented in Table 2.4.

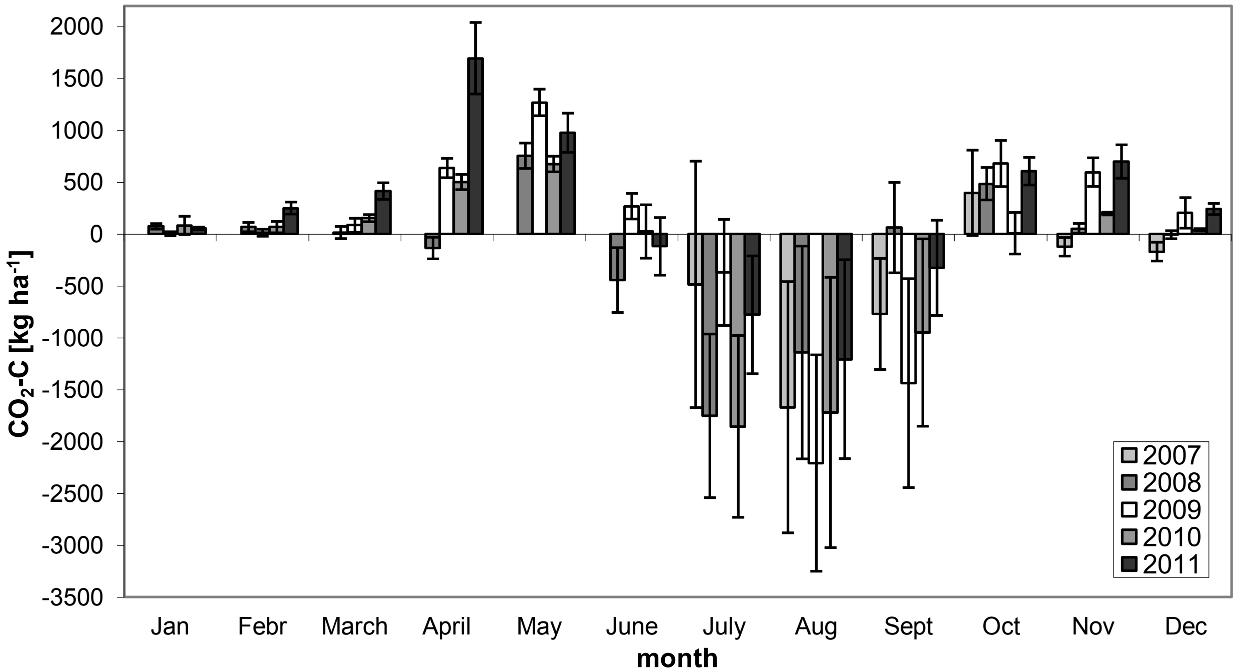

Fig. 2.9: Monthly cumulated net ecosystem exchange (NEE) of the cropland site, without import and export of C through harvest and fertilizer. Note: 2007 only from July to Dec. Error bars are standard errors.

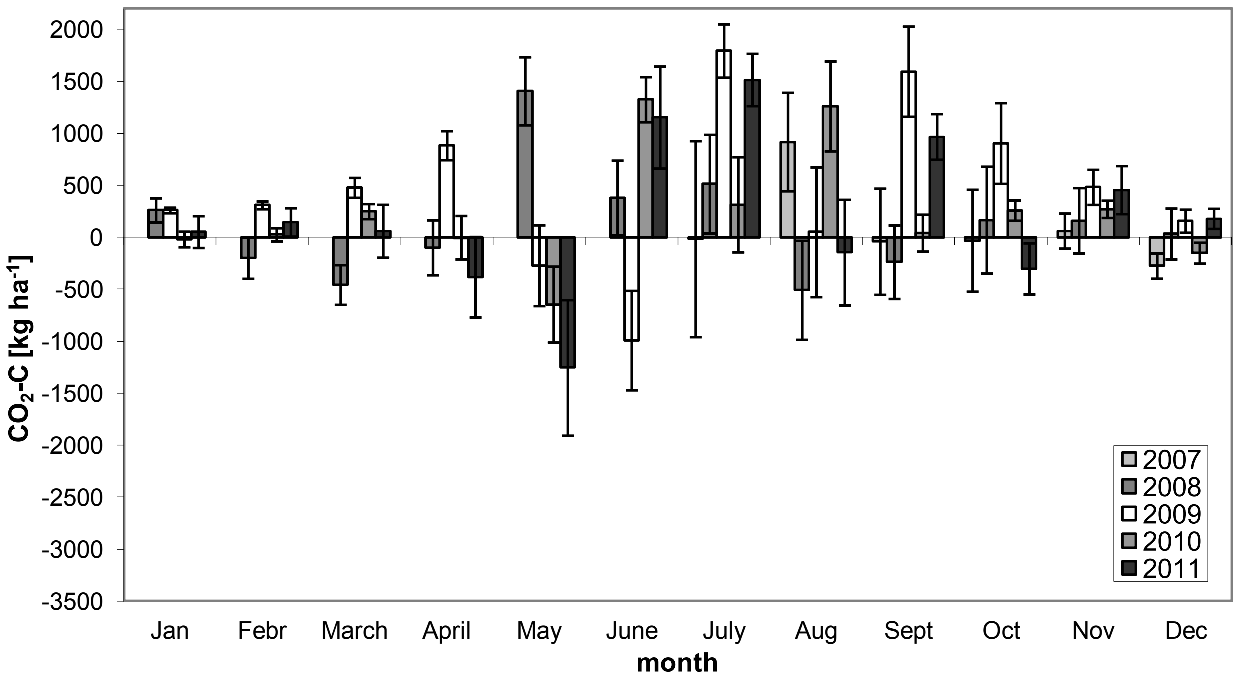

Fig. 2.10: Monthly cumulated net ecosystem exchange (NEE) of the grassland site, without import and export of C through harvest. Note: 2007 only from July to Dec. Error bars are standard errors.

Tab. 2.4: Daily maximum uptake and maximum release of CO_2-C of the cropland and the grassland site. Mean of the three collars and standard error (s.e.).

site	max uptake +/- s.e. [g CO_2-C $m^{-2}d^{-1}$]	max release +/- s.e. [g CO_2-C $m^{-2}d^{-1}$]
cropland	-15.9 +/- 3.9	9.7 +/- 2.6
grassland	-14.6 +/- 4.0	15.3 +/- 3.4

2.3.5.4 Annual carbon dioxide balance

Annual net ecosystem exchange (NEE) without carbon import and export through fertilizer and harvest in 2008, 2009 and 2010 differed significantly between the cropland and the grassland site. In 2011, the balances were not significantly different. At both sites, the balances were significantly different between the years, except between 2008 and 2010 (cropland site) and between 2010 and 2011 (grassland site).

Annual NEE inclusive C import and export through fertilizer and harvest at the cropland and the grassland site varied from -542 +/- 1,965 kg CO_2-C ha^{-1} (2008) to 4,174 +/- 1,576 kg CO_2-C ha^{-1} (2011) and 1,424 +/- 1,440 kg CO_2-C ha^{-1} (2008) to 8,801 +/- 1,439 kg CO_2-C ha^{-1} (2009), respectively (Tab.2.5). On average, a net emission of 1,070 +/- 948 kg CO_2-C ha^{-1} and 5,221 +/- 1,365 kg CO_2-C ha^{-1} were observed at the cropland and grassland site, respectively. At the grassland site, the emissions were higher but the variation was smaller than at the cropland site. Whereas at the cropland site the annual balances were negative in 2008 and positive in 2009, 2010 and 2011, at the grassland site the balances were always positive.
There was a weak trend at the cropland site from 2008 until 2011 (in 2007 no full year is available) to increasing emissions with time.
At the grassland site, the year with the highest emissions (2009) coincided with a conversion of the management: Until early summer 2009, the cut grass was left in the field. From July 2009 on, the mowed biomass was removed and therefore included in the balance.

Tab. 2.5: Annual and average balances for CO_2-C (incl. and excl. C import/ export through fertilizer and harvest), N_2O-N, CH_4-C exchange, NECB (net ecosystem carbon balance) and GWP (global warming potential) balances for the time spans of 20, 100 and 500 years of the cropland and the grassland site in kg ha^{-1}. M: Mean, s.e.: Standard error.

year	balances		cropland		grassland	
			m	s.e.	m	s.e.
average	CO_2 incl. Import/export	[kg CO_2-C ha^{-1} a^{-1}]	1070	948	5221	1365
	CO_2 excl. Import/export	[kg CO_2-C ha^{-1} a^{-1}]	-890	1048	3114	807
	N_2O	[kg N_2O-N ha^{-1} a^{-1}]	1.45	0.62	0.56	0.37
	CH_4	[kg CH_4-C ha^{-1} a^{-1}]	6.51	1.27	-0.92	0.52
	GWP 20	[kg CO_2-eq. ha^{-1} a^{-1}]	5183	3478	19312	5005
	GWP 100	[kg CO_2-eq. ha^{-1} a^{-1}]	4811	3478	19376	5005
	GWP 500	[kg CO_2-eq. ha^{-1} a^{-1}]	4335	3478	19268	5005
	NECB	[kg CO_2-C ha^{-1} a^{-1}]	1102	948	5245	1365
2008	CO_2 incl. Import/export	[kg CO_2-C ha^{-1} a^{-1}]	-542	1965	1424	1440
	CO_2 excl. Import/export	[kg CO_2-C ha^{-1} a^{-1}]	-1954	1736	1424	1440
	N_2O	[kg N_2O-N ha^{-1} a^{-1}]	1.41	0.44	2.05	0.97
	CH_4	[kg CH_4-C ha^{-1} a^{-1}]	12.46	0.93	3.17	0.67
	GWP 20	[kg CO_2-eq. ha^{-1} a^{-1}]	-195	7207	6446	5278
	GWP 100	[kg CO_2-eq. ha^{-1} a^{-1}]	-928	7207	6284	5278
	GWP 500	[kg CO_2-eq. ha^{-1} a^{-1}]	-1527	7207	5745	5278
	NECB	[kg CO_2-C ha^{-1} a^{-1}]	-504	1965	1453	1440
2009	CO_2 incl. Import/export	[kg CO_2-C ha^{-1} a^{-1}]	591	2009	8801	1439
	CO_2 excl. Import/export	[kg CO_2-C ha^{-1} a^{-1}]	-1367	1954	5652	1335
	N_2O	[kg N_2O-N ha^{-1} a^{-1}]	0.37	0.14	0.05	0.06
	CH_4	[kg CH_4-C ha^{-1} a^{-1}]	-0.24	0.64	-2.56	0.47
	GWP 20	[kg CO_2-eq. ha^{-1} a^{-1}]	2312	7368	32057	5276
	GWP 100	[kg CO_2-eq. ha^{-1} a^{-1}]	2332	7368	32212	5276
	GWP 500	[kg CO_2-eq. ha^{-1} a^{-1}]	2253	7368	32259	5276
	NECB	[kg CO_2-C ha^{-1} a^{-1}]	616	2009	8825	1439
2010	CO_2 incl. Import/export	[kg CO_2-C ha^{-1} a^{-1}]	56	2642	5915	1095
	CO_2 excl. Import/export	[kg CO_2-C ha^{-1} a^{-1}]	-2759	2492	2934	1037
	N_2O	[kg N_2O-N ha^{-1} a^{-1}]	2.73	1.44	0.15	0.30
	CH_4	[kg CH_4-C ha^{-1} a^{-1}]	-0.79	0.59	-3.11	0.45
	GWP 20	[kg CO_2-eq. ha^{-1} a^{-1}]	1372	9686	21466	4014
	GWP 100	[kg CO_2-eq. ha^{-1} a^{-1}]	1458	9686	21656	4014
	GWP 500	[kg CO_2-eq. ha^{-1} a^{-1}]	854	9686	21692	4014
	NECB	[kg CO_2-C ha^{-1} a^{-1}]	81	2642	5938	1095
2011	CO_2 incl. Import/export	[kg CO_2-C ha^{-1} a^{-1}]	4174	1576	4742	1409
	CO_2 excl. Import/export	[kg CO_2-C ha^{-1} a^{-1}]	2521	1561	2446	1338
	N_2O	[kg N_2O-N ha^{-1} a^{-1}]	1.29	0.47	0.00	0.13
	CH_4	[kg CH_4-C ha^{-1} a^{-1}]	14.60	2.90	-1.16	0.49
	GWP 20	[kg CO_2-eq. ha^{-1} a^{-1}]	17244	5778	17281	5168
	GWP 100	[kg CO_2-eq. ha^{-1} a^{-1}]	16380	5778	17351	5168
	GWP 500	[kg CO_2-eq. ha^{-1} a^{-1}]	15759	5778	17377	5168
	NECB	[kg CO_2-C ha^{-1} a^{-1}]	4215	1576	4767	1409

The parameters for the GPP-model (GP_{max} and α) are correlated with the biomass (Tab.2.6). The regressions can be described by a rectangular hyperbola (Michaelis-Menten-equation) and an exponential equation by combining GP_{max} and α with complete biomass, dry mass of complete biomass, green biomass and dry mass of green biomass. Best fit was achieved with green biomass. Greater amounts of green biomass mean higher C fixation rates.

Tab. 2.6: Regression equations and coefficient of determination between green biomass (x) and the model parameters maximum rate of carbon fixation at PAR infinite (GP_{max}) and light use efficiency (α).

site	parameter	regression equations	coefficient of determination
cropland	Gpmax	$y = -326.10*x/(0.704+x)$	$R^2 = 0.73$ ***
cropland	α	$y = -0.062*x/(0.072+x)$	$R^2 = 0.74$ ***
grassland	Gpmax	$y = -39.16*(1-e^{-20.34x})$	$R^2 = 0.36$ ***
grassland	α	$y = -0.063*x/(0.019+x)$	$R^2 = 0.15$ **

*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$; R^2= coefficient of determination (Pearson)

2.3.6 Nitrous oxide

Emissions of nitrous oxide were generally low at both sites, despite high nitrate contents in the soil. The annual course of the N_2O fluxes at the cropland site was marked by very low flux rates (most of them not different from 0), interrupted by peaks with very high emissions, which indicates, that single events caused these peaks (Fig.2.11). In most cases fertilization with pig slurry and/or tillage took place, prior to peaks. Immediately after the fertilization, the NH_4^+ content peaked for a short time, followed by the NO_3^- and N_2O peaks, which lasted longer (Fig.2.11). The peaks following fertilization lasted for about seven to twelve weeks. Approximately 11 g N m^{-2} were applied as pig slurry. The N_2O emission amounted to 70 (2008), 279 (2010) and 85 mg N_2O-N m^{-2} (2011) during the subsequent seven to twelve weeks. Thus, only a very small portion of the applied N was converted to N_2O. Spatial variability in N_2O fluxes (expressed as standard errors) was very high. The maximum release was detected on 02.06.2010. (Tab.2.7). Occasionally, N_2O uptake took place.

At the grassland site most N_2O fluxes were not different from 0 and a seasonal pattern was not detectable. Positive and negative fluxes were observed in every season. Highest emission occurred on 03.06.2008 (Tab.2.7). The spatial variability was high as well.

Correlations between N_2O fluxes and site parameters were not significant ($p < 0.05$).

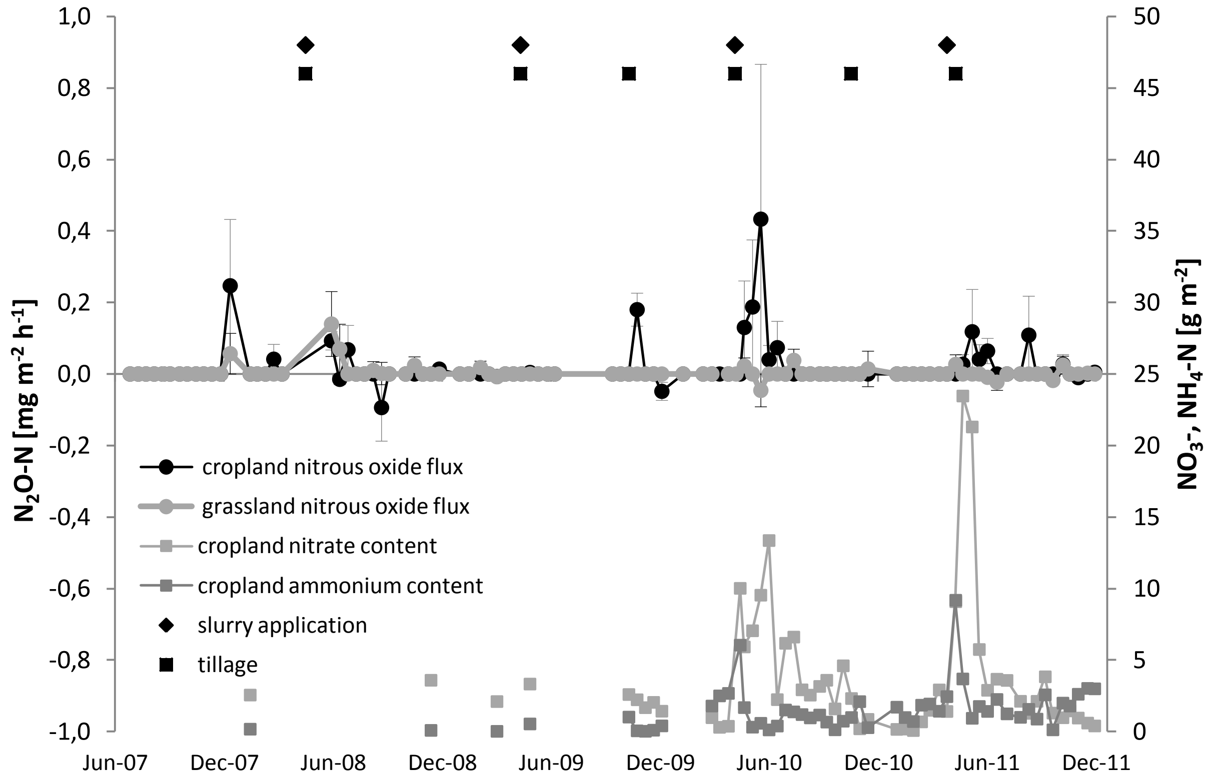

Fig. 2.11: Annual course of N_2O flux of the two sites (left axis). Mean of the 3 collars, error bars are standard errors. Annual courses of nitrate and ammonium content in the 0-20 cm soil-layer (right axis). Fertilizing events and tillage events at the cropland site are plotted.

Tab. 2.7: Hourly maximum uptake and maximum release of N_2O-N (left) and CH_4-C (right) of the cropland and the grassland site. Mean of the three collars and standard error (s.e.).

site	max uptake +/- s.e. [mg N_2O-N m^{-2} h^{-1}]	max release +/- s.e. [mg N_2O-N m^{-2} h^{-1}]	max uptake +/- s.e. [mg CH_4-C m^{-2} h^{-1}]	max release +/- s.e. [mg CH_4-C m^{-2} h^{-1}]
cropland	-0.09+/- 0.09	0.43 +/- 0.43	-0.14+/- 0.14	1.94 +/- 0.32
grassland	-0.05 +/- 0.05	0.14 +/- 0.09	-0.18 +/- 0.15	1.14 +/- 0.48

Annual N_2O emissions at the cropland site ranged from 0.37 +/- 0.14 to 2.73 +/- 1.4 kg N_2O-N ha^{-1} a^{-1}, on average 1.45 +/- 0.62 kg N_2O-N ha^{-1} a^{-1} (Tab.2.5). At the grassland site the annual balances were lower; the lowest value was less than 0.01 +/- 0.13 kg N_2O-N ha^{-1} a^{-1}, the highest one was 2.05 +/- 0.97 kg N_2O-N ha^{-1} a^{-1} (Tab.2.5). The average value was 0.56 +/- 0.37 kg N_2O-N ha^{-1} a^{-1}. Whereas the annual N_2O balances of the cropland and grassland sites were not significantly different in 2008 and 2009, they differed significantly in 2010 and 2011 (Tab.2.5). Averaged over the whole period of four years annual N_2O emissions were almost three times higher at the cropland than at the grassland site.

2.3.7 Methane

Methane emissions were generally low at both locations and occurred mainly in summer (Fig.2.12). At the cropland site there were CH_4 peaks in May and June 2008, and in August and September 2011. Highest emissions were measured on 31.08.2011 (Tab.2.7). These highest CH_4 fluxes were observed after a period of heavy rainfall with subsequent raising wl (August 2011). During the other time the CH_4 flux alternated around 0. Several measurements had no detectable fluxes. On 03.09.2007 and 16.12.2009 the highest CH_4 uptake was assessed.

At the grassland site the highest CH_4 emissions occurred in the beginning of the measurement period in summer 2007 and in February 2008. On 13.06.2007 the highest flux rate was determined (Tab.2.7). The highest uptake of CH_4 has been measured on 17.06.2008.

Correlations between CH_4 fluxes and site parameters were not significant ($p < 0.05$).

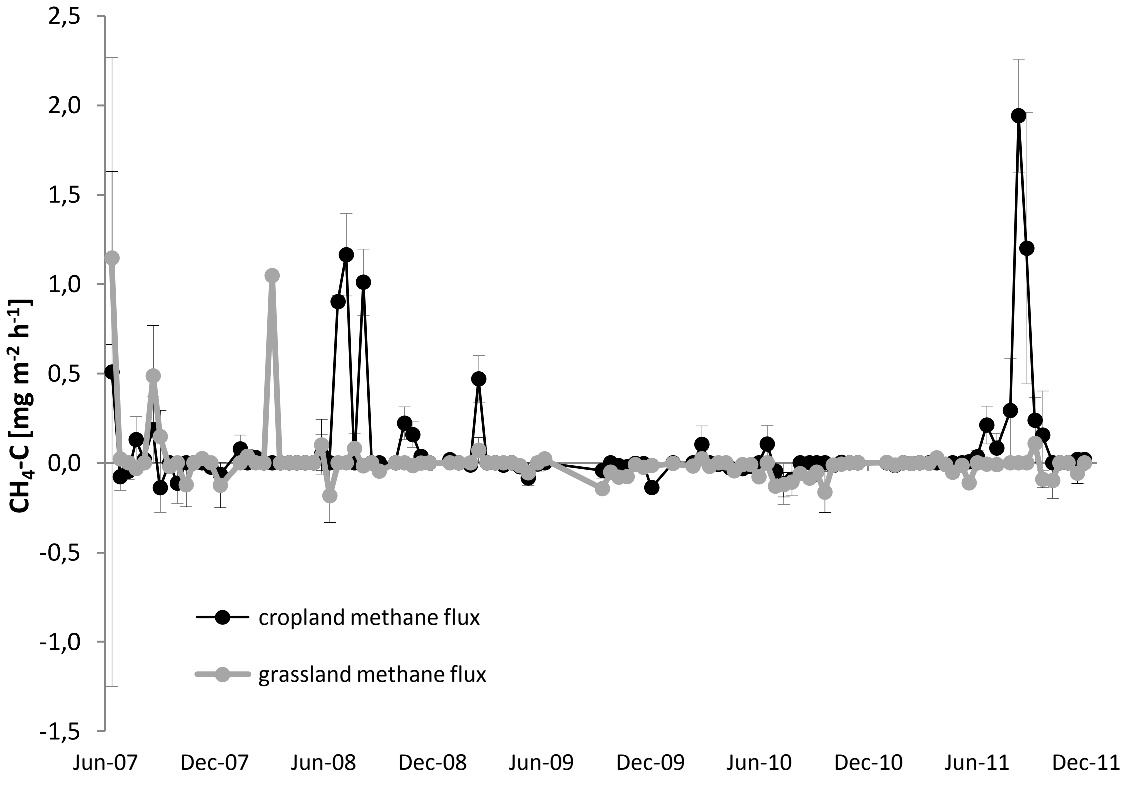

Fig. 2.12: Methane flux of the cropland and the grassland site (from June 2007 until Dec 2011) in mg m^{-2} h^{-1}

In 2008 and 2011 the cropland site emitted 12.5 +/- 0.9 and 14.6 +/- 2.9 kg CH_4-C ha^{-1} a^{-1} (Tab.2.5). In contrast, the years 2009 and 2010 featured very small uptakes. On average over the four years a small release was detected. At the grassland site only in 2008 a positive balance was observed, whereas the fluxes were negative in the other years (Tab.2.5). On average over the four years the site was a methane sink.

2.3.8 Net ecosystem carbon balance and global warming potential

NECB at the cropland site ranged between -504 +/- 1,965 kg CO_2-C ha^{-1} a^{-1} and 4,215 +/- 1,576 kg CO_2-C ha^{-1} a^{-1} (Tab.2.5). The NECB at the grassland site was higher and ranged from 1,453 +/- 1,440 kg CO_2-C ha^{-1} a^{-1} to 8,825 +/- 1,439 kg CO_2-C ha^{-1} a^{-1} (Tab.2.5). The difference between the NEE (including C import/export through fertilizer and harvest) and the NECB was small, because carbon-release was mainly determined by respiration and C import/export through fertilizer and harvest.

GWP100 balances at the cropland site ranged between -928 +/- 7,207 kg CO_2-eq. ha^{-1} a^{-1} and 16,380 +/- 5,778 kg CO_2-eq. ha^{-1} a^{-1} (Tab.2.5). In 2009 and 2011 it was mainly the CO_2 gas exchange that determined the GWP100 balance. In contrast, in 2008 and 2010 also N_2O and CH_4 played a significant role. At the grassland site the GWP 100 balances ranged from 6,284 +/- 5,278 to 32,212 +/- 5,276 kg CO_2-eq. ha^{-1} a^{-1} (Tab.2.5). In contrast to the cropland site, the GWP100 balance at the grassland site was almost only determined by the CO_2 emissions. Changing the time perspective of the GWP assessment from 100 to 500 years did not make a big difference for both sites, because of the high contribution of CO_2 to the greenhouse gas emissions (Tab.2.5).

2.4 Discussion

2.4.1 Carbon dioxide

2.4.1.1 Evaluation of methodology

The CO_2 concentration change over time inside the chamber was usually significantly linear. This is in contrast to Kutzbach et al. (2007) who suppose a non linear change of the gas concentration. Thus, if the chambers are big enough and the measurement is short, no saturation occurs in the beginning of the measurement and a linear equation for gas flux calculation can be adapted. However, the linearity must be monitored, in order not to under- or overestimate the gas fluxes, which leads to false annual balances.

The PAR should be constant (< 5 cv %) during measurement, because only small changes in PAR influences directly the gas concentration curve over time.

To fit the CO_2 exchange dynamics, the models of Lloyd & Taylor (1994) and Michaelis & Menten (1913) were used. These regression models account for the main short term driving forces (temperature and PAR) and were already applied by numerous authors leading to appropriate calculations of gas fluxes using site parameters (Bubier et al. 1998, Frolking et al. 1998, Drösler 2005, Veenendaal et al. 2007, Elsgaard et al. 2012, Beetz et al. 2013). Including wl as a short term variable does not improve the models (Elsgaard et al. 2012).
In general, stable values for every measurement campaign were obtained. The fit of all measured and all modeled results is very accurate with $R^2 = 0.95$ at the two sites. However, occasionally the relationship is weak, leading to a high standard error of the fluxes.
The processes respiration (R_{eco}) and photosynthesis (GPP) were separated in two components with different driving forces, in order not to underestimate highest and lowest values (Bubier et al. 1999).

The parameters at each measurement campaign were fitted separately, or at least bimonthly (mostly in winter or late autumn) to account for the different conditions throughout the year (long term and medium term variables: e.g. phenology, vegetation, wl, management). Bubier et al. (1999) used the entire data set to determine the parameters, which is less accurate. They achieved much smaller coefficients of determination ($R^2 = 0.79$-0.83) than at the cropland and grassland site ($R^2 = 0.89$-0.95). Drösler (2005) took the data set from the entire year for the parameterisation of the R_{eco}-model, because he found no seasonal effect on the respiration-temperature relationship.
Between the measurement campaigns linear interpolation was conducted, thus assuming that long term and medium term factors also change linearly. The time span between measurement campaigns was kept reasonably short, in order to include these mean term effects on carbon dioxide fluxes (cf. Beetz et al. 2013). Before and after specific events, e.g. tillage or harvest, additional measurement campaigns were conducted.
Immediately after harvesting events, it was assumed that no photosynthesis occurs. A measurement directly after harvest often is not possible for organizational reasons and might disturbe the system. Setting GPP to 0 is plausible, but leads to a slight underestimation of

GPP and, thus, to an overestimation of net emissions. At the cropland site, indeed, no living plant biomass remained after tillage or harvest and the assumption is correct.

Despite these shortcomings, the advantages of the chamber method are: using transparent and opaque chambers, R_{eco} and NEE were measured and modeled separately. The gas exchange is measured directly and in a site-specific way within a small scale mosaic of different land-uses. There is no need for an electrical connection. The method is cheap and applicable under all weather conditions. Identical chambers were used by Drösler (2005) and Beetz et al. (2013). On the one hand, the size of the chambers makes them suitable for handling by one person. On the other hand, the chambers are large enough to include a large proportion of the field heterogeneity of gas fluxes, and the coefficient of variation cannot be reduced considerably by even larger chambers (Kaiser et al. 1996). Moreover, the side length of the collar is equal to the row distance of the maize. With three to five plants per collar, the conditions inside the chambers are representative for the field. Carbon exported through harvest could be determined very precisely, because it was measured directly from the harvested biomass in the collars. This is crucial because the final NEE balance is predominantly determined by the carbon exported through harvest. Carbon imported through slurry application was estimated based on the information on organic fertilization given by the farmer, containing a higher uncertainty. However, the error is less than 200 kg ha^{-1}, which is small compared to R_{eco}, GPP and export.

Bubier et al. (1999) found a gradient of GP_{max} from bog across poor fen and intermediate fen to rich fen. Rich fen had the highest GP_{max} value (-12 +/- 1.02 µmol CO_2 m^{-2} s^{-1}). For α there existed no trend, the rich fen shows -0.0142 +/- 0.0018 µmol CO_2-C m^{-2} s^{-1}/µmol m^{-2} s^{-1}. At the cropland and the grassland site the parameter estimates revealed higher values (Tab.2.2 & Tab.2.3). The maize on the cropland site is a highly productive plant with a high growth rate and a high CO_2 assimilation potential. And also the grassland site, though it is not fertilized, has productive grassland vegetation with a high growth potential during vegetation period. Due to the large differences between the productive vegetation period and the dormant winter season also α shows this large variation.

For calculation of NECB not all carbon fluxes were measured. Appropriate references of dissolved inorganic carbon (DIC) are not available. The combination of these errors results in a small uncertainty, however all reviewed references did not consider these sources of errors as well. Carbon monoxide (CO) and volatile organic C (VOC) does not occur at the examination sites.

2.4.1.2 Annual course and monthly balances of ecosystem respiration

Higher respiration in April, May and October at the grassland site compared to the cropland site can be attributed to additional autotrophic respiration (Fig.2.7 & Fig.2.8). Whereas, on the grassland site with permanent sward plants grow as soon as the temperature is warm enough, on the cropland site the soil is bare or covered with few plants outside the vegetation period of the maize, and autotrophic respiration is low during these periods.

The annual course of R_{eco} at the grassland site (Fig.2.8) is very similar to those reported by van den Bos & van de Plassche (2003b), Veenendaal et al. (2007), Peichl et al. (2011) and Kandel et al. (2012), showing a clear seasonal trend and highest emissions in June or July. Monthly R_{eco} of the grassland site is similar to that of an agricultural grassland fen (reed canary grass = RCG, wl similar to the grassland site during growing season, but lower in winter) in Denmark (Kandel et al. 2012). However, eddy covariance (EC) measurements in high intensity grasslands on fen in the Netherlands reveal a different seasonality: From approximately May until October, R_{eco} is slightly lower, and from November until March, R_{eco} is slightly higher compared to the grassland site (Veenendaal et al. 2007); also Dirks et al. (2000) observed lower R_{eco} during growing season (April, May, June, September; no flux rates for other months published) compared to the grassland site. In high intensity grasslands on gleysol with SOC concentration of 5.9 % in the 0-20 cm soil layer, R_{eco} is lower during growing season compared to the grassland site due to the low C content of the gleysol (Byrne et al. 2005, Peichl et al. 2011). During winter, the monthly R_{eco} were similar in the above cited sites and the grassland site.

The annual course of R_{eco} at the cropland site (Fig.2.7) is very similar to that of a cropland fen (spring barley = SB, wl similar to the cropland site during growing season, but lower in winter) in Denmark (Kandel et al. 2012). Monthly R_{eco} of the SB site is similar to the cropland site in all months (except in January). Another drained fen (barley under sown by grass) in Denmark revealed higher R_{eco} than the cropland site during the whole year except in

November (Petersen et al. 2012). Especially during the cold period (Oct. and Dec. - March), R_{eco} was twice as high in the Danish study compared to the cropland site. This may be attributed to the higher biomass of the under sown grass after harvest of the barley in the Danish study compared to the almost bare soil with some weeds of the cropland site. The higher biomass leads to a higher autotrophic respiration under temperate climate conditions and also to higher heterotrophic respiration due to the mineralization of dead plant debris. During most of the year, the wl at the Danish site is several cm lower than at the cropland site. Only in April, September, October and November is the wl similar at the cropland site and the Danish site.

2.4.1.3 Annual course and monthly balances of net ecosystem exchange

The grassland site sequestrated CO_2 in May, reflecting the high growth rate and carbon assimilation of the grass sward in spring before the first cut (Fig.2.10: on average -190 kg CO_2-C ha^{-1} a^{-1}). In June, the grassland site started to release CO_2 as R_{eco} outbalanced GPP because GPP was set to 0 under the assumption that the cuttings impeded the growth of the grass. The monthly NEE are similar to those of the RCG site of Kandel et al. (2012), except in June, July and August, because the RCG site was cut only once (in September), which led to a higher (more negative) GPP and, therefore, higher (more negative) NEE between June and August compared to the grassland site which was cut two to three times, starting in June or early July. EC measurements in high intensity grasslands on Dutch fens showed higher monthly net uptake and lower monthly net emissions during growing season compared to the grassland site, due to lower monthly R_{eco}: Dirks et al. (2000) found higher net uptake in April, May and June and lower net release in September (data of other months not published); Veenendaal et al. (2007) observed lower net emissions in June and higher net sequestration in April and August, while in February, March and July the fluxes were close to 0.

Peichl et al. (2011) observed much lower net monthly emissions of an Irish gleysol under intensively managed grassland than found at the grassland site. However, Peichl et al. (2011) measured the gas exchange on a loamy mineral soil, where much lower net CO_2 emissions should occur due to the low organic matter content of 5.9 %.

Monthly NEE of the cropland site (Fig.2.9) are similar to those reported from the Danish SB site (Kandel et al. 2012). However, the annual course of the monthly net CO_2 fluxes is slightly different, due to different crops. Highest net accumulation at the Danish SB site and at the cropland site (about -1,600 kg CO_2-C ha^{-1} $month^{-1}$) occurred in June (summer barley) and August (maize), respectively.

2.4.1.4 Interannual variability in balances

Both at the cropland site and the grassland site, the variability in the gas fluxes between the years was high, which is attributed to different weather conditions and management events. Especially NEE is very prone to interannual variability, because it represents the difference between the big fluxes of GPP and R_{eco} (Drösler et al. 2008). In the boreal zone, Shurpali et al. (2009) observed a high inter annual variability as well. Multiyear measurements are therefore useful.

At the cropland site the management changed from silage maize to corn-cob-mix maize (CCM) in 2007, which resulted in an imbalance of the soil-plant-system, as from 2007 on more organic material remained on the field and less carbon was exported by harvest. The management change could at least temporarily lead to lower net CO_2 emissions since plant residues may not be degraded within one year after harvest (Rochette et al. 1999).
In 2008, the cropland site was accumulating net carbon. From 2009 until 2011, the NEE showed an increasing trend. In 2011, NEE at the cropland site was similar to that of the grassland site (NEE without C import and export through fertilizer and harvest at the cropland site is not significantly different from that at the grassland site). Thus, the carbon dioxide fluxes are quite similar at the two sites which are very close to each other and have very similar peat and soil water characteristics.
Hence, consideration of land use history is of major importance.

2.4.1.5 Annual carbon dioxide balance and site parameters

At the grassland site, annual R_{eco} and NEE including C import and export through fertilizer and harvest (21,309 +/- 623 and 5,220 +/- 1,365 kg CO_2-C ha^{-1} a^{-1}, respectively on average; Tab.2.5) correspond well to literature data. Annual R_{eco} of temperate fens used as grassland range from 15,700 to 28,900 +/- 2,200 CO_2-C ha^{-1} a^{-1} (Jacobs et al. 2007, Veenendaal et al. 2007, Elsgaard et al. 2012, Kandel et al. 2012). Peatlands in colder regions and soils with lower C contents show generally lower values: According to Maljanen et al. (2010), annual

R_{eco} of boreal peatlands drained for grass swards range from 6,000 to 15,763.6 kg CO_2-C ha^{-1} a^{-1}. Peichl et al. (2011) determined an annual R_{eco} of 14,420 ± 520 kg CO_2-C ha^{-1} a^{-1} in a gleysol. The annual NEE including C import and export through fertilizer and harvest for temperate and boreal fens used as grassland range between 4,000 kg CO_2-C ha^{-1} a^{-1} (Byrne et al. 2004, Höper 2007, Veenendaal et al. 2007) and 7,900 kg CO_2-C ha^{-1} a^{-1} (Kandel et al. 2012, Elsgaard et al. 2012).

In contrast, the cropland site (annual R_{eco}: 12,829 +/- 569 kg CO_2-C ha^{-1} a^{-1}, annual NEE including C import and export through fertilizer and harvest: 4,174 +/- 1,576 kg CO_2-C ha^{-1} a^{-1}, in 2011; Tab.2.5) showed a low CO_2 exchange compared to most literature data. Moreover, CO_2 emissions were not higher than at the grassland site, which is contrary to the hypothesis. Annual R_{eco} of the Danish cropland site cultivated with spring barley was 12,880 +/- 190 kg CO_2-C ha^{-1} a^{-1} (Kandel et al. 2012), which is similar to the result of the cropland site. However, the Danish fen cultivated with barley under sown by grass reveals a higher annual R_{eco} than the cropland site (Elsgaard et al. 2012, Petersen et al. 2012). Annual NEE including C import and export through fertilizer and harvest of peatlands used as cropland range from 4,000 to 19,091 kg CO_2-C ha^{-1} a^{-1} (Kasimir-Klemedtsson et al. 1997, Byrne et al. 2004, Höper 2007, Elsgaard et al. 2012, Kandel et al. 2012).

The reason for the discrepancies lies in the different properties which drive the gas fluxes at the sites. One of the main driving forces for R_{eco}, and therefore also for NEE, is the wl. The deeper the wl the higher peat mineralization (Tuittila et al. 1999, Waddington et al. 2002, van den Bos & van de Plassche 2003b, Danevcic et al. 2010). The maximum of peat mineralization occurs at a wl depth of approximately 60 to 100 cm below ground surface in summer (Mundel 1976, Höper 2007, Oleszczuk et al. 2008, Mäkiranta et al. 2009). At the cropland site wl were considerably higher (Fig.2.1). As a consequence also wfps was high (Fig.2.2). Linn & Doran (1984) found highest microbial respiration in soils at a soil water content equivalent to 60 % wfps under laboratory conditions. The wfps at the cropland site was usually above 60 %, which led to oxygen-limiting conditions. In May and June 2010, wfps dropped to a very low value (about 40 %) for a short time period when dryness would impede peat mineralization as compared to optimal conditions (at 60 % wfps). Only in spring 2011, wfps values optimal for microbial respiration occurred.

Couwenberg et al. (2011) established a linear regression equation by:

NEE [kg CO_2 ha^{-1} a^{-1}] = 752 · mean wl [cm below ground surface] - 4,750.

Based on this equation emissions would amount to about 4,447 kg CO_2-C ha^{-1} a^{-1} at the cropland site, which correspond well to the determined NEE in 2011, four years after the conversion.

The high bulk density, high decay degree and low organic carbon content of the uppermost layer of the cropland site indicate that the peat is intensely degraded, possibly due to its long-term land-use history (Tab.2.1). Mundel (1976) assumes that peat mineralization will progressively slow down with time. Therefore, the relatively low NEE values of the cropland site may also be attributed to peat degradation. However, Elsgaard et al. (2012) found high emissions of CO_2 in fen peatlands with highly decomposed peat. The assumption of Mundel (1976) has not yet been proven by empirical results.

2.4.1.6 Model parameters and biomass

Adding the biomass as a long-term parameter into the CO_2 models can improve the interpolation procedure between the measurement campaigns. In addition, fewer measurement campaigns have to be conducted. Veenendaal et al. (2007) observed a strong correlation between GP_{max} and LAI and suggest that LAI is the main driver for GP_{max} during the growing season. They found also a significant relationship between α and LAI. Both the cropland and the grassland showed a good relationship between GP_{max} or α and the above-ground biomass. The attempt was to model GP_{max} and α by fitting non linear regression equations against biomass. This is highly significant for the cropland site and significant for the grassland site, but the variability in GP_{max} and α at great amounts of above-ground biomass is still rather high.

2.4.2 Nitrous oxide and methane

The high N_2O emission peaks at the cropland site were triggered by application of slurry manure and lasted for about seven to twelve weeks, after that emissions decreased (Fig.2.11). Increased N_2O emissions after application of slurry or other N-fertilizer are well established (Kaiser et al. 1998, Chadwick et al. 2000, Flessa & Beese 2000, Couwenberg 2011, Jassal et al. 2011). A delay of a few weeks was found, until the nitrification of the slurry NH_4^+ to NO_3^- caused the N_2O peak. *A* delay after applying organic fertilizer on terrestrial soils has been observed by several authors (Paul et al. 1993, Chadwick et al. 2000, Flessa & Beese 2000).

The N_2O peaks in 2010 and 2011 caused by the application of slurry lasted longer than one measurement period, thus the emission of these events were fairly reliably captured. However, in 2008 the application of the fertilizer (20.04.2008) was followed by only one measurement with high emissions (03.06.2008), because in April and May no measurements took place. In 2009, there was no peak at all. Thus, in 2008 and 2009 the emissions might be underestimated. Only about 0.6-1.6 % of the N or 69.9-279.4 mg N m^{-2} (2009 excluded) through the applied slurry was emitted in the form of N_2O during the following seven to twelve weeks, probably because later, maize absorbs NO_3^- and limits therefore denitrification (Danevcic et al. 2010). the results at the cropland site lie in the range of results reported by other authors (Paul et al. 1993, Kaiser et al. 1998, Chadwick et al. 2000, Flessa & Beese 2000).

The N_2O peak on 04.11.2009 followed grubbing (21.10.2009). Kasimir Klemedtsson et al. (2009) found N_2O peaks after cultivation, ploughing and harrowing The reasons for that might be that soil perturbation leads to increased soil mineralization (Regina et al. 2004, Kasimir Klemedtsson et al. 2009). In addition, roots competing for the released mineral nitrogen are not present and conditions for N_2O production are favourable anyway when soil cultivation takes place (Kasimir Klemedtsson et al. 2009).

According to Martikainen et al. (1993) soils of arable land offer very favourable conditions for N_2O production, because ploughing and fertilizing increase the availability of ammonium and nitrate.

The grassland site received no fertilizer and the content of available mineralized nitrogen (nitrate and ammonium) was lower. Consequently, the emissions were very low (Tab.2.5 & Tab.2.7). Other fens used as extensive grassland reveal higher N_2O fluxes in the range of -0.03 mg N_2O-N m^{-2} h^{-1} maximum uptake and 1.8 mg N_2O-N m^{-2} h^{-1} maximum release (Meyer 1999, Kasimir Klemedtsson et al. 2009).

Beside fertilizing and soil cultivation there are other events mentioned, like freeze/thaw events (Christensen & Christensen 1991, Flessa et al. 1998, Kaiser et al. 1998, Brumme et al. 1999, Meyer 1999, Kasimir Klemedtsson et al. 2009, Couwenberg 2011) and periodically wetness, e.g. rainfall after a dry period (Flessa et al. 1998, Meyer 1999). Freeze/thaw events did not occur at the cropland and grassland site. The peak on 31.08.2011 took place after heavy rainfall following a dry period, and might be attributed to periodically wetness (Fig.2.2 & Fig.2.11).

To detect large emission events is of a high importance, because it is the main contributor to the annual balance. Brumme et al. (1999) established three types of N_2O emission patterns: a) seasonal emission patterns, b) background emission patterns, and c) event-based emission patterns. The annual courses of the emissions at the cropland and the grassland site can be classified to the types “event-based emission patterns”, and “background emission patterns”, respectively.

It is possible that single events of high emissions were not captured, for example after fertilizing or soil cultivation, because measurements were done every two weeks. This was also recognized by Regina et al. (2004). However, a higher temporal resolution was not possible. In addition, measurement errors cannot be excluded due to the low accuracy of the gas chromatograph.

Other important driving parameters for N_2O release are wfps and wl (Flessa et al. 1998, Meyer 1999, Smith & Dobbie 2002, Augustin 2003, Maljanen et al. 2003, Regina et al. 2004, Weslien et al. 2009). According to Kaiser et al. (1998), Meyer (1999), Flessa & Beese (2000) and Maljanen et al. (2003) rates of N_2O formation are highest at high wfps (> 60 %) and optimal at about 70 to 90 %. In contrast, at the cropland and the grassland site the highest N_2O fluxes occurred at dry conditions with low wfps (Fig.2.2 & Fig.2.11), which is in accordance with the findings of Kasimir Klemedtsson et al. (2009).

Further driving forces are temperature, pH, vegetation, oxygen and carbon availability, as well as enzyme status and quality of the bacterial population (Firestone & Davidson 1989, Brumme et al. 1999, Meyer 1999, Kasimir Klemedtsson et al. 2009, Danevcic et al. 2010). Because of interaction of different factors on production, consumption and transport of N_2O, the N_2O fluxes are subject to a great temporal and spatial variability and relationships are often not detectable (Kroeze & Mosier 2002, Augustin 2003, Kasimir Klemedtsson et al. 2009).

Conditions for N_2O formation were probably not optimal at both sites, compared to other agriculturally used fen areas. In general the locations were very wet, especially during winter time. From June until October the maize at the cropland site has a great demand of NO_3^- and probably limits therefore nitrate availability for the denitrification process. Thus, detectable emissions occurred mainly in spring and early summer.

Methane exchanges at the two sites (Tab.2.7 & Fig.2.12) are low and similar to the results of comparable study sites (Flessa et al. 1998, Meyer 1999, Kasimir Klemedtsson et al. 2009). However, the cropland site shows higher emissions than the grassland site. The reasons for the comparatively high emissions of the cropland site (Tab.2.5) are the occasionally very wet conditions and the application of slurry (Shurpali et al. 1993, Macdonald et al. 1998, Nykänen et al. 1998, Flessa & Beese 2000, Chadwick et al. 2000, Christensen et al. 2003). In addition, the uptake of CH_4 after N fertilization is limited (Jassal et al. 2011, Teepe 1999), which explains the higher uptake rates at the unfertilized grassland site, in contrast to the cropland site.

Annual nitrous oxide exchange of our examination sites (Tab.2.5: 0,56 +/- 0,37 and 1,45 +/- 0,62 kg N_2O-N ha^{-1} a^{-1}, at the grassland and cropland site, respectively in average) are within the range of literature data, however at the lower end (Velthof et al. 1996, Flessa et al. 1998, Höper & Blankenburg 2000, Augustin 2003, Byrne et al. 2004, Höper 2007, Kasimir Klemedtsson et al. 2009, Couwenberg et al. 2011: -3,8 to 28 and of -3,8 to 56 kg N_2O-N ha^{-1} a^{-1} at grassland and cropland sites, respectively).

Studies show for temperate fens used as cropland a small annual CH_4 uptake with little variation (Flessa et al. 1998, Augustin 2003, Kasimir Klemedtsson et al. 2009: -0.2 to -0.1 kg CH_4-C ha^{-1} a^{-1}). At the grassland site the observed uptake is slightly higher than in other surveys in temperate fens used as grassland. The results of Flessa et al. (1998), Meyer (1999), van den Pol-van Dasselaar et al. (1999), Augustin (2003) and Kasimir Klemedtsson et al. (2009) amount to -0.7 to 1 kg CH_4-C ha^{-1} a^{-1}.

2.4.3 Global warming potential

The global warming potential was predominantly determined by the net CO_2 exchange. Consequently, the two sites show similarly high GWP100 balances, taking into account changes in management (Tab.2.5: in 2011 17,351 +/- 5,168 and 16,380 +/- 5,778 kg CO_2-eq. ha^{-1} a^{-1}, at the grassland and cropland site respectively).
The results of the grassland site (Tab.2.5: on average 19,376 +/- 5,005 kg CO_2-eq. ha^{-1} a^{-1}) are in the range of the results of similar studies (Byrne et al. 2004, Höper 2007, Maljanen et al. 2010). However, at the cropland site the GWP100 balance is lower than at other peatlands

used as cropland (Byrne et al. 2004, Höper 2007, Maljanen et al. 2010). This discrepancy is mainly because of a lower NEE balance, and, to a lesser extent, due to a lower N_2O balance. The main reason is the comparatively wet condition at the cropland site.

According to these results, the wl is the main site factor for the release of GHG from agriculturally used fens, whereas the type and intensity of land-use is of minor importance. Thus, the hypothesis that both sites emit high amounts of GHG is confirmed, while the assumption that cropland leads to higher emissions could not be confirmed.

2.5 Conclusions

The results show that cropland and grassland on fen can have a similarly high GHG exchange. R_{eco} and GPP are both higher at the grassland site, resulting in a NEE which is almost equal to the cropland site. The results confirm the mean annual wl being the best single explanatory variable for annual GHG fluxes, whereas land use type and intensity seem not to be as important. Variability in gas fluxes between the years was high, and multiyear measurements are therefore useful. Short-term changes in management lead to temporary changes in net C fluxes.

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3 Greenhouse gas emissions from agriculturally used organic soils in Lower Saxony

Abstract

Data about the exchange of greenhouse gases in agriculturally used bogs and histosols with just small peat layers are scarce, especially in the temperate zone. Histic gleysol is not peatland according to the German soil classification, however, histic gleysol is organic soil and high emissions of greenhouse gases are expected. The gas exchanges of carbon dioxide, nitrous oxide and methane as well as the global warming potentials were calculated for a bog, a bog covered with a layer of sand and a histic gleysol covered with a layer of sand used as croplands as well as a histic gleysol covered with a layer of sand used as grassland in Northern Germany. The gas exchange was measured roughly monthly year-round with a closed chamber technique from September 2009 until December 2011. Net ecosystem exchange (CO_2) was modelled in high resolution using site-specific relations between ecosystem respiration and temperature and between gross primary production and photosynthetic active radiation as model parameters. The measured and modelled values fit very well together (R^2 between 0.95 and 0.99). The CO_2 emissions were similar (approx. 6,000 +/- 700 kg CO_2-C ha^{-1} a^{-1} in average) at the cropland sites, whereas emissions were lower (approx. 4,000 +/- 365 kg CO_2-C ha^{-1} a^{-1}) at the grassland site. Also the N_2O emissions were higher at the cropland sites (between 16 +/- 11 and 22 +/- 0.1 kg N_2O-N ha^{-1} a^{-1}) compared to the grassland site (0.8 +/- 0.5 kg N_2O-N ha^{-1} a^{-1}). CH_4 fluxes were close to 0. GWP100 balances amounted to 26,800 +/- 9,500, 32,200 +/- 1,300 and 34,000 +/- 400 kg CO_2-eq. ha^{-1} a^{-1} at the bog site covered with a layer of sand, the bog site and the histic gleysol site covered with a layer of sand, respectively. The grassland site showed a much lower GWP100 balance with approx. 13,900 +/- 2,300 kg CO_2-eq. ha^{-1} a^{-1}. Neither the layer of sand nor the peat depth influenced the GHG emissions from the cropland sites. Grassland on histic gleysol covered with a layer of sand reveals a comparatively low NEE and GWP100 balance compared to other grassland on organic soil, probably due to the low carbon content. Highest N_2O fluxes occurred at a wfps between 55 and 80 %. Recommended measures to reduce GHG emissions of agriculturally used organic soils are a high water level and a low intensity land use.

3.1 Introduction

Agriculturally used organic soils are strong sources of greenhouse gases. Cultivation of organic soils implies drainage and, possibly, fertilization and soil cultivation. Drainage is known to cause mineralization of the peat (Höper & Blankenburg 2000, Oleszczuk et al. 2008, Couwenberg 2009), and lead to the release of high amounts of carbon dioxide and nitrous oxide (Mundel 1976, Höper 2007, Couwenberg 2011). Tillage practices can lead to accelerated decay (Chapman et al. 2001) and, thus to higher CO_2 emissions (Freibauer et al., 2004, Oleszczuk et al. 2008), fertilization might promote N_2O production (Paul et al. 1993, Merbach et al. 1994, Nykänen et al. 1995, Regina et al. 1996, Kaiser et al. 1998, Chadwick et al. 2000, Flessa & Beese 2000, Couwenberg 2009, Couwenberg 2011, Jassal et al. 2011). Therefore, organic soils under agriculture show a high variation in GHG emissions. An important factor is the land use intensity: The wl at cropland sites need to be lowered more than at grassland sites (Oleszczuk et al. 2008). In addition, at grassland sites no soil cultivation takes place. Extensively used grasslands are not fertilized in contrast to intensively used grassland. Moreover, gas emissions depend on the peat type (Höper 2007, Oleszczuk et al. 2008) and the climate zone (Couwenberg 2011). Fens might emit higher amounts compared to bogs. Peatlands in the temperate zone have a higher release of GHG than boreal organic soils.
In contrast to carbon dioxide and nitrous oxide, methane emissions are very small or a small uptake of CH_4 might occur.

The high variation of different organic soil types is not covered in the literature. No studies have been conducted in histic gleysol. Histic gleysol is according to the German definition not a peatland, although histic gleysol is organic soil and emissions of CO_2 and N_2O can be assumed. In agriculturally used bogs, only a few studies about the GHG exchange have been carried out (Oleszczuk et al. 2008) and only a very few in sites mixed with sand or covered with a layer of sand (Sandmisch- and Sanddeckkultur) due to the small area of these peatland types. Mundel (1976) observed in laboratory incubation experiments a remarkable reduction of CO_2 emissions in peat soil covered with a layer of sand due to a preserving effect of the sand layer. In peat soil covered with a layer of sand used as grassland, Mundel (1976) found no difference to other peat soils. According to Drösler (2005), most of the investigations carried out in bogs are concentrated in the boreal and subarctic region of Northern Europe. In many studies, no measurements were conducted during the cold period (Maljanen et al. 2010), although the winter season is important for the total annual balance (Maljanen et al. 2003b, Maljanen et al. 2009). Data about annual balances of GHG is demanded by the National Inventory Report for the German Greenhouse Gas Inventory (sectors 4 (agriculture) and 5 (Land Use, Land Use Change and forestry)).

In Lower Saxony, bogs cover an area of approximately 2,348 km², which is almost 60 % of the peatland area or almost 6 % of the total terrestrial area, the area of histosols with only small peat layers is unknown (Blankenburg et al. 2000, Höper 2007). The majority is drained for agriculture and used mainly as grassland, while 62 km² is cropland (Becker-Platen 1996, Höper 2007). However, today an increasing amount of grassland is being converted into cropland to cultivate crops for bioenergy production, thus results of bogs used as cropland gain importance.
To date, the only studies about the gas exchange of grassland in peatlands in Lower Saxony are from Meyer (1999) and Beetz et al. (2013). No measurements have been conducted in bogs or histosols with only small peat layers used as cropland. Höper & Blankenburg (2000) and Höper (2007) reported emission factors from bogs and fens in Lower Saxony, but these values were not based on measurements in Lower Saxony.

N_2O and CH_4 fluxes of drained organic soils are small compared to CO_2 emissions, but the radiative forcing capability for nitrous oxide and methane on a 100 year time scale is 298 and 25 times higher than for carbon dioxide, respectively (IPCC 2007). The calculation of the GWP expressed as CO_2-equivalents is a useful tool to establish the site-specific climatic relevance (Drösler 2005, IPCC 2007, Drösler et al. 2008). In most studies the exchange of only one or two gases was examined, not allowing full assessments of the climatic relevance (Drösler 2005).

The aim of this study is to determine gas fluxes of CO_2, CH_4 and N_2O as well as GWP balances of agriculturally used organic soils that are underrepresented in the literature. A bog, a bog covered with a layer of sand and a histic gleysol covered with a layer of sand used as croplands as well as a histic gleysol covered with a layer of sand used as grassland in Northern Germany were examined via flux measurements with closed chambers. It was hypothesized that all sites are strong sources, but that the exchange of GHG is also affected by land use type and intensity and soil characteristics. Lower emissions are expected at the

sites which are covered with a layer of sand compared to the bog site as well as at the grassland site compared to the cropland sites.
The main questions of this research are: How high are GHG emissions from agriculturally used organic soils covered with a layer of sand compared to agriculturally used organic soils without a layer of sand? How high are GHG emissions from cropland compared to grassland? Which factors control the gas fluxes? Which measures can be recommended to reduce GHG emissions of agriculturally used organic soils?

3.2 Methods

3.2.1 Site discription

Measurements were carried out in agriculturally used peatland sites at two research areas in Lower Saxony in North Germany.

One research area is located in the "Nordhümmlinger Moore", in the northwest part of Lower Saxony (see ch.4). Measurements were carried out at two locations, south of the nature reserve "Leegmoor", on the southern edge of the peatland complex. This area ("Surwold") is agriculturally used and well drained. Underneath the shallow bog peat resides fine sand with silt (Eggelsmann & Blankenburg 1990). The site S1 is a bog covered with a layer of sand (Sanddeckkultur) after it was deep ploughed in the end of the 50th. Crop rotation with winter wheat and maize as well as oilseed rape and mustard as catch crops takes place. The cropland was harrowed and ploughed and supplied with organic and mineral fertilizer. Weeds consist of *Chenopodium album* and *Galinsoga*. The site S2 is mainly used to grow maize, occasionally potatoes are cultivated. After WWII, peat was extracted at this site and then left lying fallow. In the 1970s sand was applied on top and the land has been used as cropland since then. Harrowing, ploughing and grubbing as well as fertilizing with organic and mineral fertilizer take place. Beside *Zea mays* and *Solanum tuberosum*, the vegetation consists of *Atriplex*, *Chenopodium album*, *Galinsoga*, *Poa annua* and *Echinochloa crus-galli*.

The second research area is located in the Dümmer peatland (see ch.2). The two examination sites were classified as histic gleysols (histosols with only small peat layers = Anmoorgley (AG Boden 2005)), covered with a layer of sand and are located in the "Ochsenmoor", south of Lake Dümmer, on the southern edge of the fen area. One site (cropland; O1) is used to grow maize and winter wheat. Yearly harrowing, ploughing and grubbing as well as fertilising with organic and mineral fertilizer take place. Vegetation of the cropland consists of *Chenopodium album*, *Echinochloa crus-galli* and *Persicaria lapathifolia*, beside *Zea mays* and *Titricum aestivium*. The other site (grassland; O2) is located beside and is extensively managed grassland with typical grassland-vegetation (*Anthoxanthum odoratum*, *Bromus hordeaceus*, *Alopecurus pratensis* and *Poa trivialis*). Grass is cut two to three times per year.

3.2.2 Measurements of site factors

Soil parameters: The methods for soil identification as well as determination of true density (s), pore volume (PV), gravimetric water content and water filled pore space (wfps) are described in chapter two.

The dry bulk density (ρt) was calculated using the formula in chapter two. At each site ten soil samples at the depth of 0 to 10 and 10 to 20 cm, respectively were taken with sampling rings (250 ml) in March 2011 and June 2010. The soil samples were heated to 105 °C in the drying oven to determine the dry mass (VDLUFA 1991). At O2 the dry bulk density determined in June 2010 was taken for the time period from April until September, and the value determined in March 2011 was taken for the time period from October until March. At S1, S2 and O1 a different procedure was chosen: From the date when soil cultivation took place until December, we took the value of the dry bulk density determined in June, and from January until the date when soil cultivation took place, we used the value determined in March.

With each CH_4 und N_2O flux measurement, ten soil samples were taken with a boring rod for mineralised nitrogen (N_{min}-Bohrstock) in 0-20 cm depth and subsequently mixed. Analysis of nitrate and ammonium content was carried out in the laboratory of “Landwirtschaftliches Labor Dr. Janssen” with the Continuous-Flow-analyser. The compounds were extracted with a calcium chloride $CaCl_2$ solution (VDLUFA 1991).

Meteorological parameters: Meteorological parameters such as temperatures (air temp., soil temp. at 2, 5 and 10 cm depth), photosynthetic active radiation (PAR), air pressure and precipitation were measured and saved half hourly at meteorological stations. The meteorological station for Ochsenmoor is located near the grassland site of chapter two. The station for Surwold is about 20 km northeast of Surwold (see ch.4).

Half hourly meteorological parameters at the sites were achieved by using the data from the meteorological station. The soil temperatures at each individual site were separately measured and saved half hourly with a datalogger (DN Messtechnik, Norderstedt).

Water level: All sites were equipped with tubes perforated in the peat body, close to the collars. Water level (wl) at the grassland site was measured during each gas measurement campaign with an electric contact gauge during the entire measurement period and additionally continuously recorded every half hour using a Schlumberger MiniDiver from October 2010 until December 2011. At O1, measurements with the electric contact gauge have been conducted from March 2010 until June 2010 and measurements using a Schlumberger MiniDiver from October 2010 until December 2011. In Surwold the wl was measured during each gas measurement campaign with the electric contact gauge from October 2009 until August 2010 and continuously recorded using a Schlumberger MiniDiver from June 2010 until December 2011.

In addition to the continuous records with the MiniDiver, occasional measurements with the electric contact gauge have been performed for validation purposes.

In intervals of every three months we took samples from the ground water with a bailer and analysed for pH and electrical conductivity (Lf) with pH-electrode SenTix 950 (WTW) and standard conductivity measuring cell TetraCon 925 (WTW), respectively.

Biomass: For a description of examination of biomass refer to chapter two.

Carbon import and export: In case of organic fertilizer application at S1, S2 and O1, the collars and boardwalks were removed to make sure that the fertilizer was distributed evenly through the fertilizer spreader. The amount of fertilizer applied was estimated by the farmer. We assumed a variation coefficient in spreading accuracy of less than 25 % (Frick 1999, Pöllinger 2006).

Carbon content of the dry biomass was assumed to be 45 % (KTBL 2005). C export through harvest was calculated accordingly. C/N ratio and nitrogen content of slurry and manure is 8 and 13.5 as well as 4 and 6 kg N t^{-1}, respectively (KTBL 2005). Thus, carbon content of slurry and manure amounts to 32 kg C t^{-1} (= 32 kg C m^{-3}) and 81 kg C t^{-1} (= 81 kg C m^{-3}), respectively. The carbon content of fermentation residue was assumed to be similar to slurry.

3.2.3 Measurements and modelling of carbon dioxide exchange

A description of the determination of the CO_2 exchange is performed in chapter two.
Measurement campaigns were held in intervals every four weeks, beginning in September 2009 and ending in December 2011. Additional measurements were conducted in case of management events (e.g. harvesting, tilling). If necessary, extensions for the chambers were applied (max. 230 cm).

3.2.4 Measurements of nitrous oxide and methane exchange

A description of the determination of the CH_4 and N_2O exchange is performed in chapter two. The samples were analyzed in the gas chromatograph “Perkin Elmer Auto System”. A FID-Detector identified CH_4, while an ECD-Detector was used to detect N_2O.
Measurement campaigns were held in intervals every two weeks, beginning in September 2009 and end in December 2011.

3.2.5 Net ecosystem carbon balance and global warming potential

To obtain complete carbon balances of the examination sites, the net ecosystem carbon balance (NECB) was calculated (Chapin et al. 2006; see ch.2). DOC was estimated to 26 kg C $ha^{-1}a^{-1}$ according to Moore (1987). Values of DIC, CO and VOC are assumed to be negligible and not considered.
The global warming potential (GWP) was calculated according to IPCC (2007) (see ch.2). In general, the global warming potential over a time span of 100 years is taken (Drösler 2005). Positive values represent efflux of CO_2-equivalents into the atmosphere.

3.2.6 Statistical analyses

Unless otherwise stated, Microsoft® Excel was used.
Average values are arithmetic means +/- standard error.
Error analysis of CO_2 gas fluxes was conducted by calculating the standard error for each calibrated regression model. Analogous to the interpolation of the half-hourly gas fluxes, standard errors were interpolated. The monthly and annual standard errors were calculated using appropriate error propagation equation. The standard errors of the means of the exported carbon through harvest were included.

For CH_4 and N_2O the standard error of the replicate chamber measurements of each measurement campaign were calculated and interpolated between the measurement campaigns analogous to the interpolation of the fluxes. The annual standard errors were calculated using appropriate error propagation equations.

Significant linearity of slope of the changes in gas concentration was tested following Huber (1984). To test if slopes are significantly different from 0, a t-test was performed (Neter et al. 1996). The variability of the slopes was calculated as the standard deviation of the residuals (s_{yx}). For the variability in PAR the coefficient of variability (cv %) was calculated.

Correlation and regression analysis was conducted providing the coefficient of determination (quadrate of Pearson Correlation Coefficient = R^2) and tested for significance using a t-test.

Significant ($p < 0.05$) differences between the annual gas exchange balances were tested with the Permutation test “diffmean” (1000 permutations) using R script 0.97.237 (version 2.15.2) (simba package).

3.3 Results

3.3.1 Land use and carbon import and export

Land use of the sites S1, S2 and O1 were similar. At S1 winter wheat was growing from October 2009 until July 2010, similarly, at O1 winter wheat was cultivated from October 2009 until August 2010. At S2 potatoes were growing from Mai 2010 until September 2010. In 2011, at all three sites maize was cultivated from end of April or beginning of May until end of September or October. In addition, S1 was covered with oilseed rape and mustard as catch crops from August 2010 until April 2011. Soil cultivation and fertilizing were similar as well: S1 was fertilized with slurry and mineral fertilizer in both years. At O1 the farmer applied slurry and mineral fertilizer in 2010 and slurry, cattle manure and mineral fertilizer in 2011. S2 was supplied with fermentation residue and mineral fertilizer in both years. At all three sites soil cultivation took place in both years.

At the grassland site (O2), the only management practice was haymaking. The grass was cut three times in 2010 (June, August and October) and 2011 (July, August, September), respectively.

Carbon export through harvest exceeded carbon import through organic fertilizer by far (Tab.3.1). At S2 the carbon export in 2010 was low compared to the other sites and compared to 2011. In comparison to S1 and S2, at O1 the farmer applied high amounts of organic fertilizer.

At O2, the hay harvest in 2010 (3,771 kg C ha^{-1}) was much higher than in 2011 (1,881 kg C ha^{-1}).

Tab. 3.1: Carbon import and export at S1, S2, O1 and O2 in 2010 and 2011. Carbon import through application of manure, carbon export through harvest (mean and standard error).

site	2010			2011		
	organic fertilizer m^3 ha^{-1}	C import kg ha^{-1}	C export kg ha^{-1}	organic fertilizer m^3 ha^{-1}	C import kg ha^{-1}	C export kg ha^{-1}
S1	23	736	6069 +/- 310	20	640	9785 +/- 659
S2	20	640	2531	25	800	6175 +/- 541
O1	15	480	8521 +/- 170	10	1215	6946 +/- 135
O1	15	320	-	25	800	-
O2	-	-	2267 +/- 411	-	-	1223 +/- 81
O2	-	-	796 +/- 98	-	-	597 +/- 31
O2	-	-	708 +/- 44	-	-	61 +/- 7

3.3.2 Soil parameters

The soil identification according to AG Boden (2005) revealed that S1, O1 and O2 are characterized by an approximately 40 cm thick peat layer overlaid by a layer which consisted mainly of sand (Tab.3.2). All sites showed no $CaCO_3$ content. The carbon content of the upper layer is comparatively low at S1, O1 and O2, while at S2 the carbon content is high. At all sites, the highest carbon content is not found in the most upper layer but in the second or third layer. The C/Norg ratio is highest at S2 and lowest at O1 and O2.

Nitrate stock was highest at S1 (in average over the whole measurement period: 75 kg NO_3^--N ha^{-1} in 0-20 cm depth). S2 and O2 showed a stock of 65 and 61 kg NO_3^--N ha^{-1}, respectively. At O2 NO_3^- stock was low (24 kg NO_3^--N ha^{-1}). The ammonium stock was highest at S2 (41 kg NH_4^+-N ha^{-1}), while the lowest ammonium stock was found at O1 (13 kg NH_4^+-N ha^{-1}). S1 and O2 showed both ammonium stocks of about 20 kg NH_4^+-N ha^{-1}.

Wfps was similar at S1 and S2 (in average over the whole measurement period: 60 and 63 % in 0-20 cm depth). At O1 a higher wfps (77 %) was observed, while at O2 the wfps was 58 %.

Tab. 3.2: Soil properties of the examination sites. No nitrogen content of the upper layer at the sites in Surwold is available due to measurement error.

a) S1

depth [cm]	soil horizon [a]	peat substrate [a]	humus [a]	$CaCO_3$ [%]	pH_{CaCl2}	Corg %/TS	N %/TS	C %/TS	Corg:N	Dry bulk density $g\ cm^{-3}$
0-20	jAp	fSms	h4	0	5.0	8.8				0.97
20-50	hHw	Hh	h7	0	3.7	53.9	2.8	55.1	19.2	0.22
50-58	nHw	Hnp	H7	0		12.9	0.3	13.7	37.1	
58-60	fFr	Fmu	h7	0	4.0	2.2	0.1	2.8	23.9	0.73
60-70	Ghw	fSms	h7	0	4.6	0.1	0.0	0.1	12.4	
70-85	Gro	fSms	h1	0	4.8	11.6	0.5	12.7	24.8	

b) S2

depth [cm]	soil horizon [a]	peat substrate [a]	humus [a]	$CaCO_3$ [%]	pH_{CaCl2}	Corg %/TS	N %/TS	C %/TS	Corg:N	Dry bulk density $g\ cm^{-3}$
0-20	Hvp	Ha,fs	h7	0	4.1	31.0				
20-45	hHw	Ha	h7	0	4.1	47.2	1.3	48.4	37.3	0.22
45-50	fFw	Fmu	H6	0		30.8	0.8	32.3	37.1	
50-65	Gw	fSms	h3	0		2.5	0.1	2.8	25.7	
65-85	Gro	fSms	h1	0	4.0	0.1	0.0	0.2	12.1	

c) O1

depth [cm]	soil horizon [a]	peat substrate [a]	humus [a]	$CaCO_3$ [%]	pH_{CaCl2}	Corg %/TS	N %/TS	C %/TS	Corg:N	Dry bulk density $g\ cm^{-3}$
0-10	Aap1	fSms	h6	0	4.9	7.4	0.5	7.8	14.1	
10 30	Aap2	fSms	h6	0	4.7	7.0	0.5	7.2	13.8	1.11
30-55	nHa	Ha,S	h7	0	4.8	11.7	0.8	12.4	13.9	
55-70	nHaw	Ha,S	h7	0	4.3	5.8	0.5	6.3	11.8	
70-90	Gor	fSms	h1	0	4.4	0.4	0.0	0.5	19.7	
90-100	Gr	fSms		0						

d) O2

depth [cm]	soil horizon [a]	peat substrate [a]	humus [a]	$CaCO_3$ [%]	pH_{CaCl2}	Corg %/TS	N %/TS	C %/TS	Corg:N	Dry bulk density $g\ cm^{-3}$
0-10	Aap1	fSms	h6	0	5.3	7.7	0.6	8.0	13.2	1.02
10 30	Aap2	fSms	h6	0	4.8	5.7	0.5	7.0	10.9	
30-40	nHa	Ha,S	h7	0	4.9	14.3	1.0	15.2	14.6	0.38
40-70	nHaw	Ha,S	h7	0	4.9	4.8	0.1	5.0	37.9	
70-90	Gor	fSms	h1	0	4.9	1.2	0.0	1.5	35.9	
90-100	Gr	fSms		0						

[a] According to AG Boden (2005)

3.3.3 Water

At all examination sites wl were low and year round below ground surface (Fig.3.1 & Fig.3.2). A seasonal pattern with low wl in summer and high wl in winter was apparent. The values at O1 and O2 were very similar due to their nearness. In Surwold the pattern of the wl were very similar, but at S1 the values were much lower. The averaged wl was -116 and -120 cm in 2010 and 2011, respectively at S1. The averaged wl in summer (May to Oct.) amounted to -136 and -131 cm in 2010 and 2011, respectively. At S2 the averaged wl was -95 (summer: -79 cm) and -99 cm (summer: -106 cm) in 2010 and 2011, respectively. The Ochsenmoor was wetter: At O1 the averaged wl was -62 (summer: -65 cm) and -68 cm (summer: -68 cm) in 2010 and 2011, respectively. The grassland site O2 showed averaged wl of -66 (summer: -89 cm) and -76 cm (summer: -91 cm), in 2010 and 2011, respectively.

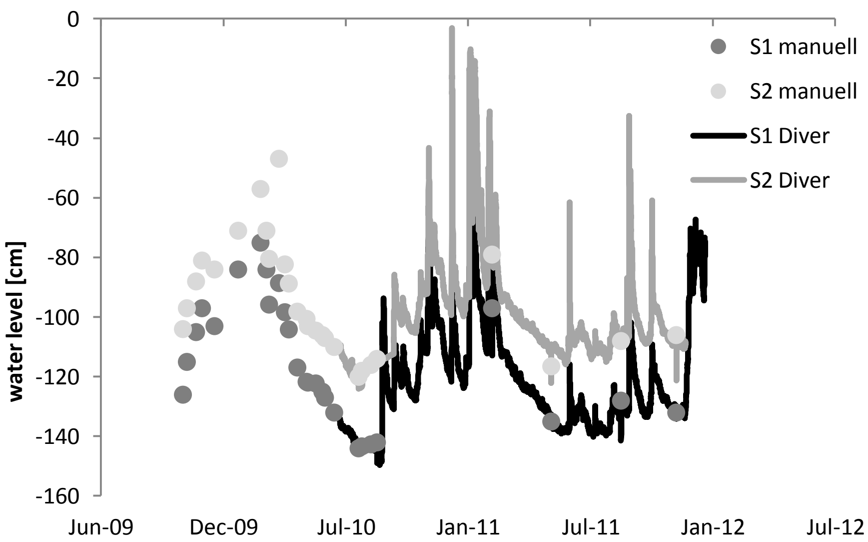

Fig. 3.1: Water level of the examination sites in Surwold. (from Sept. 2009 until Dec 2011) in cm above ground surface.

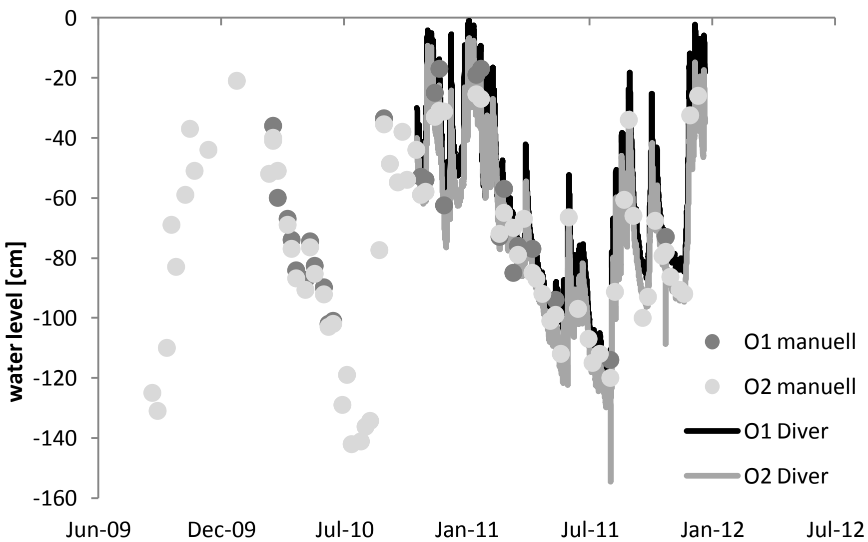

Fig. 3.2: Water level of the examination sites in Ochsenmoor (from Sept. 2009 until Dec 2011) in cm above ground surface.

The pH of the ground water was similar at the examination sites (Tab.3.3) and amounted in average over the whole measurement period to about 5.4 (S2: 5). Electrical conductivity (Lf) was highest at O1 with 964 S m^{-1}, followed by S1 and O2 with lower values (Tab.3.3). At S2 Lf was lowest (375 S m^{-1}).

Tab. 3.3: pH and electrical conductivity (Lf, S m^{-1}) of the water at the examination sites.

	S1		S2			O1		O2	
date	pH	Lf	pH	Lf	date	pH	Lf	pH	Lf
10.03.2010		620		121	17.03.2010		1438		510
05.05.2010	5.9	946	5.4	341	11.05.2010	5.4	565	5.6	502
17.08.2010			5.7	355	31.08.2010	4.9	1783	4.9	641
11.11.2010	4.9	647	4.3	936	24.11.2010	5.4	686	5.3	504
10.02.2011	5.1	871	4.8	109	26.01.2011	5.3	545	5.3	446
11.05.2011	5.8	749	5.0	410	19.05.2011	5.5	754	5.4	422
25.08.2011	5.3	690	5.1	385	09.08.2011	5.8	779	6.1	569
17.11.2011	5.3	682	4.9	346	02.11.2011	5.4	1162	5.4	495

3.3.4 Biomass

The development of biomass at the cropland sites shows a strong seasonal pattern with increasing values from spring until summer and subsequently decreasing values until autumn (Fig.3.3). Outside the vegetation period, biomass was mostly time 0. However, at S1 the green biomass reached a value up to 1.5 t dry mass ha^{-1} in winter 2010/2011 due to the cultivation of catch crop. The green biomass of the maize showed highest values in August. Winter wheat and potatoes developed highest green biomass in July. While in spring green biomass and total biomass were quite similar, in autumn the values differed strongly. Only potatoes showed during the whole growing period similar numbers.

The annual pattern of biomass at O2 differed strongly (Fig.3.3). The site was covered with vegetation year round. A seasonal pattern with low amounts of biomass in winter is evident, but also during the vegetation period the biomass increases and decreases several times due to the grass cuttings. The highest amount of green biomass was measured in June 2010 with 4 t dry mass ha^{-1}. In 2011, the green biomass reached only a maximum of 2.7 t dry mass ha^{-1} (May 2011).

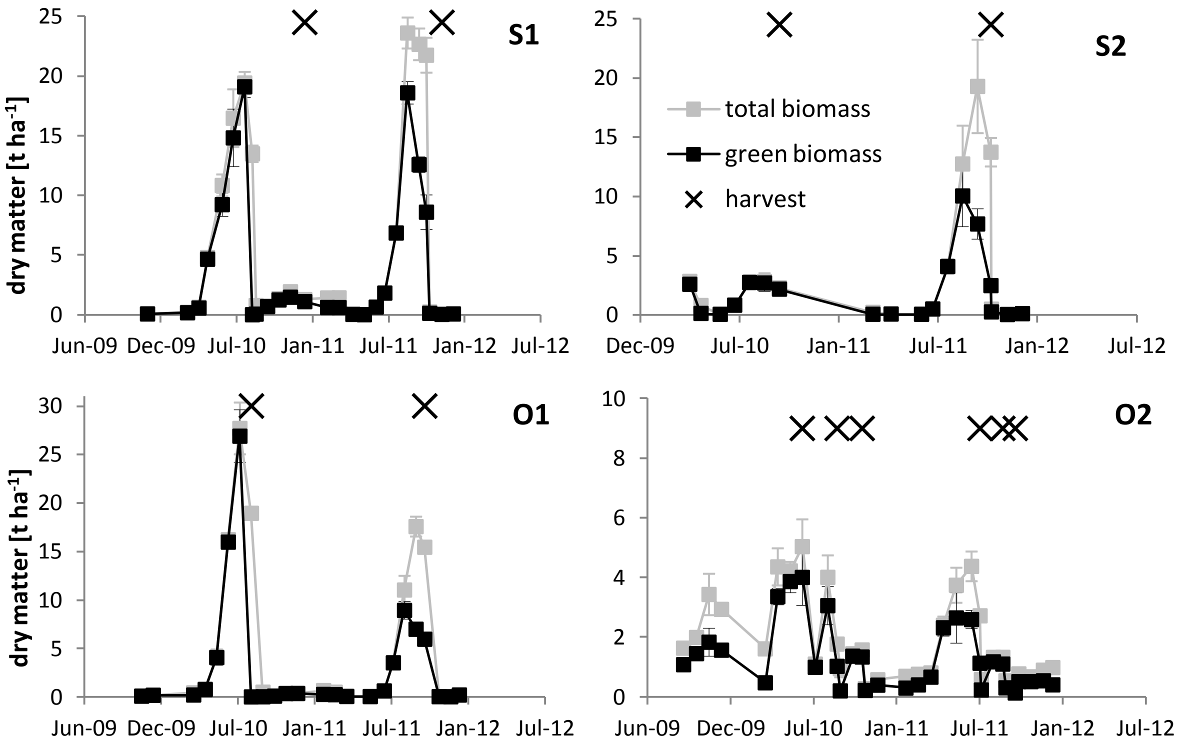

Fig. 3.3: Total and green above-ground biomass (dry matter) at the examination sites.

3.3.5 Weather

The weather station at Surwold registered an average annual air temperature of 8.4 and 10.2 °C in 2010 and 2011, respectively. In Ochsenmoor an average annual air temperature of 9.9 °C in 2010 and 11.1 °C in 2011 was observed. However, the warmest month over the measurement period was July 2010 (Fig.3.4). The winters 2009/2010 and 2010/2011 were quite cold with daily mean temperatures below 0 °C, while the winter 2011/2012 was mild. In 2009, the month November was exceptionally warm.

During winter, the PAR was in both years higher in Ochsenmoor, while during the vegetation period, Surwold showed a higher PAR. The monthly mean values of the PAR were in general highest in May, June and July (Fig.3.4). From March until May, the monthly mean values were higher in 2011, compared to 2010. In contrast, from June until August/September, 2010 revealed higher monthly mean values.

At both locations, the precipitation was quite evenly distributed over the year (Fig.3.5). Surwold had more days with precipitation than Ochsenmoor. However, days with high amounts of precipitation were rather found in Ochsenmoor. In average, Surwold showed a higher annual precipitation (623.1 and 711.7 mm in 2010 and 2011, respectively) than Ochsenmoor (549.1 and 559.3 mm in 2010 and 2011, respectively). At both sites, spring and autumn 2011 were very dry, compared to 2010. Summer precipitation in 2011 at Surwold was higher than in 2010. Exceptionally high precipitation with almost 150 mm was observed in August 2010 at Ochsenmoor.

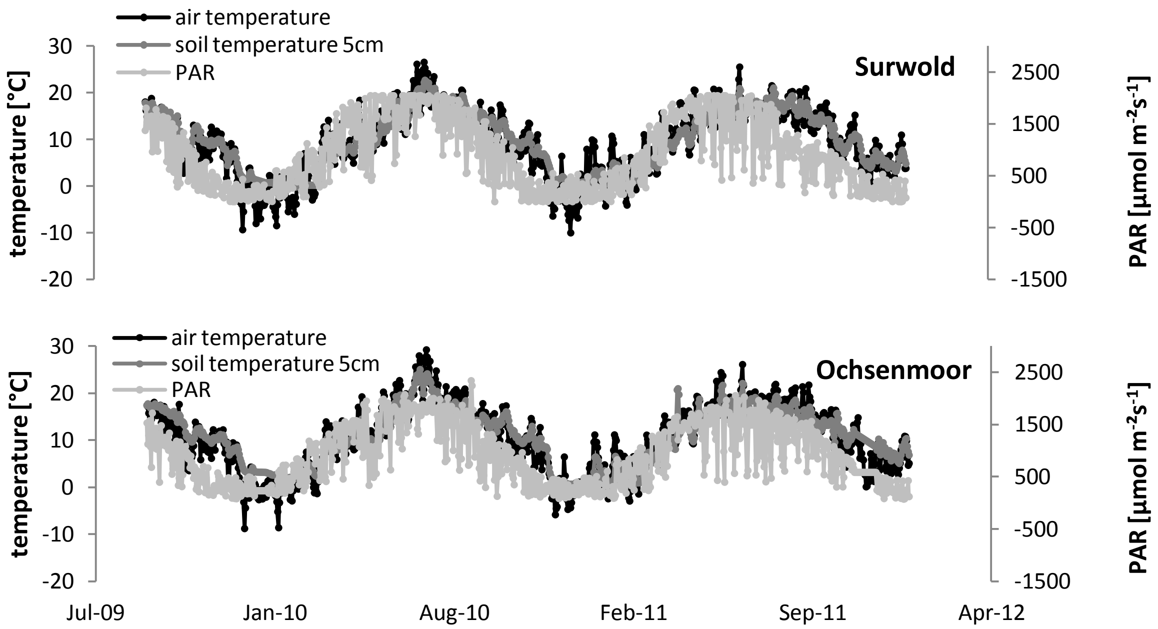

Fig. 3.4: Annual course of air temperatures and soil temperatures in 5 cm depth (daily mean of half-hourly values), and annual course of PAR (photosynthetically active radiation: daily maximum of half-hourly values) at the weather station near Surwold (left) and at the weather station near Ochsenmoor (right).

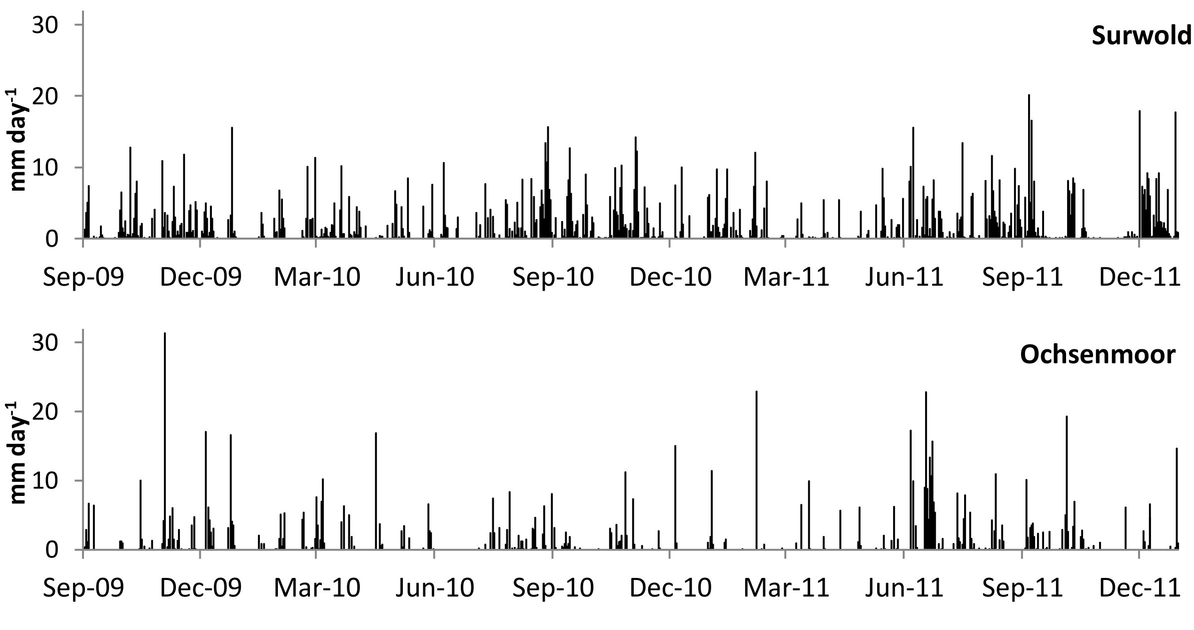

Fig. 3.5: Precipitation (mm/day) at weather station near Surwold and weather station near Ochsenmoor.

3.3.6 Carbon dioxide

3.3.6.1 Evaluation of methodology

During the carbon dioxide measurements, significant linearity ($p < 0.05$) of the slope for gas-concentration was usually assured. The coefficient of variability of the PAR during the CO_2 measurement was always less than 5 % with a very few exceptions. Thus, the driving forces of the models for the CO_2 gas exchange (temperature and PAR) were quite constant during measurement.

The regressions between measured and modelled flux rates of each measurement campaign at the examination sites (Tab.3.4-3.7) were in most cases significant ($p < 0.1$). However, in a very few cases the regressions between measured and modelled R_{eco} flux rates were not significant and pooling of two measurement dates was necessary. If pooling was also not possible, the parameter E_0 were set to 0 and R_{ref} was replaced by the mean value of the measured values. On 17.11.2011, the measurement plots at S2 were almost completely free of vegetation and there was almost no GPP observable, thus GP_{max} and α were set to 0.

A seasonal pattern of R_{ref} and E_0 was visible at each site. R_{ref} was highest during summer, while E_0 was highest in winter or autumn. However, at S2 E_0 was generally low, only in December 2011 it reached a high value. At S2 and O1 a clearly seasonal pattern of GP_{max} and α with high values in summer and low values in winter was observed. At S1, only GP_{max} showed a seasonal pattern. GP_{max} and α at O2 dropped to low values after the grass cuts.

The regressions between all modelled and measured values were at all four sites significant ($p < 0.0001$) and followed almost the 1:1 line (Fig.3.6). At S1 the coefficients of determination of the regressions between modelled and measured R_{eco} and modelled and measured NEE were both $R^2 = 0.99$. The coefficients of determination at S2 were $R^2 = 0.98$ and 0.99, respectively. At O1 coefficients of determination of 0.98 (R_{eco}) and 0.99 (NEE) were found, while at O2 coefficients of determination of 0.94 (R_{eco}) and 0.96 (NEE) were observable. Standard errors of the regressions between all modelled and measured values were 0.51 (R_{eco}) and 1.65 (NEE), 0.45 (R_{eco}) and 1.43 (NEE), 0.76 (R_{eco}) and 1.51 (NEE), 0.58 (R_{eco}) and 1.44 $\mu mol\ CO_2\text{-}C\ m^{-2}\ s^{-1}$ (NEE) at S1, S2, O1 and O2, respectively

Tab. 3.4: Parameters for the R_{eco} and NEE models of S1: Left: Date of measurement campaign. Middle: E_0: Activation energy like parameter [K], R_{ref}: Respiration at the reference temperature [µmol CO_2-C m^{-2} s^{-1}], R²: Coefficient of determination (Pearson) between modelled and measured values. S.e.: Standard error of the model [µmol CO_2-C m^{-2} s^{-1}], n: Number of samples, temp: Best fit temperature for R_{eco} model [air temp. or soil temp. in cm below ground surface]. Right: GP_{max}: Maximum rate of carbon fixation at PAR infinite [µmol CO_2-C m^{-2} s^{-1}], α: Light use efficiency [µmol CO_2-C m^{-2} s^{-1}/µmol m^{-2} s^{-1}], R²: Coefficient of determination (Pearson) between modelled and measured values. S.e.: Standard error of the model [µmol CO_2-C m^{-2} s^{-1}], n: Number of samples. Maximum and minimum values are printed in bold. Eventually measurement campaigns were pooled together. 18.11.2011, 15.12.2011: No significant correlation between measured and modelled values. E_0 was set to 0.

date	E_0	R_{ref}	R²	s.e.	n	temp	GP_{max}	α	R²	s.e.	n
01.10.09	235.1	2.39	0.17**	0.47	24	air	-9.37	-0.0049	0.74****	0.46	75
28.10.09	60.2	1.82	0.13**	0.15	39	soil2					
26.11.09	604.5	2.96	0.57***	0.26	14	air	-7.09	-0.0180	0.27****	0.44	54
04.03.10	**25.6**	**0.93**	0.48***	0.05	17	air	-4.02	**-0.0019**	0.83****	0.20	56
01.04.10	279.1	**9.84**	0.39**	1.52	15	air	-19.00	-0.0460	0.79****	1.66	33
22.04.10	194.6	6.57	0.95****	0.28	18	soil2	-46.58	-0.0521	0.88****	2.24	37
28.05.10	122.0	7.72	0.85****	0.52	18	air	-85.22	-0.0651	0.98****	2.61	45
24.06.10	191.2	8.32	0.97****	0.88	18	air	-78.47	-0.0583	0.97****	2.04	32
22.07.10	192.3	6.37	0.24**	0.48	18	soil5	-28.88	-0.0241	0.96****	0.88	39
19.08.10	157.2	2.43	0.16**	0.71	39	soil2	-0.18	-0.1266	0.20***	0.30	39
24.08.10							-2.03	-0.0099	0.45****	0.34	61
16.09.10	385.9	2.21	0.80****	0.32	15	soil2	-39.34	-0.0420	0.97****	1.03	36
14.10.10	131.6	3.55	0.44***	0.11	16	soil5	-31.76	-0.0453	0.96****	0.49	45
11.11.10	86.4	1.47	0.18**	0.19	27	air	-12.06	-0.0517	0.95****	0.52	33
16.12.10							-0.98	**-0.2328**	0.61****	0.14	27
10.02.11	172.6	2.32	0.62****	0.19	15	air	-16.27	-0.0326	0.98****	0.22	39
10.03.11	308.2	3.89	0.32**	0.21	15	soil5	-9.92	-0.0268	0.91****	0.33	24
13.04.11	86.6	3.54	0.27**	0.79	15	air	-1.89	-0.0132	0.21***	0.24	33
11.05.11	78.9	3.96	0.80****	0.28	15	soil2	**0.08**	-0.0502	0.63****	0.26	42
09.06.11	322.1	2.84	0.90****	0.56	18	soil2	-37.86	-0.0122	0.95****	1.07	33
30.06.11	222.0	7.79	0.88****	0.70	15	air	-94.29	-0.0761	0.95****	4.21	35
28.07.11	298.6	7.72	0.99****	0.59	12	air	**-213.29**	-0.1405	0.98****	4.79	23
25.08.11	223.6	9.32	0.94****	0.76	12	air	-145.69	-0.1253	0.99****	2.98	27
22.09.11	**809.3**	3.47	0.54***	0.84	12	soil5	-64.76	-0.0666	0.97****	2.31	26
18.10.11	0.0	1.87	0.11	0.30	12	soil2					
25.10.11	49.6	1.94	0.06*	0.17	39	soil5					
17.11.11	168.3	2.12	0.6***	0.08	10	soil2	-2.07	-0.0020	0.84****	0.10	23
15.12.11	0.0	0.89	0.13	0.52	11	air	-2.80	-0.0110	0.23**	0.35	23

* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$; **** $p < 0.001$

Tab. 3.5 [next page]: Parameters for the R_{eco} and NEE models of S2 (see Tab.3.4). Eventually measurement campaigns were pooled together.

Tab. 3.6 [next page]: Parameters for the R_{eco} and NEE models of O1 (see Tab.3.4). Eventually measurement campaigns were pooled together. 04.08.2010: No significant correlation between measured and modelled values. E_0 was set to 0.

date	E_0	R_{ref}	R²	s.e.	n	temp	GP_{max}	α	R²	s.e.	n
28.10.09	144.6	2.44	0.80****	0.17	38	air					
26.11.09	260.0	1.02	0.69****	0.16	35	soil5					
04.03.10											
01.04.10	181.7	**0.55**	0.40**	0.08	15	air	-0.82	-0.0015	0.79****	0.07	33
22.04.10	99.8	2.47	0.79****	0.08	18	soil5	-5.83	-0.0028	0.77****	0.31	39
06.05.10	75.1	2.82	0.30****	0.27	63	soil5					
28.05.10	87.6	3.55	0.62****	0.23	18	soil5	-2.18	-0.0011	0.84****	0.12	48
24.06.10	128.8	3.30	0.80****	0.35	18	soil5	-5.49	-0.0078	0.41****	0.70	36
22.07.10	**64.5**	5.77	0.44***	0.34	18	air	-31.55	-0.0299	0.94****	1.34	39
19.08.10	143.7	5.53	0.87****	0.43	17	air	-43.83	-0.0367	0.98****	1.12	28
16.09.10	244.1	4.26	0.77****	0.47	18	soil2	-29.17	-0.0404	0.88****	2.07	36
14.10.10	70.5	2.56	0.39**	0.13	15	soil2					
11.11.10	85.6	0.91	0.23*	0.05	15	air					
16.12.10	265.0	0.81	0.35**	0.01	12	air					
10.02.11	195.9	0.83	0.30**	0.13	15	air					
10.03.11	225.6	1.12	0.28**	0.13	18	soil2	-0.58	-0.0097	0.39***	0.08	20
13.04.11	95.8	2.45	0.19**	0.54	21	soil2	-5.89	-0.0030	0.59****	0.53	33
11.05.11	288.4	2.02	0.92****	0.54	18	soil2					
09.06.11	350.1	1.28	0.98****	0.15	18	soil2	-0.86	**-0.0010**	0.64****	0.40	33
30.06.11	186.6	3.93	0.65****	0.74	15	soil2	-25.89	-0.0241	0.98****	0.74	31
28.07.11	284.7	**5.94**	0.90****	1.98	12	air	-112.54	-0.0725	0.97****	2.59	27
25.08.11	299.5	5.67	0.93****	0.97	12	air	**-133.97**	**-0.0901**	0.97****	3.95	26
22.09.11	211.8	5.49	0.45**	1.10	12	air	-71.40	-0.0818	0.99****	1.50	26
18.10.11	275.6	2.02	0.34**	0.28	12	air	-4.48	-0.0264	0.96****	0.30	24
17.11.11	421.8	1.77	0.77****	0.02	15	soil5	0.00	0.0000	0.08	0.00	27
15.12.11	**810.8**	1.63	0.36**	0.04	12	soil5	**-0.13**	-0.0230	0.2**	0.04	24

* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$; **** $p < 0.001$

date	E_0	R_{ref}	R²	s.e.	n	temp	GP_{max}	α	R²	s.e.	n
14.10.09	88.8	**0.48**	0.14**	0.16	21	air	-6.40	**-0.0004**	0.45***	0.06	15
11.11.09	**1181.4**	1.78	0.22*	0.46	14	soil2	-8.29	-0.0079	0.33***	0.23	24
09.12.09	370.3	1.22	0.34**	0.15	12	air	-8.51	-0.0122	0.86****	0.39	32
17.03.10	257.9	0.95	0.73****	0.18	15	air	-4.97	-0.0032	0.85****	0.23	37
14.04.10	183.4	3.77	0.82****	0.47	18	soil2	-22.22	-0.0240	0.99****	0.47	47
12.05.10	260.4	5.11	0.44***	0.38	18	air	-52.81	-0.0435	0.95****	0.80	33
09.06.10	354.7	7.63	0.81****	1.02	18	soil5	-113.46	-0.0751	0.99****	2.21	40
07.07.10	115.5	8.67	0.97****	0.45	18	air	-88.43	-0.0400	0.97****	2.09	45
04.08.10	0.0	5.32	0.05	0.27	18	air	-17.64	-0.0008	0.78****	0.20	45
01.09.10	188.9	2.54	0.26**	0.40	18	soil5					
29.09.10	132.9	2.52	0.46***	0.31	15	soil2	-9.09	-0.0145	0.82****	0.90	36
27.10.10	846.9	2.69	0.80****	0.26	15	soil2	-13.35	-0.0305	0.91****	0.38	30
24.11.10	232.2	1.79	0.31**	0.13	15	air	-9.78	-0.0442	0.97****	0.28	27
26.01.11	362.9	2.22	0.50***	0.07	15	air	-4.77	-0.0253	0.90****	0.35	27
23.03.11	161.7	2.68	0.83****	0.27	16	air	**-1.36**	-0.0142	0.53****	0.20	36
20.04.11	96.2	6.80	0.29**	2.15	14	soil5					
19.05.11	**69.3**	4.30	0.30**	0.51	15	air	-5.28	-0.0078	0.87****	0.25	36
22.06.11	265.6	3.68	0.88****	0.54	18	air	-46.38	-0.0418	0.91****	2.38	36
14.07.11	297.7	7.43	0.75****	0.99	12	air	-92.08	**-0.1179**	0.97****	2.39	30
10.08.11	148.3	**10.89**	0.69***	1.56	12	air	**-134.33**	-0.0915	0.96****	4.22	36
07.09.11	164.9	9.08	0.26*	2.67	12	air	-83.04	-0.0810	0.98****	2.13	38
06.10.11	124.6	3.82	0.41**	0.33	14	air					
02.11.11	114.2	1.47	0.28*	0.19	11	air	-1.55	-0.0247	0.37****	0.34	32
30.11.11	438.6	2.31	0.21*	0.34	15	soil5	-3.47	-0.0178	0.90****	0.27	27
21.12.11	581.7	0.61	0.63***	0.03	12	soil2	-2.49	-0.0130	0.89****	0.17	24

* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$; **** $p < 0.001$

Tab. 3.7: Parameters for the R_{eco} and NEE models of O2. (see Tab.3.4). Eventually measurement campaigns were pooled together.

date	E_0	R_{ref}	R^2	s.e.	n	temp	GP_{max}	α	R^2	s.e.	n
15.09.09	378.6	3.21	0.76****	0.26	12	air	-42.88	-0.0433	0.92****	0.84	65
14.10.09	65.2	3.65	0.80****	0.21	18	air	**-77.63**	-0.0149	0.89****	1.23	51
11.11.09	410.8	4.35	0.34**	0.25	15	air	-14.50	-0.0597	0.94****	0.39	27
09.12.09	802.0	3.53	0.57***	0.12	12	soil2	-24.56	-0.0467	0.98****	0.51	33
17.03.10	141.7	2.49	0.84****	0.21	15	air	-10.92	-0.0206	0.83****	0.80	36
14.04.10	113.5	5.46	0.97****	0.21	18	air	-47.04	-0.0498	0.97****	1.26	48
12.05.10	104.3	6.18	0.30**	0.24	17	air	-19.46	-0.0838	0.92****	0.86	33
09.06.10	69.3	5.93	0.50****	0.79	35	air	**-3.33**	**-0.0049**	0.36****	0.32	45
07.07.10							-22.07	-0.0953	0.83****	1.78	45
04.08.10	91.0	4.39	0.41***	0.64	18	air	-32.36	-0.0420	0.99****	0.67	41
01.09.10	225.5	3.65	0.65****	0.39	18	soil2	-12.89	-0.0149	0.88****	0.64	33
29.09.10	137.9	5.63	0.88****	0.37	15	air	-28.65	-0.0711	0.96****	1.09	35
27.10.10	136.1	3.75	0.27**	0.42	15	air	-4.94	-0.0110	0.44****	0.25	27
24.11.10	**828.1**	3.99	0.84****	0.11	15	soil2	-9.85	-0.0663	0.98****	0.26	21
26.01.11	193.4	**1.93**	0.25*	0.29	15	air	-9.09	-0.0237	0.87****	0.47	24
23.03.11	240.0	5.01	0.67****	0.68	18	soil2	-23.33	-0.0495	0.84****	2.16	33
20.04.11	120.1	6.91	0.86****	1.16	13	air	-35.44	-0.0747	0.75****	2.54	57
19.05.11	**38.8**	**7.68**	0.27*	0.39	12	air	-30.74	-0.0647	0.87****	1.86	33
22.06.11	247.6	5.56	0.27**	0.97	18	soil5	-29.96	-0.0480	0.93****	1.49	33
14.07.11	147.4	5.31	0.31*	0.68	10	air	-4.37	-0.0236	0.32***	0.73	30
10.08.11	143.4	7.21	0.66***	1.02	12	air	-31.00	-0.0903	0.91****	2.03	33
07.09.11	178.5	6.33	0.30**	1.36	14	air	-22.63	-0.0621	0.83****	1.92	35
06.10.11	69.7	5.25	0.14*	0.75	22	air	-13.33	**-0.1366**	0.86****	1.16	36
02.11.11							-31.54	-0.0593	0.98****	0.70	24
30.11.11	56.3	2.41	0.31**	0.27	15	air	-17.12	-0.0493	0.94****	0.83	27
21.12.11	526.3	5.08	0.81****	0.23	9	air	-22.47	-0.0347	0.81****	0.90	24

* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$; **** $p < 0.001$

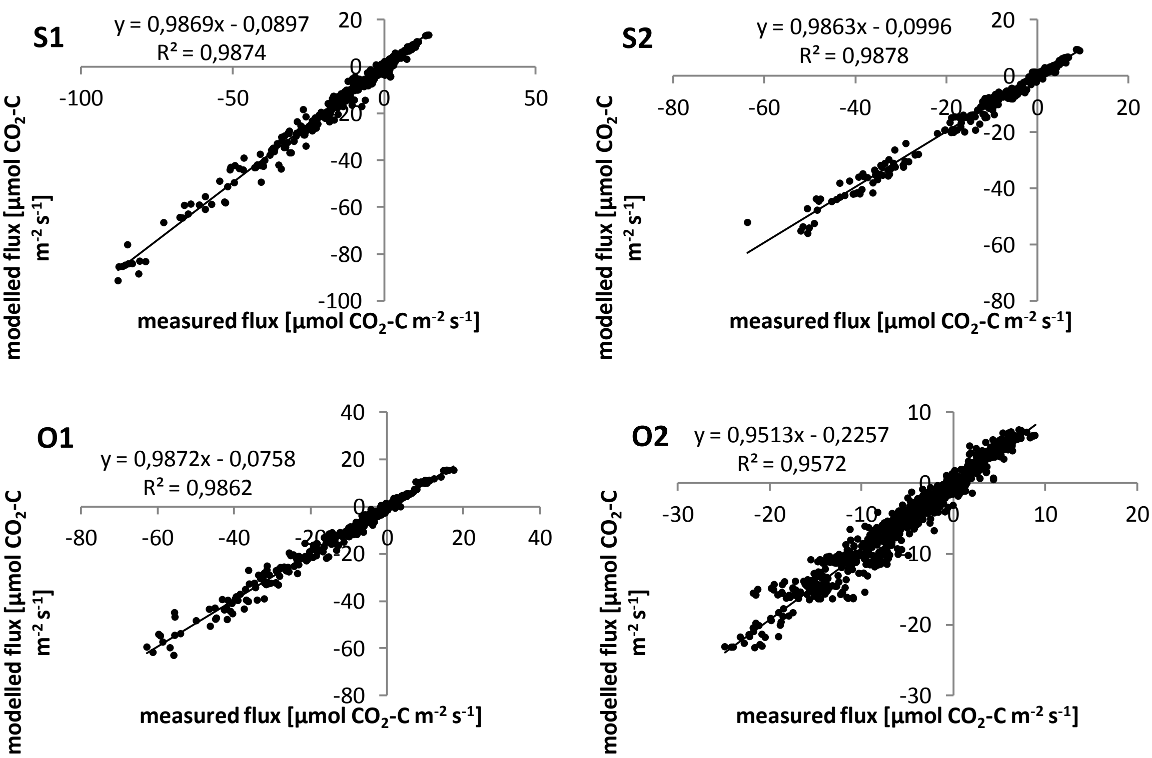

Fig. 3.6: Fit of modelled with measured NEE at the examination sites.

3.3.6.2 Ecosystem respiration

The ecosystem respiration of the examination sites showed a clearly seasonal pattern with highest values in June, July or August and lowest values from December until February (Fig.3.7-3.10). Highest monthly cumulated R_{eco} occurred under maize and lowest under potatoes. The monthly values during the vegetation period were very similar at S1 and O1 in both measurement years. In 2010, the months May, July and August were not significantly different between the two sites. In 2011, the months June, July, August and September were not significantly different between the two sites. In contrast, monthly cumulated R_{eco} at S2 were significantly different from the R_{eco} at S1 and O1 (except in November 2011, where R_{eco} differed not significantly between S2 and S1). The monthly cumulated R_{eco} differed significantly between the two years 2010 and 2011 (except in June at S2).

At O2 the monthly cumulated R_{eco} was significantly higher in 2011 compared to 2010 (and 2009), despite the same management. Only in October, the monthly cumulated R_{eco} of 2010 and 2011 were not significantly different. In 2010, highest monthly cumulated R_{eco} was observable in June, whereas in 2011 the highest value was found in August.

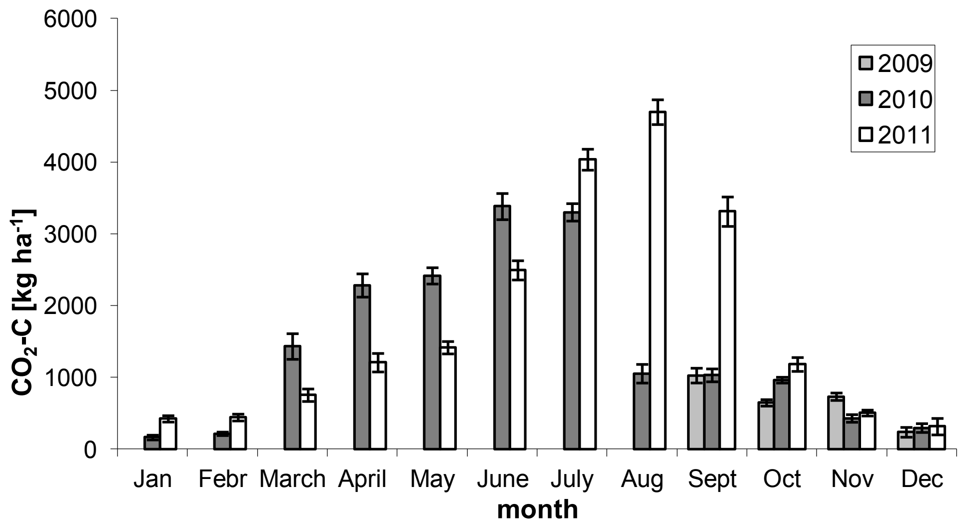

Fig. 3.7: Monthly cumulated ecosystem respiration (R_{eco}) of S1. Note: 2009 only from September to December. Error bars are standard errors.

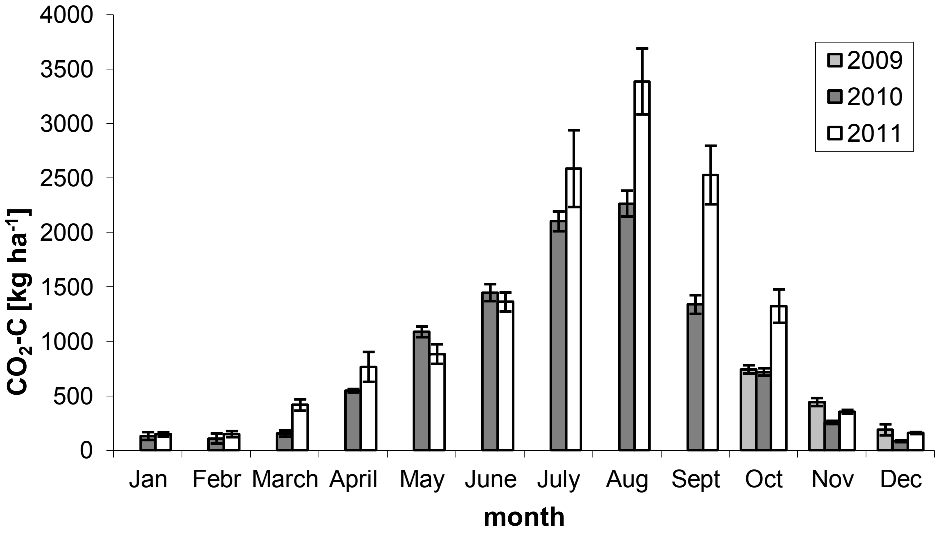

Fig. 3.8: Monthly cumulated ecosystem respiration (R_{eco}) of S2. Note: 2009 only from October to December. Error bars are standard errors.

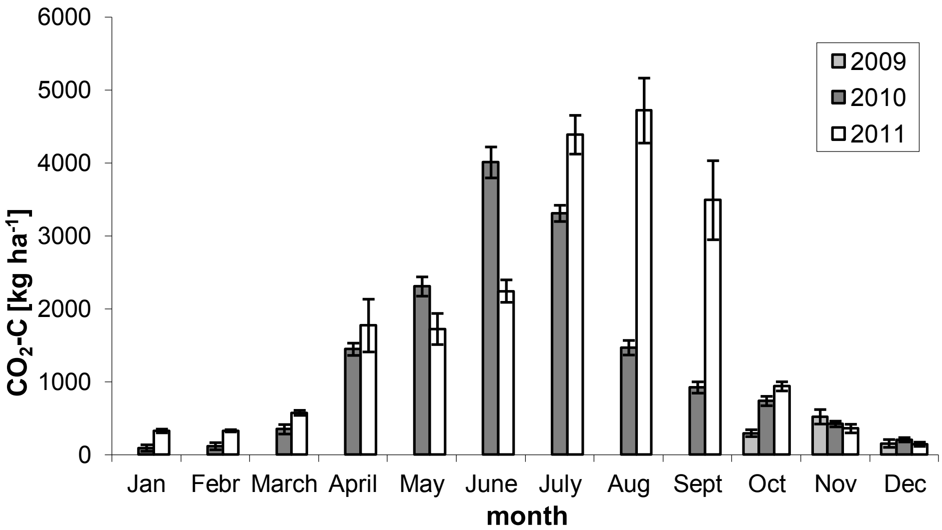

Fig. 3.9: Monthly cumulated ecosystem respiration (R_{eco}) of O1. Note: 2009 only from October to December. Error bars are standard errors.

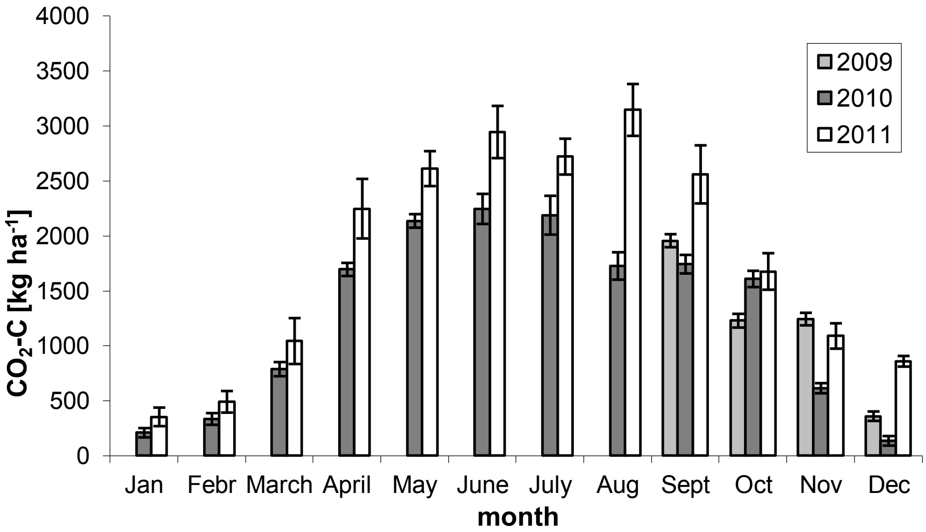

Fig. 3.10: Monthly cumulated ecosystem respiration (R_{eco}) of O2. Note: 2009 only from September to December. Error bars are standard errors.

3.3.6.3 Net ecosystem exchange

The net ecosystem exchange of the cropland sites showed a seasonal pattern, but differently to the R_{eco} (Fig.3.11-3.13). Highest net uptake during 2010 occurred in June or August, and during 2011 in July. Highest net release in 2010 was found in March and August at S1, in May at S2 and in August at O1. In 2011, highest net release was observed in April and May at S1, in May and June at S2 and in April at O1. From December until February, the flux rates were generally low at all three sites.

The monthly cumulated NEE and the annual course of cumulated NEE during the vegetation period in 2010 were very similar at S1 and O1 (Fig.3.11, Fig.3.13 & Fig.3.15). The months April, June, July and October did not differ significantly between the two sites in 2010. In contrast, monthly cumulated NEE at S2 were significantly different to S1 and O1 during the whole year (Fig.3.12 & Fig.3.15). S2 accumulated CO_2 in July and August, during the remaining part net emissions occurred.

In 2011, when all cropland sites had a similar management, differences were nevertheless great (Fig.3.11-3.13 & Fig.3.16). In May, August and September, monthly cumulated NEE did not differ significantly between S2 and O1, whereas the month June was not significantly different between S1 and O1.

The monthly cumulated NEE differed significantly between the two years 2010 and 2011 (except in February at S1 and in November at S2).

The annual courses of NEE at O2 show different patterns (Fig.3.14 & Fig.3.17). Highest monthly net uptake occurred in both years in April. However, highest monthly net release was highest in June 2010 as well as in July and September 2011. While in January, February, July and December 2010 a monthly net uptake of CO_2 was observable, in 2011 the same months showed a net release of CO_2. Only in October and November, the monthly cumulated NEE was not significantly different between the two years.

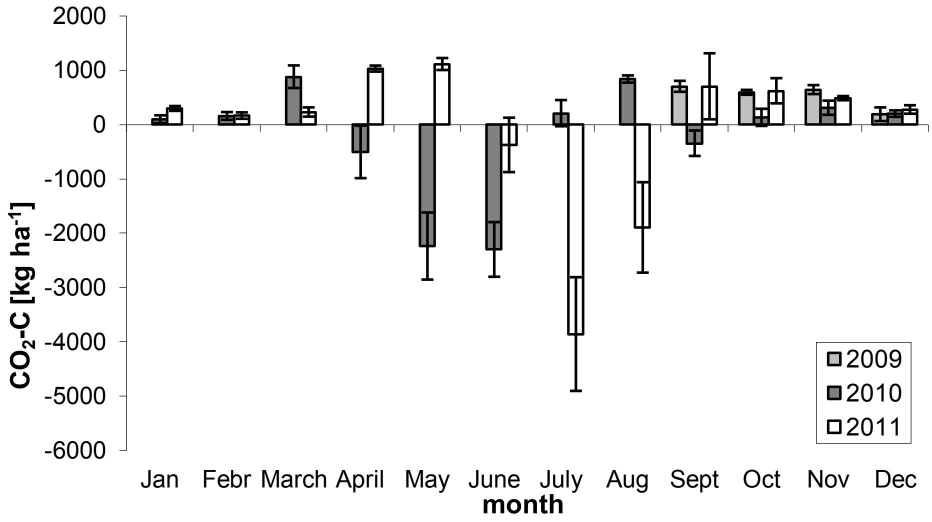

Fig. 3.11: Monthly cumulated net ecosystem exchange (NEE) of S1. Note: 2009 only from September to December. Error bars are standard errors.

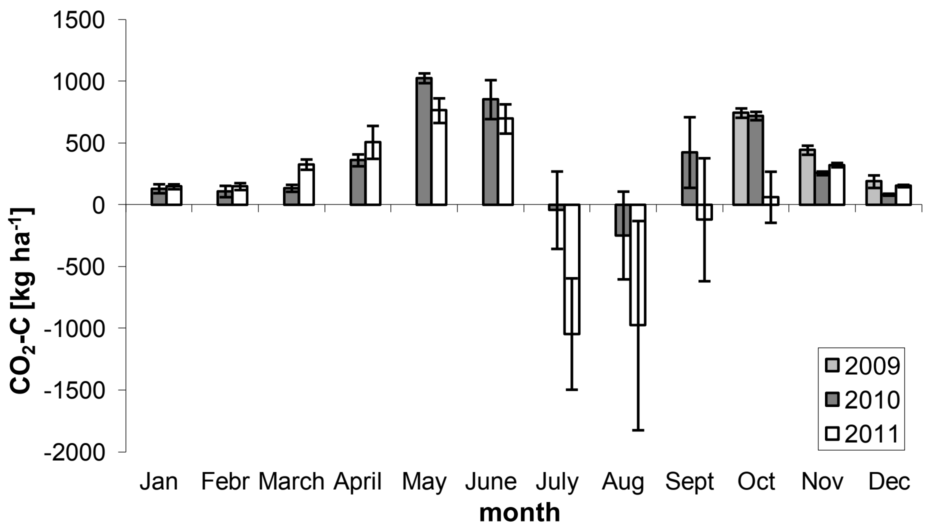

Fig. 3.12: Monthly cumulated net ecosystem exchange (NEE) of S2. Note: 2009 only from October to December. Error bars are standard errors.

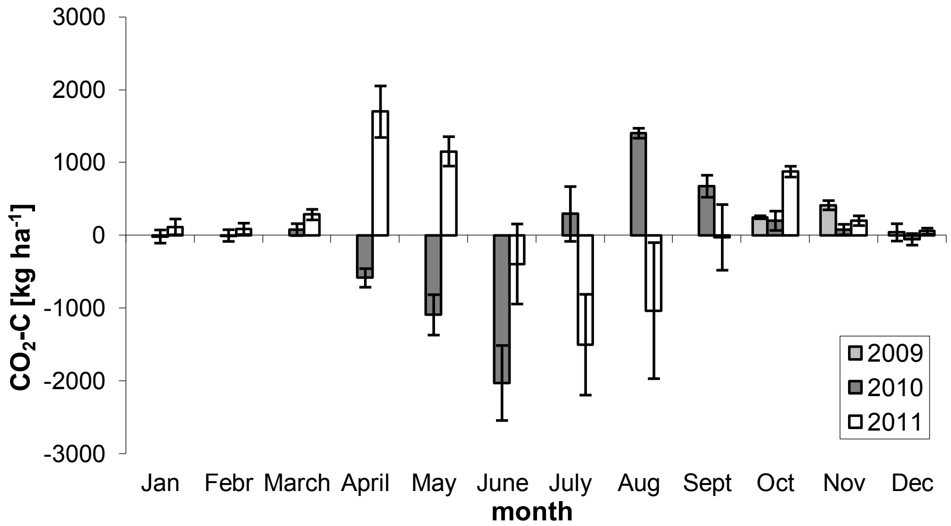

Fig. 3.13: Monthly cumulated net ecosystem exchange (NEE) of O1. Note: 2009 only from October to December. Error bars are standard errors.

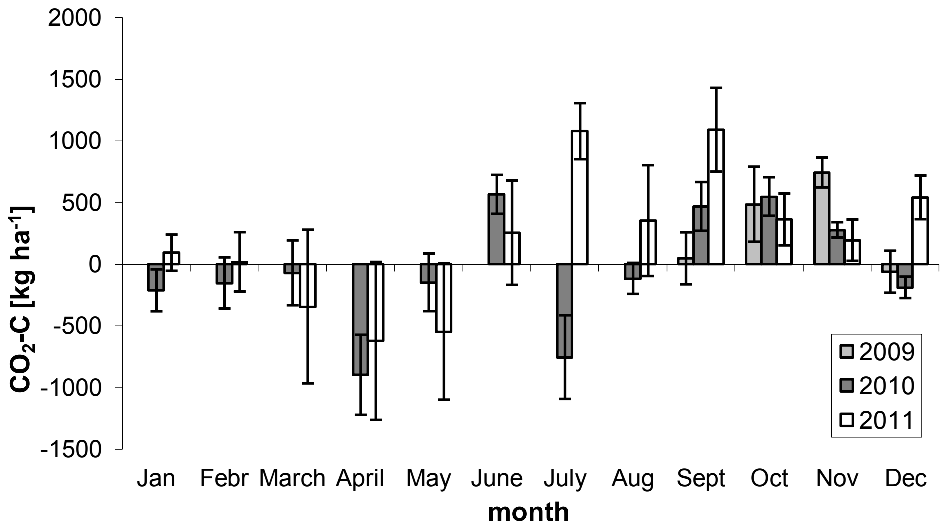

Fig. 3.14: Monthly cumulated net ecosystem exchange (NEE) of O2. Note: 2009 only from September to December. Error bars are standard errors.

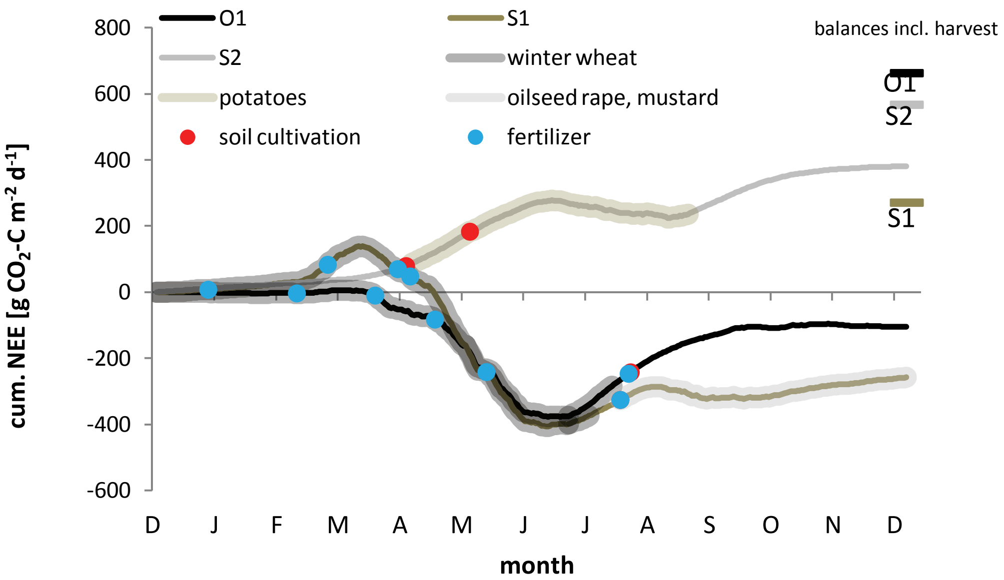

Fig. 3.15: Annual courses of cumulated NEE and agricultural management at S1, S2 and O1 in 2010. Annual balances incl. C import and export through fertilizer and harvest.

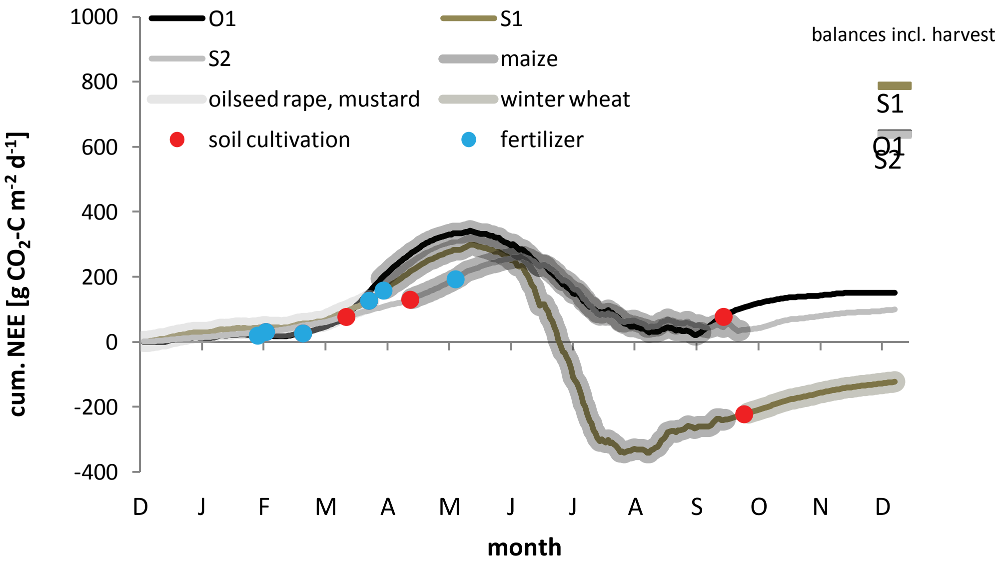

Fig. 3.16: Annual courses of cumulated NEE and agricultural management at S1, S2 and O1 in 2011. Annual balances incl. C import and export through fertilizer and harvest.

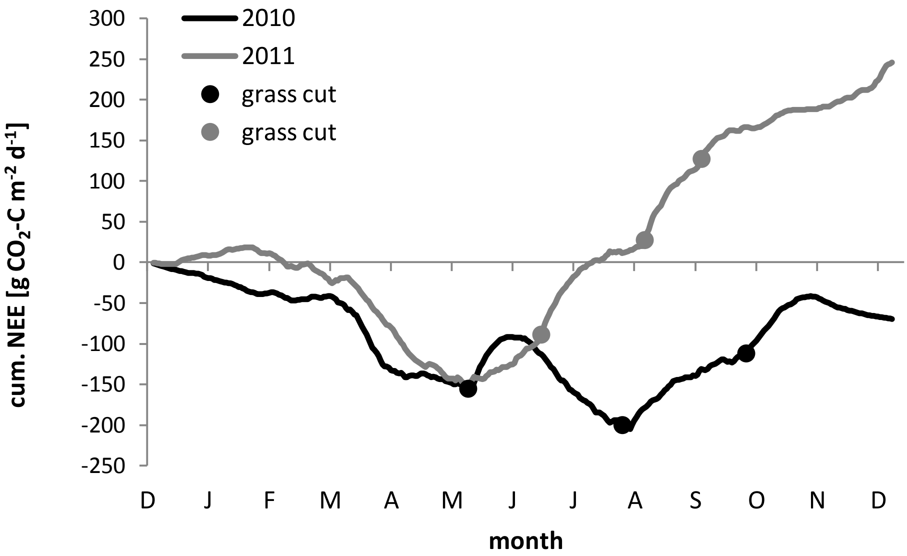

Fig. 3.17: Annual courses of cumulated NEE and agricultural management at O2 in 2010 and 2011.

The maximum net CO_2 uptake and release at the examination sites is presented in table 3.8.

Tab. 3.8: Daily maximum uptake and release of CO_2-C of the examination sites. Mean of the three collars and standard error (s.e.).

site	max uptake +/- s.e. [g CO_2-C $m^{-2}d^{-1}$]	max release +/- s.e. [g CO_2-C $m^{-2}d^{-1}$]
S1	-28.1 +/- 4.9	11.1 +/- 2.7
S2	-11.2 +/- 3.0	7.9 +/- 2.7
O1	-13.8 +/- 2.1	7.2 +/- 2.1
O2	-6.1 +/- 1.3	8.0 +/- 0.2

3.3.6.4 Annual carbon dioxide balance

In 2010, the annual R_{eco} at O1 and O2 were not significantly different (Tab.3.9). In 2011, the annual R_{eco} was significantly higher than in 2010 at all sites, and S1, O1 and O2 did not differ significantly. In average over the two measurement years, the annual R_{eco} was highest at S1 and lowest at S2.

The annual NEE balance without carbon import and export through fertilizer and harvest was in average over the two measurement years highest at S2 (Tab.3.9).

In 2010, O1 and O2 did not differ significantly. In 2011, annual accumulation of S1 was lower, but not significantly different to 2010. The annual balances between S2 and O1 as well as between O1 and O2 were not significantly different.

High amounts of carbon were exported through harvest (Tab.3.1). Carbon is also imported through organic fertilizer. If these carbon fluxes are considered in the net CO_2 balance, all sites were strong CO_2 sources. Annual NEE (incl. C import and export through fertilizer and harvest) at S2 and O1 were in both years very similar. In average over the two years, S1, S2 and O1 showed similarly high net emissions (5,294 +/- 2,587, 6,041 +/- 337 and 6,515 +/- 110 kg CO_2-C ha^{-1} a^{-1}, respectively). The net emissions at O2 were lower, with 3,975 +/- 365 kg CO_2-C ha^{-1} a^{-1}, in average over the two years.

Tab. 3.9: Annual and average balances for R_{eco}, NEE, CH_4-C, and N_2O-N exchange in kg ha^{-1}. M: Mean, s.e.: Standard error. *: incl. imported/exported C through harvest/fertilizer; ** without imported/exported C through harvest/fertilizer.

year	balances		2010		2011		average	
			m	s.e.	m	s.e.	m	s.e.
S1	R_{eco} CO_2	[kg CO_2-C ha^{-1} a^{-1}]	22271	799	29901	1324	26086	3815
	NEE CO_2 *	[kg CO_2-C ha^{-1} a^{-1}]	2707	1451	7882	2428	5294	2587
	NEE CO_2 **	[kg CO_2-C ha^{-1} a^{-1}]	-2586	1333	-1228	2017	-1907	679
	CH_4	[kg CH_4-C ha^{-1} a^{-1}]	-0.61	0.25	-0.30	0.28	-0.45	0.12
	N_2O	[kg N_2O-N ha^{-1} a^{-1}]	26.6	5.9	4.8	1.14	15.7	8.9
S2	R_{eco} CO_2	[kg CO_2-C ha^{-1} a^{-1}]	12104	242	19455	742	15779	3675
	NEE CO_2 *	[kg CO_2-C ha^{-1} a^{-1}]	5704	640	6378	1790	6041	337
	NEE CO_2 **	[kg CO_2-C ha^{-1} a^{-1}]	3813	640	991	1398	2402	1411
	CH_4	[kg CH_4-C ha^{-1} a^{-1}]	-0.28	0.11	3.15	1.71	1.43	1.40
	N_2O	[kg N_2O-N ha^{-1} a^{-1}]	18.2	1.5	24.8	2.9	21.5	2.7
O1	R_{eco} CO_2	[kg CO_2-C ha^{-1} a^{-1}]	23069	500	25899	1070	24484	1415
	NEE CO_2 *	[kg CO_2-C ha^{-1} a^{-1}]	6626	981	6405	1657	6515	110
	NEE CO_2 **	[kg CO_2-C ha^{-1} a^{-1}]	-1051	942	1518	1631	233	1285
	CH_4	[kg CH_4-C ha^{-1} a^{-1}]	0.84	0.57	-0.42	0.29	0.21	0.52
	N_2O	[kg N_2O-N ha^{-1} a^{-1}]	21.5	4.5	21.8	3.4	21.6	0.13
O2	R_{eco} CO_2	[kg CO_2-C ha^{-1} a^{-1}]	19210	622	23642	759	21426	2216
	NEE CO_2 *	[kg CO_2-C ha^{-1} a^{-1}]	3078	1069	4339	1590	3709	631
	NEE CO_2 **	[kg CO_2-C ha^{-1} a^{-1}]	-693	915	2458	1574	882	1576
	CH_4	[kg CH_4-C ha^{-1} a^{-1}]	-1.37	0.71	-2.28	0.39	-1.83	0.37
	N_2O	[kg N_2O-N ha^{-1} a^{-1}]	0.12	0.30	1.45	0.61	0.79	0.54

3.3.7 Nitrous oxide

A seasonal pattern of nitrous oxide fluxes was not visible at the examination sites. At S1 (Fig.3.18) most flux rates were very low (some of them not different from 0). Occasionally (September and November 2010), peaks with high emissions occurred (Tab.3.10).

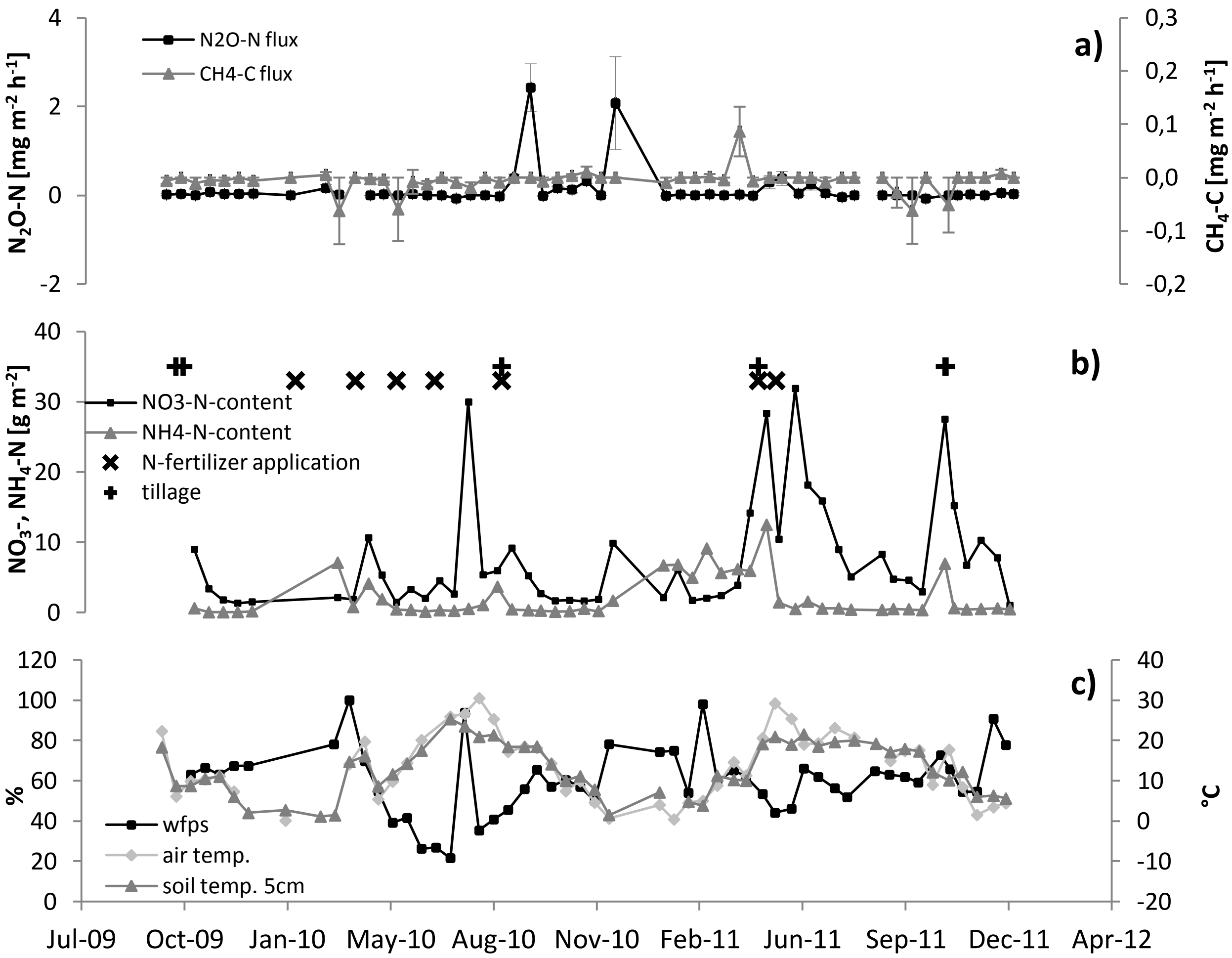

Fig. 3.18: a) Annual course of N_2O and CH_4 flux of S1. Mean of the three collars, error bars are standard errors.
b) Annual course of nitrate and ammonium content in the 0-20 cm soil-layer. Fertilizing events and tillage events are plotted.

c) Annual course of water filled pore space (wfps) of S1. Annual course of air temperature and soil temperature in 5 cm depth.

The maximum releases at the other sites were lower than at S1 (Tab.3.10). S2 and O1 showed a scattered pattern of fluxes (Fig.3.19 & Fig.3.20). S2 had peaks during all seasons, whereas at O1 peaks were only observed from spring until autumn.

At O2 lowest fluxes could be observed (Fig.3.21 & Tab.3.10). Maximum emissions occurred in February 2011. During the remaining part of the year, fluxes were near 0.

Uptake rates were very low at the sites (Tab.3.10).

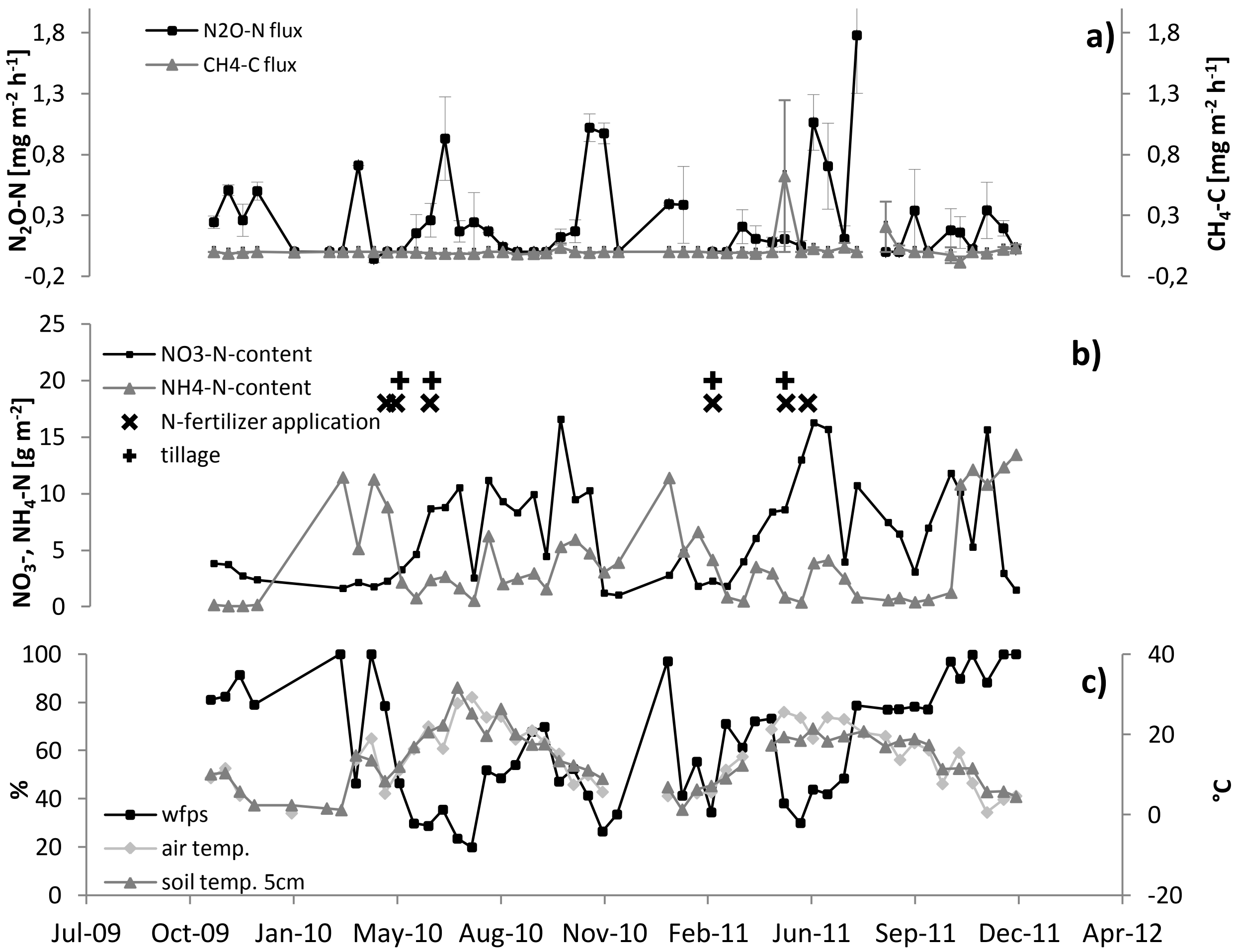

Fig. 3.19: a) Annual course of N_2O and CH_4 flux of S2. Mean of the three collars, error bars are standard errors.
b) Annual course of nitrate and ammonium content in the 0-20 cm soil-layer. Fertilizing events and tillage events are plotted.

c) Annual course of wfps of S2. Annual course of air temperature and soil temperature in 5 cm depth.

Correlations between N_2O fluxes and driving parameters were not significant.
Some of the peaks took place after the application of mineral N-fertilizer or organic fertilizer (Fig.3.18-3.20): This was the case at S1 in September 2010. From April until June 2011, NO_3^- - and NH_4^+ content as well as N_2O fluxes increased, immediately after fertilizer application and soil cultivation. S2 received fertilizer in April and May 2010; from May on, NO_3^- content and N_2O fluxes increased. Similarly, in March, May and June 2011, fertilizer was applied, and NO_3^--content and N_2O fluxes increased. O1 was supplied with fertilizer in March, April and May 2010, NO_3^--content increased from March until June, while N_2O fluxes increased from April until June 2010. In August 2010, fertilizer was applied, and N_2O fluxes increased in September and October 2010. In February, March and April 2011, fertilizer was applied, NO_3^- content and N_2O fluxes increased from April until June 2011.

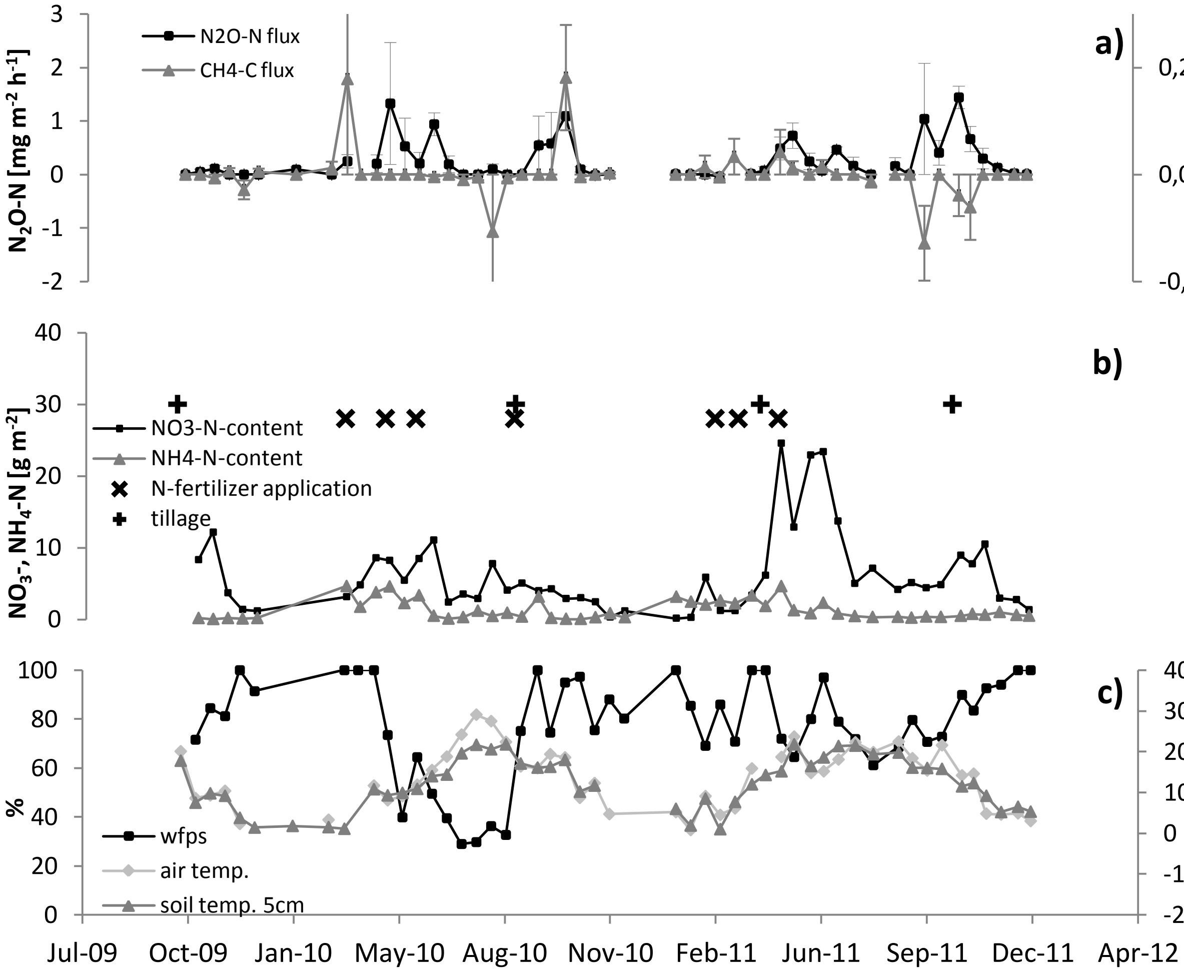

Fig. 3.20: a) Annual course of N_2O and CH_4 flux of O1. Mean of the three collars, error bars are standard errors.
b) Annual course of nitrate and ammonium content in the 0-20 cm soil-layer. Fertilizing events and tillage events are plotted.

c) Annual course of wfps of O1. Annual course of air temperature and soil temperature in 5 cm depth.

The highest N_2O fluxes occurred at wfps between 55 and 80 % (Fig.3.22). At higher or lower wfps the N_2O emissions decrease. However, even at optimal wfps, very low fluxes take place. At O2 the N_2O fluxes were close to 0 during the whole measurement period (Fig.3.21). Maximum fluxes could be observed on 02.02.2011 (Tab.3.10). On 02.06.2010, the site took up -0.07 +/- 0.07 mg N_2O-N m^{-2} h^{-1}.

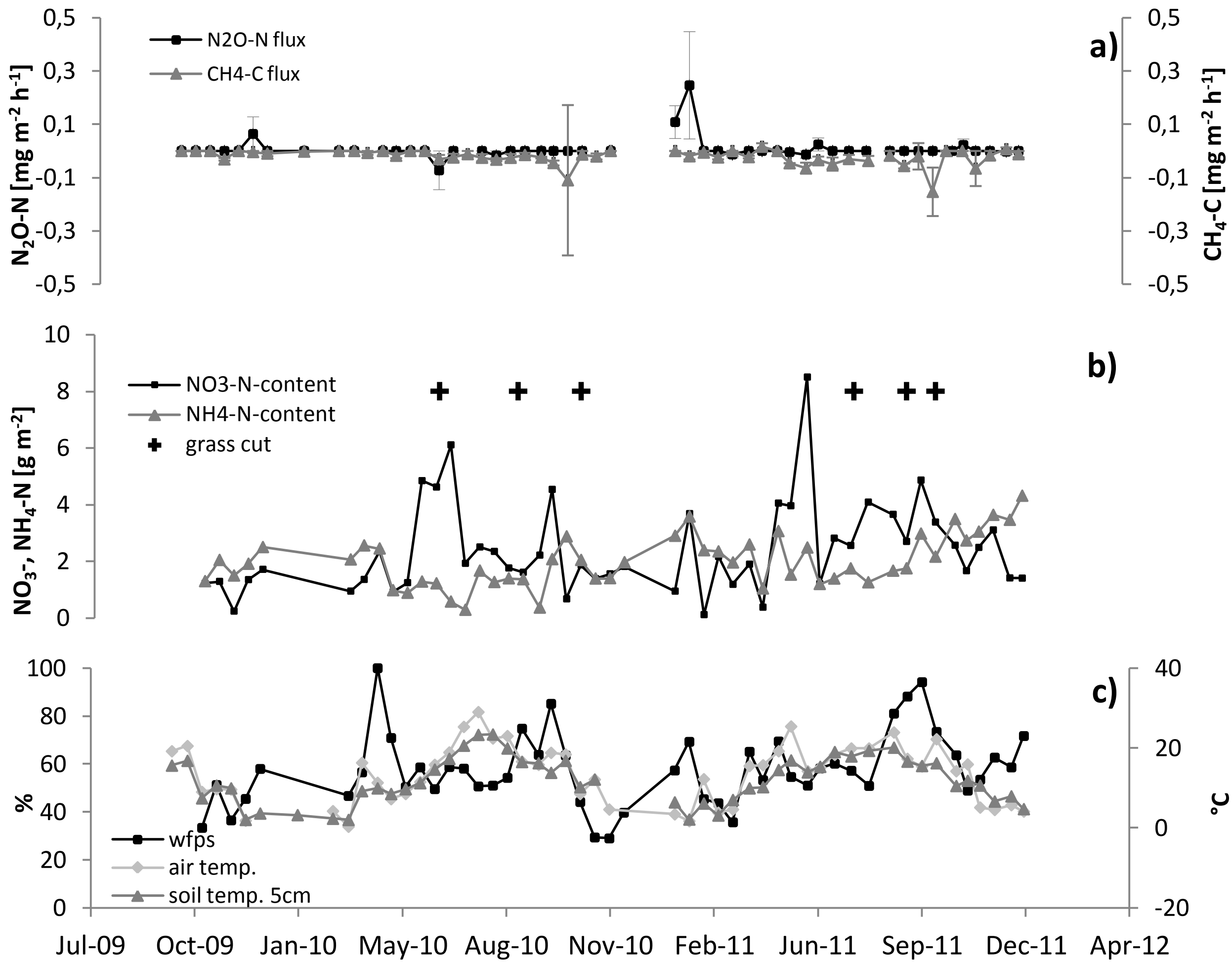

Fig. 3.21: a) Annual course of N_2O and CH_4 flux of O2. Mean of the three collars, error bars are standard errors.
b) Annual course of nitrate and ammonium content in the 0-20 cm soil-layer. Grass cutting events are plotted.

c) Annual course of wfps of O2. Annual course of air temperature and soil temperature in 5 cm depth.

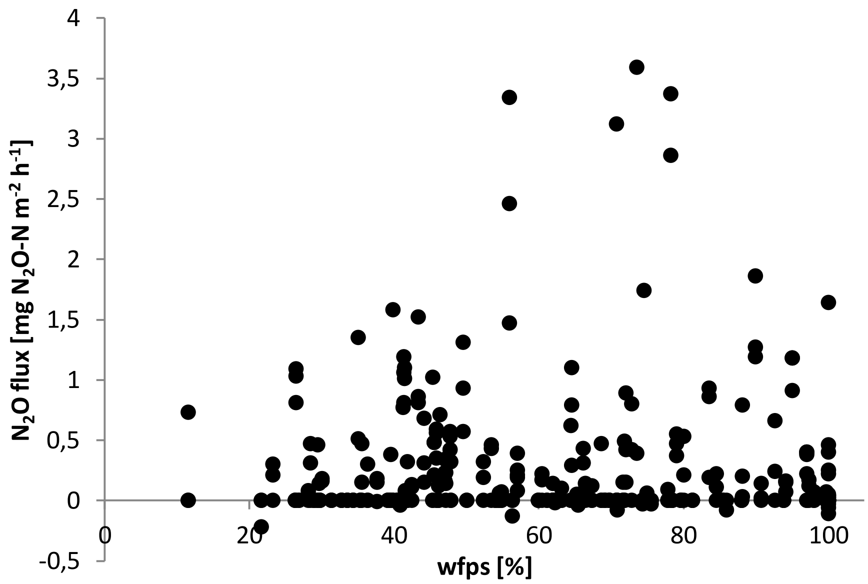

Fig. 3.22: wfps vers. N_2O flux at the cropland sites.

Tab. 3.10: Hourly maximum uptake and maximum release of N_2O-N (left) and CH_4-C (right) of S1, S2, O1 and O2. Mean of the three collars and standard error (s.e.).

site	max uptake +/- s.e. [mg N_2O-N m^{-2} h^{-1}]	max release +/- s.e. [mg N_2O-N m^{-2} h^{-1}]	max uptake +/- s.e. [mg CH_4-C m^{-2} h^{-1}]	max release +/- s.e. [mg CH_4-C m^{-2} h^{-1}]
S1	-0.07 +/- 0.07	2.42 +/- 0.54	-0.06 +/- 0.06	0.09 +/- 0.05
S2	-0.06 +/- 0.03	1.78 +/- 0.48	-0.08 +/- 0.05	0.62 +/- 0.62
O1	-0.04 +/- 0.03	1.44 +/- 0.21	-0.13 +/- 0.07	0.18 +/- 0.10
O2	-0.07 +/- 0.07	0.25 +/- 0.20	-0.15 +/- 0.09	0.02 +/- 0.01

During several measurement campaigns, no significant N_2O gas flux could be detected. If all three measurements on that date revealed a slope of gas concentration change over time that was not significantly different from 0, the flux rate on that date was set to 0. This was caused by low flux rates and a low accuracy of the gas chromatograph. At S1 18 of 53 measurement dates revealed 0-fluxes. One measurement date (23.03.2010) had to be removed from the time row because of measurement errors. S2 and O1 showed 14 out of 50 measurement dates and 15 out of 51 measurement dates with 0-fluxes, respectively. At O1, two measurement dates (24.03.2010 and 16.03.2011) had to be removed from the time row due to measurement errors. At O2 40 of 51 measurement dates had 0-fluxes. Two measurement dates (30.06.2010 and 03.11.2010) had to be removed from the time row.

In 2010, the annual nitrous oxide balances of the cropland sites were similar (Tab.3.9). The balances at S1 and S2 as well as S1 and O1 did not differ significantly. Whereas in 2011, S2 and O1 showed similar N_2O balances, but at S1 the annual N_2O emission was much lower. In average over the two years, S2 and O1 had almost identical N_2O balances (21.5 +/- 2. 7 and 21.6 +/- 0.13 kg N_2O-N ha^{-1} a^{-1}, respectively), while S1 showed a slightly lower annual emission with 15.7 +/- 8.9 kg N_2O-N ha^{-1} a^{-1}. The annual balances at S2 and O1 did not differ significantly between the years 2010 and 2011.
The annual nitrous oxide balances at O2 were significantly different to the balances of the cropland sites. In average over the two years, the site showed annual emissions of 0.79 +/- 0.54 kg N_2O-N ha^{-1} a^{-1}.

3.3.8 Methane

Similar to the annual course of the nitrous oxide fluxes, a seasonal pattern of methane fluxes was not observable (Fig.3.18-3.21). Fluxes were generally close to 0 at all sites. The highest maximum CH_4 emissions (mean of the three plots) were below 0.7 mg CH_4-C m^{-2} h^{-1}

(Tab.3.10). At O2 the maximum uptake was higher than the highest release. Noticeable is the CH_4 peak at S2 on 10.05.2011: two plots showed fluxes near 0, while a flux rate of 1.87 mg CH_4-C m^{-2} h^{-1} was observed at the third plot (mean of the three plots: 0.62 mg CH_4-C m^{-2} h^{-1}). No significant CH_4 fluxes could be detected during several measurement campaigns. This was the case on 31, 27, 30 and 17 measurement dates at S1, S2, O1 and O2, respectively. These flux rates were set to 0.

Methane balances were generally low at all sites, and mostly an annual uptake was observed (Tab.3.9). In average over the two years, S1 and O2 were small sinks of CH_4 (-0.45 +/- 0.12 and -1.83 +/- 0.37 kg CH_4-C ha^{-1} a^{-1}, respectively). S2 and O1 were small sources of CH_4 (1.43 +/- 1.40 and 0.21 +/- 0.52 kg CH_4-C ha^{-1} a^{-1}, respectively).

3.3.9 Global warming potential

In average over the two years, the GWP100 balances were quite similar at S2 and O1 (32,278 +/- 1,237 and 34,035 +/- 405 kg CO_2-eq. ha^{-1} a^{-1} respectively), whereas S1 showed a lower GWP100 balance (Tab.3.11: 26,787 +/- 9,511 kg CO_2-eq. ha^{-1} a^{-1}). At O2, the averaged balance was only 14,883 +/- 1,337 kg CO_2-eq. ha^{-1} a^{-1}. The second measurement year (2011) revealed a higher GWP100 balance than the first measurement year (2010) at S1, S2 and O2. In contrast, the GWP100 balance at O1 was lower in 2011.

The annual GWP100 balances at the examination sites were mainly determined by net CO_2 emissions. At S2 and O1, CO_2 contributed about 70 % to the GWP100 balance, whereas nitrous oxide contributed only about 30 %. The proportion of CO_2 on the GWP100 balance at O2 was even 97.5 %, while the proportion of N_2O was only 2.5 %. Similarly, at S1 a contribution of CO_2 of 93 % was observed in 2011. However, in 2010 comparatively low net CO_2 emissions and high N_2O emissions were observed. Consequently, N_2O contributed 56 % and CO_2 contributed 44 % to the GWP100 balance. Methane played a minor role at all sites.

Changing the time frame from 100 years to 500 years leads to slightly lower values at the cropland sites. However, at O2 the GWP balances remain similar.

Tab. 3.11: Annual and average NECB (net ecosystem carbon balances), and GWP (global warming potential) balances for the time spans of 20, 100 and 500 years in kg ha^{-1} a^{-1}. M: Mean, s.e.: Standard error.

year	GWP / NECB		2010		2011		average	
			m	s.e.	m	s.e.	m	s.e.
S1	GWP 20	[kg CO_2-eq. ha^{-1} a^{-1}]	21956	5323	31118	8904	26537	9511
	GWP 100	[kg CO_2-eq. ha^{-1} a^{-1}]	22369	5323	31205	8904	26787	9511
	GWP 500	[kg CO_2-eq. ha^{-1} a^{-1}]	16318	5322	30105	8904	23212	9510
	NECB	[kg CO_2-C ha^{-1} a^{-1}]	2732	1451	7919	2593	5325	2593
S2	GWP 20	[kg CO_2-eq. ha^{-1} a^{-1}]	29180	2348	34941	6563	32060	1237
	GWP 100	[kg CO_2-eq. ha^{-1} a^{-1}]	29455	2348	35102	6563	32278	1237
	GWP 500	[kg CO_2-eq. ha^{-1} a^{-1}]	25302	2347	29380	6563	27341	1236
	NECB	[kg CO_2-C ha^{-1} a^{-1}]	5730	640	6407	1790	6069	337
O1	GWP 20	[kg CO_2-eq. ha^{-1} a^{-1}]	34135	3599	33348	6076	33742	405
	GWP 100	[kg CO_2-eq. ha^{-1} a^{-1}]	34388	3599	33682	6076	34035	405
	GWP 500	[kg CO_2-eq. ha^{-1} a^{-1}]	29471	3598	28723	6076	29097	405
	NECB	[kg CO_2-C ha^{-1} a^{-1}]	6652	981	6430	1657	6541	110
O2	GWP 20	[kg CO_2-eq. ha^{-1} a^{-1}]	11214	3918	16360	5828	13787	2312
	GWP 100	[kg CO_2-eq. ha^{-1} a^{-1}]	11299	3918	16518	5828	13908	2312
	GWP 500	[kg CO_2-eq. ha^{-1} a^{-1}]	11302	3918	16238	5828	13770	2312
	NECB	[kg CO_2-C ha^{-1} a^{-1}]	3103	1069	4363	1590	3733	631

3.4 Discussion

3.4.1 Carbon dioxide

3.4.1.1 Evaluation of methodology

As pointed out in chapter two, the applied chamber technique is a suitable method to determine the gas exchange in a small scale mosaic of different land uses. The size of the collars and the chambers is appropriate.

To calculate gas fluxes from the change of gas-concentration over time inside the chamber a linear equation can be used. However, linearity of the slope of gas concentration inside the chamber and constancy of the explaining variables should be monitored.

The modeling of the carbon dioxide exchange led to very appropriate results (Tab.3.4-3.7 & Fig.3.6). Only in a very few cases was measurement campaign specific calibration of the models not possible.

The parameters E_0 and R_{ref} at the wheat plots (Tab.3.4 & Tab.3.6: S1, O1 in 2010) show similar values to a barley plot and a barley plot under sown with grass in Denmark (Elsgaard et al. 2012) At the potato plot (S2 in 2010), R_{ref} and E_0 was lower than at the wheat plots (Tab.3.5: S2 in 2010), this was also observed by Elsgaard et al. (2012). In their study, R_{ref} was similar, E_0 was slightly higher compared to S2. Compared to the maize plots in chapter two, R_{ref} and E_0 in this study are similar (Tab.3.4-3.6).
At O2 E_0 and R_{ref} (Tab.3.7) are in the same range as grassland on bog in Germany and Denmark (Elsgaard et al. 2012, Beetz et al. 2013).

The interpolation between the measurement campaigns was conducted linearly. Since the long term driving parameters such as wl and biomass do not always change linearly, the time span between two measurement campaigns was kept as short as possible (see ch.2, Beetz et al. 2013).
One of the advantages of the chosen method is that specific events, e.g. tillage or harvest are considered in the time row of CO_2 gas fluxes (see ch.2). This led to precisely modeled gas fluxes before and after specific events. Directly after grass cut events at O2, it was assumed that no photosynthesis occurs and GPP was set to 0. Therefore, GPP might be underestimated and, thus, net emissions overestimated. However, directly after grass cuts the system is disturbed. Thus, measurements directly after grass cuts were avoided, because they might have led to misleading results (see ch.2).
As already mentioned in chapter two, the carbon exported through harvest was determined very precisely, and consequently the annual NEE balances could be determined very exactly. Determination of carbon imported through application of organic fertilizer is less precise, because it was estimated based on the information on fertilization given by the farmer (Tab.3.1). The sites were supplied with slurry in each measurement year, and the error is less than 200 kg ha^{-1}, except in 2011 at O1, which is small compared to R_{eco}, GPP, and carbon export. In 2011, O1 was supplied with a high amount of slurry and manure, which might lead to an error of up to 425 kg ha^{-1}.

3.4.1.2 Ecosystem respiration

A clearly seasonal pattern with highest values in June, July or August and lowest values from December until February was also observed by Kandel et al. (2012) and Petersen et al. (2012), who investigated peatlands used as cropland in Denmark. Maize and potatoes showed highest monthly cumulated R_{eco} in August, whereas the plots planted with winter wheat had highest monthly cumulated R_{eco} already in June (Fig.3.7-3.9). Winter wheat is already sown in the previous year, thus the vegetation develops earlier than maize or potatoes, leading from May until June to a higher monthly R_{eco} and from July until October to a lower monthly R_{eco} compared to maize or potatoes. Potatoes and maize are both planted in April or May and harvested in autumn, however, maize develops a much greater amount of biomass and the monthly R_{eco} is higher (Fig.3.3).

During the vegetation period of 2010, S1 and O1 (both winter wheat) revealed similar monthly values as organic soils planted with barley in Denmark (Kandel et al. 2012, Petersen et al. 2012).
During the vegetation period of 2011, higher monthly values at S1 (maize), S2 (maize) and O1 (maize) were observed (except at S2 in May) compared to the cropland site (maize) in chapter two. During vegetation period, R_{eco} is mainly determined by the autotrophic respiration of the vegetation. Since the amount of green biomass of the maize at the cropland site in chapter two was comparable with the amount of green biomass at O1 and S2, it can be assumed that the heterotrophic respiration is higher at O1 and S2 (Fig.3.3). The cropland site (maize) in chapter two shows a lower R_{eco} mainly due to a very high wl (see ch.2).

At O2 the annual course of R_{eco} shows a clear seasonal trend as well, but different than at the cropland sites due to year round presence of the grassland vegetation and several cuttings of the grass during the vegetation period (Fig.3.10). A similar annual pattern was described at the grassland site in chapter two as well as by van den Bos & van de Plassche (2003b), Veenendaal et al. (2007), Kandel et al. (2012) and Beetz et al. (2013) on grassland sites in drained peatlands. A grassland site on gleysol showed also a similar pattern (Peichl et al. 2011).

3.4.1.3 Net ecosystem exchange

The annual courses of the NEE at all sites are predominantly characterized by the land use/ vegetation. Cultivating winter wheat led to a net accumulation of carbon dioxide already from April on, because it was sown in the previous year and developed fast in spring. Until June, a high amount of CO_2 was net accumulated due to the formation of high amounts of biomass (Fig.3.11, Fig.3.13 & Fig.3.15). In June, the amount of green biomass was highest leading to the highest net accumulation of CO_2. This was also observed in a spring barley field on organic soil in Denmark by Kandel et al. (2012). In July, a net release of CO_2 occurred, because grain development and maturation took place, thus there was almost no green biomass for photosynthesis. The monthly balances are in a similar range as in the study of Kandel et al. (2012). A boreal spring barley field under-sown with grass on organic soil accumulated net CO_2 from end of June until the beginning of August, thus for a period of less than six weeks (Lohila et al. 2004). Maize and potatoes are planted in April or May, consequently biomass develops later than at the winter wheat cultivating sites and net accumulation of CO_2 starts later in the year (Fig.3.11-3.13, Fig.3.15 & Fig.3.16). Maize is a fast growing plant compared to potato. A few weeks after sowing, high amounts of CO_2 are sequestrated (see ch.2). In contrast, potatoes accumulate less CO_2. In spring, the soil is not covered with vegetation, leading to high net emissions due to very favourable conditions for R_{eco} at the maize and potatoes plots (see ch.2). The annual course of cumulated NEE at S2 (maize) and O1 (maize) is similar, because the development of biomass is only slightly different (Fig.3.16). In 2011, the cropland site of chapter two (maize) showed a similar annual pattern. In contrast, S1 (maize) had a higher amount of biomass and thus a different annual course of NEE (Fig.3.3).

At the end of the growing period, photosynthesis decreases strongly, while the decrease of the respiration is weaker (Lohila et al. 2004). This leads to high net emissions.

Maximum net uptake and release were higher in the study sites than in organic soils in the boreal zone (Maljanen et al. 2001a, Lohila et al. 2004) due to higher temperatures and higher PAR (Tab.3.8).

O2 showed a similar pattern as other grassland sites on organic soils (ch.2, Dirks et al. 2000, Nieveen et al. 2005 and Veenendaal et al. 2007) with highest net uptake in spring and with net release in summer and autumn, which demonstrates the high growth rate and carbon assimilation of the grass sward in spring (Fig.3.14 & Fig.3.17). The monthly cumulated fluxes are in a similar range (Nieveen et al. 2005, Veenendaal et al. 2007). After the first grass cut, net emissions occurred, because the growth of the grass is impeded. Due to several cuttings during the vegetation period, monthly NEE showed mostly a net release of CO_2. Also Maljanen et al. (2004) observed in a boreal peatland used as grassland a net uptake in spring/summer before the first grass cut, while after the first cut only rarely net uptake occurred, but mostly a net release. A strong decrease of GPP after the grass cut, followed by a slowly increase observed at O2 was also observed at the study sites of Maljanen et al.

(2001a), Lohila et al. (2004) and Beetz et al. (2013). This led to net emissions in June at O2. The annual course in the vegetation period 2010 (Fig.3.17) is very similar to the findings of Lohila et al. (2004) with uptake before the first and the second grass cut and release after the first and the second grass cut. Nieveen et al. (2005) and Dirks et al. (2000) examined grazed grasslands on organic soils and observed a net uptake still in June because no grass cuttings took place. Beetz et al. (2013) concluded that the cutting regime is the main driver of the NEE. EC measurements in grasslands on gleysol, which has a low carbon content, showed also in average over six years highest net uptake in April and May, while a reduction of net uptake after grass cuttings in June and August is visible (Byrne et al. 2005, Peichl et al. 2011).

On the one hand, the several cuttings throughout the year cause a long accumulation period, because the grass was kept in the vegetative stage (Lohila et al. 2004). On the other hand, the accumulation period was interrupted by periods of several days with net emissions, immediately after the cuttings, which was also observed by Lohila et al. (2004) and Beetz et al. (2013). At S1, S2 and O1, the net accumulating time period was shorter than at O2 in 2010, but more CO_2 was accumulated during this time, with the exception of the potato plot. However, in 2011 only net emissions occurred (on a daily basis) from June on, except for very short periods in August and October, at O2. In this year, the first cut took place comparatively late, while the second cut was conducted already seven weeks later and the third cut four weeks after the second cut. Thus, the time span between the cuts might not be long enough for the grass to develop enough green biomass for photosynthesis to outbalance respiration. Also in an intensively used grassland site in a bog in Northern Germany, high amounts of CO_2 were net accumulated before the first cut, while after the first cut only net emissions occurred, except for very short time periods (Beetz et al. 2013). The highest GPP in their study was -16.2 +/- 1.8 g CO_2-C m^{-2} d^{-1}. At O2 the highest GPP occurred also before the first cut and was in the same range (-12 g CO_2-C m^{-2} d^{-1}). In the study of Maljanen et al. (2001a), GPP dropped rapidly after the first mowing of the grassland and did not reach the level before mowing. After the second mowing, GPP remained at a low level.

3.4.1.4 Annual carbon dioxide balance

At S1 the annual NEE was much higher in 2011 (Tab.3.9: 7,882 +/- 2,428 kg CO_2-C ha^{-1} a^{-1}) than in 2010 (Tab.3.9: 2,707 +/- 1,451 kg CO_2-C ha^{-1} a^{-1}). The catch crops (mustard and oilseed rape) accumulated carbon, which led to low annual net emissions in 2010. In 2011, the vegetation died after frost and remained in the field, contributing to a higher annual R_{eco} in 2011 and consequently higher net CO_2 emissions. In average over the two years, the annual CO_2 balance at S1 is comparable to the other two cropland sites.

Data about carbon dioxide balances of bogs used as cropland in the temperate zone are scarce. A bog grown with potatoes in Denmark has a similar NEE including carbon import and export through fertilizer and harvest (Elsgaard et al. 2012), while Danish fens grown with barley show either higher or lower annual balances (Elsgaard et al. 2012, Kandel et al. 2012) compared to S1, S2 and O1. According to Höper & Blankenburg (2000) and Höper (2007), who achieved carbon balances through measuring the peat subsidence, annual carbon loss amounts to 4,400 kg CO_2-C ha^{-1} a^{-1}. The average of the four annual balances of the bogs in this study is 5,671 kg CO_2-C ha^{-1} a^{-1}. The difference is small and might be due to a different methodological approach. There are no studies examining GHG emissions from histosols with only small peat layers used as cropland. The similarly high net emissions of the different sites in this study indicate that not organic soil type but other factors determine the exchange of CO_2. Couwenberg et al. (2011) found also no difference between different organic soil types in a metaanalysis of available annual CO_2 flux data. They were able to explain the variation by the different wl. The higher the wl the lower the emissions (Tuittila et al. 1999, Waddington et al. 2002, van den Bos & van de Plassche 2003b, Danevcic et al. 2010, Kløve et al 2010). According to Höper (2007), Oleszczuk et al. (2008) and Mäkiranta et al. (2009), the relationship is not linear, the maximum of peat mineralization occurs at a wl depth of approximately 60 to 90 cm below ground surface in summer (see above). This might explain the variation of the net carbon dioxide emissions averaged over the two years: highest averaged emissions occurs at O1 (averaged summer wl: -66 cm) and decrease with increasing summer wl depth (S2: -92 cm, S1: -134 cm). The annual balance averaged over the two years at S1 might be also lower than at S2 and O1, because of the land use management: At S1 mustard and oilseed rape was sown in late summer 2010. Since these crops were not harvested but remained in the field, they were probably not completely mineralized until the end of 2011. However, it cannot be finally determined if the slightly lower emissions at S1 were due to wl or management practice.

The results are in contrast to Mundel (1976), who found in a laboratory incubation experiment much smaller peat mineralization in peat covered with a layer of sand (Sanddeckkultur) and only small differences between cropland, grassland, peat without added sand (Schwarzkultur) and peat mixed with sand (Sandmischkultur).

According to this study, the balances of histic gleysol covered with a layer of sand and bogs covered with a layer of sand are roughly the same as drained bogs without addition of sand in the temperate zone. Accordingly, emissions of deeply drained cropland on organic soil in the temperate zone amount to about 6,000 kg CO_2-C ha^{-1} a^{-1}. While peatlands grown with maize and wheat show similar balances (about 6,500 kg CO_2-C ha^{-1} a^{-1}), peatlands cultivated with potatoes might release slightly less net CO_2 (about 5,700 kg CO_2-C ha^{-1} a^{-1}). Elsgaard et al. (2012) explain the lower value by the short vegetation period and the drying of the soil between the potato plants.

Carbon dioxide balances of fens used as grassland in Germany, Denmark and the Netherlands range from 4,200 to 7,900 kg CO_2-C ha^{-1} a^{-1} (Veenendaal et al. 2007, Elsgaard et al. 2012, Kandel et al. 2012, ch.2). Similarly, Couwenberg (2009) reported a range of 4,100 to 7,600 kg CO_2-C ha^{-1} a^{-1} at peatlands used as grassland in the temperate zone. These values are higher than the results at O2 (Tab.3.9: 3,078 +/- 1069 and 4,339 +/- 1590 kg CO_2-C ha^{-1} a^{-1}). At a bog used as grassland in North Germany, Beetz et al. (2013) found 4,340 kg CO_2-C ha^{-1} a^{-1} in the year 2008, whereas Elsgaard et al. (2012) determined in a grassland-bog in Denmark much higher values (10,400 to 11,500 kg CO_2-C ha^{-1} a^{-1}). A literature review of fens used as grassland, conducted by Byrne et al. (2004) and Höper (2007) revealed an emission factor of 4,000 kg CO_2-C ha^{-1} a^{-1}, which is in accordance with the results in this study. In summary, the balances at O2 are at the lower end of the range of cited values. The reason might be the low carbon content of O2 (Tab.3.2: 7.7 % Corg/dry mass in the upper horizon).
A gleysol with a SOC concentration of 5.9 % used as high intensity grassland was a sink of CO_2 (Byrne et al. 2005, Peichl et al. 2011). The annual NEE (averaged over 6 years) amount to -2,770 +/- 460 kg CO_2-C ha^{-1} a^{-1} (C import and export not included) and -1,840 +/- 570 kg CO_2-C ha^{-1} a^{-1} (C import and export included).

Hence, all sites are strong sources. The differences in net CO_2 balances is explainable by land use type and intensity: cropland has higher net emissions (about 6,000 kg CO_2-C ha^{-1} a^{-1}), while grassland has lower net emissions (about 4,000 kg CO_2-C ha^{-1} a^{-1}). Cropland soils have a higher peat mineralization mainly due to ploughing (Höper & Blankenburg 2000) and slurry application (Flessa & Beese 2000). Maljanen et al. (2001a) identified also type and phenology of vegetation as influencing parameters of the carbon balance.

A recommendation to reduce the release of large amounts of CO_2 from agriculturally used organic soils is low intensity land use instead of high intensity land use, and a high wl.

Factors for interannual variation of the carbon balances are the weather conditions (ch.2, Maljanen et al. 2001a Shurpali et al. 2009). However, in this study the influence of the meteorological conditions seems to be very small in comparison to the influence of the cultivated plants. This was also observed by Jacobs et al. (2007).

3.4.2 Nitrous oxide

The event-based emission pattern (according to Brumme et al. 1999) at the cropland sites with generally low fluxes and high peaks (Fig.3.18-3.20) was also observed in several studies examining cropland sites in peatlands. Also the maximum releases (Tab.3.10) are in the range of literature data (Flessa et al. 1998, Maljanen et al. 2003a, Maljanen et al. 2004, Regina et al. 2004, Maljanen et al. 2007, Kasimir Klemedtsson et al. 2009, Kløve et al. 2010, Petersen et al. 2012). Most of the peaks were caused by application of fertilizer (Kaiser et al. 1998, Chadwick et al. 2000, Flessa & Beese 2000, Couwenberg 2009, Couwenberg 2011, Jassal et al. 2011, see ch.2) or by tillage (Regina et al. 1996, Regina et al. 2004, Kasimir Klemedtsson et al. 2009).

In contrast to that, at O2 (Fig.3.21) a background emission pattern (according to Brumme et al. 1999) with low emissions can be found because no fertilizer was applied (Chadwick et al. 2000, Kasimir Klemedtsson et al. 2009, Petersen et al. 2012). The annual course and flux rates are similar to other grasslands on peat (Flessa et al. 1998, Maljanen et al. 2003a, Grønlund et al. 2006, Kasimir Klemedtsson et al. 2009, Petersen et al. 2012).

Nykänen et al. (1995), Meyer (1999), Maljanen et al. (2003a), Regina et al. (2004) and Weslien et al. (2009) found a relationship between N_2O fluxes and wfps. A favourable wfps is between 82 and 85 % (Meyer 1999) or between 70 and 90 % (Maljanen et al. 2003a). According to the measurements at the cropland sites, the highest N_2O emissions occur at a wfps that ranges from 55 to 80 % (Fig.3.22). Kasimir Klemedtsson et al. (2009) observed greatest N_2O emissions at the drier areas (< 60 % average wfps) of their study.

A relationship between N_2O fluxes and wl was not visible, as opposed to the findings of Regina et al. (1996), Augustin et al. (1998), Flessa et al. (1998), Maljanen et al. (2001b), Maljanen et al. (2003a), Maljanen et al. (2004) and Weslien et al. (2009). An effect of rain events reported by Maljanen et al. (2004) and Regina et al. (2004) was also not visible. A relation between N_2O fluxes and wl or between N_2O fluxes and precipitation is difficult to detect, because too dry as well as too wet conditions inhibit N_2O production. Flessa et al. (1998), Maljanen et al. (2001b), Maljanen et al. (2003a), Regina et al. (2004), Couwenberg (2009) and Kasimir Klemedtsson et al. (2009), described increased fluxes caused by frost thaw cycles. The winter of the examination sites is quite mild and the soil temperatures dropped very rarely below 0 °C, and thus no emissions due to frost were recognized.

The N_2O emissions originate mainly from two processes: Nitrification and denitrification (Firestone & Davidson 1989, Schlesinger 1997, Maljanen et al. 2003a, Höper 2007). A complex pattern of different processes regulate the N_2O fluxes from peat soils (Conrad 1996, Regina et al. 1996, Jungkunst et al. 2006). Thus, correlations between fluxes and environmental parameters are difficult to detect. Kasimir Klemedtsson et al. (2009), Danevcic et al. (2010) and Beetz et al. (2013) could not find any significant relationship in their studies.

The annual nitrous oxide balances in this study are well in the range of the published values, which vary strongly (ch.2, Velthof et al. 1996, Flessa et al. 1998, Höper & Blankenburg 2000, Augustin 2003, Byrne et al. 2004, Höper 2007, Kasimir Klemedtsson et al. 2009, Couwenberg et al. 2011, Petersen et al. 2012).

According to the results, annual nitrous oxide emissions from organic soils used as cropland are about 15 to 20 kg N_2O-N ha^{-1} a^{-1}, whereas grassland on organic soil emit with in average 0.8 kg N_2O-N ha^{-1} a^{-1} more than 10 times less N_2O (Tab.3.9). The difference might be partly explainable by the fact that cropland receive fertilizer (see above). N-fertilized soils have higher annual N_2O emissions than unfertilized (Augustin et al. 1996, Jungkunst et al. 2006, Höper 2007). Another reason for higher N_2O emissions from the cropland sites might be soil cultivation (see above; Regina et al. 1996, Maljanen et al. 2004, Regina et al. 2004, Maljanen et al. 2007, Kasimir Klemedtsson et al. 2009).

An effect of C/N ratio was not observable at the examination sites. In opposition to Klemedtsson et al. (2005), Maljanen et al. (2007) and Maljanen et al. (2010), who found a negative relationship between N_2O emissions and soil C/N ratios. However, a comparison of different nationwide data revealed no correlation between N_2O losses and C/N ratios, too (Jungkunst et al. 2006). Weslien et al. (2009) observed a positive relationship between N_2O emissions and soil C/N ratios.

The low balance of S1 in 2011 is noticeable. The maize grown in 2011 developed a much higher amount of biomass compared to S2 and O1, and thus had probably a higher demand of nitrogen and competed with nitrification and denitrification for the released mineral nitrogen (Danevcic et al. 2010).

A difference between the peatland types drained bog and drained bog covered with a layer of sand could not be found. The sites S2 and O1 had in average almost identical balances. In 2010, S1 showed a slightly higher value, while in 2011, S1 had a lower value. Also Maljanen et al. (2004) found similar annual emissions at Sandmischkultur and thin peat (30 cm).

3.4.3 Methane

Drained organic soils show generally low flux rates of methane due to the thick aerobic soil layer, where methane is oxidized (Augustin et al. 1998, Van den Bos & van de Plassche 2003a, Drösler 2005). Emissions are expected when wl and temperatures are high (Roulet et al. 1993, Shurpali et al. 1993, Macdonald et al. 1998, Nykänen et al. 1998, Christensen et al. 2003), which happened very rarely at the examination sites.
The year round fluxes close to 0 without a seasonal pattern (Fig.3.18-3.21) were also observed at the study sites of Kasimir Klemedtsson et al. (2009), Danevcic et al. (2010) and Beetz et al. (2013). Maximum emissions at deeply drained grasslands on organic soil in Germany and Sweden (Flessa et al. 1998 and Kasimir Klemedtsson et al. 2009) are similar to the value of O2 (Tab.3.10). Grasslands with a high wl and a high wfps reveal higher maximum releases (Kasimir Klemedtsson et al. 2009, ch.2).

Annual methane fluxes of organic soils used as cropland and grassland are generally negligible compared to carbon dioxide and nitrous oxide fluxes (Tab.3.9), which was also established by Kasimir-Klemedtsson et al. (1997) and Schäfer et al. (2012). The annual balances for the cropland sites and the grassland site in this study are in the range of published values at similar sites (Flessa et al. 1998, Meyer 1999, Van den Pol-van Dasselaar et al. 1999, Augustin 2003, Maljanen et al. 2004, Regina et al. 2007, Kasimir Klemedtsson et al. 2009, Petersen et al. 2012). In contrast, the cropland site of chapter two has a higher CH_4 balance, which is due to occasionally very wet conditions. Petersen et al. (2012) found in a fen used as grassland in Denmark much higher emissions (37 kg CH_4-C ha^{-1} a^{-1}), probably caused by tussocks of *Juncus effuses*, which are aerenchymous plants (Joabbson et al. 1999, Joabbson & Christensen 2001, Petersen et al. 2012).

3.4.4 Global warming potential

In average over the two years, the GWP100 balance at the cropland sites ranged between 26,787 and 34,035 kg CO_2-eq. ha^{-1} a^{-1}, while at O2 the GWP100 balance was only half as high (Tab.3.11: 13,908 kg CO_2-eq. ha^{-1} a^{-1}). Also Maljanen et al. (2004) observed a higher GWP100 balance in organic soils under barley than in organic soils under grass. The high content of mineral soil at S1 and O1 seems to have no influence for the GWP100 balance. Maljanen et al. (2004) found no difference between the GWP100 balance of peat mixed with sand (Sandmischkultur) and the GWP100 balance of a shallow peatland (30 cm thick peat).
Höper & Blankenburg (2000) and Höper (2007) estimate the GWP100 balance of cropland on bog to be lower (16,133 kg CO_2-eq. ha^{-1} a^{-1}). Whereas a bog cultivated with potatoes in Denmark showed higher values (Elsgaard et al. 2012, Petersen et al. 2012: 54,282 kg CO_2-eq. ha^{-1} a^{-1}), which is attributed to higher CO_2 and higher N_2O emissions.

Fens and bogs used as grassland in Lower Saxony show similar GWP100 balances. The fen in chapter two emits 19,376 +/- 5,005 kg CO_2-eq. ha^{-1} a^{-1}, a bog releases 11,409 kg CO_2-eq. ha^{-1} a^{-1} (Beetz et al. 2013). However, in other studies of peatlands used as grassland higher GWP100 balances were determined (Nykänen et al. 1995, Byrne et al. 2004, Höper 2007, Elsgaard et al. 2012, Petersen et al. 2012). Thus, compared to other peatlands the GWP100 balance at a histic gleysol covered with a layer of sand is low.

The GWP100 balance consists mainly of carbon dioxide emissions. Maljanen et al. (2004), Grønlund et al. (2006), Maljanen et al. (2007) and Maljanen et al. (2010) reported that CO_2 contributed about 78–95 % to the climate-warming potential of cultivated peatlands, while nitrous oxide has a proportion of about 5–22 %. Methane plays a minor role. However, N_2O can contribute up to 35 % at croplands (Petersen et al. 2012). The extraordinarily high contribution of N_2O in 2010 at S1 was due to a very low CO_2 balance on the one hand and a comparatively high N_2O balance on the other hand.

The hypothesis that all sites are strong GHG sources and that the differences can be explained by land use type and intensity can be confirmed: cropland is a stronger source than grassland. The hypothesis that soil characteristics are dependent variables cannot be proven with the data.

The results confirm the findings of Freibauer et al. (2004), Grønlund et al. (2006) and Oleszczuk et al. (2008). In order to reduce GHG emissions, a low intensity land use and a moderate drainage should be preferred to a high intensity land use and a deep drainage as well as grassland should be favored to cropland. Both agriculturally used bog and agriculturally used bog with added sand show high emissions. However, also grasslands have a high GWP100 balance. Rewetting would lead to a further reduction of the GWP100 balance or even convert the area into a sink (compare ch.4).

3.5 Conclusions

It can be concluded that agriculturally used organic soils covered with a layer of sand do not necessarily release less GHG than organic soils without a cover of sand. Cropland shows higher GHG emissions than grassland. Measures to reduce the release of large amounts of CO_2 from agriculturally used organic soils are a low intensity land use instead of a high intensity land use, and a moderate drainage instead of deep drainage.

In average over the two measurement years, a bog, a bog covered with a layer of sand and a histic gleysol covered with a layer of sand used as croplands and deeply drained released 6,041 +/- 337, 5,300 +/- 2,593 and 6,515 +/- 110 kg CO_2-C ha^{-1} a^{-1}, respectively. In contrast, histic gleysol covered with a layer of sand used as grassland emit 3,709 +/- 631 kg CO_2-C ha^{-1} a^{-1}. Also the nitrous oxide emissions were higher at the cropland sites (16 +/- 11 to 22 +/- 0.1 kg N_2O-N ha^{-1} a^{-1}) than at the grassland site (0.8 +/- 0.5 kg N_2O-N ha^{-1} a^{-1}). Methane fluxes were generally low. The resulting GWP100 balance at the cropland sites ranged from 26,787 +/- 9,511 to 32,278 +/- 1,237 and 34,035 +/- 405 kg CO_2-eq. ha^{-1} a^{-1}, at the bog covered with a layer of sand, the bog and the histic gleysol covered with a layer of sand respectively. The histic gleysol covered with a layer of sand used as grassland showed a GWP100 balance of 13,908 +/- 2,312 kg CO_2-eq. ha^{-1} a^{-1}.

Correlations between N_2O fluxes and driving forces were not significant, however, highest N_2O fluxes occurred at a wfps between 55 and 80 %.

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4 Greenhouse gas emissions from restored bogs in North Germany

Abstract

During the last three decades, an increasing part of drained peatlands has become rewetted with the aim to convert the ecosystem from a source back into a sink or at least into a much smaller source of greenhouse gases (GHG). However, available data is still scarce, especially about the long-term rewetting effect in the temperate zone and in *Sphagnum* cultivating sites (paludiculture).

In this study, the exchange of carbon dioxide, methane and nitrous oxide was measured about monthly from September 2009 until December 2011 with transparent and opaque closed chambers at three rewetted sites with a gradient from dry conditions to wet conditions and at a *Sphagnum* cultivating site in a Northern German bog. The ecosystem respiration (CO_2) and the net ecosystem exchange (CO_2) were modelled in high resolution with site parameters. Measured and modelled values fit very well together. Annual gas exchanges, net ecosystem carbon balances (NECB) and global warming potentials (GWP) were determined.

The annual net ecosystem exchange (CO_2) varies strongly (from -2,017 +/- 1,268 to 297 +/- 1,127 kg CO_2-C ha^{-1} a^{-1}) at the rewetted sites due to different weather conditions, water level and vegetation. The *Sphagnum* cultivating site was a sink of CO_2 (-1188 +/- 481 and -786 +/- 398 kg CO_2-C ha^{-1} a^{-1}). Annual CH_4 balances ranged between 161.8 +/- 21.6 and 241.6 +/- 49.8 kg CH_4-C ha^{-1} a^{-1} at two inundated sites, while one rewetted site with a comparatively low water level and the *Sphagnum* farming site show CH_4 fluxes close to 0. N_2O balances were low, and not significantly different between the four sites. Annual NECB was between -1,829 +/- 1,269 and 525 +/- 1,128 kg CO_2-C ha^{-1} a^{-1} at the rewetted sites and -1132 +/- 481 and -744 +/- 398 kg CO_2-C ha^{-1} a^{-1} at the *Sphagnum* cultivating site. Annual GWP100 balances ranged from -2,356 +/- 3,353 to 7,490 +/- 4,137 kg CO_2-eq. ha^{-1} a^{-1} at the rewetted sites. In contrast, the *Sphagnum* farming site had a cooling impact on the climate in both years (-3,408 +/- 1,765 and -2,269 +/- 1,459 kg CO_2-C ha^{-1} a^{-1}). If the exported carbon through the harvest of the *Sphagnum* biomass is considered, NECB and GWP100 balances are near neutral.

Peat mining sites can become net carbon sinks and a peat accumulating peatland within 30 years after rewetting, but the GWP100 balance can still be positive. A recommended measure for rewetting is to achieve a water level of a few centimetres below ground surface.

Sphagnum farming is a climate friendly alternative to conventional commercial use of bogs. A year round constant water level of a few centimetres below ground level should be maintained.

4.1 Introduction

Over many centuries, peatlands have been drained and used for peat extraction, agriculture and forestry worldwide and in particular in Germany (Couwenberg 2011). The consequences are accelerated mineralisation of high amounts of carbon that have been accumulated over thousands of years, and the promotion of the formation of nitrous oxide as a byproduct of nitrification and a product of incomplete denitrification (Mundel 1976, Firestone & Davidson 1989, Scheffer 1994, Schlesinger 1997, Meyer 1999, Höper 2007, Kasimir Klemedtsson et al. 2009). Tremendous amounts of the climate relevant gases CO_2 and N_2O are released into the atmosphere. About three decades ago, restoration programmes started in Germany (Höper & Blankenburg 2000). Today, a small area is rewetted, with an increasing tendency. In Lower Saxony, about 12,000 ha of former peat mining sites have been rewetted (Caspers 2011). The reasons for peatland restoration are the restoring of the ecosystem, the protection of rare species and biodiversity as well as the improvement of tourism (Höper & Blankenburg 2000, Gorham & Rochefort 2003, Höper et al. 2008). Since recently, the mitigation of GHG emissions has become the focal point. The restoration of a drained peatland converts the area from a source of CO_2 back into a sink of CO_2, or at least to a much smaller source. N_2O emissions are turned back to a minimum. Otherwise, peatlands that are not drained emit methane, which is produced under anoxic conditions in the waterlogged soil (Waddington & Roulet 1996, Le Mer & Roger 2001, Houghton 2004). Drained soils, in contrast, emit almost no methane because the produced CH_4 is oxidised by methanotrophic bacteria in the aerobic peat layer during transport (Christensen et al. 2003, Byrne et al. 2004, Drösler 2005).
To determine the climatic impact of a peatland, all three trace gases (CO_2, CH_4 and N_2O) have to be considered. Each gas has an individual radiative forcing capability, thus in addition it is necessary to multiply the emission of each gas by the corresponding global warming potential (GWP) to establish the climatic impact (Drösler 2005, IPCC 2007, Drösler et al. 2008).

In Germany, peatlands cover an area of about 13,648 km², about 25 % of the area is covered with bogs (3,214 km²). More than about half of the bog area in Germany is under agricultural use, mainly as grassland, but also a small amount as cropland and as forestry. About 8 % of the bog area is under peat extraction, about 20 % is degenerated and only 8 % is pristine.
In Lower Saxony, the distribution is similar (Höper 2007). About 10 % of the land surface is covered with peatland, which is much more than in most other states. More than half of the peatland area is bog, and most of the nationwide bogs are located in Lower Saxony (Höper

2007). The annual emissions from bogs in Lower Saxony have a proportion of about 3.2 % of the total emissions of climate relevant gases in Lower Saxony (Höper and Blankenburg, 2000).

However, the available data is not sufficient for recommendations for the management of peatlands and to supply the sectors four (agriculture) and five (land use, land use change and forestry) of the National Inventory Report for the German Greenhouse Gas Inventory with country-specific emission factors (Byrne et al. 2004, Drösler et al. 2008, Couwenberg 2011).

Until today, research studies about the gas exchange in peatlands were conducted mainly in the boreal region (Alm et al. 1997, Nykänen et al. 1998, Joiner et al. 1999, Tuittila et al. 1999, Höper et al. 2008), one example is the „Boreal Ecosystem-Atmosphere Study“ (Sellers et al. 1995). In Scandinavian countries, measurements were mostly carried out during the summer months. For the remaining time period, the values are estimated or modeled fluxes (Byrne et al. 2004). For a complete annual balance, measured flux rates from the colder period are crucial. Most studies have considered only one or two gases, without calculating the GWP (Drösler et al. 2008). To determine the climatic relevance, all three gases (CO_2, CH_4, N_2O) have to be considered.

The only studies with direct gas exchange measurements in peatlands in Lower Saxony are from Meyer (1999) and Beetz et al. (2013).

Most studies in restored peatlands are from recently rewetted sites. Investigations about the gas exchange and the GWP of peatlands having a longer history of rewetting are needed because the gas exchange pattern changes with time (Joosten & Augustin 2006).

Up to now, no research has been performed in *Sphagnum* cultivating sites (paludiculture) for harvesting. *Sphagnum* farming constitutes a sustainable alternative to conventional peat extraction and a climate friendly use of abandoned cut-over bogs (Gaudig et al. 2012).

This study shows the results of bogs rewetted for a longer time, and a bog used for cultivation of peat mosses. To date, no research about trace gas emissions has been done in the examination area.

The aim of this study is to determine the exchange of CO_2, CH_4 and N_2O as well as net ecosystem carbon balances (NECB) and GWP balances of different sites in a former peat cut bog which was rewetted about 30 years ago and one site in a test area to cultivate *Sphagnum* in Northern Germany. It is hypothesized that the rewetted bog has a nearly neutral GWP balance, while the test site is a GWP sink (cooling effect).

The main questions of this research are: a) What is the amount of the GHG exchange approximately 30 years after rewetting began?, b) What can be said about the GHG exchange of rewetted and partly restored former peat cut bogs compared to natural bogs?, c) How is the GWP of rewetted bogs used for cultivation of *Sphagnum* compared to ordinary rewetted bogs? and d) Which measures should be conducted for mitigation of GHG emissions and for promotion of carbon accumulation?

For determination of gas flux rates, the closed chamber method was used. This technique is frequently-used (Maljanen et al. 2010) and recently improved by Drösler (2005). The advantages are its ability to measure flux rates in a small scale environment, its suitability for field conditions and its low cost. The vegetation plays an important role in peat degradation processes and in soil-atmosphere gas exchange, but the function of the vegetation is not fully determined (Meyer 1999, van den Bos 2003, Drösler et al. 2008). The vegetation in the measurements is included and transparent and opaque chambers were used to yield the most appropriate estimates (Drösler 2005). To obtain annual balances modeling and interpolation were carried out. Additional field and laboratory measurements of driving parameters were conducted.

4.2 Methods

4.2.1 Site discription

The research area, Nordhümmlinger Moore, is located in the northwest part of Lower Saxony in Germany (53 °N latitude, 7.32 ° longitude, about 5 m a.m.s.l.). The approximately 111 km² bog area developed in the Hunte-Leda glacial valley and on the northern edge of the Hümmling. The insufficient drainage capability caused by the small slope led to this widespread peatland. Bogs developed on top of marshy inorganic soil in hollows and in higher places with podsolised fine sand (Eggelsmann & Blankenburg 1990, Nick 1993). First human intervention occurred at the beginning of the 18th century: The peat was burned and converted to cropland, with the consequence that heathland moor developed. Sheep farming led to fertilization and formation of duff. In the middle of the 20th century, industrial peat mining began (Eggelsmann & Blankenburg 1990).

The climate of the region is temperate, with a 30-year (1951-1980) mean annual temperature of 8.6 °C and annual precipitation of 795 mm (Eggelsmann & Blankenburg 1990). The warmest month is July (16,4 °C) and the coldest month is January (0.8 °C). Total precipitation is quite evenly distributed among the 12 months of the year. The annual potential evaporation amounts to 490 mm, the climatic water balance is 305 mm (Eggelsmann & Blankenburg 1990).

One research area is the 450 ha large "Leegmoor", which is part of the "Timpemoor", south of the coast channel. This former peat mining site was rewetted in 1983. Underneath the bog peat resides fine sand with silt (Eggelsmann & Blankenburg 1990). Three measurement sites were installed: The *Molinia* site is vegetated with *Molinia*, *Erica tetralix*, *Sphagnum cuspidatum* and *Eriophorum angustifolium*. Peat thickness is about 160 cm. The site is classified as Sapric Histosol (German soil classification: Norm-Erdhochmoor (KHn), AG Boden 2005). This site is comparatively dry and about 15 cm higher than the *Eriophorum* site. 50 m west is the *Eriophorum* site located, which is covered with *Eriophorum angustifolium*, *Molinia*, *Sphagnum cuspidatum* and *Betula pendula*. The mean of water level during summer is slightly below ground level. The third site is just beside, but lies in a hollow about 10 cm deeper, and consists of *Sphagnum cuspidatum*, *Eriophorum angustifolium* and *Molinia*. The *S. cuspidatum* site has a mean water level during summer just above ground level. The two sites are Fibric Histosols (German soil classification: Norm-Hochmoor (HHn), AG Boden 2005). Peat thickness is about 95 cm.

The other research area is a peat mining area in the "Westermoor" and about 15 km northeast of Leegmoor. The measurement site (*S. papillosum* site) is a 60 x 20 m test area, which was agriculturally used until 2000, subsequently under peat extraction, and rewetted in 2004 in order to cultivate *Sphagnum*. The vegetation consists of *Sphagnum papillosum*, *S. cuspidatum*, *S. palustre*, *S. fallax*, *Eriophorum angustifolium*, *Erica tetralix*, *Juncus effusus*, *Betula pendula* and *Drosera* as well as mushrooms. Peat thickness is 195 cm (9 cm highly decomposed peat, 186 cm weakly decomposed peat), underneath resides medium to fine sand. The site is classified as Fibric Histosol (German soil classification: Norm-Hochmoor (HHn), AG Boden 2005). The water level is kept year round quite constant just below ground level with the aid of a pump. Up to now, no harvesting has taken place.

4.2.2 Measurements of site factors

Soil identification (soil horizon, peat substrate, $CaCO_3$ content, pH) was conducted according to AG Boden (2005). Decay degree was determined according to von Post-scale.

Aboveground biomass at the *S. papillosum* site was sampled (cut by hand) from the measurement plots down to the original peat and separated in green (green biomass) and brown (dead biomass) plant parts as well as in *Sphagnum* and vascular plants. Dry matter was determined by drying the samples in a drying oven at a temperature of 105 °C for two days (until constant weight). Fresh and dry biomass was quantified using a laboratory balance.
The dried samples were heated to 550 °C in a drying oven for about three days to ash the biomass, and subsequently analysed in an elemental analyser (Elementar vario plus CNS-analyser) to achieve carbon and nitrogen contents.

The *Molinia* site, the *Eriophorum* site and the *S. papillosum* site were equipped with tubes perforated in the peat body, close to the collars. Water levels (wl) were manually measured during each gas measurement campaign with an electric contact gauge. In addition, at the *Eriophorum* site and the *S. papillosum* site the wl were continuously (half-hourly) recorded from June 2010 until December 2011 through Schlumberger MiniDiver. The missing time periods could be filled by interpolation between the manual measurements.
In intervals of every three months samples from the ground water were taken with a bailer and analysed for pH and electrical conductivity (Lf) with pH-electrode SenTix 950 (WTW) and standard conductivity measuring cell TetraCon 925 (WTW), respectively.

Meteorological parameters, such as temperatures (air temperature, soil temperature at 2, 5 and 10 cm depth), photosynthetic active radiation (PAR), air pressure and precipitation were measured and saved half hourly at the meteorological station near the *S. papillosum* site.
In addition, soil temperatures were measured and saved half hourly with a datalogger (DN Messtechnik, Norderstedt) at the *Molinia* site and the *S. papillosum* site. The data of the *Molinia* site were used for the *Molinia* site, *Eriophorum* site and *S. cuspidatum* site.

4.2.3 Measurements and modeling of carbon dioxide exchange

For determination of CO_2 flux rates between the ecosystem (soil and vegetation) and the atmosphere, a temperature controlled closed portable chamber technique was applied (Drösler

2005, Beetz et al. 2013). A description of this technique and the arrangement of the research plots is performed in chapter two.

Measurement campaigns were held in intervals every four weeks, beginning in September 2009 and ending in December 2011. Parallel to the gas exchange measurements, temperatures (air temperature, soil temperature at 2, 5 and 10 cm depth), photosynthetic active radiation (PAR), wl and air pressure were measured.

For calculation of gas flux rates refer to chapter two.
Ecosystem respiration (R_{eco}) was modelled with an exponential regression equation against temperature (see ch.2). The temperature (air temp., soil temp. at 2 cm depth or soil temp. at 5 cm depth) with the best fit was chosen.
Net ecosystem exchange was modelled with a rectangular hyperbola against the photosynthetic active radiation (PAR) (see ch.2). NEE is calculated as the difference between gross primary production (GPP), which has a negative sign and R_{eco}, with a positive sign. The measured photosynthetic active radiation (PAR) used for modelling was reduced by 5 % (Drösler 2005).
The interpolation procedure is described in chapter two. Monthly and annual balances were achieved by accumulation.

4.2.4 Measurements of methane and nitrous oxide exchange

A description of the determination of the CH_4 and N_2O exchange is performed in chapter two. The samples were analyzed in the gas chromatograph "Perkin Elmer Auto System". A FID-Detector identified CH_4, while an ECD-Detector was used to detect N_2O.
Measurement campaigns were held in intervals every two weeks, beginning in September 2009 and end in December 2011.

4.2.5 Net ecosystem carbon balance and global warming potential

To obtain a complete carbon balance of a peatland, all fluxes of carbon must be considered (Chapin et al. 2006). Beside CO_2 flux rates, CH_4 flux rates, dissolved organic carbon (DOC), dissolved inorganic carbon (DIC), carbon monoxide (CO) and volatile organic C (VOC) are factored in the net ecosystem carbon balance (NECB). DOC was estimated to 26 kg C $ha^{-1}a^{-1}$

according to Moore (1987). Values of DIC, CO and VOC were assumed to be negligible and not considered.

A widely-used technique to establish the climatic relevance of the GHG exchange at each site, expressed as CO_2-equivalents, is the global warming potential (GWP) methodology (IPCC 2007). In general, the global warming potential over a time span of 100 years is taken (Drösler 2005). Positive values represent efflux of CO_2-equivalents into the atmosphere.

The equations to calculate the NECB and GWP balance are performed in chapter two.

4.2.6 Statistical analyses

Unless otherwise stated, Microsoft® Excel was used.

Error analysis of CO_2 gas fluxes was conducted by calculating the standard error for each calibrated regression model. Analogous to the interpolation of the half-hourly gas fluxes, standard errors were interpolated. The monthly and annual standard errors were calculated using appropriate error propagation equation. The standard errors of the means of the exported carbon through harvest were included.

For CH_4 and N_2O the standard error of the replicate chamber measurements of each measurement campaign were calculated and interpolated between the measurement campaigns analogous to the interpolation of the fluxes. The annual standard errors were calculated using appropriate error propagation equations.

Significant linearity of slope of the changes in gas concentration was tested following Huber (1984). To test if slopes are significantly different from 0, a t-test was performed (Neter et al. 1996). The variability of the slopes was calculated as the standard deviation of the residuals (s_{yx}). For the variability in PAR the coefficient of variability (cv %) was calculated.

Correlation and regression analyses was conducted providing the coefficient of determination (quadrate of Pearson Correlation Coefficient = R^2) and tested for significance using a t-test.

In order to develop a model for the methane exchange, a mechanistic approach was chosen. The main driving forces for CH_4 fluxes are wl and soil temperature (Shurpali et al. 1993, Macdonald et al. 1998, Nykänen et al. 1998, Christensen et al. 2003). Christensen et al. (2003) and Drösler (2005) determined a threshold value of the wl above which the CH_4 emissions increase steeply, and observed a temperature dependence of the fluxes which occur at wl above this threshold value. Non-linear 3D-models with wl and soil temperature as dependant variables and with a threshold value of the wl were fitted using TableCurve 3D® V

4.0 of STATCON. The fitting parameters were achieved through iteration (Procedure: Lev-Marq, minimization: Least Squares). R^2 and adjusted R^2 were calculated.
Significant ($p < 0.05$) differences between the annual gas exchange balances were tested with the Permutation test “diffmean” (1000 permutations) using R script 0.97.237 (version 2.15.2) (simba package).

4.3 Results

4.3.1 Soil parameters

The *Molinia* site consisted of highly decomposed peat with a high decay degree (z10), amorphous peat substrate, and had a very low pH (Tab.4.1). Peat thickness was approximately 160 cm. The uppermost horizon was a reduced bog-peat and had a very low decay degree (z1). pH was 3.7. Peat thickness at the *Eriophorum* and *S. cuspidatum* site was lower at 95 cm. The peat of the *Eriophorum* site consisted mainly of herbs, while at the *S. cuspidatum* site *Sphagnum* peat was found. The *S. papillosum* site was 195 cm thick and the uppermost horizon (reduced bog-peat) had also a decay degree of z1, but a higher pH (3.9). There was no $CaCO_3$ at the sites.

Tab. 4.1: Soil properties of the examination sites.

a) *Molinia* site

depth [cm]	**soil horizon** [a]	**peat substrate** [a]	**decay degree** [b]	**$CaCO_3$** [%]	**pH_{CaCl2}**
0-10	hHv	Ha	z10	0	3.4
10 50	hHw	Hhs	z8	0	3.3
50-80	hHr1	Hhs	z9	0	3.5
80-105	hHr2	Hhs	z9	0	3.6
105-130	hHr3	Hhs	z9	0	4.0
130-160	hHr4	Hhs	z9	0	4.1
160-170	Ghr	fS		0	4.2

b) *Eriophorum* site

depth [cm]	**soil horizon** [a]	**peat substrate** [a]	**decay degree** [b]	**$CaCO_3$** [%]	**pH_{CaCl2}**
0-20	hHr	Hhe	z1	0	3.7
20-50	fHv-hHr	Hhs	z9	0	4.0
50-95	hHr	Hhs	z9	0	3.7
95-110	fBh-Gr	fS		0	3.6
110-140	fBsh-Gr	fS		0	4.4

c) *S. cuspidatum* site

depth [cm]	**soil horizon** [a]	**peat substrate** [a]	**decay degree** [b]	**$CaCO_3$** [%]	**pH_{CaCl2}**
0-20	hHr	Hhs	z1	0	3.7
20-50	fHv-hHr	Hhs	z9	0	4.0
50-95	hHr	Hhs	z9	0	3.7
95-110	fBh-Gr	fS		0	3.6
110-140	fBsh-Gr	fS		0	4.4

d) *S. papillosum* site

depth [cm]	**soil horizon** [a]	**peat substrate** [a]	**decay degree** [b]	**$CaCO_3$** [%]	**pH_{CaCl2}**
0-9	hHr1	Hhs	z1	0	3.9
9 15	hHr2	Hhs	z3	0	4.0
15-45	hHr3	Hhs	z9	0	4.1
45-100	hHr4	Hhs	z9	0	4.4

[a] According to AG Boden (2005), [b] According to von Post-scale

4.3.2 Biomass

Analysis of aboveground biomass was conducted in May of the last measurement year at the *S. papillosum* site (Tab.4.2). The entire vegetation, which was growing on top of the original peat since the beginning of *Sphagnum* cultivation, was cut. The dry mass of the vegetation consisted primarily of *Sphagnum*. Nitrogen stock of the *Sphagnum* and the vascular plants was 12.6 +/- 0.7 and 0.4 +/- 0.1 g m^{-2}, respectively. In total, the nitrogen stock was 12.9 +/- 0.8 g m^{-2}. Carbon stock of the *Sphagnum* and the vascular plants was 633.0 +/- 34.9 and 82.7 +/- 22.3 g m^{-2}, respectively. The total carbon stock was therefore 715.8 +/- 57.2 g m^{-2}.

Tab. 4.2: Dry mass, total nitrogen stock and total carbon stock of *Sphagnum*, vascular plants and total biomass at the *S. papillosum* site. Mean and standard error.

		Sphagnum		**vascular plants**		**total biomass**	
		m	s.e.	m	s.e.	m	s.e.
dry mass	[g m^{-2}]	1288.0	+/- 71.0	183.8	+/- 49.6	1471.1	+/- 88.8
total N	[%]	1.0	+/- 0.04	0.2 [a]			
total C	[%]	49.2	+/- 0.2	45 [a]			
total N	[g m^{-2}]	12.6	+/- 0.7	0.4	+/- 0.1	12.9	+/- 0.8
total C	[g m^{-2}]	633.0	+/- 34.9	82.7	+/- 22.3	715.8	+/- 57.2

[a] According to KTBL (2005)

4.3.3 Water

The wl of the *Molinia* site was subject to fluctuation (Fig.4.1). Annual mean of the wl in 2010 and 2011 was 16.1 and 10.8 cm below ground surface, respectively. Summer mean (May – Oct.) was in 2010 and 2011 34 and 21 cm below ground surface, respectively.

At the *Eriophorum* site the annual mean of 2010 and 2011 was 4.4 and 3.8 cm above ground surface, respectively. Summer mean in 2010 and 2011 was 4.9 and 2.5 cm below ground surface, respectively. The *S. cuspidatum* site was located about 10 cm lower than the *Eriophorum* site. The site was mostly inundated.

The *S. papillosum* site had a different water regime, because the wl was regulated. The variability was very small, and the wl usually remained below ground surface. Annual mean in 2010 and 2011 was 6.1 and 9.2 cm below ground surface, respectively. Summer mean in 2010 and 2011 was 6.3 cm and 8.5 cm below ground surface, respectively.

pH of the ground water was 4.1 (+/- 0.1), 4.3 (+/- 0.1) and 4.5 (+/- 0.1) in average over the measurement period at the *Molinia* site, the *Eriophorum* site and the *S. papillosum* site, respectively. Electrical conductivity (Lf) of the ground water amounted to 105 (+/- 16.3), 78 (+/- 2.8) and 103 (+/- 17.1) S m^{-1} in average over the measurement period at the *Molinia* site, the *Eriophorum* site and the *S. papillosum* site, respectively. Due to the closeness of the *S. cuspidatum* site to the *Eriophorum* site, the same values may be assumed.

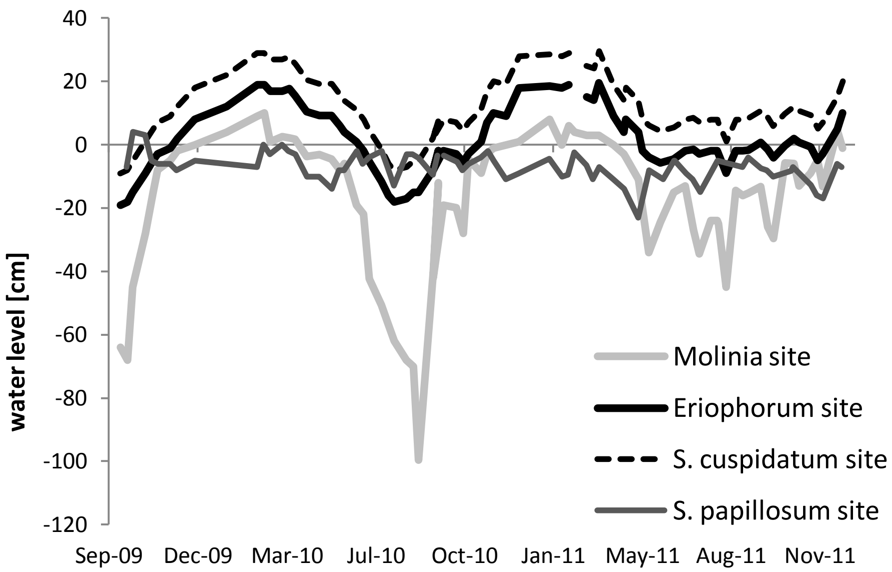

Fig. 4.1: Water level of the examination sites (from Sept. 2009 until Dec. 2011) in cm above ground surface.

4.3.4 Weather

The yearly precipitation was in average 623.1 and 711.7 mm in 2010 and 2011, respectively. Average annual air temperature was 8.4 and 10.2 °C in 2010 and 2011, respectively. The 30 year average (1951-1980) amounts to 795 mm per year and 8.6 °C (Eggelsmann & Blankenburg 1990).

In 2011, spring and autumn were very dry, compared to 2010, while during the summer precipitation in 2011 was higher. From March until April 2011 and from September until November 2011, precipitation was 26 and 124.7 mm, respectively. In 2010, the precipitation was 68.5 and 192.5 mm, respectively. From May until August 2011 precipitation amounted to 262.7 mm, while in 2010 precipitation was 213 mm. In January, February and December 2010 the monthly mean of air temperature dropped below 0. The months January, February, April, May and December were much warmer in 2011, compared to 2010. In 2009, the month November was exceptionally warm. In contrast, the month July was very warm in 2010.

The monthly mean values of the PAR were in general highest in May, June and July (Fig.4.2). From March until May, the monthly mean values were higher in 2011, compared to 2010. In contrast, from June until September, 2010 revealed higher monthly mean values. The monthly mean of September and October were highest in 2009.

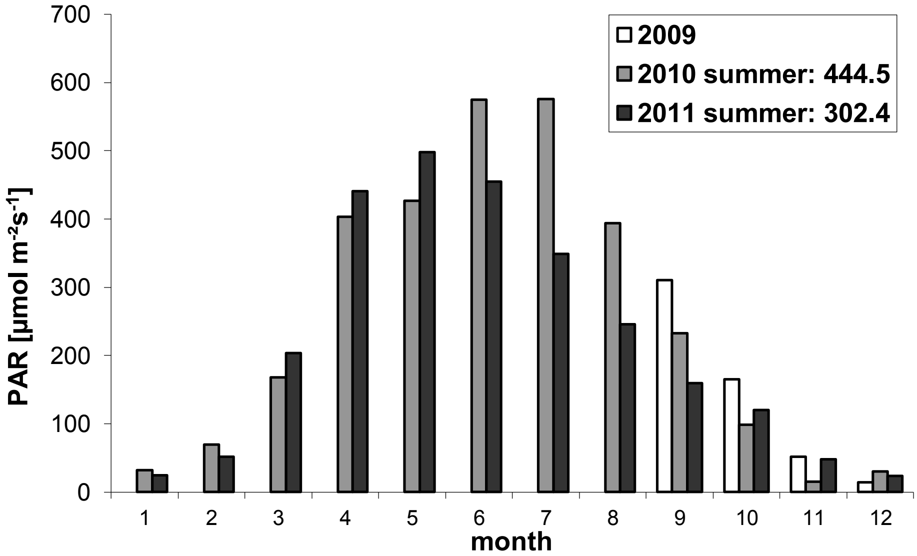

Fig. 4.2: Monthly mean of PAR (photosynthetic active radiation), calculated from the daily maximum of half-hourly values. Note: 2009 only from September to December. Upper right corner: summer-values of PAR (June to September).

4.3.5 Carbon dioxide

4.3.5.1 Evaluation of methodology

During the CO_2 measurements, linearity of the slope for gas flux determination and a constant PAR was usually assured. In almost all cases linearity was significant ($p < 0.05$), and the coefficient of variability of the PAR during the CO_2 measurement was less than 5 %.

The regressions between measured and modelled flux rates for R_{eco} and NEE of each measurement campaign at the *Molinia* site were in all cases significant ($p < 0.1$; Tab.4.3).
At the other three sites, in a few cases, mostly in winter, the span between the lowest and the highest temperature was too small for modelling the R_{eco} (Tab.4.4-4.6). In these cases, E_0 was set to 0 and R_{ref} was replaced by the mean value of the measured values. This is a conservative way to obtain an accurate result. The measurements on 09.02.2011 at the *S. cuspidatum* site had to be discarded because the data was not satisfactory. At the *S. papillosum* site the regressions between measured and modelled flux rates for R_{eco} of the measurements in Sept/Oct 2009, Nov/Dec 2010 and June 2011 were not significant. In these cases it was possible to pool the results of two measurement campaigns together to achieve significant regressions. The measurement campaign-specific regressions between measured and modelled flux rates for the NEE were in all cases significant ($p < 0.1$).

Tab. 4.3: Parameters for the R_{eco} and NEE models of the *Molinia* site: Left: Date of measurement campaign. Middle: E_0: Activation energy like parameter [K], R_{ref}: Respiration at the reference temperature [µmol CO_2-C m^{-2} s^{-1}], R²: Coefficient of determination (Pearson) between modelled and measured values. S.e.: Standard error of the model [µmol CO_2-C m^{-2} s^{-1}], n: Number of samples, temp: Best fit temperature for R_{eco} model [air temp. or soil temp. in cm below ground surface]. Right: GP_{max}: Maximum rate of carbon fixation at PAR infinite [µmol CO_2-C m^{-2} s^{-1}], α: Light use efficiency [µmol CO_2-C m^{-2} s^{-1}/µmol m^{-2} s^{-1}], R²: Coefficient of determination (Pearson) between modelled and measured values. S.e.: Standard error of the model [µmol CO_2-C m^{-2} s^{-1}], n: Number of samples. Maximum and minimum values are printed in bold. Eventually measurement campaigns were pooled together.

date	E_0	R_{ref}	R²	s.e.	n	temp	GP_{max}	α	R²	s.e.	n
30.09.09	850.5	2.34	0.59***	0.41	12	soil5	-13.09	-0.0203	0.59****	0.98	23
29.10.09	748.1	2.04	0.32**	0.41	13	soil5	-6.25	-0.0057	0.19**	0.34	21
25.11.09	**1106.8**	0.35	0.46**	0.04	10	soil2	-0.89	-0.0052	0.45***	0.09	21
03.03.10	68.2	0.36	0.45***	0.03	15	air	-0.59	-0.0053	0.67****	0.09	25
31.03.10	55.2	0.67	0.84****	0.02	15	air	-1.73	-0.0027	0.79****	0.19	26
21.04.10	723.9	0.68	0.60****	0.05	14	soil5	-0.78	-0.0014	0.55****	0.13	28
27.05.10	175.4	2.32	0.30**	0.28	14	soil2	-5.18	-0.0089	0.87****	0.41	30
23.06.10	49.1	4.52	0.68****	0.38	18	air	-15.39	-0.0441	0.94****	1.02	30
21.07.10	330.9	3.29	0.71****	0.69	16	soil2	-24.08	-0.0659	0.90****	2.15	30
18.08.10	332.3	1.69	0.28**	0.58	15	soil2	-29.19	-0.0261	0.87****	1.68	21
15.09.10	92.4	1.63	0.44***	0.14	15	air	-27.50	-0.0195	0.95****	1.11	27
13.10.10	632.2	2.23	0.24*	0.21	15	soil5	-8.92	-0.0393	0.94****	0.73	21
09.11.10	332.7	1.99	0.58***	0.10	12	air	-2.77	-0.0063	0.77****	0.20	21
15.12.10	565.6	2.14	0.52**	0.06	11	air	-0.51	-0.0014	0.29**	0.07	21
09.02.11	63.4	0.57	0.95****	0.03	12	air	-3.75	-0.0015	0.59****	0.15	21
09.03.11	220.6	**0.32**	0.46**	0.06	12	air	-1.20	**-0.0013**	0.64****	0.08	21
14.04.11	**19.1**	1.07	0.29**	0.09	15	air	-1.40	-0.0032	0.51****	0.23	27
03.05.11	131.3	1.43	0.88****	0.14	15	air	-2.69	-0.0038	0.56****	0.27	24
07.06.11	216.8	4.19	0.63***	0.03	12	soil5	-37.12	-0.0282	0.83****	3.11	27
29.06.11	273.1	2.33	0.48**	1.43	11	air	**-61.46**	-0.0312	0.952****	2.18	23
27.07.11	62.6	5.77	0.70****	0.52	15	air	-42.03	-0.0412	0.94****	2.04	30
24.08.11	43.9	**6.98**	0.30**	0.40	14	air	-30.56	-0.0459	0.81****	2.69	24
21.09.11	33.0	3.58	0.60**	0.05	9	air	-31.69	-0.0529	0.99****	0.64	21
20.10.11	789.1	2.06	0.93****	0.08	12	soil2	-15.33	-0.0069	0.88****	0.59	21
16.11.11	533.8	1.40	0.59***	0.02	10	soil2	-0.71	-0.0282	0.46****	0.16	21
14.12.11	574.9	1.29	0.41**	0.06	12	soil2	**-0.50**	**-0.8479**	0.80****	0.11	15

* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$; **** $p < 0.001$

Tab. 4.4 [next page]: Parameters for the R_{eco} and NEE models of the *Eriophorum* site (see Tab. 4.3). Eventually measurement campaigns were pooled together. 25.11.2009, 15.12.2010, 14.12.2011: No significant correlation between measured and modelled values. E_0 was set to 0.

date	E_0	R_{ref}	R^2	s.e.	n	temp	GP_{max}	α	R^2	s.e.	n
30.09.09	**799.8**	1.93	0.40**	0.40	11	soil5	-42.75	-0.0144	0.63****	0.85	20
29.10.09	222.0	2.88	0.28**	0.09	15	soil5	-22.28	-0.0107	0.64****	0.56	24
25.11.09	0.0	1.06	0.10	0.23	12		-55.97	-0.0127	0.90****	0.16	21
03.03.10	442.0	2.72	0.60****	0.10	15	soil5	-1.99	-0.0039	0.64****	0.22	25
31.03.10	36.6	2.29	0.27*	0.22	13	air	-7.02	-0.0089	0.77****	0.65	29
21.04.10	472.2	2.37	0.30*	0.42	15	soil2	-9.78	-0.0301	0.87****	0.94	30
27.05.10	132.5	2.60	0.48***	0.51	15	air	-20.40	-0.0302	0.90****	1.22	30
23.06.10	170.9	3.12	0.78****	0.88	18	air	-15.56	-0.0394	0.91****	0.93	30
21.07.10	110.3	**4.62**	0.24**	2.04	18	air	-18.26	-0.0427	0.85****	1.65	30
18.08.10	169.9	2.85	0.21*	0.55	15	soil2	-21.52	**-0.0513**	0.86****	1.77	24
15.09.10	152.7	1.82	0.41**	0.13	10	soil2	-29.23	-0.0227	0.81****	2.17	26
13.10.10	389.5	1.69	0.32**	0.42	14	soil2	-37.51	-0.0223	0.74****	2.38	18
09.11.10	440.8	1.53	0.34**	0.09	12	soil2	-6.82	-0.0180	0.97****	0.16	18
15.12.10	0.0	0.28	0.04	0.13	12		**-1.25**	-0.0126	0.84****	0.14	21
09.02.11	**23.4**	**1.39**	0.47**	0.07	12	air	-54.19	**-0.0022**	0.82****	0.20	18
09.03.11	250.8	2.12	0.25*	0.47	12	air	-4.80	-0.0045	0.23**	0.33	19
14.04.11	115.1	2.33	0.47***	0.77	15	air	-19.20	-0.0089	0.88****	0.86	24
03.05.11	500.6	2.18	0.73****	0.45	12	soil2	-19.65	-0.0151	0.92****	1.03	24
07.06.11	145.9	4.53	0.28*	0.71	13	air	-17.95	-0.0334	0.82****	1.98	27
29.06.11	147.8	4.32	0.21*	0.83	14	air	**-72.79**	-0.0283	0.94****	1.44	23
27.07.11	259.6	3.08	0.75****	0.97	15	soil2	-33.18	-0.0286	0.90****	1.50	30
24.08.11	483.1	1.74	0.55***	1.08	15	soil2	-29.23	-0.0356	0.93****	1.24	24
21.09.11	625.0	**1.39**	0.25*	0.53	12	soil2	-32.84	-0.0436	0.95****	1.30	24
20.10.11	391.1	1.96	0.59***	0.29	12	soil2	-21.47	-0.0265	0.84****	1.59	24
16.11.11	308.4	2.23	0.31*	0.20	12	air	-39.93	-0.0142	0.93****	0.25	21
14.12.11	0.0	1.40	0.02	0.56	24		-7.09	-0.0064	0.73****	0.38	12

* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$; **** $p < 0.001$

Tab. 4.5: Parameters for the R_{eco} and NEE models of the *S. cuspidatum* site (see Tab. 4.3). Eventually measurement campaigns were pooled together. 31.03.2010, 21.04.2010, 18.08.2010, 15.12.2010: No significant correlation between measured and modelled values. E_0 was set to 0.

date	E_0	R_{ref}	R^2	s.e.	n	temp	GP_{max}	α	R^2	s.e.	n
30.09.09	136.4	**2.33**	0.43*	0.27	9	air	**-17.89**	-0.0157	0.74****	0.68	23
29.10.09	425.3	1.17	0.20*	0.15	15	soil5	-13.91	-0.0178	0.95****	0.29	24
25.11.09	**29.4**	0.51	0.43*	0.01	9	air	-4.64	-0.0161	0.90****	0.17	24
03.03.10	247.7	0.53	0.26*	0.04	12	soil2	-4.89	**-0.0001**	0.21**	0.03	25
31.03.10	0.0	0.42	0.00	0.27	15		-17.35	-0.0003	0.55****	0.10	27
21.04.10	0.0	0.42	0.00	0.27	15		-2.83	-0.0045	0.94****	0.18	28
27.05.10	183.7	0.98	0.44***	0.15	15	soil2	-9.46	-0.0253	0.95****	0.50	30
23.06.10	231.8	1.74	0.86****	0.53	18	air	-13.46	-0.0224	0.91****	0.72	30
21.07.10	247.5	1.64	0.17*	0.47	18	soil5	-4.39	-0.0130	0.65****	0.67	30
18.08.10	0.0	2.49	0.02	0.57	15		-11.82	-0.0195	0.86****	0.94	24
15.09.10	175.8	1.04	0.47**	0.21	12	air	-13.80	-0.0170	0.74****	1.32	27
13.10.10	297.1	1.09	0.25*	0.26	15	soil2	-9.80	**-0.0360**	0.92****	0.74	21
09.11.10	404.8	1.23	0.66**	0.07	8	soil2	-3.19	-0.0190	0.66****	0.39	18
15.12.10	0.0	0.08	0.16	0.02	12		**-0.58**	-0.0026	0.71****	0.08	18
09.03.11	100.7	0.45	0.56**	0.03	8	air	-0.66	-0.0010	0.29**	0.07	21
14.04.11	110.0	1.23	0.40**	0.45	15	air	-9.80	-0.0047	0.74****	0.70	24
03.05.11	217.7	1.52	0.68****	0.56	15	air	-10.33	-0.0131	0.65****	1.21	24
07.06.11	267.6	2.25	0.39**	0.62	15	air	-12.20	-0.0237	0.88****	1.01	27
29.06.11	213.8	2.00	0.35**	0.64	14	air	-15.02	-0.0344	0.89****	1.18	24
27.07.11	197.9	1.99	0.68****	0.80	15	air	-13.62	-0.0269	0.80****	1.01	30
24.08.11	335.1	1.43	0.74****	0.52	13	soil5	-17.71	-0.0282	0.74****	1.23	24
21.09.11	**1069.0**	**0.39**	0.41**	0.36	12	soil5	-15.98	-0.0294	0.90****	0.81	24
20.10.11	253.1	0.84	0.62***	0.20	12	air	-9.14	-0.0180	0.86****	0.72	24
16.11.11	396.5	1.33	0.42**	0.08	12	air	-5.46	-0.0168	0.96****	0.14	21
14.12.11	308.6	2.29	0.56**	0.16	12	air	-3.45	-0.0032	0.82****	0.13	12

* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$; **** $p < 0.001$

Tab. 4.6: Parameters for the R_{eco} and NEE models of the *S. papillosum* site (see Tab. 4.3). Eventually measurement campaigns were pooled together.

date	E_0	R_{ref}	R^2	s.e.	n	temp	GP_{max}	α	R^2	s.e.	n
29.09.09	277.8	0.91	0.43****	0.41	26	soil5	-6.12	-0.0194	0.86****	0.46	36
27.10.09							-4.73	-0.0114	0.79****	0.29	39
24.11.09	969.8	0.39	0.40*6	0.07	9	soil5	-2.16	-0.0231	0.83****	0.20	27
02.03.10	772.4	0.66	0.34**	0.05	12	soil2	-4.59	**-0.0014**	0.62****	0.24	41
30.03.10	264.9	0.48	0.61****	0.15	18	air	-3.46	-0.0102	0.96****	0.12	45
20.04.10	97.3	1.04	0.34**	0.22	18	air	-4.10	-0.0125	0.95****	0.21	47
26.05.10	144.6	1.70	0.19*	0.52	17	soil5	-12.56	-0.0051	0.87****	0.43	50
22.06.10	300.7	1.45	0.73****	0.70	18	soil2	-11.89	-0.0116	0.84****	0.66	57
20.07.10	301.3	1.29	0.26**	1.08	18	soil5	-9.72	-0.0190	0.67****	0.86	57
17.08.10	930.2	**0.26**	0.54****	0.82	18	soil5	-10.81	-0.0273	0.83****	0.81	48
14.09.10	430.2	0.84	0.18*	0.62	18	soil5	**-15.20**	-0.0262	0.88****	0.43	33
12.10.10	694.6	0.70	0.48***	0.25	15	soil5	-7.70	-0.0219	0.94****	0.46	42
10.11.10	240.1	0.35	0.64****	0.05	27	soil2	-3.03	-0.0317	0.90****	0.21	42
14.12.10							**-0.37**	-0.0028	0.74****	0.04	27
08.02.11	406.5	0.65	0.50***	0.09	15	soil2	-3.05	-0.0146	0.92****	0.18	35
08.03.11	648.1	2.20	0.21*	0.09	15	soil5	-1.65	-0.0193	0.86****	0.18	24
12.04.11	94.0	0.76	0.24**	0.08	18	soil2	-3.41	-0.0142	0.89****	0.30	46
08.06.11	**67.2**	**2.30**	0.33***	0.44	30	air	-6.78	-0.0286	0.93****	0.31	33
28.06.11							-11.15	-0.0212	0.91****	0.69	57
26.07.11	322.6	1.22	0.67****	0.29	18	soil2	-13.84	-0.0304	0.98****	0.49	57
23.08.11	225.0	1.57	0.44***	0.20	14	soil2	-13.78	-0.0275	0.97****	0.58	44
20.09.11	229.5	1.43	0.89****	0.23	18	soil2	-14.17	-0.0294	0.95****	0.58	45
19.10.11	88.2	1.11	0.50***	0.16	12	air	-6.44	-0.0237	0.94****	0.31	30
15.11.11	114.4	0.62	0.23*	0.04	15	air	-2.57	-0.0244	0.95****	0.10	33
13.12.11	**1015.1**	1.81	0.51**	0.07	11	soil5	-1.43	**-0.0624**	0.93****	0.09	27

* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$; **** $p < 0.001$

The annual course of the parameter R_{ref} showed at all four sites a seasonal trend with low values during the colder period and higher values in summer (Tab.4.3-4.6). The parameter E_0 did not reveal any pattern in the course of the year.

GP_{max} and α of the *Molinia* site showed a seasonal trend with high negative values in summer and low negative values in winter (Tab.4.3). At the *Eriophorum* site and the *S. cuspidatum* site α had also a seasonal trend, but the seasonality of GP_{max} was detectable only in 2011 (Tab.4.4 & Tab.4.5). At the *S. papillosum* site the seasonal trend of GP_{max} was evident, but α did not show a seasonal trend (Tab.4.6).

At each site the regressions between all modelled and measured values for R_{eco} and NEE were always significant ($p < 0.0001$; Fig.4.3). Coefficient of determination for R_{eco} and NEE at the *Molinia* site was very high ($R^2 = 0.98$ and 0.94, respectively). Standard errors were 0.36 and 1.45 µmol CO_2-C m^{-2} s^{-1}, respectively. At the *Eriophorum* site a $R^2 = 0.90$ and 0.92, respectively, and standard errors of 0.70 and 1.32 µmol CO_2-C m^{-2} s^{-1}, respectively, were determined. Coefficient of determination at the *S. cuspidatum* site was similar ($R^2 = 0.92$ and 0.91, respectively), the standard errors amounted to 0.39 and 0.83 µmol CO_2-C m^{-2} s^{-1}, respectively. At the *S. papillosum* site coefficient of determination for R_{eco} was comparatively low ($R^2 = 0.88$), coefficient of determination for NEE was $R^2 = 0.94$. Standard errors were 0.41 and 0.53 µmol CO_2-C m^{-2} s^{-1}, respectively.

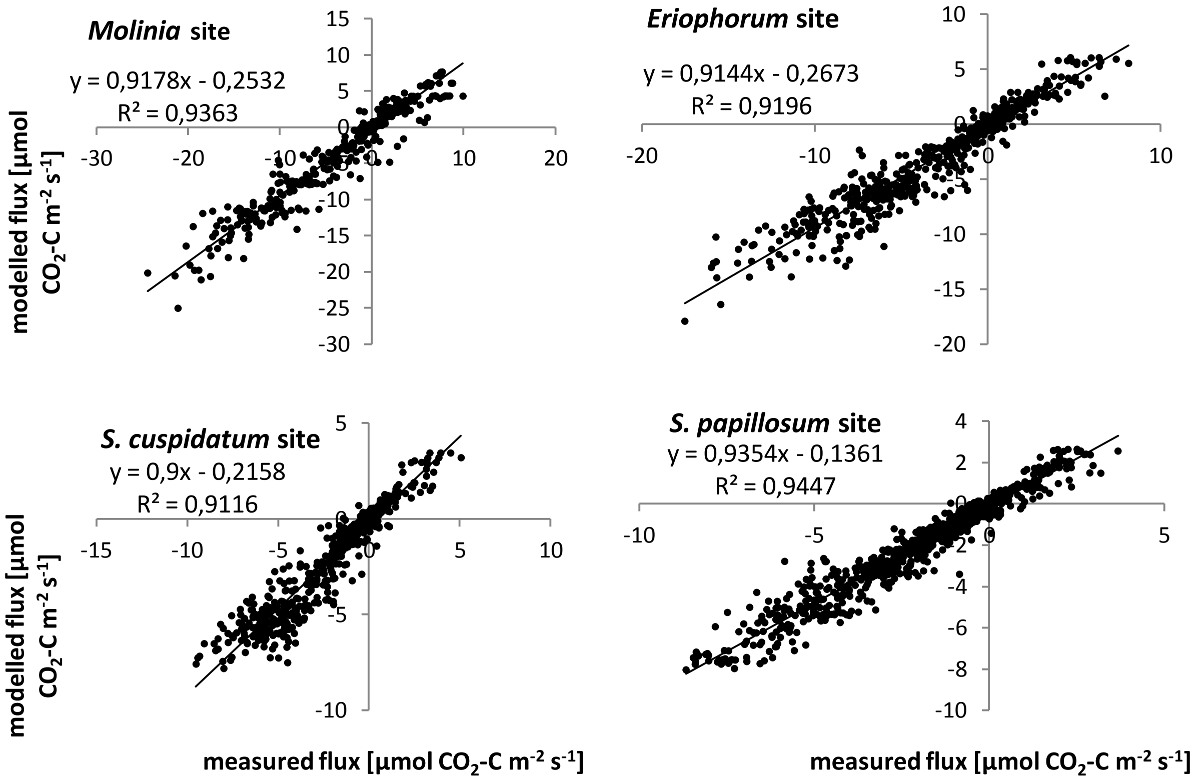

Fig. 4.3: Fit of modelled with measured NEE at the examination sites.

4.3.5.2 Ecosystem respiration

Figure 4.4 indicates a similar annual course of daily R_{eco} at the *Molinia* site and the *Eriophorum* site for the most part of the year. However, at the beginning of the vegetation period, gas fluxes at the *Eriophorum* site started to increase much earlier than at the other sites. The annual pattern of the *S. cuspidatum* site and the *S. papillosum* site differed strongly from the course of the *Molinia* site and the *Eriophorum* site. As mentioned above, the *S. cuspidatum* site and the *S. papillosum* site revealed both much lower R_{eco}. By comparing the annual course of the R_{eco} with the course of the temperature, it appeared that there is a lag in the development of the vegetation in spring, with the exception of the *Eriophorum* site. In late summer and autumn, when temperatures were still high, R_{eco} dropped already.

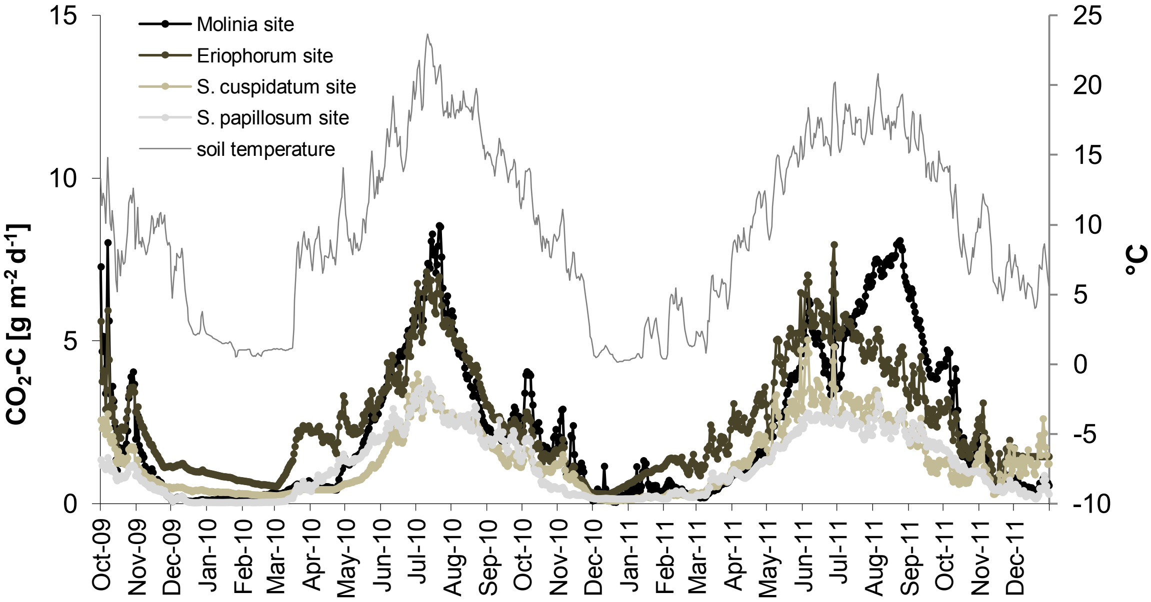

Fig. 4.4: Annual courses of daily R_{eco} (left axis) and soil temperature (right axis) of the measurement sites.

4.3.5.3 Net ecosystem exchange

Much like R_{eco}, NEE showed a characteristic seasonal pattern at all four sites (Fig.4.5-4.8). In summer, gross uptake of CO_2 through GPP outbalanced the release through R_{eco}, while during the colder months net fluxes were near 0 or net emissions occurred. At the *Eriophorum* site and *S. cuspidatum* site highest monthly cumulated net uptake of CO_2 occurred in average in June, at the *Molinia* site the highest averaged uptake of CO_2 was detected in July and at the *S. papillosum* site in August. There was a gradient from highest net uptake at the *Molinia* site to lowest net uptake at the *S. papillosum* site during the summer months June until August. During the remaining part of the year, the *Molinia* site emitted net CO_2, the *Eriophorum* site emitted also net CO_2, but less than the *Molinia* site. The *S. cuspidatum* site and the *S. papillosum* site sequestrated net CO_2, but the *S. papillosum* site sequestrated more net CO_2.

Monthly cumulated NEE was mostly highly significantly different between the sites, especially in winter and spring. The *Eriophorum* site and the *S. cuspidatum* site revealed comparatively often similar monthly cumulated NEE compared to the other sites, while monthly cumulated NEE at the *Molinia* site was very seldom similar to monthly cumulated NEE of the *S. cuspidatum* site and the *S. papillosum* site, respectively.

Maximum daily uptake and release at the examination sites are presented in table 4.7.

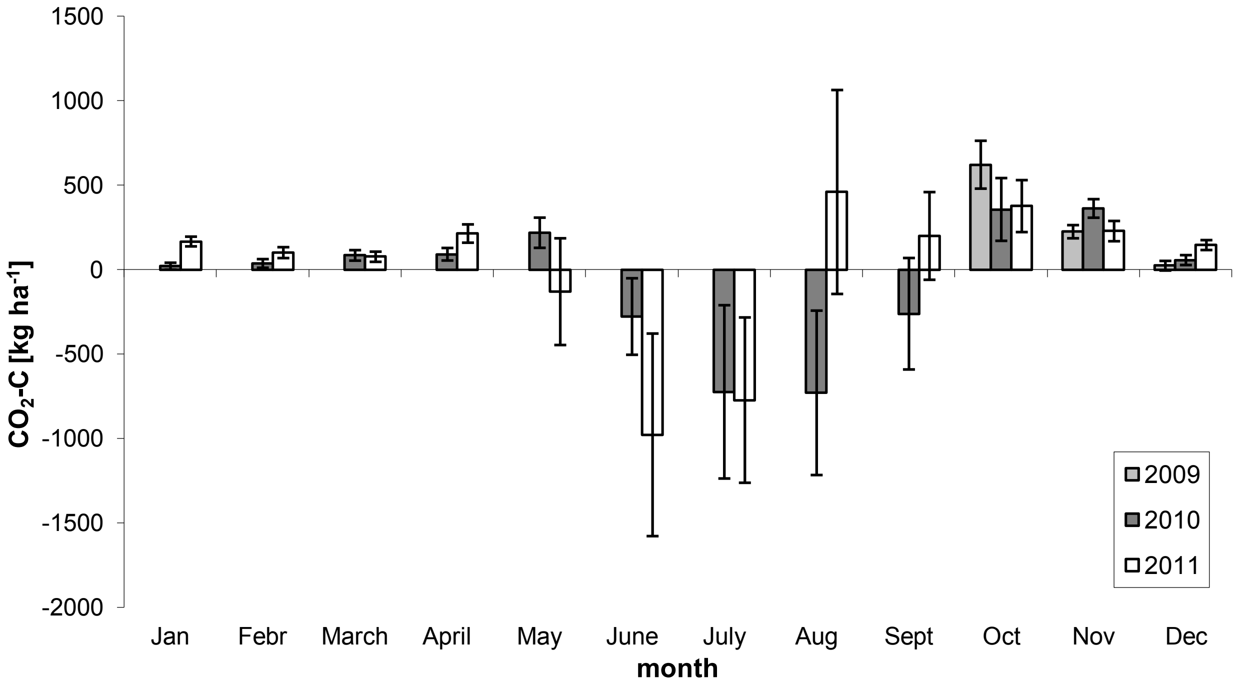

Fig. 4.5: Monthly cumulated net ecosystem exchange (NEE) of the *Molinia* site. Note: 2009 only from October to December. Error bars are standard errors.

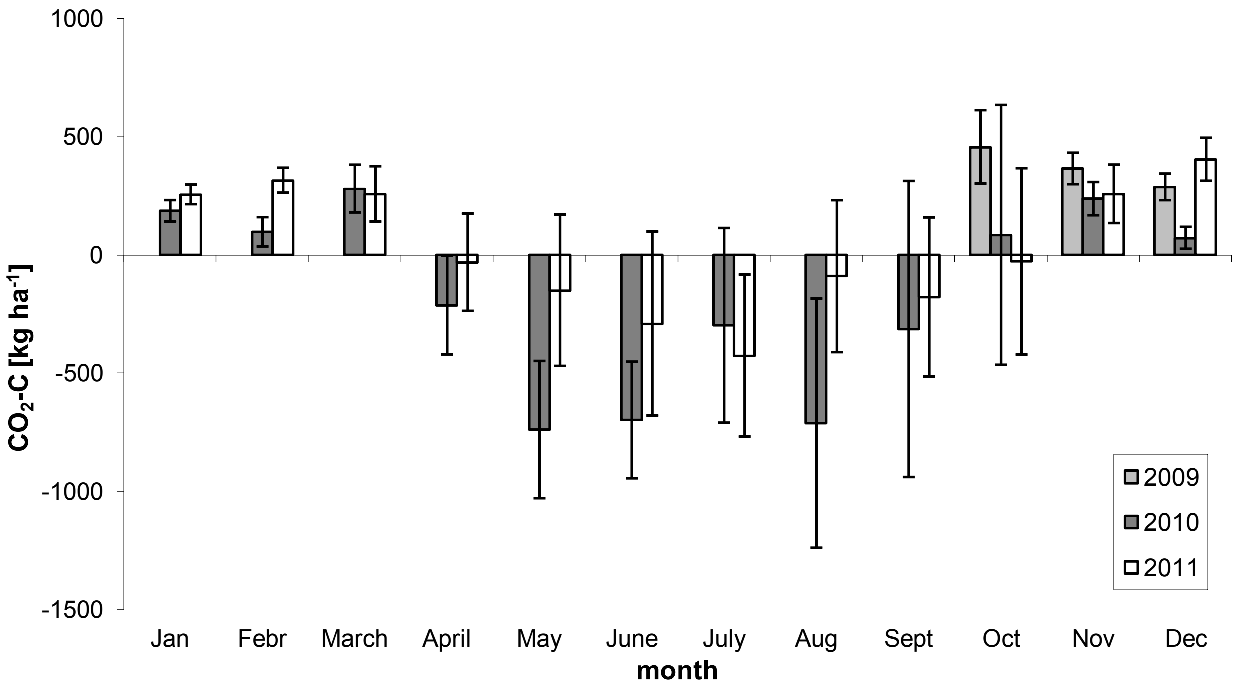

Fig. 4.6: Monthly cumulated net ecosystem exchange (NEE) of the *Eriophorum* site. Note: 2009 only from October to December. Error bars are standard errors.

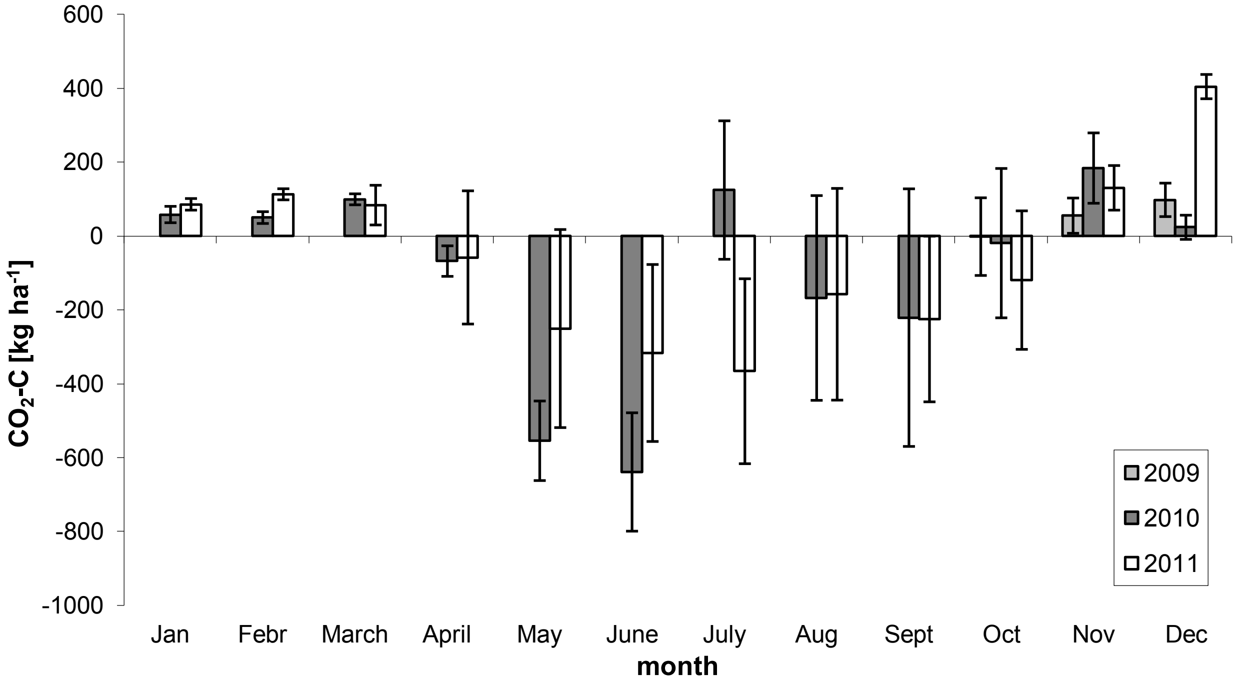

Fig. 4.7: Monthly cumulated net ecosystem exchange (NEE) of the *S. cuspidatum* site. Note: 2009 only from October to December. Error bars are standard errors.

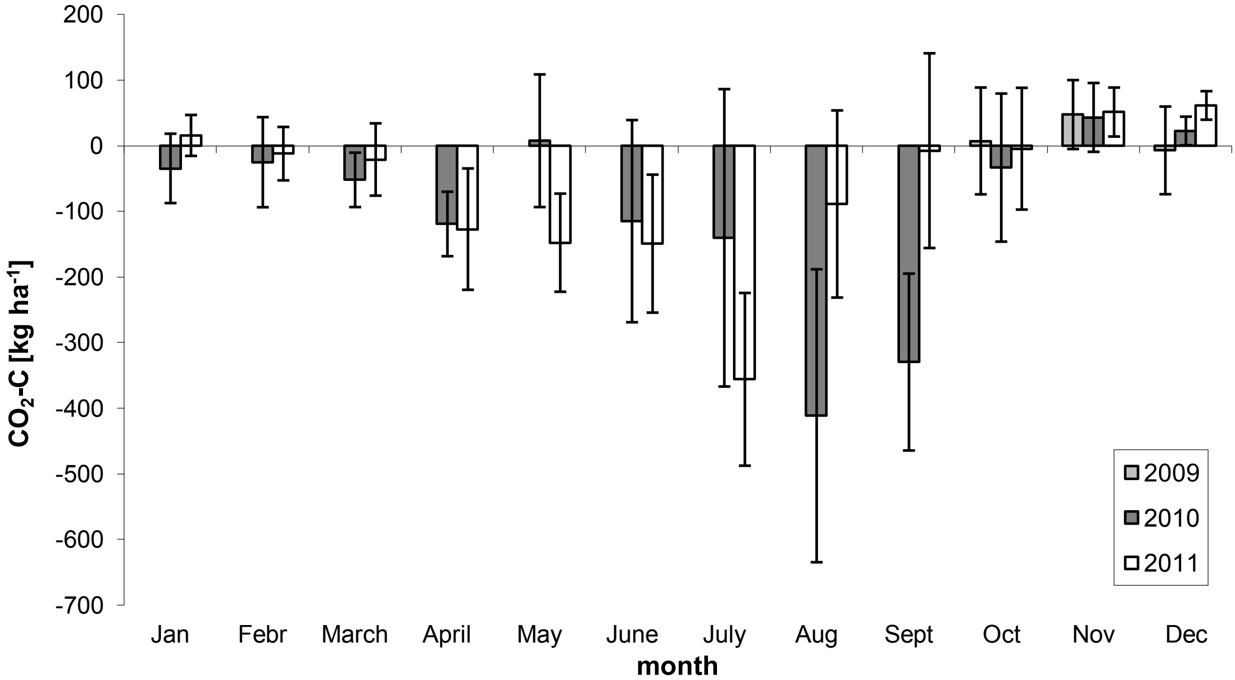

Fig. 4.8: Monthly cumulated net ecosystem exchange (NEE) of the *S. papillosum* site. Note: 2009 only from October to December. Error bars are standard errors.

Tab. 4.7: Daily maximum uptake and release of CO_2-C of the examination sites. Mean of the three collars and standard error (s.e.).

site	max uptake +/- s.e. [g CO_2-C m^{-2} d^{-1}]	max release +/- s.e. [g CO_2-C m^{-2} d^{-1}]
***Molinia* site**	-7.2 +/- 2.2	13.1 +/- 1.0
***Eriophorum* site**	-5.3 +/- 1.5	8.9 +/- 0.9
***S. cuspidatum* site**	-3.3 +/- 0.6	2.6 +/- 0.1
***S. papillosum* site**	-3.0 +/- 0.6	1.8 +/- 0.6

The variability between the years was in general high, but in several cases monthly cumulated NEE were similar. At the *Molinia* site the coefficient of variation was extremely high in August and September (cv = 626 % and cv = 1,079 %, respectively), because in 2010 monthly net uptake occurred, while in 2011 CO_2 was released. Contrastingly, at the *S. cuspidatum* site monthly balances in September were almost identical (cv = 1 %). In contrast to monthly R_{eco}, monthly NEE were not as often significantly different between the two years 2010 and 2011, but inter annual variation of gas fluxes was still high.

The differences of the annual courses of NEE between the years 2010 and 2011 are apparent in figure 4.9, which show the cumulated daily NEE. In the Leegmoor all sites exhibited an annual course that can be divided into three units: Release in winter and spring, uptake in summer as well as release in autumn and winter. At the *Molinia* site the course in 2011 was shifted towards the past for one or two months, compared to 2010. CO_2 uptake in the summer was similar between the two years, but during the remaining part of the year CO_2 release was higher in 2011, leading to different balances. At the *Eriophorum* site higher emissions were also observed in winter/spring and autumn/winter in 2011 compared to 2010. In addition, during the summer months there was a much higher uptake during 2010. Consequently, the two examination years had very different gas balances. The annual courses at the *S. cuspidatum* site were quite similar, except from May until July and in December. In May and June, uptake rates in 2010 were much higher, but in July 2010 the site released CO_2. The *S. papillosum* site sequestrated almost year round CO_2 with highest uptake rates in July and August. The two years exhibited similar courses, however in 2010 uptake rates were higher.

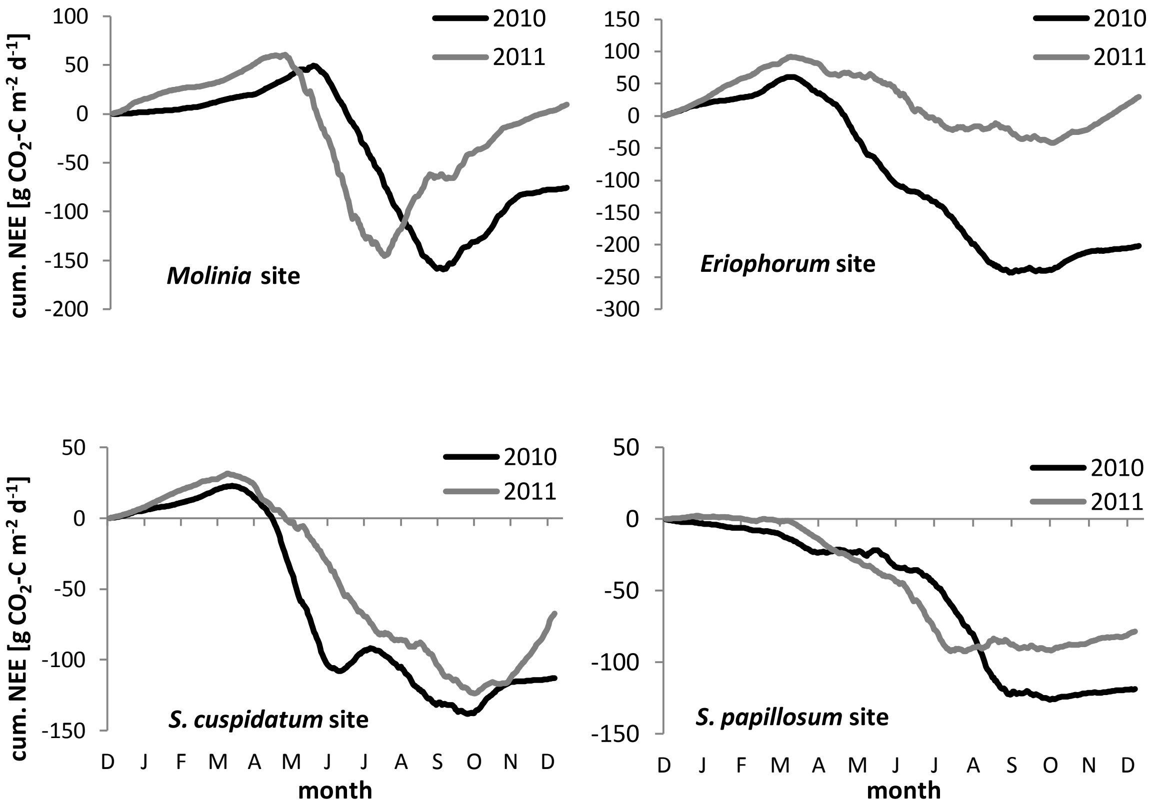

Fig. 4.9: Annual courses of cumulated NEE the examination sites.

Annual course of daily GPP at the *Molinia* site was similar to the pattern at the *Eriophorum* site, while the annual course at the *S. cuspidatum* site was analogous to the pattern at the *S. papillosum* site (Fig.4.10). However, as already established, the vegetation at the *Eriophorum* site developed earlier than the vegetation at the other sites. In July 2010, the GPP at the *S. cuspidatum* site was contrary to the general trend, and dropped to lower values. Subsequently, it increased again. By comparing the annual course of the GPP with the course of the PAR, there is a delay visible, similar to the delay of the R_{eco} (see above).

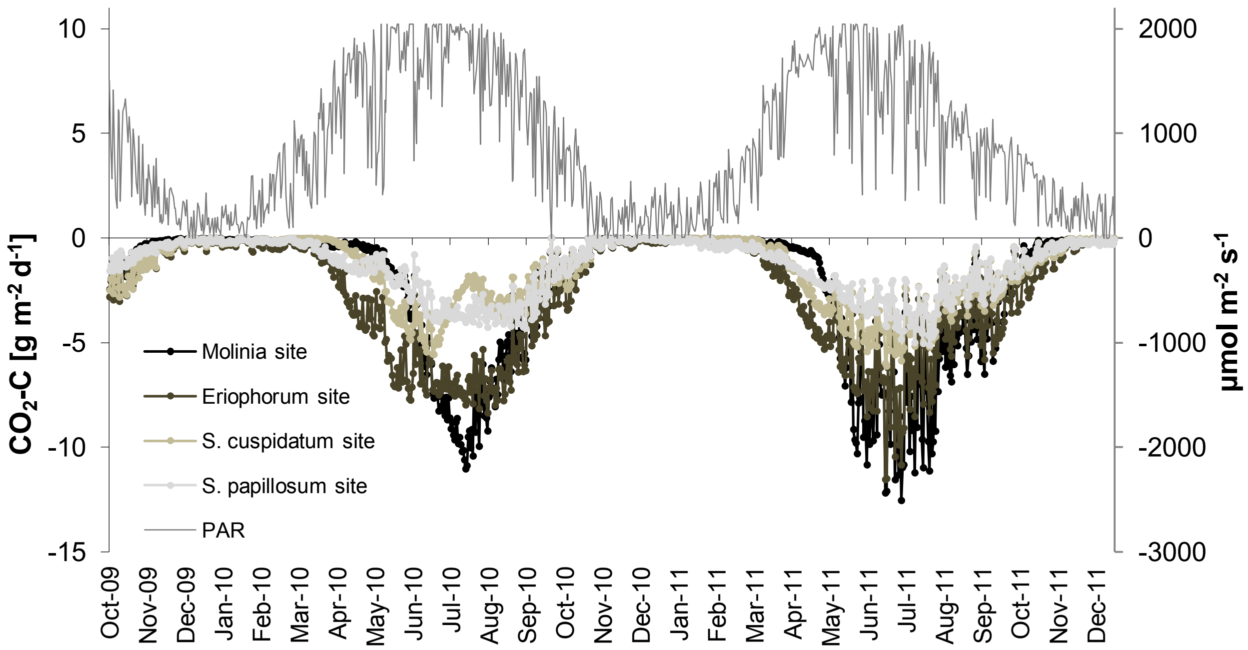

Fig. 4.10: Annual courses of daily GPP (left axis) and PAR (right axis) of the measurement sites.

4.3.5.4 Annual carbon dioxide balance

In 2010, the *Molinia* site and *Eriophorum* site revealed both significantly higher R_{eco} than the *S. cuspidatum* site and *S. papillosum* sites (Tab.4.8). In 2011, annual R_{eco} was significantly higher than in 2010 at all four sites. As in 2010, highest R_{eco} was found at the *Eriophorum* site, followed by the *Molinia* site, the *S. cuspidatum* site and the *S. papillosum* site. In average over the two years, annual R_{eco} was high at the *Molinia* site and *Eriophorum* site compared to the *S. cuspidatum* site and *S. papillosum* site.

Annual NEE (in average over the two years) showed a gradient from the *Molinia* site with a smaller uptake to the *S. papillosum* site with a higher uptake (Tab.4.8). In 2010, net CO_2 uptake at the *Molinia* site was significantly lower than at the *Eriophorum* site and the *S. papillosum* site. At the *Eriophorum* site CO_2 uptake was significantly higher than the uptake at the other sites. The balances at the *S. cuspidatum* site and *S. papillosum* site were about the same. In contrast, in 2011 the *Molinia* site and *Eriophorum* site released net CO_2. The difference was not significant. The difference of the balances between the *S. cuspidatum* site and the *S. papillosum* site was also not significant.

Tab. 4.8: Annual and average balances for R_{eco}, NEE, CH_4-C, and N_2O-N exchange in kg ha^{-1}. M: Mean, s.e.: Standard error. Letters indicate that balances are not significantly different.

site	balances		2010		2011		average	
			m	s.e.	m	s.e.	m	s.e.
***Molinia* site**	R_{eco} CO_2	[kg CO_2-C ha^{-1} a^{-1}]	7595	299	9973 f	374	8784	1189
	NEE CO_2	[kg CO_2-C ha^{-1} a^{-1}]	-758 a	914	92 g	1389	-333	425
	CH_4	[kg CH_4-C ha^{-1} a^{-1}]	0.45 c	0.28	1.09 i	0.36	0.77	0.26
	N_2O	[kg N_2O-N ha^{-1} a^{-1}]	0.88 d	0.57	-0.25 l	0.24	0.31	0.46
***Eriophorum* site**	R_{eco} CO_2	[kg CO_2-C ha^{-1} a^{-1}]	8563	662	10522 f	628	9543	980
	NEE CO_2	[kg CO_2-C ha^{-1} a^{-1}]	-2017	1268	297 g	1127	-860	1157
	CH_4	[kg CH_4-C ha^{-1} a^{-1}]	161.8	21.57	202.3 k	28.09	182.1	16.5
	N_2O	[kg N_2O-N ha^{-1} a^{-1}]	0.45 d	0.30	-0.21 l	0.12	0.12	0.27
***S. cuspidatum* site**	R_{eco} CO_2	[kg CO_2-C ha^{-1} a^{-1}]	4203 e	294	5845	435	5024	821
	NEE CO_2	[kg CO_2-C ha^{-1} a^{-1}]	-1136 ab	613	-762 h	796	-949	225
	CH_4	[kg CH_4-C ha^{-1} a^{-1}]	223.7	36.6	241.6 k	49.8	232.7	7.3
	N_2O	[kg N_2O-N ha^{-1} a^{-1}]	-0.42 d	0.21	-0.09 l	0.16	-0.26	0.13
***S. papillosum* site**	R_{eco} CO_2	[kg CO_2-C ha^{-1} a^{-1}]	4145 e	506	4901	240	4523	378
	NEE CO_2	[kg CO_2-C ha^{-1} a^{-1}]	-1188 b	481	-786 h	398	-987	201
	CH_4	[kg CH_4-C ha^{-1} a^{-1}]	30.8 c	1.7	16.3 i	2.1	23.5	5.9
	N_2O	[kg N_2O-N ha^{-1} a^{-1}]	-0.08 d	0.15	0.19 l	0.10	0.05	0.11

Since differences between the *S. cuspidatum* site and the *S. papillosum* site were not significant, the two sites can be grouped together. The *Molinia* site revealed a much lower uptake, while the balances at the *Eriophorum* site oscillated strongly, which makes it difficult to determine an average value of the balances at the *Eriophorum* site.

At all sites the annual NEE balance was significantly different between the two years, caused by higher R_{eco} in 2011, compared to 2010. The *Molinia* site and *Eriophorum* site revealed a net uptake in 2010 and a net release in 2011. The *S. cuspidatum* site and *S. papillosum* site were in both years CO_2 sinks, but the uptake in 2010 was higher than in 2011.
The standard errors were very high, compared to the annual balances, especially at the *Molinia* site and in 2011. In addition, the difference between the two years was very high, particularly at the *Molinia* site and *Eriophorum* site, where the standard errors were much higher than the mean values. The *S. papillosum* site showed the most stable values.

4.3.6 Methane

4.3.6.1 Annual course of methane

At the sites in the Leegmoor the annual courses of methane fluxes showed no seasonal trends, but rather a diffuse pattern (Fig.4.11 & Fig.4.12). At the *S. papillosum* site methane emissions elevated in spring and dropped in autumn analogous to the increasing temperatures in spring and decreasing temperatures in autumn (Fig.4.13). In 2010, wl and emissions were higher than in 2011.

The highest CH_4 flux rate at the *S. cuspidatum* site amounted to 15.7 +/- 27.1 (Tab.4.9). The other three sites showed much lower values. CH_4 uptake did not occur or was lower than uptake.

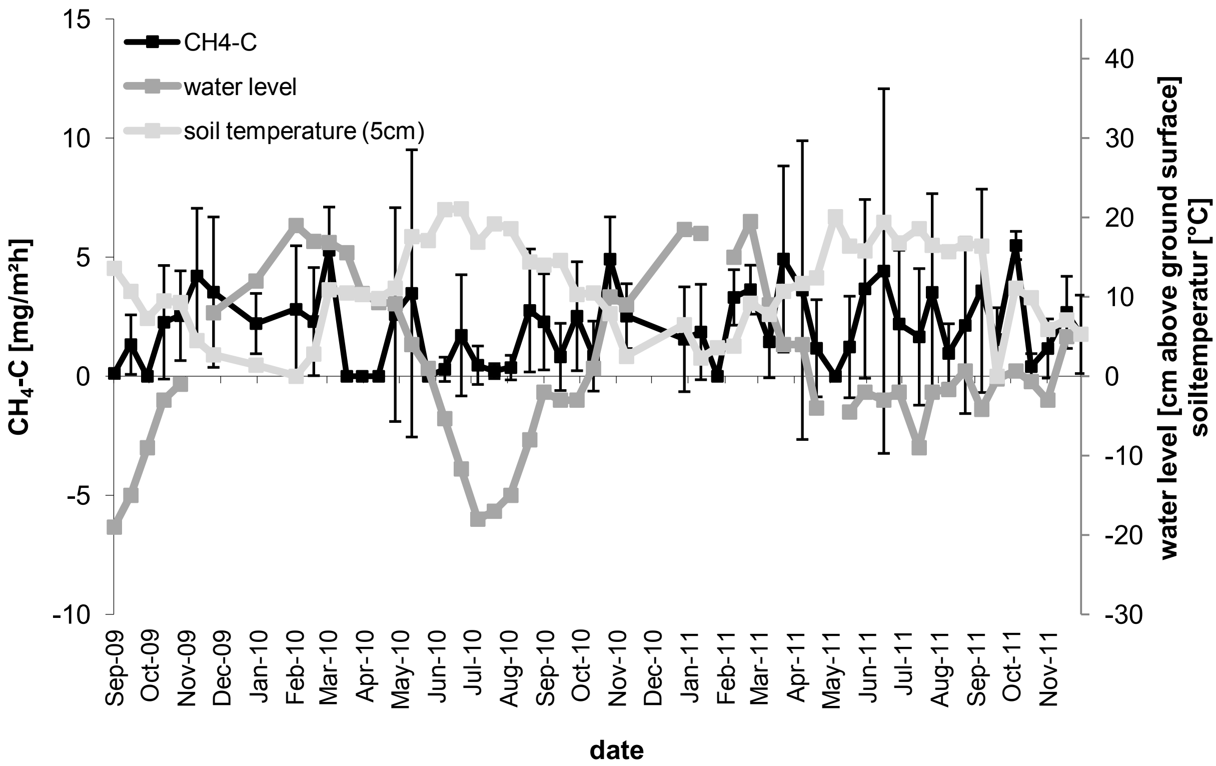

Fig. 4.11: Annual course of CH_4 flux of the *Eriophorum* site (left axis). Mean of the three collars, error bars are standard errors. Annual courses of wl and soil temperature in 5 cm depth (right axis).

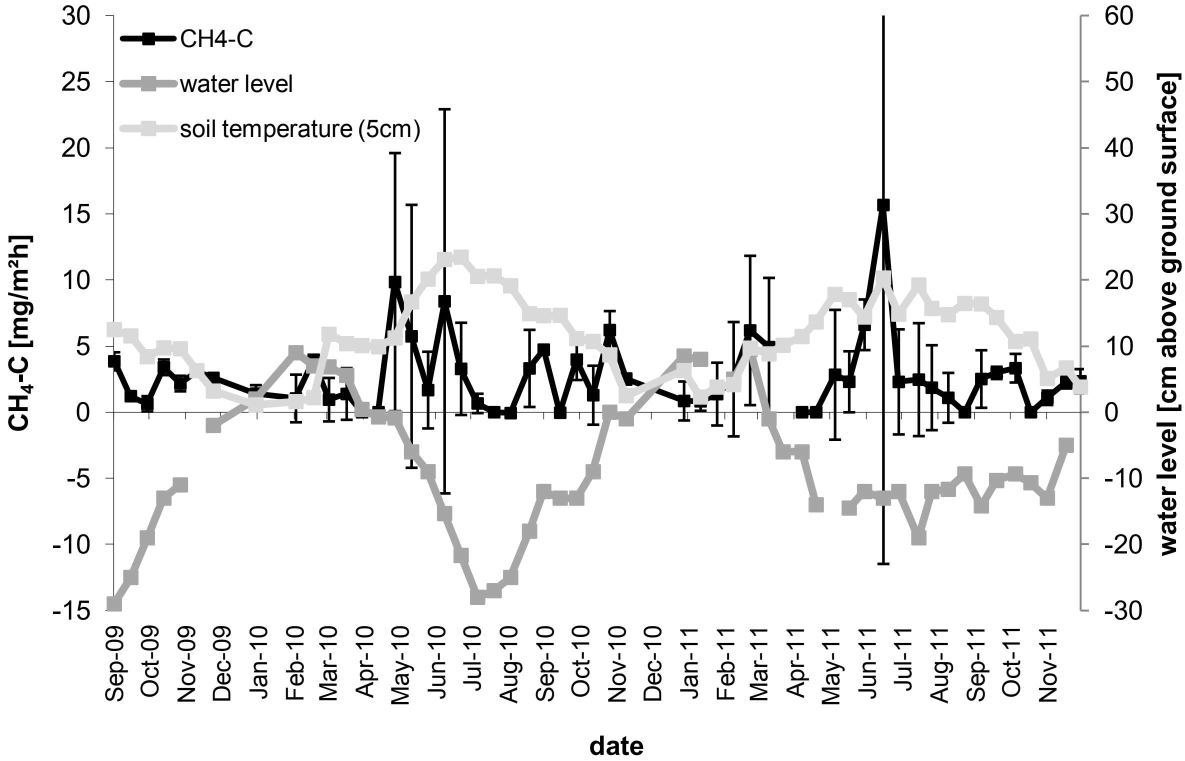

Fig. 4.12: Annual course of CH_4 flux of the *S. cuspidatum* site (left axis). Mean of the three collars, error bars are standard errors. Annual courses of wl and soil temperature in 5 cm depth (right axis).

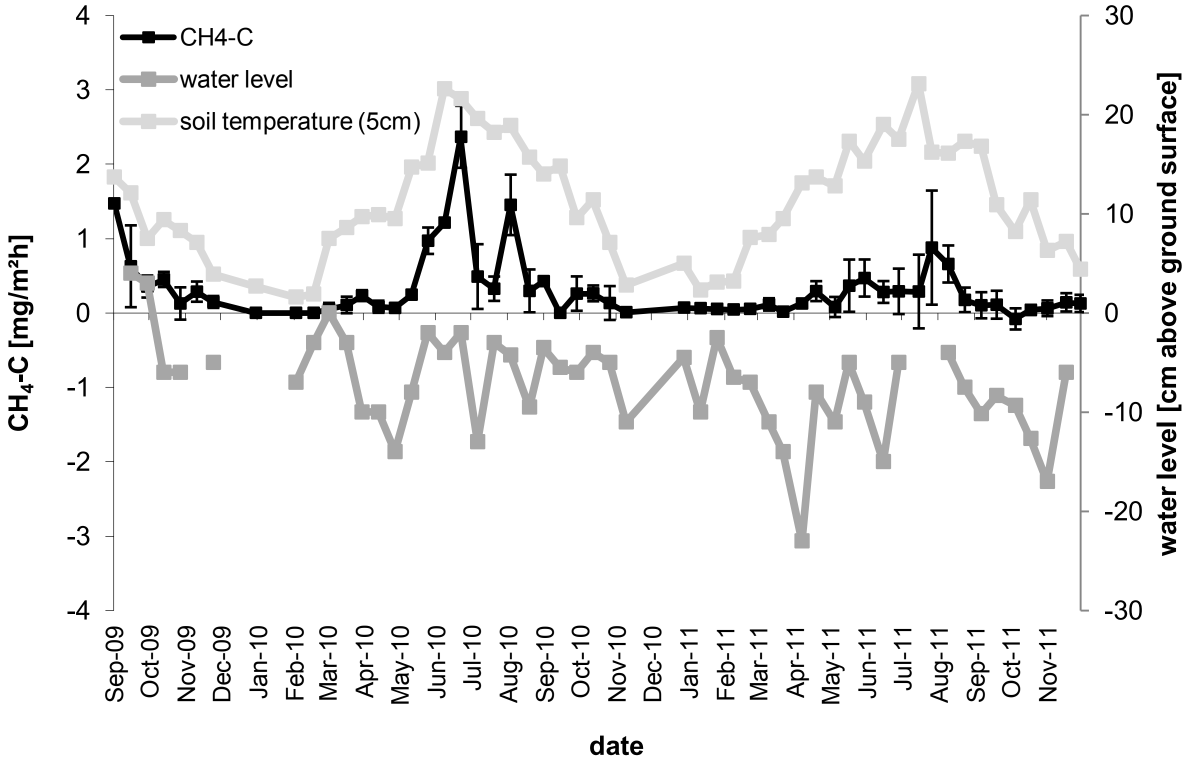

Fig. 4.13: Annual course of CH_4 flux of the *S. papillosum* site (left axis). Mean of the three collars, error bars are standard errors. Annual courses of wl and soil temperature in 5 cm depth (right axis).

Tab. 4.9: Hourly maximum uptake and release of CH_4-C (left) and N_2O-N (right) of the examination sites. Mean of the three collars and standard error (s.e.).

site	max uptake +/- s.e. [mg CH_4-C m^{-2} h^{-1}]	max release +/- s.e. [mg CH_4-C m^{-2} h^{-1}]	max uptake +/- s.e. [mg N_2O-N m^{-2} h^{-1}]	max release +/- s.e. [mg N_2O-N m^{-2} h^{-1}]
Molinia **site**	-0.03 +/- 0.06	0.09 +/- 0.11	-0.07 +/- 0.07	0.09 +/- 0.16
Eriophorum **site**	0 +/- 0	5.49 +/- 0.59	-0.05 +/- 0.04	0.07 +/- 0.12
S. cuspidatum **site**	-0.07 +/- 0.12	15.68 +/- 27.15	-0.05 +/- 0.09	0.04 +/- 0.07
S. papillosum **site**	-0.08 +/- 0.14	2.37 +/- 0.42	-0.06 +/- 0.05	0.05 +/- 0.04

Significant relationships between CH_4 fluxes and wl (R^2 = 0.32) as well as between CH_4 fluxes and soil temperatures (R^2 = 0.59) were found at the *S. papillosum* site (Tab.4.10). At the other sites no significant correlations were evident. However, at the *Molinia* site high CH_4 fluxes were only observable at high wl. At the *Eriophorum* site a weak trend from low fluxes at low wl to higher fluxes at high wl was evident (R^2 = 0.07). Taking the measurements from all sites, fluxes correlate significantly with wl (R^2 = 0.25). It was obvious that at a wl of less than 20 cm below ground level, the CH_4 fluxes were around 0, and at a wl of above 20 cm below ground level, the CH_4 fluxes raised. The highest fluxes could be determined at a wl of around 0.

At all sites strong negative collinearities existed between the soil temperatures and the wl, except at the *S. papillosum* site. The wl was high in winter, when temperatures were low, and low in the summer, when temperatures were high. At the *S. papillosum* site the wl was at the same level the whole year round. Thus, only at the *S. papillosum* site was it possible to find relationships between fluxes and soil temperatures as well as wl.

Thus, CH_4 emissions were driven by a combination of wl and temperature.

Tab. 4.10: Correlation coefficients (Pearson) of methane fluxes versus site parameters. p: p-value, n.s.: not significant

	S. papillosum **site**	**All sites**
CH_4 flux - soil temp. (2 cm depth)	0.58 ($p<0.0001$)	n.s.
CH_4 flux - soil temp. (5 cm depth)	0.59 ($p<0.0001$)	n.s.
CH_4 flux - wl	0.32 ($p = 0.0002$)	0.25 ($p<0.0001$)

The analysis of non-linear 3D-regression which includes a threshold value for the wl showed a significant relationship between methane fluxes and soil temperature as well as wl. Including the fluxes of all four sites, the model could explain 21 % ($p < 0.00001$; $R^2_{adj} = 0.21$) of the variation with a non-linear power function (model 1: Fig.4.14):

$$\mathbf{F = a \cdot wl^{b} \cdot tsoil^{b}}$$

F	= CH_4 flux (mg CH_4-C m^{-2} h^{-1})
Wl	= Water level (cm above ground level)
Tsoil	= Soil temperature in 5 cm depth (°C)
a	= Fitting parameter
b	= Fitting parameter

If only the fluxes of the Leegmoor sites were included, 34 % ($p < 0.00001$; $R^2_{adj} = 0.32$) could be explained by a non-linear lorentzian cumulative function, which showed the best fit (model 2: Fig.4.14):

$$\mathbf{F = a+b(0.5+atan((wl-c)/d)/\pi)\cdot(0.5+atan((tsoil-e)/f)/\pi)}$$

F	= CH_4 flux (mg CH_4-C m^{-2} h^{-1})
Wl	= Water level (cm above ground level)
Tsoil	= Soil temperature in 5 cm depth (°C)
π	= 3.14159265359
e	= 2.71828182846 (Euler's number)
a-f	= Fitting parameters

In both models, residual fluxes are not normally distributed (Fig.4.15). The positive residual fluxes show higher values than the negative residual fluxes. Residual fluxes along the temperature gradient are quite homogenously distributed. However, residual fluxes along the wl gradient are not homogenously distributed.

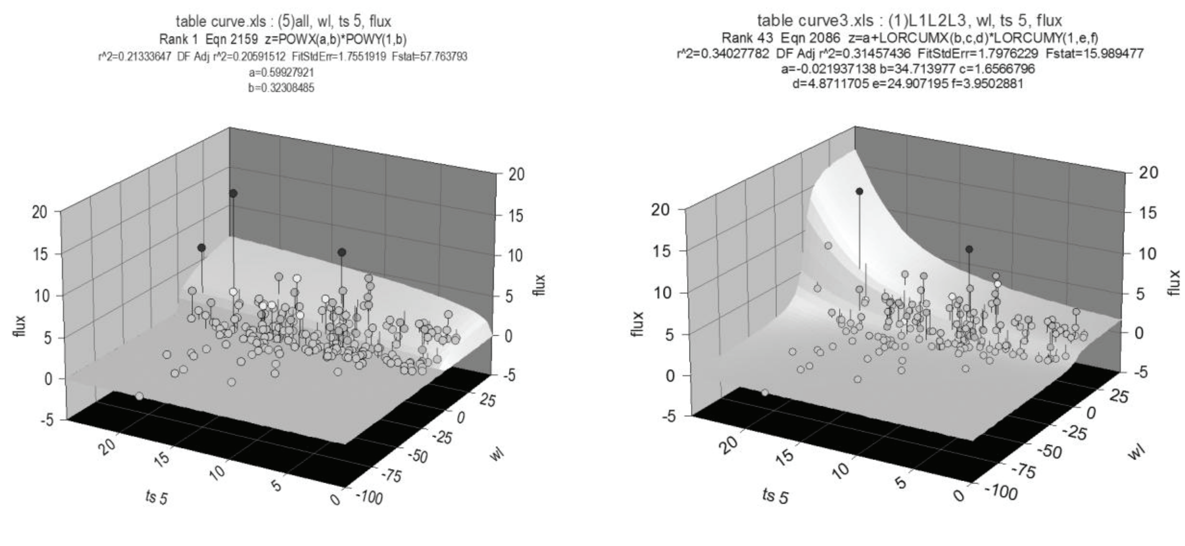

Fig. 4.14: 3D-modells and measured values of CH_4 flux (mg CH_4-C m^{-2} h^{-1}) versus water level (cm above ground surface) and soil temperature in 5 cm depth (°C). a) model 1: all sites, b) model 2: only Leegmoor.

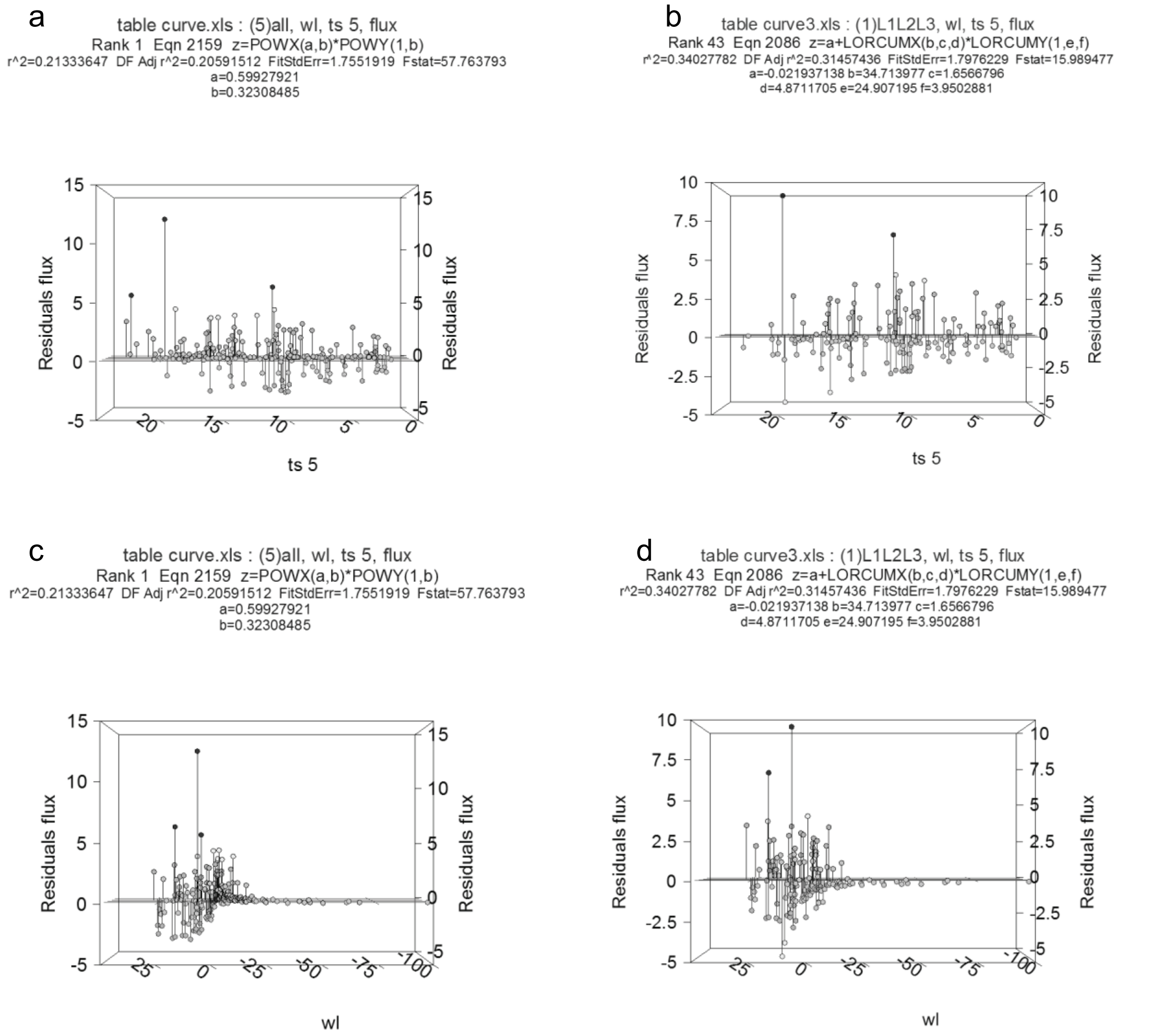

Fig. 4.15: Pattern of residuals fluxes. a) model 1: residuals fluxes vers soil temp., b) model 2: residuals fluxes vers soil temp., c) model 1: residuals fluxes vers water level, d) model 2: residuals fluxes vers water level.

4.3.6.2 Annual methane balance

Annual methane balances were very low at the *Molinia* site and not significantly different to the *S. papillosum* site (Tab.4.8). The *Eriophorum* site revealed much higher annual flux rates. Highest methane emissions occurred at the *S. cuspidatum* site (232.7 +/- 7.3 kg CH_4-C ha^{-1} a^{-1} in average). In 2011, CH_4 emissions of the *Eriophorum* site and the *S. cuspidatum* site were not significantly different. Thus, there was a gradient from the *Molinia* site to the *S. cuspidatum* site towards higher CH_4 emissions. Since the annual balances of the *Molinia* site and the *S. papillosum* site did not differ significantly, the two sites can be grouped together.

CH_4 emissions were higher in 2011 than in 2010, except at the *S. papillosum* site. However, the differences between the two years were not significant.

The correlation analyses revealed highly significant correlations between CH_4 balance and mean wl ($R^2 = 0.96$; $p = 0.0001$) as well as between CH_4 balance and mean summer wl ($R^2 = 0.82$; $p = 0.013$). Both relations can be described with a function which has an exponential course and continuous logarithmic after a threshold. The threshold is at a mean wl or mean summer wl just a few cm below ground level. This means, as long as the mean wl remains more than about 5 cm below ground level, the CH_4 balance is low, but as soon as the mean wl is higher than 5 cm below ground level, the methane balance is high.
CH_4 balances showed also a significantly negative relationship to electric conductivity (Lf) at the examination sites ($R^2 = 0.64$).

4.3.7 Nitrous oxide

The annual course of N_2O fluxes did not show any seasonal pattern. Maximum release and uptake of N_2O were similarly low at the examination sites (Tab.4.9).

Annual N_2O balances were very low and did not differ significantly at all sites in both years (Tab.4.8). While the *S. cuspidatum* site was a weak sink for nitrous oxide in both years, at the other sites there was an uptake in one year and a release in the other year. In average, the *Molinia* site, *Eriophorum* site and *S. papillosum* site were small sources. Thus, highest emissions occurred at the dry sites, and lowest emissions or uptake emerged at the wetter sites. Values of 2010 and 2011 did not show a significant difference, except at the *Eriophorum* site.

4.3.8 Net ecosystem carbon balance and global warming potential

NECB were similar to the annual NEE, because NECB was mainly determined by NEE. At the *Eriophorum* site and the *S. cuspidatum* site the GWP100 balance revealed a different picture than the NECB, because methane exerted a greater impact (Tab.4.11). The *S. cuspidatum* site was a GWP100 source in both years (in average: 3,878 +/- 687 kg CO_2-eq. ha^{-1} a^{-1}). The *Eriophorum* site and *Molinia* site were sinks in one year and sources in the other year. In average, the *Eriophorum* site and *Molinia* site revealed 2,754 +/- 4,243 and -1,051 +/-

1,560 kg CO_2-eq ha^{-1} a^{-1}, respectively. The *S. papillosum* site was GWP100 sink in both years (in average: -2,838 +/- 738 kg CO_2-eq. ha^{-1} a^{-1}). The gradient shifted to the sequence *S. cuspidatum* site – *Eriophorum* site – *Molinia* site – *S. papillosum* site.

The *S. cuspidatum* site was in both years a carbon sink, but a GWP100 source (Tab.4.11). The *Eriophorum* site was a strong carbon sink but a weak GWP100 sink in 2010 and a weak carbon source, but a strong GWP100 source in 2011. The *S. papillosum* site was a smaller GWP100 sink than NECB sink, but the difference was small. Consequently, the *S. papillosum* site was the only site which was in both years a NECB and a GWP100 sink. At the *Molinia* site NECB and GWP100 balance had about the same values. In 2010, the *Molinia* site was a sink, in 2011 a source.

Changing the time perspective of the GWP assessment from 100 to 500 years would lead to the conversion of the *Eriophorum* site and the *S. cuspidatum* site from a GHG source to a GHG sink. The *S. papillosum* site and the *Molinia* site would become stronger sinks.

Tab. 4.11: Annual and average NECB (net ecosystem carbon balances), and GWP (global warming potentials) balances for the time spans of 20, 100 and 500 years in kg ha^{-1} a^{-1}. M: Mean, s.e.: Standard error.

year	balances/ GWP		2010		2011		average	
			m	s.e.	m	s.e.	m	s.e.
***Molinia* site**	GWP 20	[kg CO_2-eq. ha^{-1} a^{-1}]	-2341	3353	324	5094	-1008	1560
	GWP 100	[kg CO_2-eq. ha^{-1} a^{-1}]	-2356	3353	255	5094	-1051	1560
	GWP 500	[kg CO_2-eq. ha^{-1} a^{-1}]	-2566	3353	288	5094	-1139	1560
	NECB	[kg CO_2-C ha^{-1} a^{-1}]	-741	914	110	1389	-315	425
***Eriophorum* site**	GWP 20	[kg CO_2-eq. ha^{-1} a^{-1}]	7790	4657	19716	4144	13753	4246
	GWP 100	[kg CO_2-eq. ha^{-1} a^{-1}]	-1982	4653	7490	4137	2754	4243
	GWP 500	[kg CO_2-eq. ha^{-1} a^{-1}]	-5705	4651	3013	4134	-1346	4243
	NECB	[kg CO_2-C ha^{-1} a^{-1}]	-1838	1269	516	1128	-661	1157
***S. cuspidatum* site**	GWP 20	[kg CO_2-eq. ha^{-1} a^{-1}]	16354	2282	19529	2973	17941	690
	GWP 100	[kg CO_2-eq. ha^{-1} a^{-1}]	2829	2259	4928	2941	3878	687
	GWP 500	[kg CO_2-eq. ha^{-1} a^{-1}]	-2080	2251	-456	2928	-1268	686
	NECB	[kg CO_2-C ha^{-1} a^{-1}]	-895	614	-503	799	-699	187
***S. papillosum* site**	GWP 20	[kg CO_2-eq. ha^{-1} a^{-1}]	-1548	1765	-1287	1459	-1417	740
	GWP 100	[kg CO_2-eq. ha^{-1} a^{-1}]	-3408	1765	-2269	1459	-2838	738
	GWP 500	[kg CO_2-eq. ha^{-1} a^{-1}]	-4077	1765	-2678	1459	-3377	737
	NECB	[kg CO_2-C ha^{-1} a^{-1}]	-1141	481	-753	398	-947	201

4.4 Discussion

4.4.1 Evaluation of methodology

In order to achieve appropriate gas fluxes from chamber measurements, it is necessary to ensure linearity of the slope of the gas concentration inside the chamber and to assure that the explaining variables, i.e. PAR remain constant (see ch.2).

Generally, it was possible to fit the models of CO_2 exchange for every measurement campaign. However, in a few cases the span between the lowest and the highest temperature was too small. A solution for this problem could be to extend the measurement campaign from one day to two days at the particular site. This makes sense, if the long-term parameters like wl and phenology do not change at least for the most part, but the temperatures and/or the PAR are different. With such an intensive measurement program, as in this case, it was not possible to include additional measurement days. However, the cases where model calibration was not possible were generally in winter, when gas fluxes were low. The measurement campaigns at times with high gas fluxes were normally appropriate for model calibration. Another possibility to deal with measurement campaigns where model calibration was not possible, is to pool two (or more) measurement campaigns. This makes only sense, if the long-term parameters remain identical or at least very similar. This was the case at the *S. papillosum* site, hence pooling of measurement campaigns were justifiable in some cases.

E_0 and R_{ref} of rewetted and natural bogs in Germany (own data unpublished, Drösler 2005, Beetz et al. 2013) are similar to those of the study sites.

GP_{max} and α of the *S. cuspidatum* site and *S. papillosum* site were similar to the values in previous studies in rewetted and natural bogs, while the *Eriophorum* site and *Molinia* site showed higher values of GP_{max} and α (own data unpublished, Bubier et al. 1999, Lafleur et al. 2001, Waddington & Warner 2001, Drösler 2005, Beetz et al. 2013). The seasonal trend of α and GP_{max} was also observed by Drösler (2005).

The fit of all measured and all modeled results ranged between $R^2 = 0.88$ and 0.98. Thus, the models offer very appropriate results for R_{eco} and NEE.

As in chapter two, only temperatures and PAR were used for the measurement-campaign specific modeling, while other influencing factors such as soil moisture were not considered on a short term (i.e. daily), but only on a long term (i.e. monthly), disregarding that these factors might also change in the course of the day. Petrone et al. (2003) suppose that soil moisture is the primary controlling factor of GPP, instead of PAR. However, the coefficients of determination (Pearson) between modeled and measured values of the NEE, which were well above $R^2 = 0.5$ (Tab.4.3-4.6) confirm that temperature and PAR are the main driving forces on a short term. The linear interpolation between measurement campaigns provided that long term influencing factors change also linearly, which is certainly not the case. For this reason the time span between two measurement campaigns was kept as short as possible (compare ch.2 and Beetz et al. 2013).

Drösler (2005) used the data from the whole year to calibrate the R_{eco} model in a low productive bog in South Germany, because no seasonal effect on the respiration-temperature relationship was evident. In the examination area different seasonal behaviors of the R_{eco} at the diverse sites were found (Fig.4.4). Therefore, campaign specific calibration leads to more precise results.

4.4.2 Temporal pattern of GHG fluxes

4.4.2.1 Ecosystem respiration

Compared to natural bogs in Canada, the range of R_{eco} at the study sites are greater. According to Waddington & Warner (2001), R_{eco} ranged from 0.41 to 5.21, 0.63 to 3.68 and 0.35 to 6.3 g CO_2-C $m^{-2}d^{-1}$ in natural hummocks, natural lawns and mined sites, respectively.
At all sites the seasonal pattern of the R_{eco} followed basically the course of the temperature. The deviations from this course were due to the phenology of the vegetation. In spring, when temperatures are raised already, the vegetation is not fully developed, while in late summer and autumn, senescence occurs, although temperatures are still quite high. Thus, only heterotrophic respiration contributes to R_{eco}, while autotrophic respiration is low. In July, temperatures are highest and the vegetation is fully developed, thus highest R_{eco} occurs during July, which is consistent with Beetz et al. (2013). Another driving factor for R_{eco} is the wl (Silvola et al. 1996, Flessa et al. 1997, Waddington et al. 2002). However, an effect was not observable because it was overshadowed by other influencing factors. Thus, beside temperature, vegetation is probably the main driving force for the seasonal variation in R_{eco}.

4.4.2.2 Net ecosystem exchange

The results at the *Molinia* site were in accordance with a Dutch bog, which takes up CO_2 during June, July and August, while the rest of the year, from September until May, the bog emits CO_2 (Nieveen et al. 1998). Mean summer NEE (June to Sept.) varied between -1,010 and -1,810 kg CO_2–C ha^{-1} in *Eriophorum* dominated rewetted former peat cut sites in Finland (south boreal zone) (Kivimäki et al. 2008). This complies with the summer flux rates of the *Molinia* site and *Eriophorum* site. Lafleur et al. (2003) and Drösler (2005) found seasonal flux rates similar to the *S. cuspidatum* site and the *S. papillosum* site in natural bogs. However, they found lower maximum net release and maximum net uptake rates.

Important factors for GPP, beside PAR, are phenology and type of the vegetation (Lafleur et al. 1997, Tuittila et al. 1999). According to Buchmann & Schulze (1999) and Wilson et al. (2007), GPP is related to leaf area index (LAI) and vascular green area (VGA). Daily GPP of the *Molinia* site and *Eriophorum* site on the one hand, and the *S. cuspidatum* site and *S. papillosum* site on the other hand were similar, due to similar types of vegetation, respectively. The delayed course of the photosynthesis in spring (compared to the course of the PAR) was due to the smaller LAI or VGA, while the decrease of photosynthetic activity in late summer was caused by the onset of senescence (Wilson et al. 2007). In comparison to the other sites, at the *Eriophorum* site GPP increased early in spring and decreased late in autumn. *Eriophorum* has a high potential for photosynthesis early in the season and throughout most of the season (Tuittila et al. 1999).

Another important driver of the gas exchange is the wl (Titus et al. 1983, Schipperges & Rydin 1998, Tuittila et al. 1999, Waddington & Warner 2001, Lafleur et al. 2003, Wilson et al. 2007). The strong decrease of GPP in July 2010 at the *S. cuspidatum* site was caused by the extreme decline of the wl in connection with warm and dry weather, leading to a dry-out of the *Sphagnum*. *Sphagnum* mosses are very exposed to wl changes, and photosynthesis decreases with decreasing tissue water content (Titus et al. 1983, Schipperges & Rydin 1998). The moss capitula might even not recover from drought if the plants are dried above their water compensation point (Schipperges & Rydin 1998, Lafleur et al. 2003). However, during the following measurement campaign in August 2010, the *Sphagnum* had recovered from drought. Prior to this measurement campaign, there was more precipitation, less global radiation and consequently a higher wl. In contrast, the other sites were not affected by the dry period in July 2010, because the *Molinia* site and *Eriophorum* site were not dominated by

Sphagnum, but by species like *Eriophorum* which are less vulnerable for wl changes. These plants are able to keep their stomata open during dry periods because the roots go deep into the ground (Tuittila et al. 1999). At the *S. papillosum* site the wl was maintained high all year round, thus also during the summer. Consequently, the *Sphagnum* mosses did not dry out. The clearly visible effect of the dry period at the *S. cuspidatum* site proves the ability of the models to account for such influencing parameters.

4.4.2.3 Methane

Methane emissions of bogs range between less than 1 to more than 500 mg CH_4-C m^{-2} d^{-1} (Crill et al. 1988, Moore & Knowles 1989, Freeman et al. 1993, Waddington & Price 2000, Sommer & Fiedler 2002). At the study sites the results were well below 500 mg CH_4-C m^{-2} d^{-1}. The maximum CH_4 uptake and maximum CH_4 release of the study sites are in agreement with the results of Drösler (2005), who found a maximum methane uptake of -0.10 mg CH_4-C m^{-2} h^{-1} and a maximum methane release of 10.30 mg CH_4-C m^{-2} h^{-1} in rewetted bogs in South Germany as well as a maximum CH_4 uptake of 0 mg CH_4-C m^{-2} h^{-1} and a maximum CH_4 release of 18.54 mg CH_4-C m^{-2} h^{-1} in natural bogs in South Germany.

The main driving forces for CH_4 emissions are wl and soil temperature. Methane is built by methanogenic bacteria in the saturated (anaerobic) zone, and is oxidized to CO_2 in the aerobic layer by methanotrophic bacteria (Munk 2001). While Roulet et al. (1993) declared that the zone of maximal potential for CH_4 production is located in the uppermost part of the saturated zone and the maximum of CH_4 oxidation is situated directly above the saturated zone, Kettunen et al. (1999), established that the maximal CH_4 production is on average about 20 cm below the wl and the maximal CH_4 oxidation about 10 cm below wl. However, only a few dm of the aerobic layer is sufficient for complete oxidization of the produced methane (Roulet et al. 1993, Meyer et al. 2001).
The models demonstrate that fluxes increase with rising wl and rising soil temperatures and that there is a threshold value of the wl above which the fluxes increase sharply (Fig.4.14). This confirms the findings of Christensen et al. (2003) and Drösler (2005). A significant proportion of the variance can be explained by the models. However, the regressions are not satisfactory. Firstly, not even half of the variance could be explained. Secondly, the residuals fluxes are not normally distributed, but are skewed to the right (Fig.4.15). Thirdly, the residuals show a decreasing trend plotted against wl (Fig.4.15). The skewed distribution may

not be a major issue and is because soils can emit high amounts of CH_4, but take up only small amounts, thus most values are close to 0, while a few values show high positive values. A reason for the trend of the residuals is the bad quality of the raw data. In several cases, when gas-concentrations of the gas samples were low, and thus the slope was flat, no significant fluxes could be determined because the analysis of the samples in the gas chromatograph revealed too imprecise gas-concentrations.

Including more variables might improve the models. Granberg et al. (1997) used wl and soil temperature as important variables in their methane-model, but included also substrate effects in the model. Updegraff et al. (1998) and Kettunen et al. (1999) observed hysteresis effects. Moreover, Granberg et al. (1997) used temperature values of the anoxic and oxic parts of the profile in order to model methane production and methane consumption, whereas in this study the soil temperatures were measured at a fixed depth (2 cm and 5 cm), with the consequence that sometimes the temperature was measured in the oxic zone and sometimes in the anoxic zone. According to Le Mer & Roger (2001), higher temperatures promote methanogenesis, whereas methanotrophy is less temperature-dependent. However, Granberg et al. (1997) discovered that the temperatures from the oxic and the anoxic zones explained 21 % of the variance, while the temperatures at a fixed depth explained only 5 %. The final models of Granberg et al. (1997) revealed coefficients of determination between $R^2 = 0.49$ and $R^2 = 0.75$.

According to the model, methane emissions are expected mainly in spring and autumn. This is in line with Beetz et al. (2013), who measured highest emissions in spring and autumn. If the wl is kept at a high level in summer, the highest methane fluxes are expectable in summer. However, at the *Eriophorum* site and the *S. cuspidatum* site occasional measurement dates showed comparatively high wl and high temperatures, but CH_4 emissions were low. Hence, there might be other factors, e.g. air pressure, which exert influence (Tokida et al. 2007).

The results are important for the management of peatlands. In order to keep CH_4 emissions low, the wl should be kept below ground surface.

4.4.2.4 Nitrous oxide

The erratic pattern with high temporal variability in the course of the year was also described by Drösler (2005) and Beetz et al. (2013). Periodical wetness probably induced the N_2O peaks (Flessa et al. 1998, Meyer 1999). Drösler (2005) determined at rewetted sites a maximum release of 0.028 mg N_2O-N m^{-2} h^{-1} and a maximum uptake of -0.022 mg N_2O-N m^{-2} h^{-1}. Natural sites exhibit lower emissions (maximum release: 0.016 mg N_2O-N m^{-2} h^{-1}, maximum uptake: -0.030 mg N_2O-N m^{-2} h^{-1}). The values at the study sites were higher.

4.4.3 Influence of water table and vegetation on GHG balances

A meta-analysis of the data of the research sites and own unpublished data from a bog near Bremerhaven as well as published data of rewetted (mostly former peat cut sites) peatlands was conducted to examine the impact of the wl and vegetation. Only results of temperate bogs were used, because exchange rates might depend on peatland type and climate zone (Höper et al. 2008).

Important drivers for CO_2 gas fluxes are wl (Bubier et al. 1998, Tuittila et al. 1999, Drösler 2005, Glatzel et al. 2006) and vegetation (Lafleur et al. 1997, Tuittila et al. 1999, Buchmann & Schulze 1999, Wilson et al. 2007, Kivimäki et al. 2008). CO_2 balances (research sites, own data unpublished, Drösler 2005, Bortoluzzi et al. 2006, Beetz et al. 2013) in relation to mean wl make clear that the CO_2 release decreases or the CO_2 uptake increases with rising mean wl (Fig.4.16).

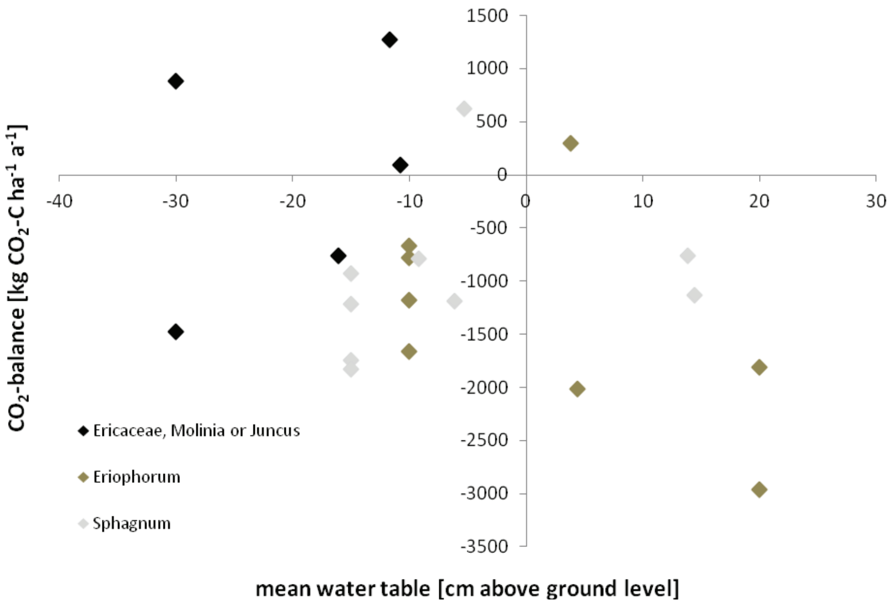

Fig. 4.16: Annual NEE balance versus mean water level (bogs in temp. zone: research sites, own data unpublished, Drösler 2005, Bortoluzzi et al. 2006, Beetz et al. 2013).

Inundated bogs reveal usually a net CO_2 uptake. Most bogs have a mean wl of 0 to 20 cm below ground level, and the majority of these sites are carbon sinks. The *Eriophorum*- and

Sphagnum-type bogs are usually sinks, while the *Ericaceae*, *Molinia* or *Juncus* dominated sites are often sources. However, small differences of mean wl between the sites lead to vanishingly small differences in gas fluxes. Thus, the *S. cuspidatum* site and *S. papillosum* site were not significantly different, while the *Eriophorum* site revealed a slightly lower net CO_2 uptake due to a different type of vegetation, and the *Molinia* site showed a much lower net accumulation, because of different vegetation and a much lower wl in summer.

The high variation of the annual CH_4 emissions of the sites and other studies in rewetted (mostly former peat cut sites) bogs in the temperate zone (research sites, own data unpublished, Drösler 2005, Bortoluzzi et al. 2006, Beetz et al. 2013) can be mainly explained with the variation of the mean wl ($R^2 = 0.78$, $p < 0.001$) (Fig.4.17).

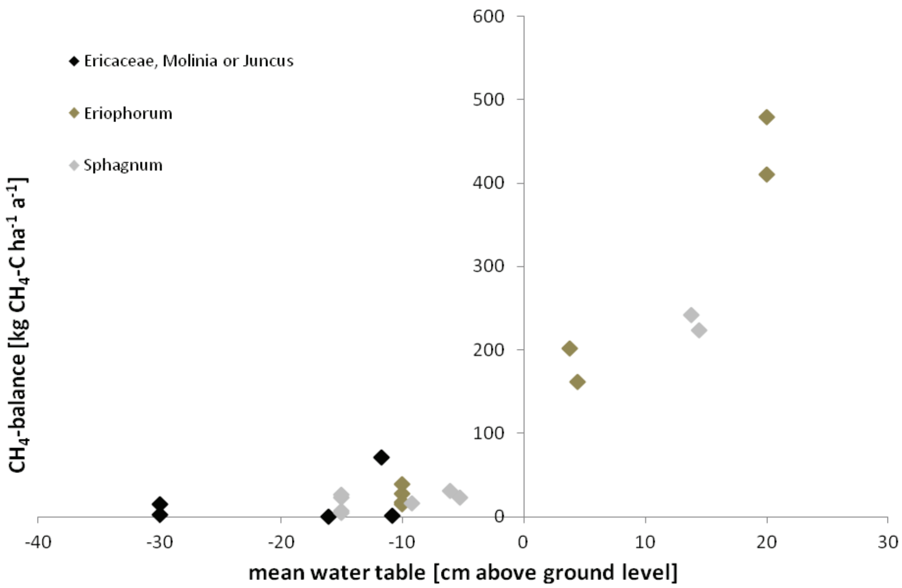

Fig. 4.17: Annual CH_4 balance versus mean water level (bogs in temp. zone: research sites, own data unpublished, Drösler 2005, Bortoluzzi et al. 2006, Beetz et al. 2013).

The relationship between CH_4 balances and mean wl was also described by Drösler (2005) and Couwenberg et al. (2011). Therefore, the *Eriophorum* site and *S. cuspidatum* site revealed significantly higher annual methane emissions than the *Molinia* site and *S. papillosum* site. The meta-analysis revealed a threshold value for the mean annual wl of about 10 cm below ground level. The *Eriophorum* (*E. vaginatum* and *E. angustifolium*) dominated rewetted sites show slightly higher CH_4 balances compared to the *Ericaceae*, *Molinia* or *Juncus* dominated sites and *Sphagnum* dominated sites with a similar averaged wl. *E. vaginatum* and *E. angustifolium* are plants with aerenchymous leafs and contribute to the methane emissions because methane is transported through the aerenchym (Joabbson et al. 1999, Joabbson &

Christensen 2001, Drösler 2005, Couwenberg et al. 2011). One *Ericaceae* dominated site showed unusually high CH_4 emissions. This site was a drained *Calluna vulgaris* heathland, which was rewetted about 10 years ago (Drösler 2005). The vegetation still consists mainly of *C. vulgaris* although the wl is too high for this type of vegetation. *C. vulgaris* is found at places with a lower wl (Poschlod 1988, Drachenfels 2011).

Highest nitrous oxide emissions occurred at the dry sites, and lowest emissions or uptake emerged at the wetter sites. The relationship between N_2O fluxes and wl is well established (Velthof et al. 1996, Langeveld et al. 1997, Flessa et al. 1998, Augustin 2003, Drösler 2005).
GWP100 balances (research sites, own data unpublished, Drösler 2005, Bortoluzzi et al. 2006, Beetz et al. 2013) in relation to mean wl shows that inundated bogs are generally GWP100 sources, due to the high methane emissions (Fig.4.18). At a mean wl between 0 and 20 cm below ground level, most rewetted bogs seem to be GWP100 sinks. At a lower mean wl an increase in GHG emissions is expected due to higher CO_2 emissions. However, changing the time perspective from 100 years to 500 years alters the relationship and mean values, because the impact of methane is decreased. In average, the bogs are GWP500 sinks. A correlation between balances and wl is not any more evident and most of the inundated bogs are GWP500 sinks.

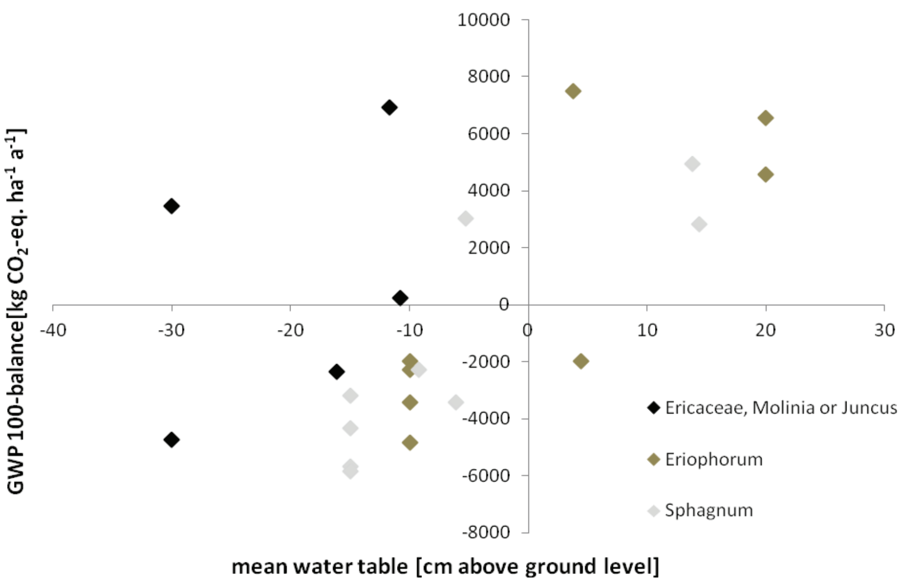

Fig. 4.18: Annual GWP100 balance versus mean water level (bogs in temp. zone: research sites, own data unpublished, Drösler 2005, Bortoluzzi et al. 2006, Beetz et al. 2013).

The results are similar to the findings of Couwenberg et al. (2011). They considered literature data of all kind of peatlands, not only rewetted and natural bogs for a meta-analysis. Mean wl and vegetation are good proxies for GHG fluxes. While the vegetation affects the gas exchange, the wl drives both, the gas exchange and the vegetation. Glatzel et al. (2006) suggest that keeping the wl close to the surface is the most important measure for the restoration of peat bogs in northwest Germany.

According to the results, recommended measures for the restoration of drained bogs are:

1) The wl should be kept below, but near the surface (approximately 10 cm below ground surface). This leads to carbon accumulation and a greenhouse mitigation effect (cooling effect).
2) Typical vegetation like *Sphagnum* and *Eriophorum* should be adapted.

4.4.4 Long term effect of rewetting on GHG emissions

Data about peatlands that were rewetted a long time ago (for centuries) are rare. Thus, there is no experience concerning the long-term effect of rewetting. Augustin (2003) and Joosten & Augustin (2006) suggest that rewetted peatlands might become a CO_2 sink and the CH_4 emissions settle down to a low level in the long-term, but it is not possible to say at what time this will happen.

The temporal development of a drained peatland after rewetting can be divided into three phases (Joosten & Augustin 2006, Augustin & Joosten 2007):

-first phase: extremely high CH_4 emissions, low net CO_2 uptake, extremely negative climate effect.

-second phase: CH_4 emissions strongly reduced, CO_2 uptake shows its maximum, slightly positive climate effect.

-third phase: CH_4 emissions low, CO_2 uptake low, similar to situation in pristine mires, neutral climate effect.

The high CH_4 emissions during the initial phase are caused by the increased peat excavation (Höll et al. 2005) or by the decomposition of young plant material (Joosten & Augustin 2006). These emissions remain probably only for a very short time high (Joosten & Augustin 2006).

The long-term effect was investigated using the data of the investigation sites and own unpublished data from a bog near Bremerhaven as well as literature data of rewetted (mostly former peat cut sites) and natural bogs in the temperate zone (Fig.4.19-4.21).

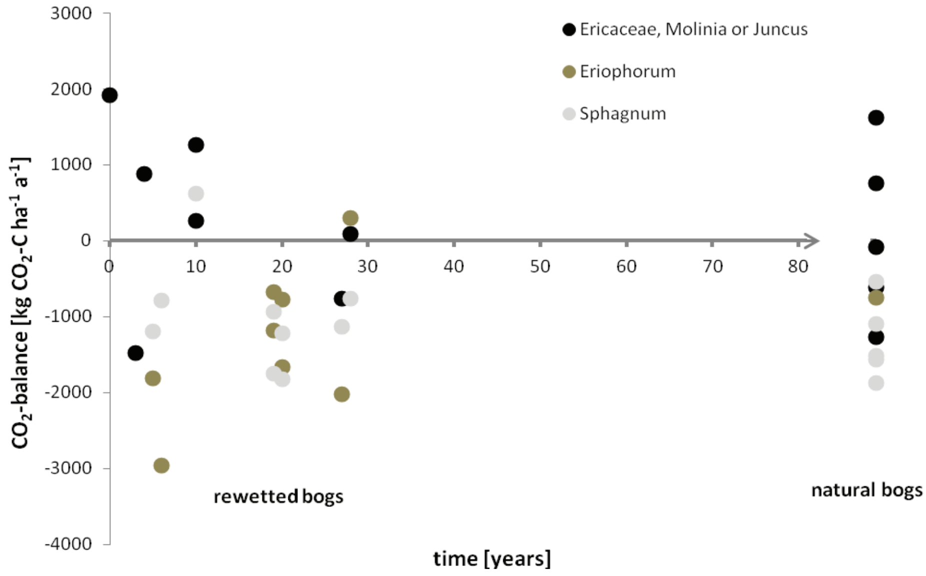

Fig. 4.19: Annual NEE balance of rewetted bogs in the temperate zone versus time. Right: Natural and near-natural bogs in the temperate zone. Data: research sites, own data unpublished, Nieveen et al. 1998, Drösler 2005, Bortoluzzi et al. 2006, Laine et al. 2006, Beetz et al. 2013.

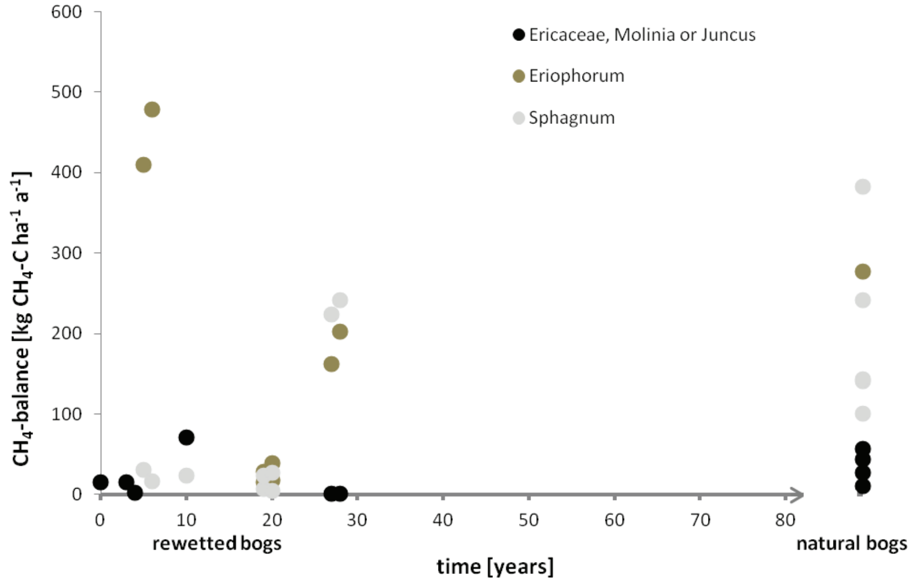

Fig. 4.20: Annual CH_4 balance of rewetted bogs in the temperate zone versus time. Right: Natural and near-natural bogs in the temperate zone. Data: research sites, own data unpublished, Drösler 2005, Bortoluzzi et al. 2006, Beetz et al. 2013.

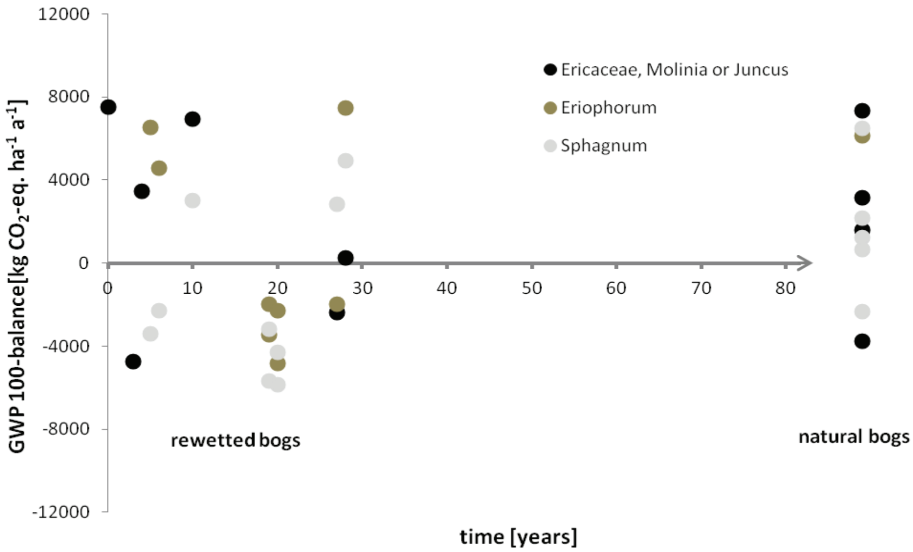

Fig. 4.21: Annual GWP100 balance of rewetted bogs in the temperate zone versus time. Right: Natural and near-natural bogs in the temperate zone. Data: research sites, own data unpublished, Drösler 2005, Bortoluzzi et al. 2006, Beetz et al. 2013.

Generally, the gas balances show a high variation. However, the trend in CO_2 balances which was described by Augustin & Joosten (2007) is visible, except in *Eriophorum*-type bogs. According to these results, the second phase starts after about 15 to 20 years.
In contrast to the findings of Augustin & Joosten (2007), the CH_4 emissions of the rewetted bogs are not higher than of the natural bogs (Fig.4.20). The differences of the CH_4 balances are probably mainly due to the different wl and not related to time.
Some of the literature sources include GWP100 balances. If no GWP100 balance was available, the GWP100 balance was calculated (in some cases data about N_2O was not available). The GWP100 balances of the rewetted bogs show no significant trend with time. In average, only rewetted *Sphagnum*-type bogs are GWP100 sinks. More data is needed to examine the long term effect of rewetting.
Natural bogs do not have lower emissions or higher accumulation rates of GHG compared to rewetted bogs.

4.4.5 Interannual variability of GHG fluxes

Annual GPP and R_{eco} are both high and of the same magnitude, consequently the annual NEE, which represents the small difference, is generally close to 0. A change in weather conditions and wl can easily convert a sink into a source and vice versa. The inter-annual fluctuation of the CO_2 balances in organic soils with years releasing net CO_2 and other years sequestering net CO_2 were observed by many authors (Tuittila et al. 1999, Lloyd 2001, Arneth et al. 2002, Roulet et al. 2007, Yli-Petays et al. 2007, Beetz et al. 2013). Natural bogs can be sources in the short term, but in average over many years sinks. Therefore, measurements should be conducted over several years.
All sites reveal higher R_{eco} in 2011, which is due to favoured weather conditions compared to 2010 (see below). At the *Eriophorum* site and *S. papillosum* site the differences of GPP between the two years is marginal, but at the *Molinia* site and *S. cuspidatum* site the measurement period of 2011 reveal higher values. However, at all sites it is the higher R_{eco} in 2011 which causes annual net CO_2 emissions at the *Molinia* site and *Eriophorum* site as well as the lower net CO_2 uptake at the *S. cuspidatum* site and *S. papillosum* site. Thus, higher GPP was not sufficient to offset higher R_{eco}.

All sites display during the periods of spring and fall a higher R_{eco} in 2011 than in 2010, because the weather was drier and warmer. The PAR was higher as well, leading to a higher

GPP. However, the effect for R_{eco} was stronger, consequently in spring and fall 2011 less CO_2 was net accumulated or more CO_2 was net released. In summer (June to Sept.), the conditions were inverse: The summer of 2011 was quite wet, the PAR was lower and it was slightly colder compared to 2010. Unexpectedly, all sites showed a higher R_{eco} in 2011. The dry conditions in 2010 might have led to a high vapour pressure deficit (VPD). This would have caused the closure of the stomata and, thus a reduced exchange of carbon dioxide (Nieveen et al. 1998). Summer-GPP at the *Eriophorum* site and the *S. papillosum* site was higher in 2010 because of higher PAR. But the *Molinia* site and the *S. cuspidatum* site revealed higher summer-GPP in 2011. At the *S. cuspidatum* site this is at least partly explainable by the drought in July 2010. The smaller GPP at the *Molinia* site in 2010 compared to 2011 is caused by the phenology of the vegetation. In 2010, the plants developed late in spring and senescence started early in late summer. As a consequence, at the *Molinia* site, *Eriophorum* site and *S. papillosum* site the summer-NEE was lower in 2011. At the *S. cuspidatum* site the net accumulation was slightly higher in 2011 because of the drought in July 2010.

In 2010, the wl was lower, but in 2011 the wl was low for a longer period. Years with low wl are expected to generate higher emissions or lower accumulation rates than years with high wl (Lafleur et al. 2003, Wilson et al. 2007). Thus, not only the average wl is important, but also the length of the period with low wl.

4.4.6 GHG exchange and global warming potential of rewetted bogs

Undisturbed mires accumulate carbon over the long term, and are therefore carbon sinks. The annual accumulation in European temperate bogs is estimated to be 350 kg ha^{-1} and the annual rising of the ground to be in the range of 0.5 to 1.5 mm (Succow & Jeschke 1990, Höper & Blankenburg 2000). The purpose of rewetting is the reestablishment of peat growing and carbon accumulation. However, rewetting a site does not lead necessarily to an accumulation of carbon (Höper & Blankenburg 2000). An appropriate method to determine the carbon balance is the NECB (Chapin et al. 2006), because it considers all carbon fluxes. If the NECB is negative, the peatland is growing and has the function as a carbon sink. All sites in this investigation revealed negative NECB in average over the two measurement years (Tab.4.11). Thus, peat growing and carbon accumulation is restored.

In general, GHG fluxes of the examination sites showed similar values compared to other studies in rewetted bogs (mostly former peat cut sites) and in natural bogs in the temperate

zone. Net CO_2 exchange and NECB alternate around 0. Mostly a small uptake occurs, but also net emissions are possible (own unpublished data, Nieveen et al. 1998, Drösler 2005, Bortoluzzi et al. 2006, Beetz et al. 2013).
The high variation of the annual CH_4 emissions between the sites are in line with the results of other studies in rewetted (mostly former peat cut sites) bogs and in natural bogs in the temperate and boreal zone (own data unpublished, Drösler 2005, Bortoluzzi et al. 2006, Yli-Petays et al. 2007, Beetz et al. 2013). Leegmoor consists of a small scale mosaic of places with different wl, hence the spatial pattern of CH_4 emissions is very heterogeneous. Methane emissions of bogs are low compared to fens, rice fields and freshwater ecosystems (Moore & Knowles 1989, Le Mer & Roger 2001, Höper et al. 2008).
The annual N_2O balances are generally low at rewetted and natural bogs as well as bogs abandoned after harvest (Martikainen et al. 1993, Kasimir-Klemedtsson et al. 1997, Byrne et al. 2004, Drösler 2005, Beetz et al. 2013).
Bogs abandoned after harvest, but not rewetted are only small CH_4 sources, however, these sites are great net CO_2 and NECB sources (Byrne et al. 2004, Drösler 2005).

Sites with a negative NECB or an annual net uptake of carbon do not necessarily show a negative GWP100 balance or a greenhouse mitigation effect (Tab.4.11). The *Eriophoru*m site and *S. cuspidatum* site have in average over the two years a small positive GWP100 balance, which means that they have a warming effect for the climate. This can be attributed to the high methane balances. Methane has a high radiative forcing, thus the emissions of this gas can compensate the uptake of carbon dioxide with the consequence that a carbon accumulating bog has a greenhouse enhancing effect (warming effect). Since the aim of rewetting is (also) the mitigation of the greenhouse effect, or at least a neutral effect, emissions of CH_4 are of great concern. In the “Leegmoor” the GWP100 balance ranged between -2,356 +/- 3,353 and 7,490 +/- 4,137 kg CO_2-eq. ha^{-1} a^{-1} (Tab.4.11). This is similar to results of Drösler (2005) and Beetz et al. (2013). The aim of a carbon accumulating bog was achieved, however, the bog has not a greenhouse mitigation effect (cooling effect), but is a small source with an averaged GWP100 balance of 19 kg CO_2-eq. ha^{-1} a^{-1}.
Changing the time frame of the GWP from 100 years to 500 years shifted the *Eriophorum* site and the *S. cuspidatum* site from being GWP sources to being GWP sinks. This was also observed in natural bogs in South Germany by Drösler (2005). Taking the 500 year time frame, the climatic impacts of the sites in the Leegmoor were very similar.

In conclusion, peat cut sites might become net carbon sinks and a growing peatland within 30 years after rewetting. However, single years might show a net loss of carbon, but in the long term a small accumulation of carbon might take place or at least a neutral balance might exist. This means that near-natural conditions are established. A high wl (above ground level) leads to the release of high amounts of methane, resulting in a net warming effect (positive GWP100 balance) instead of a cooling effect. Rewetted bogs such as Leegmoor always have a heterogeneously spatial distribution of different wl and vegetation. In addition, the wl shows inter annual variation. Hence, there might always be places with a wl which is too high and with a positive GWP100 balance due to high CH_4 emissions. On the other hand there might always be places which have a too low wl and have a positive GWP100 balance due to carbon dioxide emissions. However, the differences between the different sites in Leegmoor are not great. However, the wl should be kept a few centimetres below ground surface in the biggest part of the area and inundation should be avoided, if possible.

4.4.7 GHG exchange and global warming potential of Sphagnum farming

The *S. papillosum* site shows highest accumulation of carbon, compared to the other examination sites (Tab.4.8: -987 +/- 201 kg CO_2-C ha^{-1} a^{-1} in average over the two years). The *S. papillosum* site and *S. cuspidatum* site have a similar NEE, but the net carbon accumulation (NECB) at the *S. papillosum* site is higher due to lower methane emissions. The main difference of the site factors between the *S. papillosum* site and *S. cuspidatum* site are the wl dynamics (Fig.4.1). The wl at the *S. papillosum* site is kept quite constant at a level which is unfavourable for large CH_4 emissions.

At the *S. papillosum* site the carbon stock of the biomass grown on the old peat layers revealed that in average -1,023 +/- 82 kg C ha^{-1} a^{-1} was accumulated. This is similar to the annual NECB. The good fit of the values confirmed the results of the gas flux measurements and modelling. The roots of vascular plants in the peat layer are not included in the analyzed biomass. However, the proportion of vascular plants is low (about 15 % of whole biomass).

The *S. papillosum* site was a GWP100 sink in both examination years and was with -2,838 +/- 738 kg CO_2-eq. ha^{-1} a^{-1} the strongest sink of GHG in average over the two years, compared to Leegmoor (Tab.4.11). The annual averaged wl is about 6 to 9 cm below ground surface, which is quite unfavourable for peat mineralization, but obviously deep enough for oxidation of the most part of produced methane. Drösler (2005) determined a GWP100 balance at a rewetted *Sphagnum* lawn with a similar annual averaged wl in Bavaria of 3,019 kg CO_2-eq. ha^{-1} a^{-1}. CH_4 exchange is similar. The high discrepancy is due to net emissions of CO_2 at the *Sphagnum* lawn. The reason for this might be that the wl drops several times to about 20 cm below ground surface during summer, whereas the wl at the *S. papillosum* site was kept more constant. However, NEE at the *Sphagnum* lawn has an uncertainty of more than 100 % and could be therefore a net sink of CO_2 (Drösler, 2005). In that case, the GWP100 balances would be quite similar.

At the *S. papillosum* site no biomass was harvested up to now. If the carbon which will be exported through harvest is encountered for in the balances, NECB and GWP100 balance would be near neutral, because almost the whole biomass would be removed. In contrast, conventional commercial uses of bogs like cropland, grassland or peat mining cause high emissions of GHG.

This is the first examination of the GHG exchange of bogs used for *Sphagnum* farming. The results indicate that keeping the wl constant all year round and just a few centimetres below ground level leads to a neutral GWP balance. Providing this, a conversion from conventional farming with deep drainage to *Sphagnum* farming would lead to a great reduction of the climate impact.

4.5 Conclusions

GHG fluxes in rewetted bogs are mainly driven by temperature, PAR, water level and type of vegetation. 30 years after rewetting, bogs might become net carbon sinks and, therefore peat accumulating sites comparable to natural bogs. Highest carbon accumulation amounted to -1,838 +/- 1,269 kg CO_2-C ha^{-1} a^{-1}. Rewetted and natural bogs may be net carbon sources in single years due to inter annual variation of weather conditions, however, in the long term, they function as sinks. The GWP100 balance is very likely positive because of methane emissions under inundated conditions (up to 242 +/- 50 kg CH_4-C ha^{-1} a^{-1}) and the bog has therefore a small warming impact on climate. In order to promote carbon accumulation, the water level should be high. However, in order to achieve a climate cooling effect inundation should be avoided.

This study indicates that Sphagnum farming has a near neutral climate impact and is therefore a climate-friendly alternative land use.

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5 Climate relevance of peat mining in Northern Germany

Abstract

Substantial emissions of greenhouse gases are caused by peat extraction. Data on emission factors and global warming potentials of peat extraction sites in the temperate region to determine the climatic relevance are still scarce.

In this study, emissions of carbon dioxide, methane and nitrous oxide as well as net ecosystem carbon balances (NECB) and global warming potentials (GWP) of two peat extraction sites (old site and young site) in Northern Germany were achieved. Gas exchange was measured approx. monthly year-round with a closed chamber technique from October 2009 until December 2011. CO_2 exchange was modelled in high resolution with site parameters. Measured and modelled values fit very well together (R^2 = 0.85 and 0.91).

The young and the old peat extraction site revealed in average carbon dioxide emissions of 1,353 +/- 86 and 1,194 +/- 3 kg CO_2-C ha^{-1} a^{-1}, respectively. CO_2 emissions increased with increasing temperatures and increasing water level depth and reached a maximum at a soil temperature of 20 °C and a water level depth of 75 cm below ground surface. Methane and nitrous oxide fluxes were generally very low. In the first measurement year, the young site was a CH_4 sink. Highest emissions of N_2O occurred at a soil temperature of 15 °C and a water filled pore space of 60 %. Exported carbon through peat harvest amounted to 60,000 to 70,000 kg C ha^{-1} a^{-1}. About 2 % of the NECB was carbon released in the peat extraction site, while 98 % was carbon exported with the harvested peat. GWP100 balances at the young and the old site added up to 5,690 +/- 317 and 4,545 +/- 15 kg CO_2-eq. ha^{-1} a^{-1}, in average respectively. This study shows that temperate peat extraction sites do not have necessarily a higher global warming potential and carbon release than boreal sites. A short extraction period and a rapid restoration of abandoned cut-over sites lead to a lower climatic impact of harvested peat.

5.1 Introduction

Peatlands in Europe have been under peat extraction for millennia (Becker-Platen 1996, Chapman et al. 2003, Holmgren et al. 2008). The amount of harvested peat has increased with time. Harvested peat is used for many commercial purposes. In the past, domestic heating and energy generation were in the foreground, while today peat is utilized predominantly in horticulture and agriculture (Becker-Platen 1996, Chapman et al. 2003, Cleary et al. 2005, Caspers & Schmatzler 2009).

In Germany, almost the whole peatland area has been drained for commercial utilization. This applies also to Lower Saxony. The original peatland area in Germany amounted to 16,250 km², in 2002 the peatland covered an area of 13,000 km², and the mire area amounted merely to a very small area of 100 km² (Joosten & Clarke 2002).
In Lower Saxony, where almost all peat mining areas in Germany are located, about 12,000 ha are under peat extraction, which is about 5 % of the bog area (Caspers & Schmatzler 2009, Schmatzler 2012). During the last few decades, approximately 8 million m³ of peat per year has been extracted in Lower Saxony (Caspers & Schmatzler 2009). An extensive peat extraction area in Lower Saxony is the “Esterweger Dose”, which is part of the “Nordhümmlinger Moore”.

Peat cutting causes the release of substantial amounts of greenhouse gases, mainly carbon dioxide (Sundh et al. 2000, Höper 2007, Holmgren et al. 2008). The main loss of stored carbon comes from the use of the harvested peat itself (Höper 2007). If the peat is used for domestic heating or energy generation emissions are similar to that of burning fossil fuels. The use as a substrate for plants leads to slower mineralization (Joosten & Clarke 2002). However, Höper (2007) suggests that within 10 years, the peat is probably almost completely mineralized. Due to peat mineralization caused by the lowering of the water level, there are also emissions from the extraction site itself.

Measurements of the exchange of GHG in peat extraction sites have been done in northern peatlands, for example Finland and Sweden (Maljanen et al. 2010). According to Couwenberg (2011), there are no direct measurements from active peat extraction areas in the temperate zone. Emissions from temperate peat cut areas exceed probably those from boreal sites (Couwenberg 2011). Determination of emission factors of peat extraction sites are necessary to deliver the sectors four (agriculture) and five (Land Use, Land Use Change and forestry) of the National Inventory Report for the German greenhouse gas inventory.

The aim of this study is to determine emissions of CO_2, CH_4 and N_2O as well as net ecosystem carbon balances (NECB) and GWP balances of peat extraction sites in Northern Germany.
The main questions of this research are: a) What is the amount of the GHG emissions of different peat extraction sites?, b) Are the emissions in the temperate zone higher than in the boreal zone?, c) What can be said about the GHG emissions from the peat extraction site itself in relation to all emissions through peat cutting? and d) which factors drive the gas fluxes?

5.2 Methods

5.2.1 Site discription

The research sites are located in “Westermoor”, a part of a huge bog complex, “Nordhümmlinger Moore”. Today, “Westermoor” is a peat mining area. The description of the area is provided in chapter four.
The investigation was conducted at two peat extraction sites, owned by Torfwerk Moorkultur Ramsloh, Saterland. The young site was in agricultural use as grassland until 2008. Since then, peat has been extracted. Immediately adjacent to the south the old site is located, a formerly agricultural area and a peat cutting area since 2000. The sites are classified as Sapric Histosol (German soil classification: Norm-Erdhochmoor (KHn), AG Boden 2005) and are deeply drained through deep drainage ditches. The peat thickness of the young site is 240 cm, underneath resides medium sandy fine sand. The peat thickness of the old site is 195 cm.
During the summer months, rotary tillage takes place weekly or biweekly, and the top soil layer of the peat is removed several times per year with caterpillar vehicles and heaped up. Each year a 10 cm thick layer is harvested (Koch, personal communication 2012). In the winter, during the frost period, grubbing takes place.

5.2.2 Measurements of site factors

Soil parameters: The methods for soil identification as well as determination of true density (s), pore volume (PV), gravimetric water content and water filled pore space (wfps) are described in chapter two.

The dry bulk density (ρt) was calculated using the formula in chapter two. At each site ten soil samples at a depth of 0 to 10 and 10 to 20 cm, respectively were taken with sampling rings (250 ml) in March 2010 (representing winter) and June 2011 (representing summer). The soil samples were heated to 105 °C in the drying oven to determine the dry mass (VDLUFA 1991). From April until September, the summer values of the dry bulk density were taken, and from October until March, the winter values were used for the calculation.

With each CH_4 und N_2O flux measurement, ten soil samples were taken with a boring rod for mineralised nitrogen (N_{min}-boring rod) at 0-20 cm depth, and subsequently mixed. Analysis of nitrate and ammonium content was carried out in the laboratory of "Landwirtschaftliches Labor Dr. Janssen, Gillersheim" with the Continuous-Flow-analyser. The compounds were extracted with a calcium chloride $CaCl_2$ solution (VDLUFA 1991).

Water level: The sites were equipped with tubes perforated in the peat body, close to the collars. The bottom end was embedded in the underlaying sand. The upper end was about 50 cm below ground level, in order to allow soil cultivation. Water levels (wl) were continuously recorded through Solinst® Levelogger® Gold Model 3001. For verification of the automatically measured wl, manual measurements with an electric contact gauge were carried out.

In intervals of every three months samples were taken from the ground water with a bailer and analysed for pH and electrical conductivity (Lf) with pH-electrode SenTix 950 (WTW) and standard conductivity measuring cell TetraCon 925 (WTW), respectively.

Meteorological parameters: Meteorological parameters such as temperatures (air temp., soil temp. at 2, 5 and 10 cm depth), air pressure and precipitation were measured and saved half hourly at the meteorological station about 1.5 km to the west. The meteorological station was located in a rewetted area, thus, in addition, soil temperatures were measured and saved half hourly directly at the study plots in bare peat soil.

Height measurement: Height measurements of the ground surfaces and the water table wells were carried out with the levelling instrument Wild NA2 every few months. The reference point was the concrete base of a wind mill.

5.2.3 Measurements and modeling of carbon dioxide exchange

For determination of CO_2 flux rates between the soil and the atmosphere a temperature controlled closed portable chamber technique was applied (Drösler 2005, Beetz et al. 2013). Ecosystem respiration (R_{eco}) was measured with opaque PVC-chambers (0.78 · 0.78 m, height: 0.5 m). Since no vegetation existed in the measurement collars, the gross primary production (GPP) is 0, and the R_{eco} equates to the net ecosystem exchange (NEE). Fluxes from the soil to the atmosphere were provided with a positive sign (sign convention following IPCC 2007).

The bottom side has a closed cell rubber tube to ensure hermetic closure during the measurement. The chambers are equipped with a thermometer, a vent outlet with a rubber tube (length: 220 cm, inner diameter: 2 mm) and a pair of turnable (3 V) fans, and is connected via a tube (length: 750 cm, inner diameter: 5 mm) with a portable CO_2 gas analyser (Licor LI-820) (measures with non-dispersive infrared radiation; measurement of gas concentration every 5 sec.).

The day before measurements took place, three collars (3 mm strong PVC) were inserted at each research plot, on which the chambers were placed airtightly and mobile boardwalks were installed in order to ensure minimal disturbance to the soil. After the measurements, the equipment was removed. At each measurement campaign the same location was chosen. Parallel to the gas exchange measurements, temperatures (air temperature, soil temperature at 2, 5 and 10 cm depth) and air pressure were measured. Generally, measurement campaigns were held in intervals every four weeks, beginning in September 2009 and ending in December 2011.

To calculate flux rates the change of gas-concentration over time inside the chamber was determined. To ensure the quality and representativeness of the slope of gas-concentration the following parameters were tested: 1) linearity of the slope, 2) difference of the slope from 0, and 3) variability of the slopes. For the formula to calculate the gas flux rates refer to chapter two.

The ecosystem respiration (R_{eco}) was modelled with an exponential regression equation against temperature (see chapter two). The temperature (air temp., soil temp. at 2 cm depth or soil temp. at 5 cm depth) with the best fit was chosen.

Fitting of the parameters E_0, R_{ref}, GP_{max} and α was done using Microsoft Excel® Solver. Half-hourly flux rates between two measurement campaigns were interpolated linearly using the formula in chapter two. R_{eco} and NEE were calculated using the model parameters of both measurement campaigns n and n+1, and the two flux rates for each half-hourly time step were weighted and added together.

Finally, monthly and annual balances were calculated.

5.2.4 Measurements of methane and nitrous oxide exchange

A description of the determination of the CH_4 and N_2O exchange is performed in chapter two. The samples were analyzed in the gas chromatograph "Perkin Elmer Auto System". A FID-Detector identified CH_4, while an ECD-Detector was used to detect N_2O.

Measurement campaigns were held in intervals every two weeks, beginning in September 2009 and end in December 2011.

5.2.5 Calculation of exported carbon

To quantify the carbon which was exported yearly through the harvest of peat, the carbon-content of the upper 10 cm peat layer was calculated with the following equation:

$$Corgexp = \rho t \cdot Corg \cdot 1000$$

Corgexp= exported organic carbon (g m^{-2})

ρ = dry bulk density in summer (g cm^{-3})

Corg = organic carbon (%/DM)

5.2.6 Net ecosystem carbon balance and global warming potential

To obtain complete carbon balances of the examination sites, the net ecosystem carbon balance (NECB) was calculated (Chapin et al. 2006, see ch.2). DOC was estimated to 26 kg C $ha^{-1}a^{-1}$ according to Moore (1987). Values of DIC, CO and VOC are assumed to be negligible and not considered.

The global warming potential (GWP) was calculated according to IPCC (2007) (see ch.2). In general, the global warming potential over a time span of 100 years is taken (Drösler 2005). Positive values represent efflux of CO_2-equivalents into the atmosphere.

5.2.7 Statistical analyses

Unless otherwise stated, Microsoft® Excel was used.

Average values are arithmetic means +/- standard error.

Error analysis of CO_2 gas fluxes was conducted by calculating the standard error for each calibrated regression model. Analogous to the interpolation of the half-hourly gas fluxes, standard errors were interpolated. The monthly and annual standard errors were calculated using appropriate error propagation equation. The standard errors of the means of the exported carbon through harvest were included.

For CH_4 and N_2O the standard error of the replicate chamber measurements of each measurement campaign were calculated and interpolated between the measurement campaigns analogous to the interpolation of the fluxes. The annual standard errors were calculated using appropriate error propagation equations.

Standard errors of DOC and of the carbon which was exported through the harvest of peat cannot be calculated, because only one estimated value exists, respectively.

Significant linearity of slope of the changes in gas concentration was tested following Huber (1984). To test if slopes are significantly different from 0, a t-test was performed (Neter et al. 1996). The variability of the slopes was determined by calculating the standard deviation of the residuals (s_{yx}).

Bivariate correlation and regression analyses was conducted with coefficient of determination (quadrate of Pearson correlation coefficient = R^2) and tested for significance with t-test. To perform multiple correlation and regression analyses TableCurve 3D® v4.0 was used. R^2 and adjusted R^2 were calculated. For analysis of CO_2 fluxes, the mean of the measured values (fluxes, temperatures, wl) of the measurement campaign was taken.

Significant ($p < 0.05$) differences between the annual gas exchange balances were tested with the Permutation test “diffmean” (1000 permutations) using R script 0.97.237 (version 2.15.2) (simba package).

5.3 Results

5.3.1 Soil parameters and water table

The soil properties of the young and the old site were similar (Tab.5.1 & Tab.5.2). The upper horizon was humified bog peat (hHv), underlain by temporarily water filled (hHw) and always water filled (reduced) bog peat (hHr) according to AG Boden (2005). Underneath resides a reduced semiterrestric gley horizon (Gr). However, the hHr layers at the young site were deeper than at the old site. The peat substrate was *Sphagnum* peat (Hhs). The second horizon of the old site had a higher decay degree and a lower pH than the young site. There was no $CaCO_3$. Compared to a natural bog, the pH values at both sites were rather high. C and N content of the dry substance were above 50 and 1 %, respectively.

Tab. 5.1: Soil properties of the soil horizons at the young and the old site.

a) young site

depth cm	peat substrate [a]	decay degree [b]	soil horizon [a]	substrate type [a]	pH_{CaCl2}	Corg %/TS	N %/TS	C %/TS	Corg:N
0-10	Hhs	4	hHv	og-Hh	3.8	53.9	1.11	55.3	48.7
10-30	Hhs	5	hHw	og-Hh	4.2	53.3	1.00	55.3	53.3
30-90	Hhs	9	hHr1	og-Hh	4.0	55.0	1.04	57.3	52.9
90-200	Hhs	9	hHr2	og-Hh					
200-240	Hha	8	hHr3	og-Hh					
240-260	fSms		Gr	fg-ss					

b) old site

depth cm	peat substrate [a]	decay degree [b]	soil horizon [a]	substrate type [a]	pH_{CaCl2}	Corg %/TS	N %/TS	C %/TS	Corg:N
0-10	Hhs	3-4	hHv	og-Hh	3.9	55.4	1.08	56.9	51.1
10-25	Hhs	9	hHw	og-Hh	4.1	57.0	1.19	59.1	47.9
25-45	Hhs	9	hHr1	og-Hh	4.2	58.3	1.17	59.6	50.0
45-160	Hhs	9	hHr2	og-Hh	4.2	58.1	1.12	59.9	51.8
160-195	Hha	7-8	hHr3	og-Hh					
195-205	fSms		Gr	fg-ss					

[a] According to AG Boden (2005), [b] According to von Post-scale

At both sites nitrate content was similar with 3.1 kg NO_3^--N ha^{-1}. Ammonium content was slightly higher at the old site (34.4 kg NH_4^+-N ha^{-1}) than at the young site (27.2 kg NH_4^+-N ha^{-1}). Pore volume and dry bulk density were similar at the two sites. During the cold period, the pore volume was higher and the dry bulk density was lower, compared to the warm period.

Tab. 5.2: Soil properties of the young and the old site. Depth: 0-20 cm.

site	Pore volume (summer)	Pore volume (winter)	dry bulk density (summer)	dry bulk density (winter)	True density	NO_3-N	NH_4-N
	%	%	g cm^{-3}	g cm^{-3}	g cm^{-3}	kg ha^{-1}	kg ha^{-1}
young	91.0	92.9	0.13	0.10	1.48	3.1	27.2
old	92.5	93.1	0.11	0.10	1.46	3.1	34.4

The annual course of the wfps was similar at both sites (Fig.5.1). A seasonal pattern was not evident. The values ranged between 9 and 91 %, in average 45.4 and 43.8 % at the young and the old site, respectively, in 2010, and 60.1 and 53.4 % at the young and the old site, respectively, in 2011.

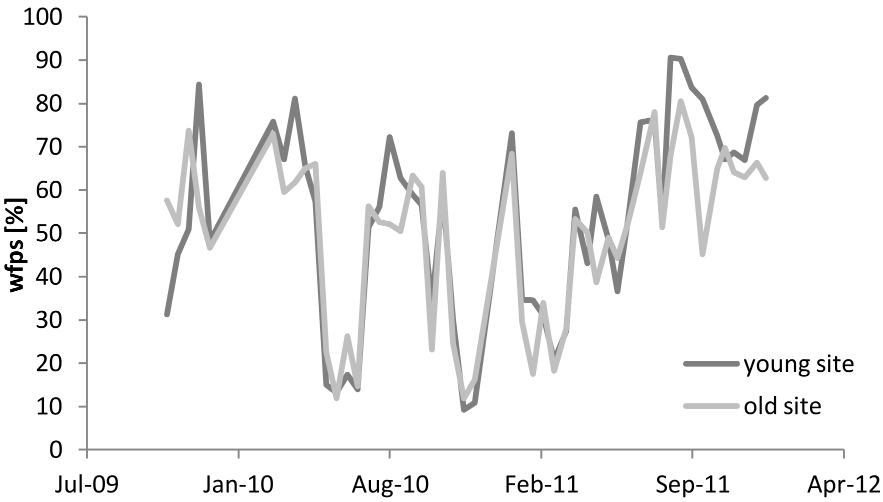


Fig. 5.1: Annual course of wfps [%] at the young and the old site.

The diver of the young site was not in operation until 10.08.2010, because of a defect. The data could be reconstructed with the aid of the stored data of the young site and the manually measured wl of the young site: The annual courses of the wl from August 2010 until December 2011 show a similar pattern, but the values of the young site were shifted closer to the ground surface (Fig.5.2). A regression of the values of the young site against the values of the old site revealed a regression equation of

$wl_{young\ site} = 0.7144 \cdot wl_{old\ site} + 2.006$

With this equation ($R^2 = 0.57$) it was possible to model the missing values and fill the gap from September 2009 until August 2010. A validation with the manually measured wl was done and confirmed an appropriate fit.

There was a clear seasonal pattern, which was more pronounced in 2010 (Fig.5.2). However, in winter the wl fluctuate strongly and can drop several decimetres below surface.

The mean wl of the young and the old site were -34.6 and -51.1 in 2010, and -34.7 and -50.3 in 2011, respectively. The summer mean wl (May to Oct.) of the young and the old site were -45.2 and -67.5 in 2010, and -37.4 and -54.5 cm in 2011, respectively. On average, the two measurement years did not differ. In 2011, the conditions in the summer were wetter.

The pH of the ground water was on average 4.6 at the young site and 4.8 at the old site. The electrical conductivity (Lf) was higher at the young site with 175 S m^{-1} compared to the old site with 145 S m^{-1}.

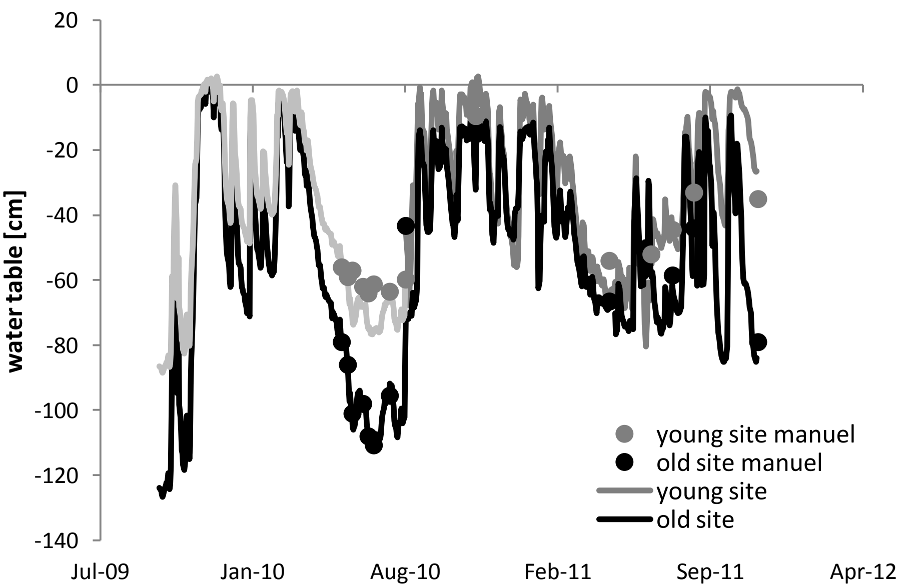


Fig. 5.2: Annual course of water level (cm above ground surface) at the young and the old site.

5.3.2 Weather

The annual precipitation was on average 623 and 712 mm in 2010 and 2011, respectively. Average annual air temperature was 8.4 and 10.2 °C in 2010 and 2011, respectively. The 30 year average (1961-1990) of the area amounts to 795 mm per year and 8.6 °C (Eggelsmann & Blankenburg 1990).

In 2011, spring and autumn were very dry, compared to 2010, while during the summer precipitation in 2011 was higher (Fig.5.3). From March until April 2011 and from September until November 2011, precipitation was 26 and 125 mm, respectively. In 2010, the precipitation was 69 and 193 mm, respectively. From May until August 2011 precipitation was 263 mm, while in 2010 precipitation was 213 mm. In January, February and December 2010 the monthly mean of air temperature dropped below 0 °C. The months January, February, April, May and December were much warmer in 2011 compared to 2010 (Fig.5.3). In 2009, the month November was exceptionally warm. In contrast, the month July was very warm in 2010.

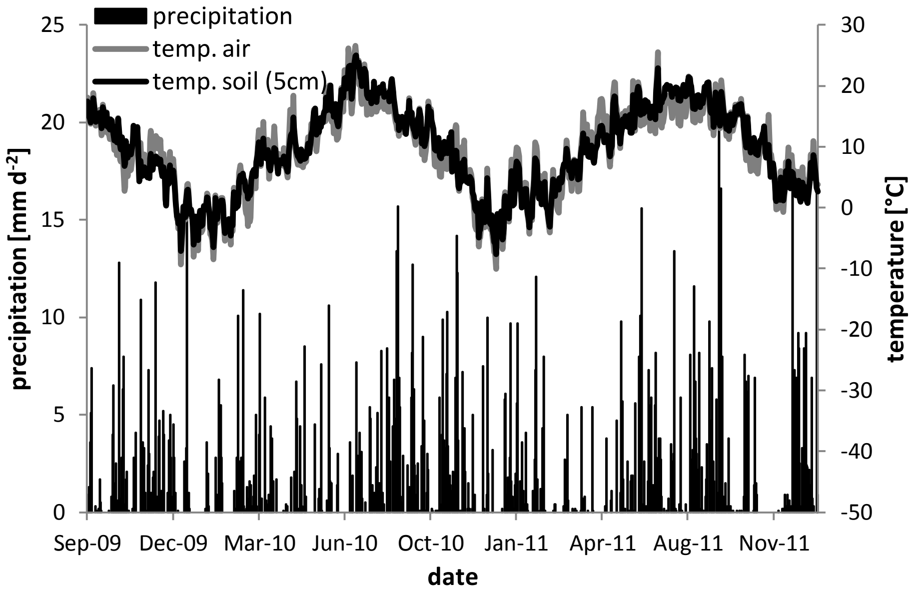


Fig. 5.3: Annual course of temperatures (°C) and precipitation (mm d^{-1}) at the young and the old site.

5.3.3 Exported carbon through peat harvest

On average, a peat-layer of about 10 cm is removed each year for harvesting (Koch, personal communication 2012). This corresponds to 70.2 and 60.5 t C ha^{-1} a^{-1} at the young and the old site, respectively. The harvested peat will be sold as culture substrate, thus the stored carbon will be released as carbon dioxide into the atmosphere during the following years. Therefore, this carbon is included in the net ecosystem carbon balance (NECB).

5.3.4 Ground level elevation

In summer, the ground surfaces declined at both sites (Fig.5.4). In winter, the ground surfaces remained constant or rose slightly. From 29.09.2009 until 15.11.2011, the young site showed a decline of more than 20 cm, while at the old site the decline was smaller (less than 20 cm). The heights of the wl tubes remained constant, proving firm anchorage in the ground. The position of the wl tubes of the young site was changed in summer 2011 which is shown in figure 5.4.

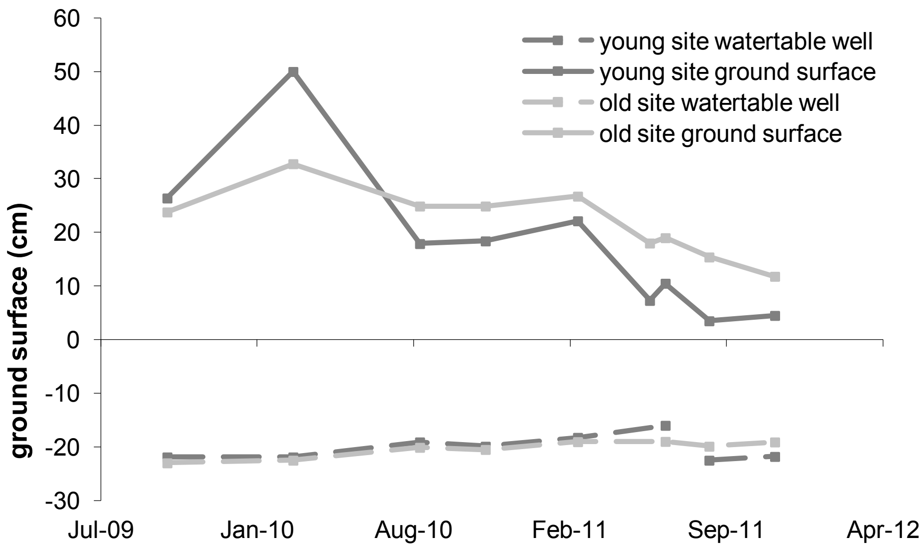


Fig. 5.4: Elevation of the ground surface and watertable wells in relation to the concrete base of a wind mill (reference point) in cm. In summer 2011, the position of the watertable well of the young site was changed.

5.3.5 Carbon dioxide

5.3.5.1 Evaluation of methodology

During carbon dioxide measurements, significant linearity ($p < 0.05$) of the slope for gas flux was usually assured. In very few cases in winter, the slope was not significantly different from 0 and, thus, was set to 0. This means that (statistically) no gas exchange occurred.

The regressions between measured and modelled flux rates for R_{eco} of each measurement campaign at the young and the old site were in most cases significant ($p < 0.1$; Tab.5.3). On 14.12.10, the regressions were not significant at both sites, thus E_0 was set to 0 and R_{ref} was replaced by the mean of the measured values.

At the young site the regressions between measured and modelled flux rates were also not significant in some other cases: 26.05.2010, 08.03.2011, 12.04.2011, 04.05.2011, 08.06.2011 and 23.08.2011. In order to get significant regressions, pooling of two measurement campaigns were carried out. The measurement campaigns of the 29.09.2009, 27.10.2009 and 24.11.2009 were also pooled, because the individual regressions were not satisfactory.

The model parameters (E_0 and R_{ref}) of the young and the old site were of the same range (Tab.5.3). E_0 was slightly higher at the old site, while R_{ref} was slightly higher at the young site. A seasonal pattern of E_0 and R_{ref} was not visible.

Tab. 5.3: Parameters for the R_{eco} models of the young and the old site: E_0: Activation energy like parameter [µmol CO_2-C $m^{-2}s^{-1}$], R_{ref}: Respiration at the reference temperature [µmol CO_2-C $m^{-2}s^{-1}$], R²: Coefficient of determination (Pearson) between modelled and measured values. S.e.: Standard error of the model [µmol CO_2-C $m^{-2}s^{-1}$], n: Number of samples, temp: Best fit temperature for R_{eco} model [air temp. or soil temp. in cm below ground surface]. Maximum and minimum values are printed in bold. Eventually measurement campaigns were pooled together. 14.12.10: No significant correlation between measured and modelled values. E_0 was set to 0.

	young site						old site					
date	E_0	R_{ref}	R²	s.e.	n	temp	E_0	R_{ref}	R²	s.e.	n	temp
29.09.09							180.3	0.31	0.57****	0.02	18	soil2
27.10.09	**521.9**	0.22	0.73****	0.09	47	soil2	622.8	0.09	0.55****	0.02	18	soil2
24.11.09							462.1	0.13	0.30**	0.02	15	soil2
02.03.10	253.4	0.21	0.31**	0.02	14	soil2	357.8	0.23	0.29**	0.01	15	soil2
30.03.10	366.2	0.17	0.68****	0.07	15	air	398.4	0.29	0.41***	0.07	15	soil5
20.04.10	110.0	0.43	0.31**	0.09	18	air	296.6	0.43	0.18*	0.07	18	soil5
26.05.10	255.9	0.51	0.50****	0.19	36	soil5	**36.7**	**0.59**	0.22*	0.05	16	soil5
22.06.10							183.3	0.38	0.40***	0.10	17	soil5
20.07.10	221.5	0.44	0.36**	0.17	17	soil5	319.7	0.27	0.46***	0.13	18	soil5
17.08.10	**88.5**	0.57	0.32**	0.09	13	air	289.3	0.31	0.78****	0.08	15	soil2
14.09.10	247.0	0.32	0.45***	0.05	15	soil2	652.2	0.09	0.51***	0.06	15	soil2
12.10.10	94.37	0.4	0.34**	0.1	12	air	147.4	0.34	0.71***	0.05	12	air
10.11.10	296.4	0.23	0.37**	0.01	12	soil5	437.2	0.23	0.45**	0.01	11	soil2
14.12.10	0.0	**0.01**	n.s.	0.01	24	air	0.0	**0.02**	n.s.	0.00	12	air
08.02.11	121.1	0.22	0.36**	0.04	12	air	296.1	0.28	0.37**	0.04	12	soil2
08.03.11	319.9	0.37	0.69****	0.10	27	soil5	307.3	0.24	0.34**	0.03	12	soil2
12.04.11							354.0	0.32	0.30**	0.03	14	soil5
04.05.11	140.3	0.33	0.17**	0.11	26	soil5	189.9	0.46	0.40**	0.03	15	soil5
08.06.11							184.0	0.39	0.46**	0.01	12	soil5
28.06.11	286.4	0.15	0.49***	0.06	18	soil5	231.0	0.24	0.30**	0.16	18	soil2
26.07.11	294.7	0.3	0.55****	0.1	30	soil2	450.2	0.18	0.54***	0.06	15	soil5
23.08.11							417.1	0.19	0.27**	0.1	15	soil5
20.09.11	216.2	0.29	0.86****	0.03	15	air	223.4	0.27	0.87****	0.03	15	soil2
19.10.11	459.5	0.22	0.79****	0.03	12	soil2	230.1	0.21	0.33*	0.02	12	soil5
15.11.11	405.3	**0.58**	0.73**	0.03	11	air	274.4	0.36	0.73****	0.01	12	air
13.12.11	372.1	0.19	0.37**	0.02	12	air	**853.2**	0.26	0.59***	0.01	12	soil5

* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$; **** $p < 0.001$

The regression between all modelled and measured values for the R_{eco} were at both sites significant ($p < 0.0001$) and followed almost the 1:1 line (Fig.5.5). At the young site the coefficient of determination was $R^2 = 0.85$, at the old site $R^2 = 0.91$. Standard errors were 0.10 and 0.06 µmol CO_2-C m^{-2} s^{-1}, respectively.

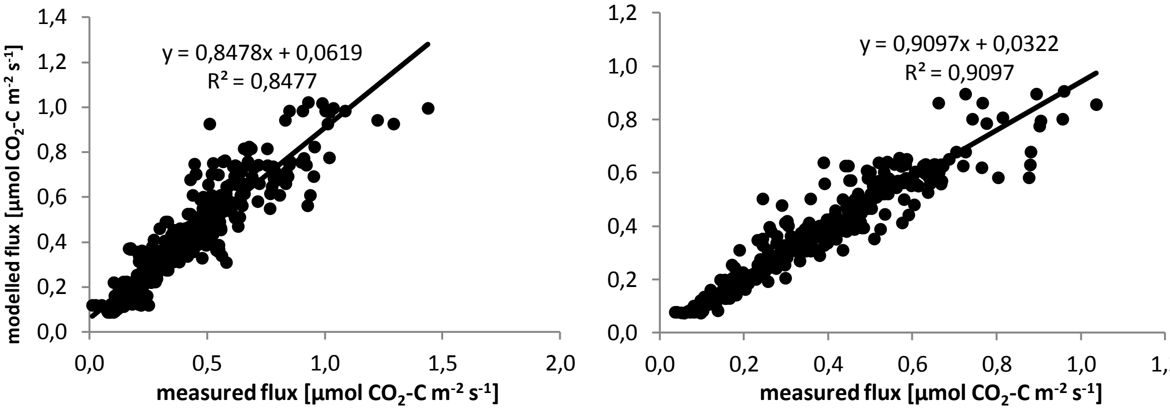


Fig. 5.5: Measured CO_2-C fluxes versus modeled CO_2-C fluxes (µmol CO_2-C m^{-2} s^{-1}) at the young (left) and the old site (right). Regression equation and coefficient of determination (R^2).

5.3.5.2 Ecosystem respiration

Both sites showed a clear seasonal pattern (Fig.5.6 & Fig.5.7). Highest emissions occurred in July and lowest in January and December. In July 2010, the young site emitted 292 +/- 44.8 kg CO_2-C ha^{-1}, and the old site emitted 228 +/- 33.9 kg CO_2-C ha^{-1}. During winter (Dec. – Febr.), monthly fluxes remained below 45 kg CO_2-C ha^{-1}. From March until May the flux rates increased strongly, and from September the flux rates decreased sharply.

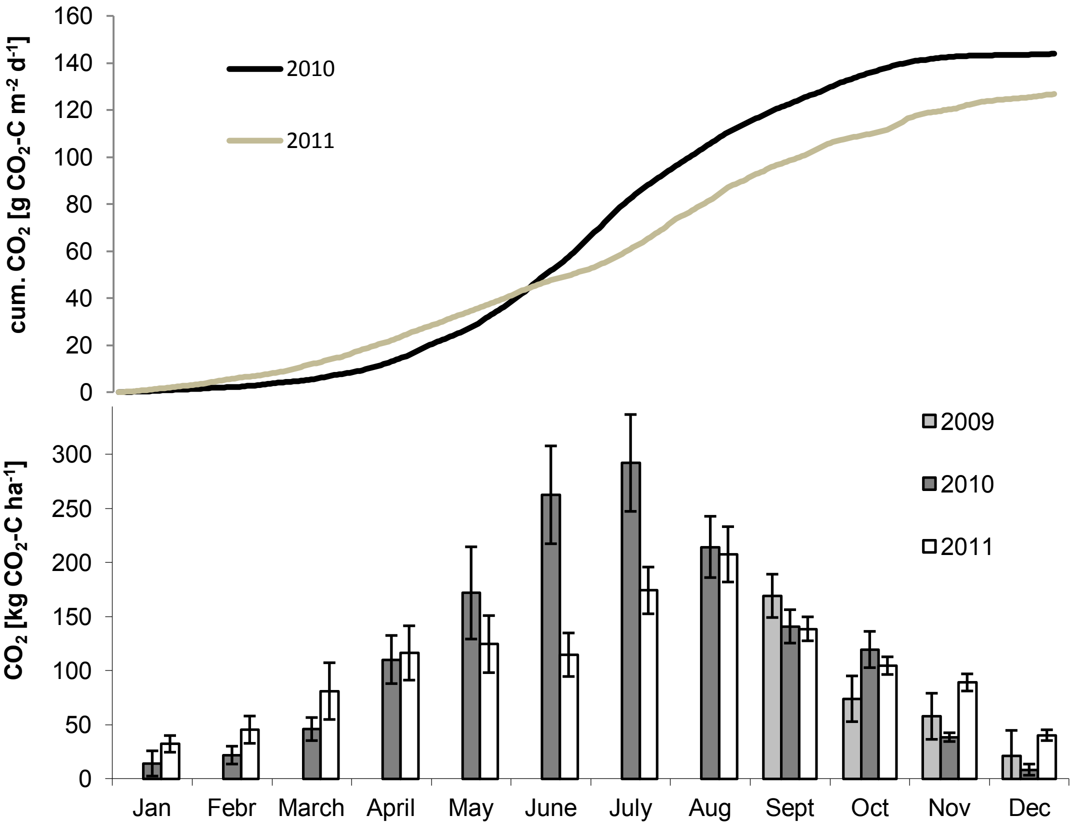


Fig. 5.6: Cumulated CO_2 fluxes (R_{eco}) at the young site. Monthly cumulated CO_2 fluxes (R_{eco}) of the young site. Note: 2009 only from Sept to Dec. Error bars are standard errors.

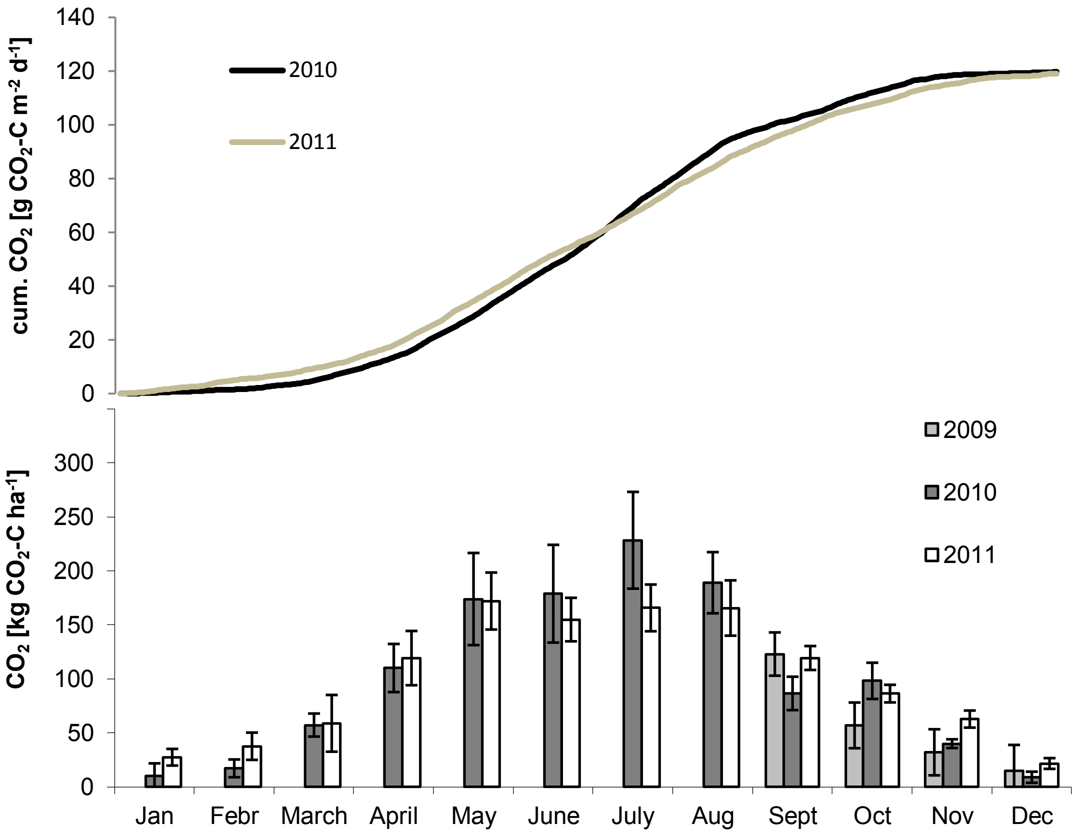


Fig. 5.7: Cumulated CO_2 fluxes (R_{eco}) at the old site. Monthly cumulated CO_2 fluxes (R_{eco}) of the old site. Note: 2009 only from Sept to Dec. Error bars are standard errors.

The monthly balances were in the same range at the young site as at the old site. However, in general the values differed significantly with few exceptions (April 2010, May 2010, Nov. 2010, April 2011 and July 2011).

In 2010, the emissions during the summer months were higher than in 2011 at both sites, whereas winter emissions were higher in 2011, compared to 2010.

At the old site the annual patterns of the two measurement years were very similar (Fig.5.6). From March until May, the monthly balances were not significantly different. The remaining months revealed significantly different monthly balances between the two years, but the differences were not great, and the cumulated daily R_{eco} of 2010 and 2011 were almost identical (Fig.5.6). At the young site a greater variability between the measurement years was observed (Fig.5.7). The monthly values of April and September were not significantly different between 2010 and 2011. Also in August, very similar balances were observed. However, in June 2010 the CO_2 emissions were more than twice that of June 2011, and also the other months showed great differences between 2010 and 2011. The cumulated daily R_{eco} of 2010 deviated from the cumulated daily R_{eco} of 2011 (Fig.5.7).

Both maximum daily release and minimum daily release were higher at the young site than at the old site (Tab.5.4).

Tab. 5.4: Daily minimum and maximum release of CO_2-C of the young and the old site. Mean of the three collars and standard error (s.e.).

site	min release +/- s.e. [g CO_2-C $m^{-2}d^{-1}$]	max release +/- s.e. [g CO_2-C $m^{-2}d^{-1}$]
young	0.009 +/- 0.074	1.17 +/- 0.18
old	0.005 +/- 0.018	0.90 +/- 0.13

Carbon dioxide flux rates of the two examination sites can be explained by soil temperature at 2 cm depth und wl (Fig.5.8: $R^2 = 0.79$; Adj. $R^2 = 0.73$; $p < 0.00001$). There seems to be an optimum at a wl depth of about -75 cm and a temperature of 20 °C. At low temperatures, the influence of the wl is quite low and increases with increasing temperatures. The highest impact of the wl is at the optimum temperature (20 °C).

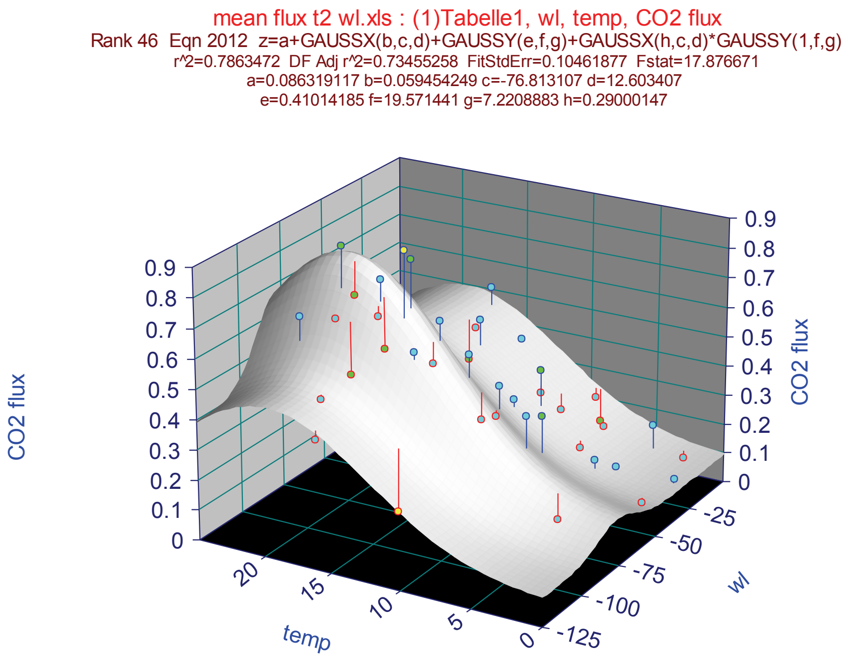


Fig. 5.8: Regression of CO_2 flux (µmol CO_2-C m^{-2} s^{-1}) against soil temperature in 2 cm depth (°C) and water level (cm above ground level). Data of young and old site.

5.3.5.3 Annual carbon dioxide balance

The annual carbon dioxide balances of the two sites were in the same order of magnitude but differed significantly (Tab.5.5). In 2010, the annual R_{eco} at the young and the old site was 1,439 +/- 106 and 1,197 +/- 66 kg CO_2-C ha^{-1} a^{-1}, respectively. The annual R_{eco} in 2011 was

1,267 +/- 80 and 1,190 +/- 50 kg CO_2-C ha^{-1} a^{-1} at the young and the old site, respectively. At the young site the CO_2-C balances were significantly different between the two measurement periods, while at the old site they were not. On average, 1,353 +/- 86 and 1,194 +/- 3 kg CO_2-C ha^{-1} a^{-1} were determined at the young and the old site, respectively.

Tab. 5.5: Annual and average balances for R_{eco} (CO_2-C), CH_4-C, N_2O-N exchange, NECB (net ecosystem carbon balance), and GWP (global warming potential) balances for the time spans of 20, 100 and 500 years in kg ha^{-1}. M: Mean, s.e.: Standard error. Letters indicate that balances are not significantly different.

site	balances		2010		2011		average	
			m	s.e.	m	s.e.	m	s.e.
young	R_{eco} CO_2	[kg CO_2-C ha^{-1} a^{-1}]	1439	106	1267	80	1353	86
	exp. C	[kg C ha^{-1} a^{-1}]	70200		70200		70200	
	CH_4	[kg CH_4-C ha^{-1} a^{-1}]	-0.31 a	0.17	2.44 c	1.97	1.06	1.12
	N_2O	[kg N_2O-N ha^{-1} a^{-1}]	2.83 b	0.73	0.14 d	0.19	1.48	1.10
	GWP 20	[kg CO_2-eq. ha^{-1} a^{-1}]	6532	389	4935	294	5734	317
	GWP 100	[kg CO_2-eq. ha^{-1} a^{-1}]	6591	389	4789	293	5690	317
	GWP 500	[kg CO_2-eq. ha^{-1} a^{-1}]	5954	389	4703	293	5329	316
	GWP 20 incl. exp. C	[kg CO_2-eq. ha^{-1} a^{-1}]	263932	389	262335	294	263134	317
	GWP 100 incl. exp. C	[kg CO_2-eq. ha^{-1} a^{-1}]	263991	389	262189	293	263090	317
	GWP 500 incl. exp. C	[kg CO_2-eq. ha^{-1} a^{-1}]	263354	389	262103	293	262729	316
	NECB	[kg CO_2-C ha^{-1} a^{-1}]	71656	106	71487	80	71571	86
old	R_{eco} CO_2	[kg CO_2-C ha^{-1} a^{-1}]	1197	66	1191	50	1194	3
	exp. C	[kg C ha^{-1} a^{-1}]	60500		60500		60500	
	CH_4	[kg CH_4-C ha^{-1} a^{-1}]	0.15 a	0.22	3.05 c	2.62	1.60	1.19
	N_2O	[kg N_2O-N ha^{-1} a^{-1}]	0.46 b	0.65	0.04 d	0.23	0.25	0.17
	GWP 20	[kg CO_2-eq. ha^{-1} a^{-1}]	4612	243	4665	187	4638	18
	GWP 100	[kg CO_2-eq. ha^{-1} a^{-1}]	4609	243	4481	185	4545	15
	GWP 500	[kg CO_2-eq. ha^{-1} a^{-1}]	4502	243	4404	185	4453	13
	GWP 20 incl. exp. C	[kg CO_2-eq. ha^{-1} a^{-1}]	226445	243	226498	187	226472	18
	GWP 100 incl. exp. C	[kg CO_2-eq. ha^{-1} a^{-1}]	226443	243	226314	185	226378	15
	GWP 500 incl. exp. C	[kg CO_2-eq. ha^{-1} a^{-1}]	226335	243	226238	185	226289	13
	NECB	[kg CO_2-C ha^{-1} a^{-1}]	61715	66	61720	50	61722	4

5.3.6 Methane

The annual courses of the methane exchange did not show a pronounced seasonal pattern (Fig.5.9). However, during the cold period the fluxes were 0 or close to 0, while during the warm period occasionally emission peaks occurred. At the young site higher emissions were found in August 2011, and at the old site emission peaks could be observed in September 2009 and April/May 2011 (Tab.5.6). During 2010, no emission peaks occurred at all.

However, even when emission peaks occurred, the flux rates were very low at both sites, leading to low annual balances.

At both sites about 50 % of the measurements revealed no detectable fluxes. One measurement date at the young site (Nov. 2010) and two measurement dates at the old site (30.11.2010 and 01.02.2011) were removed due to measurement errors.

Tab. 5.6: Hourly maximum uptake and maximum release of CH_4-C (left) and N_2O-N (right) of the young and the old site. Mean of the three collars and standard error (s.e.).

site	max uptake +/- s.e. [mg CH_4-C m^{-2} h^{-1}]	max release +/- s.e. [mg CH_4-C m^{-2} h^{-1}]	max uptake +/- s.e. [mg N_2O-N m^{-2} h^{-1}]	max release +/- s.e. [mg N_2O-N m^{-2} h^{-1}]
young	-0.14 +/- 0.22	0.62 +/- 1.23	-0.08 +/- 0.13	0.36 +/- 0.32
old	-0.04 +/- 0.04	0.44 +/- 0.22	-0.07 +/- 0.18	0.16 +/- 0.28

The annual methane balances of the sites were generally low in both measurement periods and did not differ significantly (Tab.5.5). During the second measurement period, the emissions were slightly higher than in 2010, but not significantly different. On average, both sites were very small sources of methane.

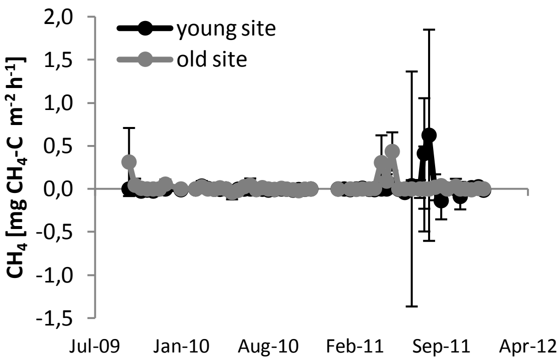
5.3.7 Nitrous oxide

During the cold period, the nitrous oxide flux rates were 0 or close to 0 (Fig.5.10). In summer and autumn, occasionally higher emissions were observed. Generally, at the young site higher emissions occurred. The annual course showed a higher fluctuation with higher release and higher uptake rates in 2010 as compared to 2011.

The maximum measured nitrous oxide release occurred in September 2010 (Tab.5.6).

On 25 and 34 measurement campaigns of the 54 measurement campaigns the N_2O fluxes were not different from 0 at the young and old site, respectively.

On three and two measurement campaigns the results were erroneous and therefore removed, at the young and old sites respectively.



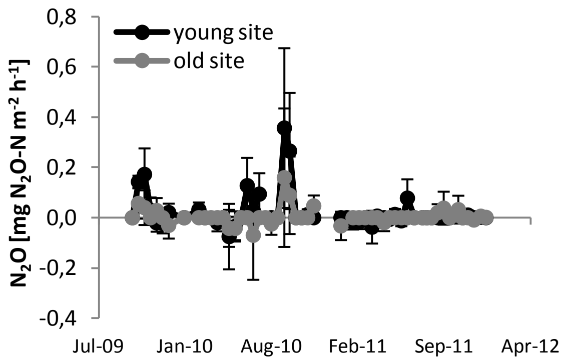


Fig. 5.9 (left): Annual course of CH_4 fluxes at the young and the old site.

Fig. 5.10 (right): Annual course of N_2O fluxes at the young and the old site.

Highest emissions of N_2O occurred at a soil temperature (2 cm depth) of about 15 °C and a wfps of 60 % (Fig.5.11: $R^2 = 0.40$; adj. $R^2 = 0.38$; $p < 0.00001$). The range of favourable conditions was very small. At higher or lower values of temperature and wfps, the fluxes decreased quickly to low values. However, within the optimum range of the wfps, also low and negative N_2O fluxes occurred which led to the conclusion that other factors play a significant role as well.

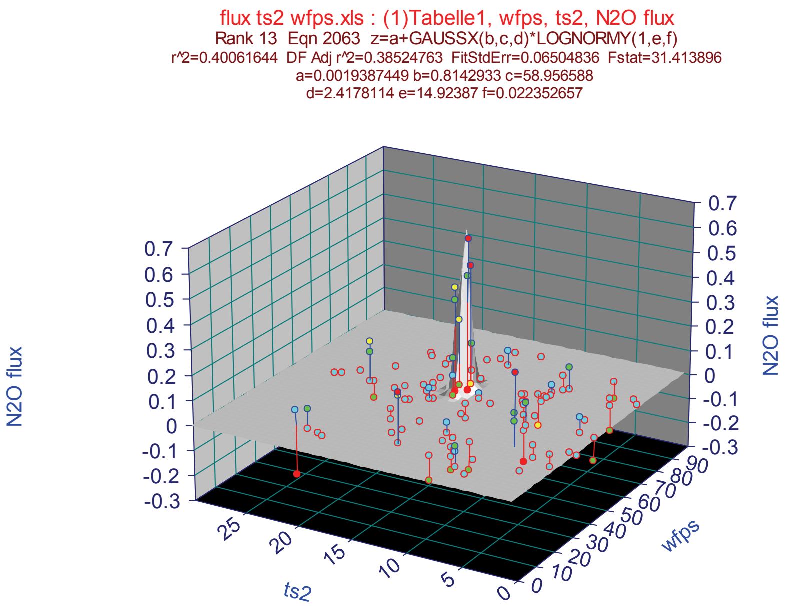


Fig. 5.11: Regression of N_2O flux rates (mg N_2O-N m^{-2} h^{-1}) against soil temperature in 2 cm depth (°C) and wfps (%). Data of young and old site.

In general, the measurement plots emitted only small amounts of nitrous oxide (Tab.5.5). The net N_2O emissions were higher at the young site than at the old site and higher in 2010 than in 2011. However, the annual N_2O emissions were not significantly different between the sites.

5.3.8 Net ecosystem carbon balance and global warming potential

At both sites huge amounts of carbon were exported through harvesting of the peat (see 3.4, Tab.5.5). Compared to this, the carbon release through respiration (R_{eco}) was small, and the lost dissolved organic carbon (DOC) which amounts to estimated 26 kg C ha^{-1} a^{-1}, is negligible. The addition of these fluxes is expressed in the NECB. In average, a NECB in the range of 60,000 to 70,000 kg CO_2-C ha^{-1} a^{-1} (Tab.5.5) was determined.
In general, the GWP100 balance without exported carbon was only slightly higher than the R_{eco} balance, because methane and nitrous oxide emissions were very low (Tab.5.5). Only the GWP100 balance of the young site in 2010 was noticeably increased. In 2010, the balances amounted to 6,591 +/- 389 and 4,609 +/- 243 kg CO_2-eq. ha^{-1} a^{-1} at the young and the old site, respectively. 2011 revealed 4,789 +/- 293 and 4,481 +/- 185 kg CO_2-eq. ha^{-1} a^{-1} at the young and the old site, respectively. The GWP100 balance including the exported carbon totalled about 245,000 kg CO_2-eq. ha^{-1} a^{-1} (Tab.5.5).

5.4 Discussion

5.4.1 Evaluation of methodology

In this study, modeling of the carbon dioxide exchange was carried out in high temporal resolution. At the times of the measurement campaigns, model calibration by curve fitting was conducted to consider the long term driving parameters (Tab.5.3). However, occasionally, curve fitting was not possible. During the cold period this was due to a too narrow temperature span. During the warm period, the correlation between flux rates and temperature was very weak on several occasions. On 04.05.2011 and 08.06.2011, the regressions between flux rates and temperature were even negative, i.e. flux rates decreased with increasing temperatures. In these cases the relationship between flux rates and temperature was overshadowed by other driving forces. In the course of the day, temperature increased until afternoon, but soil moisture of the upper soil layer and the wl might have decreased on sunny days without rain, leading to water limiting conditions, and thus lower R_{eco}.
The fit of all measured and all modeled values showed that the models at the two examination sites revealed adequate results (Fig.5.5).

5.4.2 Driving variables

Carbon dioxide emissions were mainly driven by wl and soil temperature (Fig.5.8), which was also observed in other studies on the gas exchange of soils. Bortoluzzi et al. (2006) and Flessa et al. (1997) could explain variations of CO_2 emissions by changes in wl and soil temperature. Soil temperature as explaining factor was also described by Shurpali et al. (2008). Tuittila et al. (1999), Waddington et al. (2002), van den Bos & van de Plassche (2003) and Danevcic et al. (2010) found a relationship between wl depth and peat mineralization. Optimal conditions at the peat extraction sites were observed at a wl of about -75 cm and a soil temperature of about 20 °C (Fig.5.8). This is in accordance with results of Waddington et al. (2001), Höper (2007), Oleszczuk et al. (2008) and Mäkiranta et al. (2009). Alm et al. (2007) point out that much higher emissions than the average can take place, when high temperature is combined with adequate soil moisture.

Also methane fluxes are mainly driven by wl or soil moisture and by temperature (Flessa et al. 1997, Hyvönen et al. 2009). However, relationships between CH_4 fluxes and driving forces are difficult to determine, because flux rates are low and the driving parameters are frequently intercorrelated (Hyvönen et al. 2009).

At the young site, in May, June and July 2010 much higher CO_2 emissions occurred than in 2011 (Fig.5.6). In June and July 2010, the young site showed also noticeable higher emissions than the old site (Fig.5.7). In 2010, both temperatures and wl were close to the optimum at the young site, while in 2011 temperatures were lower (Fig.5.2 & Fig.5.3). In contrast, at the old site wl in summer 2010 was below the optimum and in summer 2011 near the optimum. Thus, in summer 2010 only slightly higher emissions occurred at the old site, caused by higher temperatures, compared to summer 2011.

Another explanation for higher CO_2 emissions at the young site in the first measurement year might be that it was the second year after the conversion to a peat extraction site. According to the results of laboratory incubations of Canadian peat cut bogs (Waddington et al. 2001, Glatzel et al. 2004), peat extraction and removal of vegetation led to low substrate quality and nutrient availability and a surface layer of recalcitrant peat. Consequently, the microbial biomass is decreased, which results in decreased aerobic and anaerobic CO_2 production rates (Glatzel et al. 2004). Waddington et al. (2001) concludes from this the ecological importance of the top fibric peat layer removed during mining. Thus, it is possible that at the young site during the second harvesting year (which was the first measurement year) the substrate quality and microbial biomass was still quite high, whereas during the third harvesting year (which was the second measurement year) the substrate quality and microbial biomass was decreased, comparably to the old site, which had already been under peat extraction for ten years. At the young site the top soil layer with a low decay degree (4-5 von Post-scale) was 30 cm thick (in 2010), whereas at the old site, this layer (decay degree: 5 von Post-scale) was only 10 cm thick (Tab.5.1). The pH of the upper 30 cm layer was slightly higher at the young site than at the old site (Tab.5.1). Soils with a high pH reveal higher mineralization rates and CO_2 emissions than soils with a lower pH (Fu et al. 1987, Reth et al. 2005). The different substrate quality was also expressed in the different electrical conductivity (Lf). Thus, once the top peat layer is removed, emissions of new and old extraction sites might be similar.

The low coefficient of determination between nitrous oxide fluxes and environmental factors shows that there is a complex pattern of parameters driving N_2O fluxes (Regina et al. 1996). In addition, the flux rates were low. Hyvönen et al. (2009) could find no significant correlations in their study. Optimal conditions for nitrous oxide emissions seem to be at a wfps of about 60 % and a soil temperature of 15 °C (Fig.5.11). Kaiser et al. (1998), Meyer (1999) and Flessa & Beese (2000) observed in agriculturally used peatlands in the temperate zone highest rates of N_2O formation at high wfps (82-85 %). In contrast, Kasimir Klemedtsson et al. (2009) found in an agriculturally used peatland in Sweden highest rates under dry conditions (< 60 % wfps).

According to Flessa et al. (1997), Flessa et al. (1998) and Meyer (1999), frost-thaw cycles lead to the release of N_2O. During the study period the soil temperatures dropped very rarely beneath 0 °C and no N_2O emissions caused by frost-thaw cycles could be observed. The possibility of frost-thaw cycles cannot be excluded because measurements were held only every two weeks. However, since frost happened very rarely and only for short periods in Northwest Germany nitrous oxide emissions due to frost-thaw cycles would contribute only little to total emissions. This explains the differences in N_2O fluxes between Westermoor and the study sites in South Germany of Flessa et al. (1997).

One reason for low values might be the low nitrogen content of the soil (Flessa et al. 1997, Hyvönen et al. 2009). Both sites of this study have a high C/N ratio, and, thus, a relatively low total N content. The peat soil of the study of Hyvönen et al. (2009) has a similar C/N ratio (42.3) and even lower N_2O emissions. Klemedtsson et al. (2005) and Maljanen et al. (2007) observed a relationship between N_2O emissions and C/N ratio. There is a threshold for nitrous oxide emissions at a C/N ratio of 25 with practically no emissions at a greater C/N ratio and rapidly increasing emissions at smaller ratios (Klemedtsson et al. 2005).

Regina et al. (1996) found low numbers of nitrifiers in the peat mining area of their study, which is probably due to the removal of active nitrifiers together with the upper peat layer each summer. This might reduce the nitrification process, and consequently decreases the production of N_2O.

It can be concluded that GHG flux rates depend on a wide variety of site factors. Main driving factors are soil temperature, wl and wfps with optimums at 20 °C and -75 cm (CO_2) as well as 15 °C and 60 % (N_2O). The results indicate that the GHG exchange is not time dependent; only during the first two to three years after the conversion to peat extraction, can slightly higher emissions be expected.

5.4.3 Direct GHG emissions from peat extraction sites

Despite the great interannual variability of the monthly CO_2 fluxes, especially at the young site, the annual balances in 2010 and 2011 were similar (Tab.5.5 & Fig.5.6). This was due to higher emissions during the cold season (Nov. – April) in 2011 compared to emissions during the cold season in 2010 (Fig.5.6).

There are no previous studies about the GHG exchange of peat extraction sites in the temperate zone. Flessa et al. (1997) examined a simulated peat extraction site (fen) in South Germany and observed similar annual courses of the CO_2, CH_4 and N_2O exchange. However, maximum uptake and maximum release of CH_4 were lower and emissions of N_2O were slightly higher in the study of Flessa et al. (1997).

The annual R_{eco} balances at the peat extraction sites ranged between 1,190 and 1,439 kg CO_2-C ha^{-1} a^{-1}, whereas the CH_4 and N_2O balances were generally low (Tab.5.5). Thus, the contribution of CH_4 and N_2O emissions to the global warming potential of peat extraction sites is small (Sundh et al. 2000, Alm et al. 2007). Flessa et al. (1997) observed higher CO_2 emissions (2,910 kg CO_2-C ha^{-1} a^{-1}). Beside methodological differences, the study site used by Flessa et al. (1997) was different: They examined a fen with higher pH and higher total N content, which might have led to higher carbon dioxide emissions. CH_4 and N_2O fluxes were similarly low in the study of Flessa et al. (1997).

The GWP100 balances ranged between 4,789 and 6,591 kg CO_2-eq. ha^{-1} a^{-1} at the young site, and between 4,481 and 4,609 kg CO_2-eq. ha^{-1} a^{-1} at the old site (Tab.5.5).

Abandoned peat cut sites seem to have similarly high CO_2 emissions, if the wl is kept low (Tuittila et al. 2004). Thus, if not rewetted there is still a high peat mineralization after abandonment. Abandoned peat cut sites with high wl show lower emissions (Tuittila et al. 2004, Bortoluzzi et al. 2006, Kivimäki et al. 2008). CH_4 and N_2O fluxes remain low after peat extraction has ceased (Drösler 2005, Bortoluzzi et al. 2006).

5.4.4 GHG emissions from temperate sites compared to boreal sites

In contrast to the temperate zone, there have been several examinations in the boreal zone. The results are in line with the findings in this study. Shurpali et al. (2008) found maximum CO_2 emissions in a peat extraction site in Eastern Finland similar to the maximum value at the young site. Annual balances range between 720 and 2,600 kg CO_2-C ha^{-1} a^{-1} (Nykänen et al. 1996, Alm et al. 2007, Shurpali et al. 2008). Emissions during a dry year were much lower than during a wet year (Shurpali et al. 2008). Sundh et al. (2000) observed during growing season between 679 and 2,835 kg CO_2-C ha^{-1} a^{-1} in Sweden. However, in contrast to the sites in this study, fluxes showed no obvious seasonal trends in a peat extraction site in Sweden (Sundh et al. 2000).

CH_4 fluxes are generally low, showing both uptake and release, but no seasonal pattern (Sundh et al. 2000, Tuittila et al. 2000, Hyvönen et al. 2009). Hyvönen et al. (2009) suggest that methane produced in the lower anaerobic peat layers can be released via cracks into the atmosphere, which led to occasionally high emissions. Annual balances are low, but higher than at the sites in this study and at the sites of Flessa et al. (1997). According to Sundh et al. (2000), methane balances in Sweden range from -0.3 to 32 kg CH_4-C ha^{-1} a^{-1} during growing season. In Finland, annual fluxes range from 2 to 56 kg CH_4-C ha^{-1} a^{-1} (Nykänen et al. 1996, Alm et al. 2007, Hyvönen et al. 2009). The high methane emission rates could be due to temporarily high wl during the summer months.

In the study sites of Hyvönen et al. (2009) during the growing season more N_2O was released than in winter, which fits to the results in this examination. Annual balances range from 0.06 to 2 kg N_2O-N ha^{-1} a^{-1} (Nykänen et al. 1996, Alm et al. 2007, Hyvönen et al. 2009).

According to a literature review of peat extraction sites in Finland and Sweden in average 7,700 kg CO_2-eq. ha^{-1} a^{-1} are released (Maljanen et al. 2010). The higher result of Maljanen et al. (2010) is due to higher annually CO_2 emissions.

The results indicate that GHG emissions from peat extraction sites in the temperate region are not greater than in the boreal region.

5.4.5 GHG emissions from peat extraction

The NECB of the study sites ranged between about 60,000 and 70,000 kg CO_2-C ha^{-1} a^{-1} (Tab.5.5). The larger carbon dioxide gas exchange at the young site is of minor importance for the NECB. The results are higher than what is cited in the literature. Turetsky et al. (2002) estimates that 36,490 kg C ha^{-1} a^{-1} is removed through peat extraction in Western Canada, which result in a NECB of about 41,000 kg C ha^{-1} a^{-1}. The only values about the NECB of peat extraction sites in Germany are reported by Höper & Blankenburg (2000). The NECB of the gross peat extraction area in Lower Saxony amounts to 13,300 kg C ha^{-1} a^{-1}. They divided the whole amount of extracted peat (8 million m^3) by the whole area, i.e. also areas which are in preparation for peat cutting and places where peat extraction has ceased but which are not yet rewetted.

About 2 % of the NECB was carbon lost by microbial decomposition in the peat extraction site while 98 % was carbon exported with the extracted peat. In the study of Sundh et al. (2000), the microbial decomposition in the peat extraction site attributes about 6 % to the NECB.

The comparatively low contribution from microbial decomposition in the peat extraction site at Westermoor might be predominantly due to the large amount of peat harvested per year, which is 1,000 m^3 ha^{-1}.

In average, the GWP100 balance without the carbon exported with the harvested peat of the examination sites, amounted to approx. 5,100 kg CO_2-eq. ha^{-1} a^{-1} (Tab.5.5). Including the exported carbon, the (total) GWP100 balance would be on average approx. 245,000 kg CO_2-eq. ha^{-1} a^{-1} (under the assumption that no CH_4 and no N_2O is emitted from the harvested peat, but only CO_2). Thus, the peat extraction area itself contributes only about 2 % to the total GWP100 balance. If noteworthy emissions of CH_4 and N_2O occur from the harvested peat, the total GWP100 balance would be even higher.

The exported carbon through peat harvest at the study sites is an imprecise estimation for the whole peat mining area. The decline of the ground surface is caused mainly by the removal of peat for harvesting, but also due to peat subsidence (Schothorst 1976). At the young site the decline of the ground surface was more than 20 cm, and thus peat subsidence was observed. In contrast, at the old site the ground surface did not decline as much as expected. Hence, the harvested peat might be less than 10 cm per year at the measurement plots. However, for the whole area of the old site, the removal of 10 cm per year is a realistic assumption, and thus the calculated NECB is a realistic estimation.

When peat cutting takes place, GHG emissions occur also from stockpiles, from the ditches, from the draining phase prior to extraction, as well as from peat extraction procedure, processing, transportation and storage.
However, life cycle analyses of the peat industry revealed that the greatest contribution to the greenhouse effect comes from the extracted peat (Cleary et al. 2005, Kirkinen et al. 2007).

At the sites in this study a great amount of peat per year is extracted. This led to a short extraction period, and thus to a smaller loss of carbon through peat mineralization from the extraction site. The amount of carbon lost by mineralization in the peat extraction site is small in terms of the percentage. Therefore, a life cycle analysis would reveal a smaller climate impact of the harvested peat. Cleary et al. (2005) point out that a reduced harvest and restoration period result in a higher harvest yield of peat or a reduced drained area for peat extraction.
Restoration of abandoned cut over sites should be as fast as possible in order to reduce GHG emissions (Waddington et al. 2001, Waddington & McNeil 2002, Cleary et al. 2005). According to Zetterberg et al. (2004), restoration of abandoned cut over sites has a great impact in reduction of the climate impact of peat utilisation.

5.5 Conclusions

Studies examining the GHG exchange of active peat extraction sites have been conducted in the boreal zone, but not in the temperate zone. This study shows that GHG emissions from peat extraction sites in the temperate zone are not higher than in the boreal zone. The GHG emissions consist mainly of carbon dioxide, while methane and nitrous oxide play a minor role. A young and an old peat extraction site revealed on average carbon dioxide emissions of 1,353 +/- 86 and 1,194 +/- 3 kg CO_2-C ha^{-1} a^{-1}, respectively. Methane and nitrous oxide fluxes were generally very low. In the first measurement year, the young site was a sink for CH_4. GWP100 balances at the young and the old site added up to 5,690 +/- 317 and 4,545 +/- 15 kg CO_2-eq. ha^{-1} a^{-1}, on average respectively. Main driving forces for the exchange of GHG are temperature, water level and water filled pore space. Optimal conditions for CO_2 emissions are a soil temperature of 20 °C and a mean water level of 75 cm below ground level. Optimal conditions for N_2O production are a soil temperature of 15 °C and a wfps of 60 %. During the first two to three years after the conversion from an agriculturally used bog into a peat extraction site, GHG emissions might be slightly higher, however after three years emissions remain stable. After abandonment of peat extraction sites, similarly high emissions occur, if the area is not rewetted.

Most of the GHG emissions occur from the harvested peat, whereas emissions from the peat extraction area itself are comparatively small. A short extraction period and a rapid restoration after peat extraction has ceased reduce GHG emissions.

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6 Emission factors and climate relevance of organic soils in Northern Germany. Synthesis

6.1 Introduction

Carbon dioxide, methane and nitrous oxide are the most important greenhouse gases (GHG) which have been increasing for the last 250 years due to human activities (IPCC 2007). Ecosystems like peatlands play an important role in the global cycle of these gases. Drainage of peatlands leads to peat oxidation and high emissions of carbon dioxide occur. Nitrification and denitrification cause the release of nitrous oxide. These emissions are attributed to human activities, and Germany is therefore obliged to report them within international agreements to the United Nations Framework Convention on Climate Change (UNFCCC). GHG from drained peatlands are reported in the sections agriculture (sector 4) and land use, land use changes and forestry (sector 5) of the National Inventory Report (NIR: UBA 2012). The national emission inventories are required to be reviewed each year. The emission sources are divided into categories. Sources with emissions having a significant influence on total emissions (key categories) are highlighted in the inventory system (UBA 2012). CO_2 emissions / removals and N_2O emissions in the categories *cropland* and *grassland* are identified as key categories (UBA 2012). It is estimated that drained peatlands contribute about 5 % to the national total GHG emissions, and thus drained peatlands are the biggest national source for GHG outside the energy sector (Drösler et al. 2011). Estimating emissions requires emission factors (EF) and activity-data. Currently, EFs have been reported by Byrne et al. (2004) and Höper (2007). However, data from agriculturally used peat soils are not sufficient yet in order to report national emissions adequately. The database on the greenhouse-gas (GHG) fluxes of peatlands is still weak in comparison to other ecosystems (Byrne et al., 2004). Most studies have been conducted mainly in the boreal region and did not consider all three GHG. Moreover, the EF provided in the Guidelines for reporting GHG emissions of the IPCC (2006) does not match with current data (Couwenberg 2011).

At present, no national data for peat extraction is available, and Germany is therefore not able to report for this category. The national areas of peat extraction are included in the land-use category “Wetlands” of the NIR (UBA 2012).

The NIR of 2012 provided recommendations to fill the gaps:

a) Reporting of subdivisions of the wetlands category: land with peat extraction, fully water covered wetlands and partly water covered wetlands.
b) Determination of national EF (CO_2, N_2O und CH_4) for peat extraction.
c) Improvement and validation of national EF for organic soils used as cropland and grassland with gas flux measurements.
d) Establishment of current EF differentiated according to soil type and land use type in organic soils.

In order to meet the recommendations, the nationwide study “organic soils” was started in 2009. Two years before, the nationwide BMBF-project „Klimaschutz - Moornutzungsstrategien“ (2007-2010) was carried out. This was the first examination in Northwest Germany to consider full GHG exchange and GWP.

In Germany, the EF for organic soils is applied only for emissions from peatlands according to the German soil classification (at least a 3 dm thick layer containing at least 30 % organic matter). However, for organic soils a broader definition was chosen by the IPCC (2006), soils having a peat layer of less than 3 dm (“Anmoore”) are also included. Hence, the area and emissions of these soils has to be estimated.

In contrast to drained organic soils, mires accumulate carbon as peat; a small amount of the carbon is released as methane. Emissions or uptake rates of natural peatlands do not have to be reported to the UNFCCC. However, to assess the savings potential of mire protection and rewetting measures of drained organic soils, EFs of mires and rewetted areas have to be estimated.

The aim of this study is to determine EFs for all categories of organic soils valid for Northern Germany. Different land use types and soil types are accounted for. The EFs are compared to the default values in the NIR (UBA 2012) and of the IPCC (2006). Carbon balances and global warming potentials (GWP) of Northern German peatlands are established. The main questions of the research are:

a) How high are the differences between the EFs in this study compared to the default values in the NIR (UBA 2012) and of the IPCC (2006)?
b) How high is the EF of national peat extraction sites?
c) Are the emissions of different types of organic soils (bog, fen, gleysol) similar?
d) How much do the single GHGs contribute to the GWP?

e) What is the main driving force for the annual GWP of organic soils?
f) Are paludi cultures a climate-friendly alternative for conventional agricultural use?
g) What is the effect of rewetting on the carbon and GWP balance?

In this synthesis meta-data of the study was used.

6.2 Combination of organic soil type and land use type

In Lower Saxony, about half of the organic soil area is covered by bogs and half is covered by fens. A small area is covered by soils having a peat layer of less than 3 dm. Most of these organic soil types are used for agriculture (cropland or grassland) or peat extraction. A small part has been rewetted or is in a natural or near-natural state. Since recently, test sites for paludi cultures have been established. In this study all available combinations of the organic soil types and the land use types in Lower Saxony have been covered, except rewetted fens and grassland on bog. Rewetted fens and grassland on bog in Lower Saxony were examined by Meyer (1999) and Beetz et al. (2013). However, Meyer (1999) measured only R_{eco}, CH_4 fluxes and N_2O fluxes in vegetation-free plots, but not the NEE. Rewetted bogs were also examined by Beetz et al. (2013). GHG emissions of peat extraction sites, grassland sites on gleysol and cropland sites on gleysol have not been studied in Germany, and the GHG exchange of Sphagnum farming has not been studied at all. However, data on GHG fluxes is generally scarce. The measurements in this study were conducted over at least two years in order to account for inter annual variation.

6.3 Emission factor

The Emission factor (EF) is the typical annual gas exchange rate between the peat soil and the atmosphere, differentiated according to peatland type and management (Höper 2007). The definition applies not only for peatlands but for all soils. The NIR (UBA 2012) and the IPCC (2006) do not distinguish between organic soil types, but only between types of management. In this study the differences among organic soil types were small, while dissimilarities between management types (land use types) were great. EFs in this study were calculated by grouping the sites by land use types. One cropland site with a noticeably high water level (wl) showed a different emission pattern (ch.2) and was excluded. The arithmetic means and standard deviations were calculated.

Some of the results in this study deviate substantially from the German default values in the NIR (UBA 2012) and from the default values for the temperate zone of the IPCC (2006: Tab.6.1). The EF for CO_2 of cropland in this study is much smaller. Annual CO_2 emissions from cropland might be even lower under wet conditions. On a cropland site in a fen with high wl a CO_2 release of about 4,000 kg CO_2-C ha^{-1} a^{-1} was determined (ch.2). Also in other European countries the EFs are lower: In Poland and the UK, annual CO_2 emissions of 1,000 and 2,000 kg CO_2-C ha^{-1} a^{-1}, respectively are reported, while in Denmark and Switzerland emissions of 8,300 and 9,500 kg CO_2-C ha^{-1} a^{-1}, respectively were found (UBA 2012). In contrast, the EF of grassland in the NIR (UBA 2012) was confirmed in this study and seems to be realistic. The land use type grassland in this study corresponds to the sub-category "grassland (in the narrow sense)" of LULUCF of the NIR (UBA 2012). The EF of the IPCC (2006) is lower, compared to the results in this study and the default value in the NIR (UBA 2012).

The default values of the IPCC (2006) for nitrous oxide of cropland and grassland sites are both 8 kg N_2O-N ha^{-1} a^{-1}. In average, this might be realistic. However, cropland sites can have much higher emissions, while grassland sites can show much lower releases. In this regard, it must be distinguished between fertilized and unfertilized land. The grassland sites in this study are not fertilized. Fertilized grassland can have higher N_2O emissions compared to unfertilized (Chadwick et al. 2000, Petersen et al. 2012). In the NIR (UBA 2012), N_2O emissions are calculated as a proportion of applied N-fertilizer ($EF_{N_2O} = 0.0125$ kg kg^{-1} N_2O-N). N_2O emissions of the cropland sites in this study calculated with this equation would result to 1 to 4 kg N_2O-N ha^{-1} a^{-1}, which is far below the results achieved by measurements in this study.

Emissions from peat extraction sites can be divided into on-site and off-site emissions (IPCC 2006, Couwenberg 2011). On-site emissions arise from the soil of active peat extraction sites and from the peat decomposition in stockpiles, whereas off-site emissions come from the extracted peat during its use. In this study a slightly different approach is followed. It was distinguished between CO_2 emissions from the active peat extraction site and CO_2 emissions from the extracted peat. However, the difference between the two methodological approaches might be rather small. The IPCC (2006) cited results from boreal peatlands, which are partly under extraction (Couwenberg 2011) and used them as default values for peat extraction sites in the temperate and boreal zone. Since in Germany peat extraction takes place only in poor soils, the value of 200 kg CO_2-C ha^{-1} a^{-1} would apply. This is the first study in which direct measurements in the temperate zone have been conducted, and it shows that the annual CO_2

release is much higher. The study shows that the largest part of CO_2 emissions through peat extraction comes from the harvested peat itself. EFs of CH_4 and N_2O were not yet at all available, but the results in this study show that the exchange rates are negligible.

Rewetted sites and *Sphagnum* farming are not included in the NIR (UBA 2012). For paludi cultures like *Sphagnum* farming, only test sites have been established recently, and the area is very small up to now. Thus, EFs have no relevance yet. However, it might be an alternative land use for the future. Thus, the determination of EFs is necessary to establish the climate relevance in comparison to cropland, grassland and rewetting.

CH_4 emissions from un-drained and un-managed organic soils do not have to be reported in the inventory (IPCC 2006).

Tab. 6.1: Summary of emission factors for carbon dioxide, methane and nitrous oxide, grouped by land use types. This study as well as default values of NIR (2012) and IPCC (2006).

	study	NIR 2012	IPCC 2006	study	NIR 2012	IPCC 2006	study	NIR 2012	IPCC 2006
Land use	**kg CO_2-C ha^{-1} a^{-1}**			**kg CH_4-C ha^{-1} a^{-1}**			**kg N_2O-N ha^{-1} a^{-1}**		
cropland*	5950 +/-1740	11000	10000	0.4 +/-1.4	-	-	20 +/-8	-	8
grassland	4520 +/-1170	5000	2500	-2 +/-0.9	-	-	0.4 +/-0.7	-	8
peat extraction**	1270 +/-116	-	200**** 1100*****	1.3 +/-1.7	-	-	0.9 +/-1.3	-	-
peat extraction***	66640	-	-	-	-	-	-	-	-
rewetted	-714 +/-843	-	-	138 +/-110	-	-	0.1 +/-0.5	-	-
Sphagnum farming	-41 +/-284	-	-	24 +/-10	-	-	0.1 +/-0.2	-	-

*cropland site of chapter 2 not included, **only extraction site, ***extraction site and exported carbon through harvest, ****poor soils, *****rich soils

6.4 Net ecosystem carbon balance

The net ecosystem carbon balance (NECB) comprises all fluxes of carbon between the ecosystem and the atmosphere (Chapin et al. 2006). Mires have a negative NECB, because they accumulate carbon. In drained organic soils the stored carbon is released as CO_2, while very small amounts of CH_4 might be taken up. The NECB is therefore positive. To compare the different land use types, the study sites were grouped accordingly and the arithmetic means as well as the standard deviations were calculated. At the cropland site with high wl only one value was used (the last year of the measurement period). The NEE (CO_2), CH_4 flux, C-export through harvest and C-import through organic fertilizer were considered, while other C fluxes were not, because they are negligible at all sites.

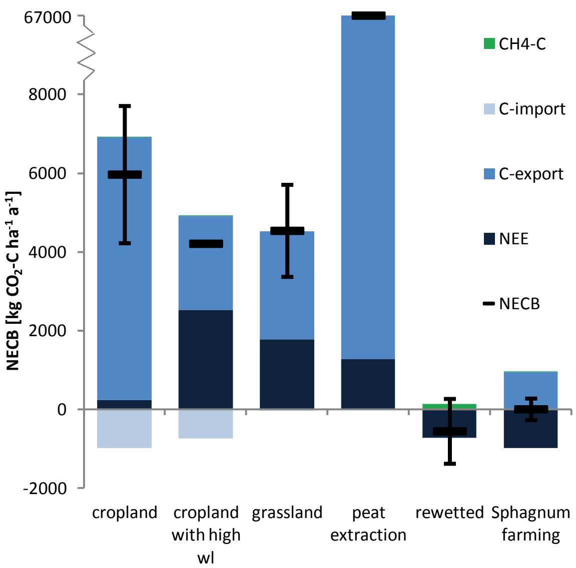

Fig. 6.1: Net ecosystem carbon balances of the study sites, grouped by land use types. Divided according to the contributing gases.

At the peat extraction sites each year high amounts of carbon are exported through the harvested peat, and thus these sites have by far the highest net carbon release (Fig.6.1). The NECB of cropland sites show a high variation. Deeply drained cropland sites show net carbon releases of around 6,000 +/- 1,700 kg CO_2-C ha^{-1} a^{-1}. A cropland site with high wl (ch.2) revealed lower emissions which are comparable to grassland sites. The agriculturally used sites develop high amounts of biomass during the growing period and are therefore characterized by high uptake rates of CO_2 through photosynthesis and high emissions through respiration, as well as by the removal of high amounts of biomass through harvest. A small amount of carbon is added into the system as fertilizer. Other carbon fluxes can be seen as negligible. At the deeply drained cropland sites almost all aboveground biomass was removed each year through harvest, while at the cropland site with high wl the biomass was only partly removed. The remaining biomass is mineralized in the field, and contributes therefore to the NEE. In contrast, *Sphagnum* farming represents an alternative type of cultivation with a neutral carbon balance. Since no heterotrophic respiration takes place due to anoxic conditions, the ecosystem takes up net CO_2 throughout the year. When *Sphagnum* is harvested, the net accumulated carbon is exported from the system. Carbon fluxes through methane are negligible, and fertilizer is not applied. Rewetted sites show a small net accumulation of CO_2, however the error is greater than 100 %, and thus these sites can be small sinks or small sources. The examination area is heterogeneous, and inundated locations contribute CH_4 emissions. However, carbon emissions through CH_4 fluxes are much smaller than carbon accumulation through NEE.

6.5 Global warming potential

Each GHG has an individual radiative forcing capability, which is expressed in the global warming potential (GWP) relative to the reference gas CO_2 in CO_2-equivalents (IPCC 2007). Due to different life time spans of the gases, the GWP can be calculated for different time periods (IPCC 2007: 20a, 100a and 500a). In the NIR (UBA 2012) the climatic relevance over a time period of 100 years (GWP100) is used. However, a time frame of 500 years (GWP500) might be also useful, because peatland ecosystems function for a long time period (Drösler 2005).

The GWP100 and GWP500 of peat extraction sites and grassland sites as well as of the cropland site with high wl are similar to the NECB, because the balances consist almost exclusively of CO_2 fluxes while CH_4 and N_2O fluxes are negligible (Fig.6.2). In deeply drained cropland sites N_2O contributes a huge amount to the GWP. Keeping the wl of cropland sites as high as possible does not only reduce net CO_2 emissions but also N_2O emissions. The higher N_2O release of the cropland sites compared to the grassland sites can be attributed to the application of nitrogen fertilizer. In the collaborative project „Klimaschutz - Moornutzungsstrategien“, similar GWP100 balances in German cropland and grassland sites were found (Drösler et al. 2011: i.e. mean balances of low intensity dry grassland are 22.5 (fen) and 20.1 t CO_2-eq. ha^{-1} a^{-1} (bog)). Emissions in low intensity grassland on bog in Lower Saxony are also in the same range (Beetz et al. 2013).

Due to small CH_4 emissions of the *Sphagnum* cultivation site, this area is a very small GWP100 source. However, considering a time span of 500 years a nearly neutral effect is visible.

Rewetted sites are GWP100 sources due to high CH_4 emissions and GWP500 sinks. However, in both cases the error is higher than 100 %. Therefore, the GWP is near neutral. In the project „Klimaschutz - Moornutzungsstrategien“ mean values for rewetted bogs range between 0.1 t CO_2-eq. ha^{-1} a^{-1} at a mean wl a few cm below ground surface and 8.3 t CO_2-eq

ha^{-1} a^{-1} at inundated bogs, which is in accordance to the results of this study (Drösler et al. 2011).

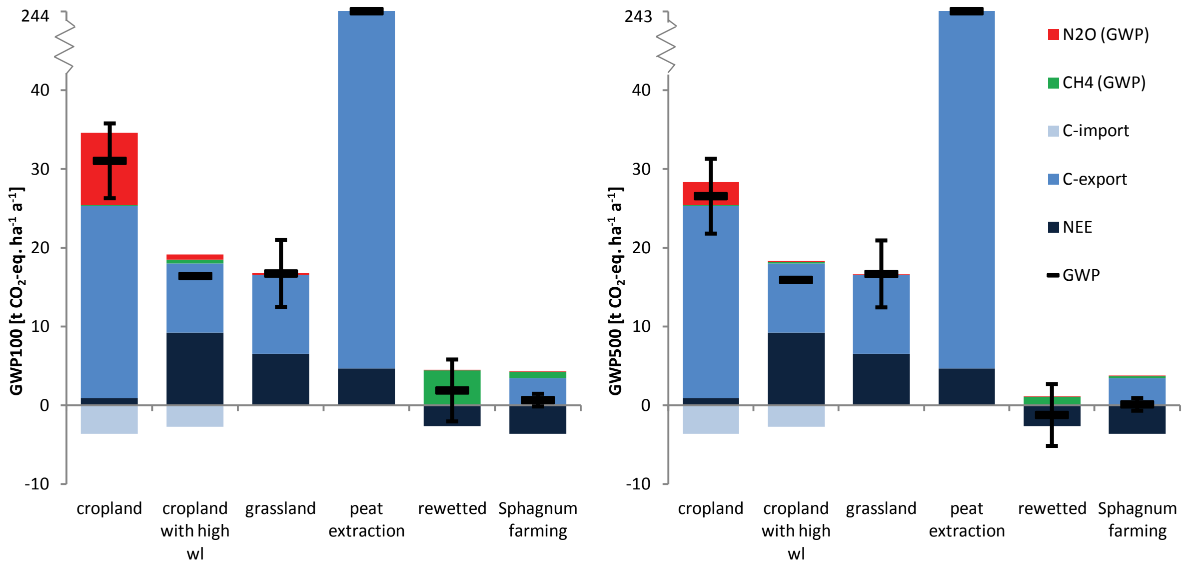

Fig. 6.2: GWP100 balances (left) and GWP500 balances (right), grouped by land use types. Divided according to the contributing gases.

The carbon balance and the GWP balance show a strong relation, because both are mainly determined by CO_2 fluxes and exported carbon through harvest which contributes also to CO_2 emissions (Fig.6.3: All annual balances, except the balances of the peat extraction sites). CH_4 and N_2O fluxes cause deviations from the linear regression, which was also observed by Drösler (2005). The relationship is stronger with the GWP500 compared to GWP100, because the radiative impact of CH_4 and N_2O decreases. Most of the examination sites were in both years NECB and GWP sources. In contrast to the GWP100 balance, the GWP500 balance was negative when the NECB was negative, which leads to the conclusion that these sites accumulate carbon and exert a cooling effect on the climate in the long-term. However, most of the samples which represent NECB sinks show very low values with comparatively large errors, and therefore near-neutral balances can be assumed.

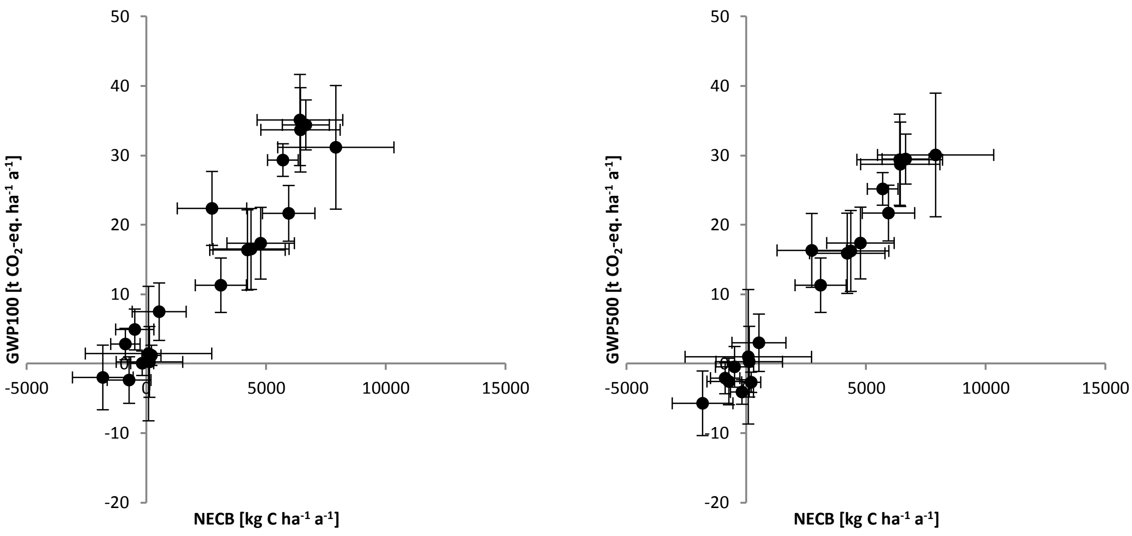

Fig. 6.3: Net ecosystem carbon balance versus GWP100 balance (left) and GWP500 balance (right). All annual balances, except the balances of the peat extraction sites.

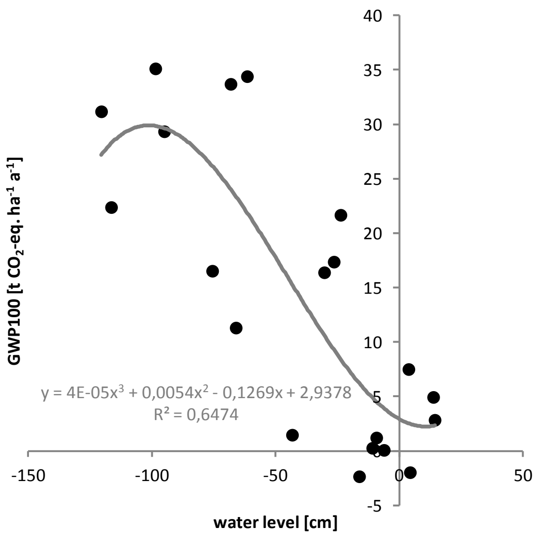

Fig. 6.4: GWP100 balance versus water level above ground surface. All annual balances, except the balances of the peat extraction sites.

A non-linear regression between GWP100 balance and mean wl shows that the variation of GWP100 balances can be mainly explained by the mean wl (Fig.6.4). No other site parameter reveals a comparably strong relationship. An optimum is obviously at a mean wl of about 100 cm below ground surface. At lower wl, CO_2 emissions probably decrease. The maximum of peat mineralization occurs at a wl depth of approximately 60 to 100 cm below ground surface in summer (Mundel 1976, Höper 2007, Oleszczuk et al. 2008, Mäkiranta et al. 2009). In a meta-data-analysis of Couwenberg et al. (2011) a similar relation is observable with an optimum at a wl of about 100cm below ground surface. Inundated sites show increasing CH_4 emissions, leading to increasing GWP100 balances.

The wl is therefore the key factor for a) converting drained organic soils into a growing carbon accumulating peatland, b) achieving a negative GWP, and therefore a cooling impact on the climate and c) reducing GHG emissions from agriculturally used organic soils.

6.6 Reduction potentials

Changing the land use management and / or raising the wl may reduce the emissions of GHG. By calculating the differences between the mean values of the grouped land use types, reduction potentials were determined.

Cropland sites are deeply drained in order to ensure accessibility for agricultural machines. Keeping the wl high represents a risk factor for the farmer in autumn when harvesting takes place. However, at one cropland site in this study the wl is kept quite high, which leads to a reduction of about 190 kg CO_2-C ha^{-1} a^{-1} and 15 t CO_2-eq. ha^{-1} a^{-1} in comparison to deeply drained cropland sites. Converting deeply drained cropland sites into grassland sites would lead to a similarly high reduction (about 160 kg CO_2-C ha^{-1} a^{-1} and 15 t CO_2-eq. ha^{-1} a^{-1}).

Rewetting of grassland sites would lead to a higher reduction of the NECB. The value decreases by 500 kg CO_2-C ha^{-1} a^{-1}. The GWP100 would be decreased by about 15 t CO_2-eq. ha^{-1} a^{-1}. An alternative land use is paludi culture. The conversion of grassland into *Sphagnum* farming has a reduction potential of 550 kg CO_2-C ha^{-1} a^{-1} and 16 t CO_2-eq. ha^{-1} a^{-1}.

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Zusammenfassung

Organische Böden stellen wichtige Kohlenstoffspeicher im globalen Kohlenstoffkreislauf dar. Im natürlichen oder naturnahen Zustand entziehen organische Böden der Atmosphäre Kohlendioxid und sind somit CO_2-Senken. Auf der anderen Seite sind diese Böden Methan-Quellen, das heißt CH_4 wird an die Atmosphäre abgegeben. CH_4-Emissionen sind allerdings um ein vielfaches geringer als die CO_2-Aufnahmeraten. Im entwässerten Zustand wird der gespeicherte Kohlenstoff mineralisiert und es werden große Mengen CO_2 emittiert. Daneben geben entwässerte organische Böden auch Distickstoffoxid (Lachgas) an die Atmosphäre ab, welches vor allem durch Prozesse der Nitrifikation und Denitrifikation entsteht. CO_2, CH_4 und N_2O gehören zu den wichtigsten anthropogenen Treibhausgasen.
In der Bundesrepublik Deutschland sind organische Böden großflächig entwässert und werden landwirtschaftlich oder für die Torfgewinnung genutzt. Die Bundesrepublik ist der zweitgrößte Emittent klimarelevanter Gase aus organischen Böden in Europa, obwohl nur ein sehr kleiner Teil der europäischen organischen Böden in der Bundesrepublik liegt. Inzwischen werden entwässerte Flächen wieder vernässt. Ein großer Teil der bundesdeutschen organischen Böden befindet sich in Niedersachsen.
Im Rahmen internationaler Abkommen hat sich die Bundesrepublik Deutschland verpflichtet, regelmäßig über den Ausstoß klimarelevanter Gase im nationalen Inventarbericht zu berichten und die Emissionen zu verringern. Obwohl entwässerte organische Böden die größte nationale Einzelquelle für Treibhausgase außerhalb des Energiesektors darstellen, ist die Bundesrepublik derzeit nicht in der Lage regelgerecht zu berichten, da belastbare Zahlen fehlen. Die in der Bundesrepublik Deutschland gebräuchliche Definition von „Moor“ stimmt weder mit der Definition für organische Böden im nationalen Inventarbericht noch mit der Definition der *World Reference Base for Soil Resources* überein.
In dieser Arbeit wurden die Kohlendioxid-, Methan- und Lachgas-Flussraten sowie der Einfluss auf das Klima und die Kohlenstoffbilanz in verschiedenen niedersächsischen Ökosystemen organischer Böden quantifiziert und die entscheidenden Einflussfaktoren auf den Gasaustausch untersucht. Das übergeordnete Ziel war die Bestimmung von Emissionsfaktoren in Abhängigkeit von Klima, Bodentyp, Nutzung und Nutzungsintensität, um die Sektoren Landwirtschaft (Sektor 4) und Landnutzung, Landnutzungsänderung und Forstwirtschaft (Sektor 5) des Nationalen Inventarberichts zum Deutschen

Treibhausgasinventar mit Daten zu versorgen. Die Ergebnisse sollen Entscheidungshilfen für die Politik und für die Durchführung von klimafreundlichen Moorschutzmaßnahmen liefern.

Zu diesem Zweck wurden zwölf Standorte, die die für Niedersachsen relevanten Kombinationen aus organischem Bodentyp und Nutzungstyp repräsentieren, über einen Zeitraum von zwei Jahren und vier Monaten intensiv untersucht: Acker auf Sanddeckkultur (Anmoor), Grünland auf Sanddeckkultur (Anmoor), Acker auf Niedermoor, Grünland auf Niedermoor, Acker auf Hochmoor, Acker auf Sanddeckkultur (Hochmoor), Torfabbau auf Hochmoor (zwei Flächen), Torfmooskultur auf Hochmoor, Wiedervernässung auf Hochmoor (drei Flächen im 1983 wiedervernässten Leegmoor). Für die beiden Niedermoorflächen lagen Daten über einen Zeitraum von insgesamt viereinhalb Jahren vor.

Gasflussraten wurden mithilfe von gasdichten manuellen Gassammelhauben ermittelt. Anhand von Modellen ist der Jahresgang der CO_2-Austauschraten mit hoher zeitlicher Auflösung und aufgeschlüsselt nach Respiration und Bruttoprimärproduktion berechnet worden. Im Anschluss konnten jährliche Bilanzen erstellt werden. Haubenmessungen zur Ermittlung der CH_4- und N_2O-Flussraten wurden in Abständen von ca. zwei Wochen durchgeführt. Zwischen den Messterminen ist linear interpoliert worden. Zusätzlich wurden meteorologische, bodenkundliche, hydrologische und vegetationskundliche Steuer- und Erklärungsparameter erfasst. Für die Standorte wurden die Netto-Ökosystem-Kohlenstoffbilanz und das globale Erwärmungspotential (GWP) für unterschiedliche Bezugszeiträume berechnet.

Der Einsatz manueller Gassammelhauben war für diese Untersuchung aufgrund der hohen räumlichen Variabilität der Flächen und des Fehlens eines Stromanschlusses die am besten geeignete Technik. Darüber hinaus konnten alle drei klimarelevanten Spurengase erfasst werden, die Kosten waren sehr niedrig und der Einsatz unter allen Wetterbedingungen war möglich.

Der für die Gasflussratenberechnung ausreichende Auswahlbereich von ein bis zwei Minuten zeigt in fast allen Fällen keine Sättigungseffekte. Somit ist die Linearität der Gaskonzentrationsänderung gegen die Zeit gegeben. Während der Messung des Netto-Ökosystem-Austausches (NEE) ist auf eine konstante PAR zu achten, da schon kleine Änderungen (*coefficient of variability* > 5 %) die Linearität der Gaskonzentrationsänderung stark beeinflussen.

Es konnte eine gute Übereinstimmung zwischen den aus den Messungen berechneten Flüssen und den modellierten Flüssen festgestellt werden. Es wurde auch ein signifikanter Zusammenhang zwischen den Modellparametern GPmax bzw. alpha und der überirdischen Biomasse beobachtet.

Das als extensives Grünland genutzte Niedermoor weist einen Netto-CO_2-Austausch inklusive Kohlenstoffimport und -export durch Düngung und Ernte im Mittel über die vier Jahre von 5.200 +/- 1.400 kg CO_2-C ha^{-1} a^{-1} auf, der angrenzende Acker hat eine ähnlich hohe Austauschrate. Die Landnutzungsform und -intensität war damit nicht als entscheidender Einflussfaktor zu identifizieren. Ein Literaturvergleich zeigte, dass der Wasserpegel für eine Ackerfläche relativ hoch, und die NEE relativ niedrig ist. Die Emissionen von Ackerflächen können also verringert werden, indem der Wasserpegel erhöht wird. Der Jahresgang der CO_2-Austauschraten wird stark durch die landwirtschaftlichen Maßnahmen, wie z.B. Anzahl und Zeitpunkte der Grünlandschnitte beeinflusst. Die N_2O-Emissionen der Ackerfläche sind aufgrund der Stickstoffdüngung (Gülledüngung) mit 1,45 +/ 0,62 kg N_2O-N ha^{-1} a^{-1} im Mittel höher als die der Grünlandfläche (0,56 +/- 0,37 kg N_2O-N ha^{-1} a^{-1} im Mittel). Die Methan-Emissionen sind gering, da der Wasserpegel deutlich unter Flur ansteht. Die Netto-Kolenstoff-Bilanz (NECB) wird fast ausschließlich vom NEE inklusive Kohlenstoff-Import und -Export durch Dünger und Ernte bestimmt (5.200 +/- 1.400 kg CO_2-C ha^{-1} a^{-1} im Mittel der Grünlandfläche). Dasselbe trifft auf das GWP100 zu (19.000 +/- 5.000 kg CO_2-Äq. ha^{-1} a^{-1} im Mittel der Grünlandfläche) und ist daher auch kaum unterschiedlich auf der Acker- und der Grünlandvariante. Die Variabilität der monatlich und jährlich akkumulierten Gasflussraten zwischen den Jahren ist groß. Änderungen der Landbewirtschaftung können kurzfristig das Gasaustauschverhalten stark modifizieren. Es ist sinnvoll mehrjährige Messungen und ein genaues Monitoring der Landbewirtschaftung durchzuführen. Da auch im Winter ein maßgeblicher Gasaustausch stattfindet, sollten Messungsprogramme ganzjährig angelegt sein.

Die Netto-CO_2-Emissionen inklusive Kohlenstoffimport und -export durch Düngung und Ernte von den tief entwässerten ackerbaulich genutzten Varianten (Hochmoor-Schwarzkultur, Hochmoor-Sanddeckkultur und Anmoor-Sanddeckkultur) unterscheiden sich nicht. Zwar zeigt der jährliche Verlauf des CO_2-Austausches große Unterschiede durch unterschiedliche Vegetation und landwirtschaftliche Maßnahmen, aber jährlich kumuliert sind kaum Differenzen zu beobachten. Im Mittel reichen die Emissionen von 5.300 +/- 2.600 bis 6.500

+/- 110 kg CO_2-C ha^{-1} a^{-1}. Extensives Grünland auf Anmoor-Sanddeckkultur hat geringere Emissionen: 3.700 +/- 631 kg CO_2-C ha^{-1} a^{-1} im Mittel. Höchste N_2O-Emissionen aus den Ackerflächen sind bei einem wassergefüllten Porenvolumen (wfps) zwischen 55 und 80 % zu beobachten. Im Mittel reichen die jährlichen Emissionen auf den Ackerflächen von 16 +/- 9 bis 22 +/- 0,1 kg N_2O-N ha^{-1} a^{-1}, auf der Grünlandfläche betragen die Emissionen im Mittel nur 0,8 +/- 0,5 kg N_2O-N ha^{-1} a^{-1}. N_2O-Flussraten zeigen ebenfalls keine Abhängigkeit vom Bodentyp, aber von der Landnutzungsform. Alle vier Untersuchungsflächen sind in einzelnen Jahren kleine Senken für Methan. Im Mittel schwankt der Austausch um den Nullpunkt. Das GWP100 wird hauptsächlich bestimmt durch NEE sowie dem C-Import und -Export, allerdings kann unter Umständen auch N_2O einen hohen Anteil am GWP100 haben. Die mittleren GWP100-Bilanzen reichen von 26.800 +/- 9.500 bis 34.000 +/- 405 kg CO_2-Äq. ha^{-1} a^{-1} auf den Ackerflächen, die mittlere GWP100-Bilanz auf der Grünlandfläche beträgt 13.900 +/- 2.300 kg CO_2-Äq. ha^{-1} a^{-1}. Zur Reduzierung von Treibhausgasemissionen sind ein möglichst hoher Wasserpegelstand und eine extensive Landnutzung zu empfehlen.

Der NEE der wiedervernässten Hochmoore im Leegmoor wurde durch Witterung, Vegetationstyp, Phänologie und Wasserpegelstände beeinflusst. Die jährlichen Bilanzen reichen im Mittel von -949 +/- 225 bis -333 +/- 425 kg CO_2-C ha^{-1} a^{-1}. Die Torfmooskulturfläche zeigte im Mittel eine Aufnahme von -987 +/- 201 kg CO_2-C ha^{-1} a^{-1}. Der CH_4-Austausch hängt hauptsächlich vom Wasserpegelstand ab, aber auch von der Präsenz aerenchymhaltiger Vegetation. Bei einem mittleren Wasserpegelstand über Flur wurden CH_4-Emissionen von bis zu 242 +/- 50 kg CH_4-C ha^{-1} a^{-1} festgestellt. Es konnte ein Schwellenwert des Wasserpegelstandes determiniert werden, der sich wenige cm unter Flur befindet. Bei Überschreitung sind ein starker Anstieg der CH_4-Emissionen und eine Temperaturabhängigkeit zu verzeichnen. Das Leegmoor hat einen ähnlichen Treibhausgasaustausch wie natürliche Hochmoore. Sowohl das Leegmoor als auch die Torfmooskulturfläche akkumuliert netto Kohlenstoff. Aufgrund der hohen interannuellen Variabilität ist das Leegmoor in einigen Jahren eine Senke und in anderen Jahren eine Quelle, aber langfristig eine leichte Senke. Mehrjährige Messungen sind zu empfehlen. Hohe CH_4-Emissionen im Leegmoor, hervorgerufen durch stellenweise hohe Wasserpegelstände, haben zur Folge, dass die Fläche eine leichte GWP100-Quelle ist (im Mittel zwischen -1.051 +/- 1.560 und 3.878 +/- 687 kg CO_2-Äq. ha^{-1} a^{-1}), während die Torfmoosfläche weitgehend klimaneutral ist, da die Wasserpegelstände gesteuert werden und ganzjährig einige cm unter Flur anstehen. Dagegen sind alle Flächen leichte GWP500-Senken. Der Wasserpegelstand

und die Vegetation sind geeignete Bestimmungsfaktoren für den Gasaustausch. Entsprechend können als Maßnahmen für die Wiedervernässung ein Wasserpegelstand leicht unter Flur und die Adaptation torfbildender Vegetation empfohlen werden. Torfmooskultur ist eine klimafreundliche Alternative zu konventioneller Bewirtschaftung oder zu herkömmlicher Wiedervernässung.
Die Analyse des C-Gehaltes der Vegetation auf der Torfmooskulturfläche zeigte, dass die jährliche Netto-C-Bilanz mit dem jährlichen Zuwachs an Biomasse annähernd übereinstimmt.

Die Torfabbauflächen zeigen einen NEE im Mittel von 1.353 +/- 86 und 1.194 +/- 3 kg CO_2-C ha^{-1} a^{-1}. Der jährliche Verlauf der Gasflussraten zeigte eine Abhängigkeit von der Temperatur und dem Wasserpegelstand. Die höchsten Emissionen traten bei 20° C und -75 cm auf. CH_4- und N_2O-Flussraten waren sehr gering. Die höchsten N_2O-Emissionen sind bei einem wassergefüllten Porenvolumen von 60 % beobachtet worden.
Der größte Anteil des freigesetzten Kohlenstoffs stammt nicht von der Fläche, sondern vom geernteten Torf. Wenn der exportierte Torf in der Berechnung berücksichtigt wird, beträgt das GWP100 im Mittel 5.690 +/- 317 und 4.545 +/- 15 kg CO_2-Äq. ha^{-1} a^{-1}.

Die beim IPCC und im nationalen Inventar als Standardwerte angegebenen Emissionsfaktoren weichen von den Ergebnissen dieser Studie teilweise ab. Tabelle 7.1 enthält die aus den Untersuchungen dieser Arbeit ermittelten Emissionsfaktoren und GWP100-Bilanzen, welche auf Niedersachsen zutreffen.

Tab. 7.1: Emissionsfaktoren und GWP100-Bilanzen für unterschiedliche Landnutzungen

Landnutzung	Kohlendioxid kg CO_2-C ha^{-1} a^{-1}		Methan kg CH_4-C ha^{-1} a^{-1}		Lachgas kg N_2O-N ha^{-1} a^{-1}		GWP100-Bilanz t CO_2-Äq ha^{-1} a^{-1}	
tief entwässertes Ackerland	5940	+/- 1740	0,4	+/- 1,4	20	+/- 8	31	+/- 5
Grünland	4520	+/- 1170	-2	+/- 0,9	0,4	+/- 0,7	17	+/- 4
Torfabbau*	1270	+/- 116	1,3	+/- 1,7	0,9	+/- 1,3	5	
Torfabbau**	67000		-		-		244	
wiedervernässt	-714	+/- 843	138	+/- 110	0,1	+/- 0,5	2	+/- 4
Torfmooskultur	-41	+/- 284	24	+/- 10	0,1	+/- 0,2	1	+/- 1

*nur Torfabbaufläche, **Torfabbaufläche und exportierter Kohlenstoff durch Ernte

Forschungsbedarf

Es bestehen Zusammenhänge zwischen den Parametern der R_{eco}- und NEE-Modelle und Erklärungsparametern wie der oberirdischen Biomasse. Diese Kausalitäten sollten genauer untersucht werden, um die CO_2-Austauschmodellierung zu verbessern.

Auch für den CH_4- und N_2O-Austausch müssen Modelle entwickelt und verbessert werden. CH_4-Emissionen durch Gasbläschen sollten identifiziert werden. Für die N_2O-Modellierung könnte der *Fuzzy Logic*-Ansatz geeignet sein.

Bisher wurde die Gassammelhauben-Technik nur manuell in einem Kampagnen-orientierten Ansatz eingesetzt. Langzeitmessungen mit automatischen Hauben sind daher notwendig, z.B. in Form eines Monitorings, um die Modellierungsergebnisse zu validieren. Derzeit werden automatische Hauben beim ZALF (Müncheberg) und beim Thünen-Institut (Braunschweig) getestet.

Forschungsbedarf besteht auch darin, den zeitlichen Einfluss auf Emissionen von wiedervernässten Mooren festzustellen.

Summary

Organic soils are important carbon storages in the global carbon cycle. In a natural or near-natural state, organic soils take up carbon dioxide and are therefore CO_2 sinks. On the other hand, these soils are methane sources, i.e. CH_4 is released into the atmosphere. However, CH_4 emissions are some magnitudes lower than the accumulation rates of CO_2. In a drained state, the stored carbon is mineralized and huge amounts of CO_2 are emitted into the atmosphere. In addition, drained organic soils release nitrous oxide, which is mainly produced during nitrification and denitrification processes. CO_2, CH_4 and N_2O belong to the most important anthropogenic produced greenhouse gases.

In Germany, organic soils are widely drained and under agricultural use or peat extraction. Germany is the second largest emitter of climate relevant gases originating from organic soils in Europe, although only a very small part of the European organic soils are located in Germany. Meanwhile, rewetting schemes have converted a small part of drained areas in rewetted areas. Lower Saxony belongs to the states which are comparatively rich in organic soils.

Germany has committed itself to international agreements and is obliged to report regularly national greenhouse gas emissions in a National Inventory Report and to reduce emissions. Although drained organic soils are the largest national source for greenhouse gases outside the energy sector, Germany is nevertheless not able to report properly due to a lack of reliable data. The German definition of "peatland" is not in line with the definitions of "organic soil" according to the national inventory or the World Reference Base for Soil Resources.

This study quantified fluxes of CO_2, CH_4 and N_2O as well as the climate impact and the carbon balance of different ecosystems of organic soils in Lower Saxony and examined the relevant drivers for the gas exchange. The overall aim was the establishment of emission factors in dependency of climate, soil type, land use and land use intensity to supply the sections agriculture (sector 4) and land use, land use changes and forestry (sector 5) of the National Inventory Report with data. The results assist policy decision making and climate friendly rewetting schemes.

For this purpose, intense examination of twelve study sites representing for Lower Saxony typical combinations of organic soil type and land used type over a time period of two years and four months was conducted: cropland on peaty soil covered with sand, grassland on peaty

soil covered with sand, cropland on fen, grassland on fen, cropland on bog, cropland on bog covered with sand, peat extraction on bog (two sites), *Sphagnum* farming on bog, rewetted bog (three sites in Leegmoor which was rewetted in 1983). For the two fen sites, data of four and a half years was available.

The gas exchange was determined using a portable chamber system. The annual course of CO_2 fluxes was modeled in a high temporal resolution and divided into the two components ecosystem respiration and gross primary production. Finally, annual balances were established. Chamber measurements for CH_4 and N_2O determination were held at intervals of approximately two weeks with linear interpolation between the measurement dates. In addition, meteorological, soil scientific, hydrologic and vegetative site factors and driving parameters were determined. The net ecosystem carbon balance and the global warming potential for different time frames were calculated.
Portable chamber technique was the most appropriate method due to the great spatial variability of areas and the absence of electrical power. Moreover, all three greenhouse gases could be assessed, costs were low and measurements could be conducted under all weather conditions.
The chosen slope of gas concentration over time inside the chamber which is sufficient for flux calculation shows no saturation with only a very few exceptions. Hence, linearity is given. During measurement of the NEE, constancy of PAR is important, because only a small change (coefficient of variability > 5 %) can influence the linearity of the gas concentration change over time.
A proper fit of measured and modeled fluxes was observed. Also, a significant relation between the model parameters GP_{max} and alpha and the aboveground biomass was established.

The low intensity grassland on fen showed a net CO_2 exchange including carbon import and export through fertilizer and harvest of 5,200 +/- 1,400 kg CO_2-C ha^{-1} a^{-1} on average over the four years. The cropland on fen nearby was very similar. Land use type and intensity could not be identified as an influencing site factor. A literature review revealed that the water level was comparatively high, while the NEE was comparatively low. Emissions of cropland can therefore be reduced by decreasing water table depth. The annual course of the CO_2 exchange is driven by the agricultural management, i.e. number and dates of grass cuttings. The cropland showed with 1.45 +/ 0.62 kg N_2O-N ha^{-1} a^{-1} on average higher N_2O emissions than

the grassland site (0.56 +/- 0.37 kg N_2O-N ha^{-1} a^{-1} on average) due to application of nitrogen fertilizer (slurry). Methane emissions were low because the water table was well below ground surface. Net ecosystem carbon balance (NECB) consisted almost entirely of NEE including carbon import and export through fertilizer and harvest (5,200 +/- 1,400 kg CO_2-C ha^{-1} a^{-1} on average at the grassland site). The same applies for the GWP100 (19,000 +/- 5,000 kg CO_2-eq. ha^{-1} a^{-1} on average at the grassland site). The difference between the grassland and the cropland site is therefore also diminishingly small. The interannual variability of monthly cumulated and annual fluxes is great. Changes of land use management can strongly alter the gas exchange in the short term. It is useful to conduct measurements over several years and to monitor the land use management exactly. Since winter fluxes contribute to the overall fluxes, measurement programmes should cover the whole year.

The net CO_2 exchange including carbon import and export through fertilizer and harvest of the deeply drained cropland sites (cropland on peaty soil, cropland on bog and cropland on bog covered with sand) are very similar. The annual course of the CO_2 exchange shows great differences due to different vegetation and land use management, however annual cumulated differences were diminishingly small. On average, emissions range from 5,300 +/- 2,600 to 6,500 +/- 110 kg CO_2-C ha^{-1} a^{-1}. The low intensity grassland on peaty soil covered with sand showed lower emissions: 3,700 +/- 631 kg CO_2-C ha^{-1} a^{-1} on average. Highest N_2O emissions from the cropland sites occurred at water filled pore spaces (wfps) of 55 to 80 %. On average, emissions of the cropland sites ranged from 16 +/- 9 to 22 +/- 0.1 kg N_2O-N ha^{-1} a^{-1}, emissions of the grassland site amounted only to 0.8 +/- 0.5 kg N_2O-N ha^{-1} a^{-1}. N_2O fluxes showed also no relation to the soil type but to the land use type. All four sites are small sinks for methane during single years. On average, the exchange oscillated around zero. The GWP100 was mainly determined by the NEE including carbon import and export through fertilizer and harvest, however N_2O fluxes might account for a large proportion under certain circumstances. On average, GWP100 balances ranged from 26,800 +/- 9,500 to 34,000 +/- 405 kg CO_2-eq. ha^{-1} a^{-1} at the cropland sites, the averaged GWP100 balance of the grassland site was 13,900 +/- 2,300 kg CO_2-eq. ha^{-1} a^{-1}. In order to reduce greenhouse gas emissions, a high water level and a low intensity land use are recommended.

The NEE of the rewetted bogs in the Leegmoor was affected by weather conditions, vegetation type, phenology and water level. The annual balances ranged on average from -949 +/- 225 to -333 +/- 425 kg CO_2-C ha^{-1} a^{-1}. The *Sphagnum* farming site took up on average -

987 +/- 201 kg CO_2-C ha^{-1} a^{-1}. The CH_4 exchange depends mainly on water level but also on the presence of aerenchymous vegetation. Inundated sites showed CH_4 emissions of up to 242 +/- 50 kg CH_4-C ha^{-1} a^{-1}. A threshold value of the water level of a few cm below ground level was evident. Exceeding the threshold value, fluxes increased sharply and showed a relation to temperature. Leegmoor has a greenhouse gas exchange comparable to natural bogs. Leegmoor and the *Sphagnum* farming site accumulated both net carbon. Leegmoor is sometimes a sink and sometimes a source due to high interannual variability. However, in the long term Leegmoor is a sink. Several years` measurements are recommended. High CH_4 emissions in the Leegmoor, caused by a partially high water level have the consequence that the area is a small GWP100 source (on average between -1,051 +/- 1,560 and 3,878 +/- 687 kg CO_2-eq. ha^{-1} a^{-1}), while the *Sphagnum* farming site was largely climate neutral, because the water table was regulated and kept a few cm below ground surface. All sites were GWP500 sinks. Water level and vegetation are appropriate determinants for the greenhouse gas exchange. Therefore, recommended measures for rewetting are to keep the water level below ground surface and to introduce typical peat-building vegetation. *Sphagnum* farming is a climate friendly alternative to conventional farming and rewetting.
The analysis of the carbon content of the vegetation at the *Sphagnum* farming site proved that the annual net carbon balance agreed with the annual growth of the biomass.

The two peat extraction sites showed a NEE of 1,353 +/- 86 and 1,194 +/- 3 kg CO_2-C ha^{-1} a^{-1}, on average. The annual pattern of the gas fluxes correlates with temperature and water level. Highest emissions occurred at a temperature of 20 °C and a water level depth of 75 cm below ground surface. CH_4 and N_2O fluxes were very low at both sites. Highest N_2O emissions were detectable at a water filled pore space of 60 %.
The majority of the released carbon through peat extraction is attributable to the harvested peat. If this peat is considered in the calculations, the GWP100 would amount to 70,000 kg CO_2-eq. ha^{-1} a^{-1}, on average.

The default values of national emission factors of the IPCC and in the national inventory partially deviate from the results of this study. Table 8.1 shows emission factors and GWP100 balances identified in the investigations of this study and which are valid for Lower Saxony.

Tab. 8.1: Emission factors and GWP100 balances for different land uses

Land use	carbon dioxide kg CO_2-C ha^{-1} a^{-1}		methane kg CH_4-C ha^{-1} a^{-1}		nitrous oxide kg N_2O-N ha^{-1} a^{-1}		GWP100 balance t CO_2-eq ha^{-1} a^{-1}	
deeply drained cropland	5940	+/- 1740	0.4	+/- 1.4	20	+/- 8	31	+/- 5
grassland	4520	+/- 1170	-2	+/- 0.9	0.4	+/- 0.7	17	+/- 4
peat extraction*	1270	+/- 116	1.3	+/- 1.7	0.9	+/- 1.3	5	
peat extraction**	67000		-		-		244	
rewetted	-714	+/- 843	138	+/- 110	0.1	+/- 0.5	2	+/- 4
Sphagnum farming	-41	+/- 284	24	+/- 10	0.1	+/- 0.2	1	+/- 1

*only extraction site, **extraction site and exported carbon through harvest

<u>Need for further research</u>

There are relationships between the parameters of the R_{eco} and NEE models and site parameters, such as above ground biomass. These relationships need further research to improve modelling of the CO_2 exchange.

Also, exchange models for the CH_4 and N_2O need to be developed and improved. CH_4 emissions through bubbles need to be captured. For the N_2O exchange, modelling with the fuzzy logic-approach might be an appropriate method.

Currently, the chamber measurements are only manually applied in a campaign-oriented way. Long-term measurements with automatic chambers are necessary, for example as a monitoring, to validate the models. At present, the ZALF and the Thünen-Institute in Braunschweig test automatic chambers.

Further research is needed to examine the temporal influence on emissions of rewetted peatlands.

Anhang

Anhang A: Bodenprofile

Aufnahmesituation

Profilnr.	TG2D1	Hochwert	5818427
Datum	07.09.2010	Rechtswert	451317
Name des Bearbeiters	Höper/Roßkopf	Höhe über NN	40
TK-Nr.			
Neigung	No	Nutzung	Acker
Exposition		Vegetation	Mais
Reliefformtyp	TS	Witterung	WT3
Reliefposition	Z	Bodenorganismen	
Bodenabtrag/-auftrag		anthr. Veränderungen	DG

Horizontbezogene Daten

Tiefe von [cm]	Tiefe bis [cm]	Verlauf	Torfart / Muddeart	ZG1	ZG2	Farbe	Humus	CaCo3	Hydrom. Merkmale	Gefüge	pH-Wert	Durch-wurzelung	sonstige Merkmale	Horizont	Substratart
0	10		Ha	10	10	10YR2/1	h7	C0		kru	4,1	W5	S,f1	nHvp	og-Ha
10	30		Ha	10	10	10YR2/1	h7	C0		sub	4,06	W5	S,f1	nHa	og-Ha
30	50		Hnr	4	5	10YR2/2	h7	C0		sub		Wf4	Bls	nHw	og-Hn
50	140		Hnr	5	6	10YR3/2	h7	C0				Wf2	Bls	nHr	og-Hn

Profilkennzeichnung

Bodentyp	Substrattyp	Bodenform	HGMT	Geologie	GWS
KVn	og-Hn	KV:og-Hn	VL		-30

Bodenansprache *cropland site* (ch.2)

Aufnahmesituation

Profilnr.	TG2D2	Hochwert	5818412
Datum	07.09.2010	Rechtswert	451319
Name des Bearbeiters	Höper/Roßkopf	Höhe über NN	40
TK-Nr.			
Neigung	No	Nutzung	Grünland
Exposition		Vegetation	Wiese
Reliefformtyp	TS	Witterung	WT3
Reliefposition	Z	Bodenorganismen	
Bodenabtrag/-auftrag		anthr. Veränderungen	DG (04.10) neu angelegt

Horizontbezogene Daten

Tiefe von [cm]	Tiefe bis [cm]	Verlauf	Torfart / Muddeart	ZG1	ZG2	Farbe	Humus	CaCo3	Hydrom. Merkmale	Gefüge	pH-Wert	Durch-wurzelung	sonstige Merkmale	Horizont	Substratart
0	10		Ha	10	10	10YR3/1	h7	C0		kru	5,84	W5	S,f1	nHv	og-Ha
10	30		Ha	10	10	10YR3/1	h7	C0		sub	5,62	W4	S,f1	nHa	og-Ha
30	45		Hnr	5	6	10YR2/2	h7	C0		sub	5,68	Wf4	Bl,Bp	nHw1	og-Hn
45	60		Hnr	5	5	10YR3/1	h7	C0			5,62	Wf2	Ble, Bb,By	nHw2	og-Hn
60	140		Hnr	5	6	10YR3/2	h7	C0			6,02		By	nHr1	og-Hnr
140	160		Hnr	7	8	10YR2/1	h7	C0			6,48			nHr2	og-Hnr
160	170		Fhl			5Y3/2	h7	C4			6,49			fFr1	og-Fhl
170	195		Fhl			5Y4/1	h7	C4			6,64			fFr2	og-Fhl
195	230		Fmu			5Y3/2	h1	C0			6,88		bae:Fms	IIfFr1	fl-Fmu
230	270		Fms			5Y3/2	h1	C4			6,84		gS	IIIfFr	fl-Fms
270	280		fSms			5Y5/1	h1	C1			6,74		gS,f1	Gr	gf-Ss

Profilkennzeichnung

Bodentyp	Substrattyp	Bodenform	HGMT	Geologie	GWS
KVn	og-Hn///og-Fhl///fl-Fmu	KV: og-Hn///og-Fhl///fl-Fms	VL		-60

Bodenansprache *grassland site* (ch.2)

Aufnahmesituation

Profilnr.	TG2O1	Hochwert	5818427
Datum	08.09.2010	Rechtswert	451315
Name des Bearbeiters	Höper/Roßkopf	Höhe über NN	40
TK-Nr.			
Neigung	No	Nutzung	Acker
Exposition		Vegetation	WWE
Reliefformtyp	TS	Witterung	WT4
Reliefposition	Z	Bodenorganismen	
Bodenabtrag/-auftrag	Sandauftrag	anthr. Veränderungen	Sandauftrag

Horizontbezogene Daten

Tiefe von [cm]	Tiefe bis [cm]	Verlauf	Torfart / Muddeart	ZG1	ZG2	Farbe	Humus	CaCo3	Hydrom. Merkmale	Gefüge	pH-Wert	Durch-wurzelung	sonstige Merkmale	Horizont	Substratart
0	10	di,e	fSms			10YR4/2	h6	C0		ein	4,91	W4		Aap1	om-ss
10	30	sc, we	fSms			10YR3/2	h6	C0		ein	4,74	W4		Aap2	om-ss
30	55		Ha,S	10	10	10YR2/2	h7	C0	ed,dif;S,fl	sub	4,8		S.bae	nHa	og-Ha
55	70		Ha,S	10	10	10YR2/1	h7	C0	ed.dif	pol	4,31		Be,fl	nHaw	og-Ha
70	90		fSms			10YR6/2	h1	C0	ed, fl,f4	ein	4,44			Gor	gf-ss
90	100		fSms					C0						Gr	gf-ss

Profilkennzeichnung

Bodentyp	Substrattyp	Bodenform	HGMT	Geologie	GWS

Bodenansprache O1 (ch.3)

Aufnahmesituation

Profilnr.	TG2O2	Hochwert	5812336
Datum	08.09.2010	Rechtswert	452732
Name des Bearbeiters	Höper/Roßkopf	Höhe über NN	38
TK-Nr.			
Neigung	No	Nutzung	Grünland
Exposition		Vegetation	Wiese
Reliefformtyp	TS	Witterung	WT4
Reliefposition	Z	Bodenorganismen	Lu
Bodenabtrag/-auftrag	Sandauftrag	anthr. Veränderungen	Sandauftrag

Horizontbezogene Daten

Tiefe von [cm]	Tiefe bis [cm]	Verlauf	Torfart / Muddeart	ZG1	ZG2	Farbe	Humus	CaCo3	Hydrom. Merkmale	Gefüge	pH-Wert	Durch-wurzelung	sonstige Merkmale	Horizont	Substratart
0	10	di,e	fSms			10YR3/2	h6	C0		ein	5,26	W6		Aap1	om-ss
10	30	sc, we	fSms			10YR3/2	h6	C0		ein	4,75	W4		Aap2	om-ss
30	40		Ha,S	10	10	10YR3/2	h7	C0	ed,dif;S,fl	sub	4,9	W2	S,fl	nHa	og-Ha
40	70		Ha,S	10	10	10YR7/3	h7	C0	ed.dif	pol	4,88	W2		nHaw	og-Ha
70	90		fSms			10YR6/2	h1	C0	ed, fl,f4	ein	4,88;ed, fl,f4			Gor	gf-ss
90	100		fSms					C0						Gr	gf-ss

Profilkennzeichnung

Bodentyp	Substrattyp	Bodenform	HGMT	Geologie	GWS

Bodenansprache O2 (ch.3)

Aufnahmesituation

Profilnr.	TG7S1	Hochwert	5872449
Datum	07.09.2010	Rechtswert	402164
Name des Bearbeiters	Höper/Roßkopf	Höhe über NN	6
TK-Nr.			
Neigung	No	Nutzung	Renaturierung
Exposition		Vegetation	Zwischefrucht Raps,WWE
Reliefformtyp	TS	Witterung	WT3
Reliefposition	Z	Bodenorganismen	
Bodenabtrag/-auftrag	evtl. Abtorfung, Sandauftrag	anthr. Veränderungen	Sanddeckkultur

Horizontbezogene Daten

Tiefe von [cm]	Tiefe bis [cm]	Verlauf	Torfart / Muddeart	ZG1	ZG2	Farbe	Humus	CaCo3	Hydrom. Merkmale	Gefüge	pH-Wert	Durch-wurzelung	sonstige Merkmale	Horizont	Substratart
0	20	de,w	fSms			10YR2/1	h4	C0		ein	5	Wf4		jAp	om-ss
20	50	di,e	Hh			7,5YR2,5/2	h7	C0		pla	3,74	Wf5	Bls,F3;Be,F1;	hHw	og-Hh
50	58		Hnp			7,5YR2,5/2	H7	C0		pla				nHw	og-Hn
58	60	di,e	Fmu			10YR3/1	h7	C0			4,01			fFr	fl-Fmu
60	70	di,e	fSms			10YR3/2	h7	C0		ein	4,63			Ghw	gf-ss
70	85		fSms			10YR6/4	h1	C0		ein	4,8		Wr	Gro	gf-ss

Profilkennzeichnung

Bodentyp	Substrattyp	Bodenform	HGMT	Geologie	GWS

Bodenansprache S1 (ch.3)

Aufnahmesituation

Profilnr.	TG7S2	Hochwert	5872428
Datum	07.09.2010	Rechtswert	402245
Name des Bearbeiters	Höper/Roßkopf	Höhe über NN	3
TK-Nr.			
Neigung	No	Nutzung	Acker
Exposition		Vegetation	Kartoffel
Reliefformtyp	TS	Witterung	WT3
Reliefposition	Z	Bodenorganismen	
Bodenabtrag/-auftrag	Abtorfung, Sandauftrag	anthr. Veränderungen	Abtorfung, DG, Sandauftrag

Horizontbezogene Daten

Tiefe von [cm]	Tiefe bis [cm]	Verlauf	Torfart / Muddeart	ZG1	ZG2	Farbe	Humus	CaCo3	Hydrom. Merkmale	Gefüge	pH-Wert	Durch-wurzelung	sonstige Merkmale	Horizont	Substratart
0	20	de,we	Ha,fs			10YR3/3	h7	C0		kru	4,1	W5		Hvp	og-Ha
20	45	de,we	Ha			10YR2/1	h7	C0		pla	4,06	W4	Bls	hHw	og-Ha
45	50	di,e	Fmu			10YR3/1	H6	C0		pla				fFw	fl-Fmu
50	65	di,e	fSms			10YR3/1	h3	C0						Gw	gf-ss
65	85		fSms			10YR6/3	h1 (bae)	C0		ein	3,97		eo+eh,f1,f3,rb,dif,f8	Gro	gf-ss

Profilkennzeichnung

Bodentyp	Substrattyp	Bodenform	HGMT	Geologie	GWS

Bodenansprache S2 (ch.3)

Aufnahmesituation

Profilnr.	TG7L1	Hochwert	5874182
Datum	06.09.2010	Rechtswert	401778
Name des Bearbeiters	Höper/Roßkopf	Höhe über NN	
TK-Nr.			
Neigung	No	Nutzung	Renaturierung
Exposition		Vegetation	Pfeifengras
Reliefformtyp	TS	Witterung	WT3
Reliefposition	Z	Bodenorganismen	
Bodenabtrag/-auftrag	bis 1986 Abtorfung	anthr. Veränderungen	bis 1986 Abtorfung, Wiedervernässung

Horizontbezogene Daten

Tiefe von [cm]	Tiefe bis [cm]	Verlauf	Torfart / Muddeart	ZG1	ZG2	Farbe	Humus	CaCo3	Hydrom. Merkmale	Gefüge	pH-Wert	Durch-wurzelung	sonstige Merkmale	Horizont	Substratart
0	10	e	Ha	10	10	10YR2/1	h7	C0		kru	3,37	W4	S,f1	hHv	og-Ha
10	50	e	Hhs	8	9	10YR2/2	h7	C0			3,3	W3		hHw	og-Hh
50	80	e	Hhs	9	9	10YR2/2	h7	C0		sub	3,48	W3	Be,f1	hHr1	og-Hh
80	105		Hhs	9	9	10YR2/2	h7	C0			3,62	W3	Bl, f1	hHr2	og-Hh
105	130		Hhs	9	9	7,5YR2,5/3	h7	C0			4,03		Bls, f4	hHr3	og-Hh
130	160		Hhs	9	9	7,5YR3/3	h7	C0			4,09			hHr4	og-Hh
160	170		fS			10YR2/2	h6	C0			4,21			Ghr	fg-ss

Profilkennzeichnung

Bodentyp	Substrattyp	Bodenform	HGMT	Geologie	GWS
KHn	og-Hh///fg-ss	KHn:og-Hh///fg-ss	RM		40

Bodenansprache *Molinia site* (ch.4)

Aufnahmesituation

Profilnr.	TG7L2	Hochwert	5874178
Datum	06.09.2010	Rechtswert	401731
Name des Bearbeiters	Höper/Roßkopf	Höhe über NN	
TK-Nr.			
Neigung	No	Nutzung	Renaturierung
Exposition		Vegetation	Wollgras, Sphagnum
Reliefformtyp	TS	Witterung	WT3
Reliefposition	Z	Bodenorganismen	
Bodenabtrag/-auftrag	bis 1986 Abtorfung	anthr. Veränderungen	bis 1986 Abtorfung, Wiedervernässung

Horizontbezogene Daten

Tiefe von [cm]	Tiefe bis [cm]	Verlauf	Torfart / Muddeart	ZG1	ZG2	Farbe	Humus	CaCo3	Hydrom. Merkmale	Gefüge	pH-Wert	Durch-wurzelung	sonstige Merkmale	Horizont	Substratart
0	20		Hhe	1	1	10YR3/1	h7	C0		kru	3,67		Bs,f4	hHr	og-Hh
20	50		Hhs	9	9	10YR3/2	h7	C0			4,01	Wf1	Wf1; Be,f1	fHv-hHr	og-Hh
50	95		Hhs	9	9	10YR2/2	h7	C0		sub	3,66	Wf1	Wf1; Be,f1	hHr	og-Hh
95	110		fS			10YR3/2	h6	C0			3,6		Be,f1	fBh-Gr	fg-ss
110	140		fS			10YR3/2	h2	C0			4,36			fBsh-Gr	fg-ss

Profilkennzeichnung

Bodentyp	Substrattyp	Bodenform	HGMT	Geologie	GWS
HHn	og-Hh//fg-ss	HHn:og-Hh//fg-ss	RM		0

Bodenansprache *Eriophorum site* (ch.4)

Aufnahmesituation

Profilnr.	TG7L3	Hochwert	5874178
Datum	06.09.2010	Rechtswert	401731
Name des Bearbeiters	Höper/Roßkopf	Höhe über NN	6
TK-Nr.			
Neigung	No	Nutzung	Renaturierung
Exposition		Vegetation	Wollgras, Sphagnum
Reliefformtyp	TS	Witterung	WT3
Reliefposition	Z	Bodenorganismen	
Bodenabtrag/-auftrag	bis 1986 Abtorfung	anthr. Veränderungen	bis 1986 Abtorfung, Wiedervernässung

Horizontbezogene Daten

Tiefe von [cm]	Tiefe bis [cm]	Verlauf	Torfart / Muddeart	ZG1	ZG2	Farbe	Humus	CaCo3	Hydrom. Merkmale	Gefüge	pH-Wert	Durch-wurzelung	sonstige Merkmale	Horizont	Substratart
0	20		Hhs	1	1	10YR6/4	h7	C0		kru	3,67		Be,f1	hHr	og-Hh
20	50		Hhs	9	9	10YR3/2	h7	C0			4,01	Wf1	Be,f1	fHv-hHr	og-Hh
50	95		Hhs	9	9	10YR2/2	h7	C0		sub	3,66	Wf1	Be,f1	hHr	og-Hh
95	110		fS			10YR3/2	h6	C0			3,6		Be,f1	fBh-Gr	fg-ss
110	140		fS			10YR3/2	h2	C0			4,36			fBsh-Gr	fg-ss

Profilkennzeichnung

Bodentyp	Substrattyp	Bodenform	HGMT	Geologie	GWS
HHn	og-Hh//fg-ss	KHn:og-Hh//fg-ss	RM		0

Bodenansprache *S. cuspidatum site* (ch.4)

Aufnahmesituation

Profilnr.	TG7W3	Hochwert	5881095
Datum	06.09.2010	Rechtswert	409416
Name des Bearbeiters	Höper/Roßkopf	Höhe über NN	
TK-Nr.			
Neigung	No	Nutzung	Torfmooskultur
Exposition		Vegetation	Sphagnum phallax
Reliefformtyp	TS	Witterung	WT3
Reliefposition	Z	Bodenorganismen	
Bodenabtrag/-auftrag	Abtorfung	anthr. Veränderungen	Abtorfung, Entwässerung

Horizontbezogene Daten

Tiefe von [cm]	Tiefe bis [cm]	Verlauf	Torfart / Muddeart	ZG1	ZG2	Farbe	Humus	CaCo3	Hydrom. Merkmale	Gefüge	pH-Wert	Durch-wurzelung	sonstige Merkmale	Horizont	Substratart
0	9	e	Hhs	1	1	10YR7/4	h7	C0		kru	3,85		Bi	hHr1	og-Hh
9	15	e	Hhs	3	4	10YR2/2	h7	C0			3,98		Bi	hHr2	og-Hh
15	45	e	Hhs	9	9	10YR3/6	h7	C0			4,11		Be,f2	hHr3	og-Hh
45	100		Hhs	9	9	10YR2/2	h7	C0			4,35		Be, f1	hHr4	og-Hh

Profilkennzeichnung

Bodentyp	Substrattyp	Bodenform	HGMT	Geologie	GWS
HHn	og-Hh	HHn:og-Hh	RM		0

Bodenansprache *S. papillosum site* (ch.4)

Aufnahmesituation

Profilnr.	TG7W1	Hochwert	5881166
Datum	07.09.2010	Rechtswert	409424
Name des Bearbeiters	Höper/Roßkopf	Höhe über NN	
TK-Nr.			
Neigung	No	Nutzung	Abtorfung
Exposition		Vegetation	
Reliefformtyp	TS	Witterung	WT3
Reliefposition		Bodenorganismen	
Bodenabtrag/-auftrag	Abtorfung	anthr. Veränderungen	Abtorfung, Entwässerung

Horizontbezogene Daten

Tiefe von [cm]	Tiefe bis [cm]	Verlauf	Torfart / Muddeart	ZG1	ZG2	Farbe	Humus	CaCo3	Hydrom. Merkmale	Gefüge	pH-Wert	Durch-wurzelung	sonstige Merkmale	Horizont	Substratart
0	10	e	Hhs	4	4	10YR2/2	h7	C0		kru	3,83		Bs	hHv	og-Hh
10	30		Hhs	5	5	10YR2/2	h7	C0			4,76		Bs,f5	hHw	og-Hh
30	90		Hhs	9	9	10YR3/6	h7	C0			3,99		Bs,f4; Bim, f1; Be,f1	hHr1	og-Hh
90	200		Hhs	9	9	10YR3/2	h7	C0					Bs, f4	hHr2	og-Hh
200	240		Hha	8	8	10YR3/3	h7	C0					Bls	hHr3	og-Hh
240	260		fSms				h1	C0						Gr	fg-ss

Profilkennzeichnung

Bodentyp	Substrattyp	Bodenform	HGMT	Geologie	GWS
KHn	og-Hh///fg-ss	KHn:og-Hh///fg-ss	RM		200

Bodenansprache *young site* (ch.5)

Aufnahmesituation

Profilnr.	TG7W2	Hochwert	5881094
Datum	06.09.2010	Rechtswert	409407
Name des Bearbeiters	Höper/Roßkopf	Höhe über NN	
TK-Nr.			
Neigung	No	Nutzung	Abtorfung
Exposition		Vegetation	
Reliefformtyp	TS	Witterung	WT3
Reliefposition		Bodenorganismen	
Bodenabtrag/-auftrag	Abtorfung	anthr. Veränderungen	Abtorfung, Entwässerung

Horizontbezogene Daten

Tiefe von [cm]	Tiefe bis [cm]	Verlauf	Torfart / Muddeart	ZG1	ZG2	Farbe	Humus	CaCo3	Hydrom. Merkmale	Gefüge	pH-Wert	Durch-wurzelung	sonstige Merkmale	Horizont	Substratart
0	10	e, de	Hhs	3	4	10YR2/2	h7	C0		kru	3,86		Be,f1	hHv	og-Hh
10	25	e	Hhs	9	9	10YR3/3	h7	C0			4,1		Be,f5	hHw	og-Hh
25	45		Hhs	9	9	10YR3/4	h7	C0			4,15		Be,f1; Bim, f1	hHr1	og-Hh
45	160		Hhs	9	9	10YR3/3	h7	C0			4,23		Be, f1,Bls	hHr2	og-Hh
160	195		Hha	7	8	10YR3/3	h7	C0					Bls, Be	hHr3	og-Hh
195	205		fSms			10YR4/2	h1	C0						Gr	fg-ss

Profilkennzeichnung

Bodentyp	Substrattyp	Bodenform	HGMT	Geologie	GWS
KHn	og-Hh///fg-ss	KHn:og-Hh///fg-ss	RM		200

Bodenansprache *old site* (ch.5)

Grassland site (ch.2) Profil (Fotos: C. Beyer)

S1 (oben links), S2 (unten links) und O1 (rechts) (ch.3) Profile (Fotos: C. Beyer)

L2 Eriophorum site (ch.4) Profil (Fotos: C. Beyer)

young site (links) und *old site* (ch.5) (rechts) Profile (Fotos: C. Beyer)

S. papillosum site (ch.4) Profil (Fotos: C. Beyer)

Anhang B: Vegetation


cropland site (links), *grassland site* (rechts) (ch.2) (Fotos: C. Beyer)


O1 2010 (links), O1 2011 (rechts) (ch.3) (Fotos: C. Beyer)

O2 (ch.3) (Foto: C. Beyer)


S1 2010 (links), S1 2011 (rechts) (ch.3) (Fotos: C. Beyer)

S2 2010 (links), S2 2011 (rechts) (ch.3) (Fotos: C. Beyer)

Molinia site (links), *Eriophorum site* (rechts) (ch.4) (Fotos: C. Beyer)

S. cuspidatum site (links), *S. papillosum site* (rechts) (ch.4) (Fotos: C. Beyer)

young site (links), *old site* (ch.5) (rechts) (Fotos: C. Beyer)

Vegetationsliste

Variante	Art	Londo
cropland site (ch.1)	Zea mays	2
Rahmen 1	Echinochloa crus-galli	r1
	Chenopodium album	r1
cropland site (ch.1)	Zea mays	3
Rahmen 2	Echinochloa crus-galli	r1
	Chenopodium album	r1
cropland site (ch.1)	Zea mays	2
Rahmen 3	Echinochloa crus-galli	r1
	Chenopodium album	r1
grassland site (ch.1)	Lolium perenne	3
Rahmen 1	Festuca pratensis	3
	Poa trivialis	p4
	Agrostis stolonifera	p2
	Rumex acetosa	1
grassland site (ch.1)	Lolium perenne	3
Rahmen 2	Festuca pratensis	3
	Poa trivialis	1
	Agrostis stolonifera	r1
	Rumex acetosa	
grassland site (ch.1)	Lolium perenne	4
Rahmen 3	Festuca pratensis	3
	Poa trivialis	1
	Agrostis stolonifera	r1
	Rumex acetosa	
S1 (ch.2)	Zea mays	7
Rahmen 1	Chenopodium album	p2
	Galinsoga parviflora	p2
S1 (ch.2)	Zea mays	7
Rahmen 2	Chenopodium album	p2
	Galinsoga parviflora	p2
S1 (ch.2)	Zea mays	6
Rahmen 3	Chenopodium album	p4
	Galinsoga parviflora	1-
S2 (ch.2)	Zea mays	3
Rahmen 1	Chenopodium album	p2
	Galinsoga parviflora	r2
	Poa annua	r4
	Solanum tuberosum	r2
	Echinochloa crus-galli	
S2 (ch.2)	Zea mays	3
Rahmen 2	Chenopodium album	r2
	Galinsoga parviflora	p2
	Poa annua	1-
	Solanum tuberosum	
	Echinochloa crus-galli	
S2 (ch.2)	Zea mays	4
Rahmen 3	Chenopodium album	p4
	Galinsoga parviflora	p2
	Poa annua	1-
	Solanum tuberosum	
	Echinochloa crus-galli	r2
Eriophorum site (ch.3)	Eriophorum angustifolium	7
Rahmen 1	Molinia	1-
	Sphagnum cuspidatum	3
Eriophorum site (ch.3)	Eriophorum angustifolium	8
Rahmen 2	Molinia	1-
	Sphagnum cuspidatum	2
	Betula pendula	r4
Eriophorum site (ch.3)	Eriophorum angustifolium	8
Rahmen 3	Molinia	p2
	Sphagnum cuspidatum	2
S. cuspidatum site	Sphagnum cuspidatum	10
(ch.3) Rahmen 1	Eriophorum angustifolium	3
S. cuspidatum site	Sphagnum cuspidatum	10
(ch.3) Rahmen 2	Eriophorum angustifolium	2
	Molinia	p2
S. cuspidatum site	Sphagnum cuspidatum	10
(ch.3) Rahmen 3	Eriophorum angustifolium	3
	Molinia	1-

Variante	Art	Londo
O1 (ch.3)	Zea mays	2
Rahmen 1	Chenopodium album	r2
	Echinochloa crus-galli	r2
	Persicaria lapathifolia	r1
O1 (ch.3)	Zea mays	3
Rahmen 2	Chenopodium album	r2
	Echinochloa crus-galli	r1
	Persicaria lapathifolia	r1
O1 (ch.3)	Zea mays	3
Rahmen 3	Chenopodium album	r1
	Echinochloa crus-galli	r1
	Persicaria lapathifolia	r1
O2 (ch.3)	Lolium perenne	3
Rahmen 1	Festuca pratensis	3
	Holcus lanatus	2
	Alopecurus pratensis	1
	Lamium album	1
	Anthriscus sylvestris	p4
	Melissa officinalis	p4
	Bromus hordeaceus	p2
O2 (ch.3)	Lolium perenne	3
Rahmen 2	Festuca pratensis	3
	Holcus lanatus	2
	Alopecurus pratensis	2
	Lamium album	1
	Anthriscus sylvestris	r2
	Melissa officinalis	1
	Bromus hordeaceus	r2
O2 (ch.3)	Lolium perenne	3
Rahmen 3	Festuca pratensis	3
	Holcus lanatus	2
	Alopecurus pratensis	2
	Lamium album	p4
	Anthriscus sylvestris	p4
	Melissa officinalis	p2
	Bromus hordeaceus	r2
Molinia site (ch.3)	Molinia	9
Rahmen 1	Erica tetralis	1
	Sphagnum cuspidatum	m2
Molinia site (ch.3)	Molinia	9
Rahmen 2	Erica tetralis	1+
	Sphagnum cuspidatum	m2
	Eriophorum angustifolium	p2
Molinia site (ch.3)	Molinia	7
Rahmen 3	Erica tetralis	2
	Sphagnum cuspidatum	m4
	Eriophorum angustifolium	1-
S. papillosum site	Sphagnum papillosum	6
(ch.3)	Sphagnum cuspidatum	p1
Rahmen 1	Sphagnum palustre	2
	Sphagnum fallax	1-
	Eriophorum angustifolium	2
	Erica tetralix	10+
	Betula pendula	r2
	Drosera	r1
S. papillosum site	Sphagnum papillosum	9
(ch.3)	Sphagnum cuspidatum	p2
	Sphagnum palustre	1
Rahmen 2	Sphagnum fallax	p2
	Eriophorum angustifolium	2
	Erica tetralix	p2
	Drosera	r1
S. papillosum site	Sphagnum papillosum	9
	Sphagnum cuspidatum	p1
(ch.3)	Sphagnum palustre	1
Rahmen 3	Sphagnum fallax	p2
	Eriophorum angustifolium	1+
	Erica tetralix	3
	Juncus effusus	r1
	Drosera	r1
	Fungi	r1

Erklärung

Hiermit erkläre ich gemäß § 31 Abs. 7 der Rahmenprüfungsordnung, dass ich die vorliegende Arbeit mit dem Titel "Greenhouse gas exchange of organic soils in Northwest Germany (Effects of organic soil cultivation, agricultural land use and restoration)" selbständig verfasst, noch nicht anderweitig für Prüfungszwecke vorgelegt, keine anderen als die angegebenen Quellen oder Hilfsmittel benutzt sowie wörtliche und sinngemäße Zitate als solche gekennzeichnet habe.

Bremen, den 07. Juli 2014

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Unterschrift