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Hendriks, D.M.D.

2009

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citation for published version (APA)

Hendriks, D. M. D. (2009). *Integrated observations of greenhouse gas budgets at the ecosystem level: changing environment and management practices in peat meadows*. Vrije Universiteit.

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6

Vegetation as indicator for methane emissions, carbon dioxide fluxes and greenhouse gas balances from peat land

This chapter was submitted to *Ecohydrology* as Hendriks, D.M.D., Van Huissteden, J., Dolman, A.J., 2009. Vegetation as indicator for methane emissions, carbon dioxide fluxes and greenhouse gas balances from peat land.

Abstract

Peat areas are potential hotspots of CH₄ and CO₂ emissions depending on the conditions. Understanding ecosystem functioning as well as the inherent vegetation characteristics provides a key to estimate CH₄ and CO₂ flux patterns and GHG balances of peat areas. Also, the response of vegetation to management and climate change is indicative for changes in carbon fluxes and GHG balances. In this article the vegetation and soil characteristics of a temperate peat land were assessed with respect to variability of CH₄ and CO₂ fluxes and the GHG balance. CH₄ fluxes and ecosystem respiration were measured with the flux chamber technique during two growing seasons for seven vegetation types. Simultaneously, soil water level, soil temperature, electrical conductivity, pH, porosity, C- and N-content of soil and plants, root mass and depth and amounts of aboveground dead and living biomass were monitored.

Vegetation was found to be a good indicator of CH₄ fluxes, C-balances and GHG balances. Spatial variability was best explained by root characteristics: areas with deep rooting wetland plants were sources of CH₄ and CO₂. Temporal variability of CH₄ fluxes was best explained by respiration combined with dead biomass. However, for saturated conditions pH explained the CH₄ fluxes almost entirely. Overall, the area was a net sink of carbon and GHG. CH₄ emissions contributed only slightly to the net GHG balance, while for wetland plants the contribution of CH₄ was relatively large. An increase in wetland plants could increase the CH₄ emissions dramatically and the area could be turned into a GHG source.

6.1 Introduction

Although peatlands and wetlands are the most important natural source of methane (CH₄), under natural and stable circumstances carbon is accumulated in these ecosystems (Forster et al., 2007; Drösler et al., 2008). The typically wet conditions inhibit aerobic oxidation of organic material and lead to low rates of soil respiration. Carbon that is taken up from the atmosphere by plants through photosynthesis is fixed in the soil through the root system and by accumulation of litter under the water table. The wet soil conditions however, enable anaerobic production and emission of CH₄, thereby reducing the net carbon sink.

When the natural situation of peat areas is disturbed by management or climate change, carbon dioxide (CO₂) and CH₄ fluxes change and in most cases the net uptake of carbon is reduced or turned into a net emission (Drösler et al., 2008; Heathwaite, 1993). Besides acting as a carbon source, CH₄ emissions have a strong effect on the climate. Since the global warming potential (GWP) of CH₄ is 25 times stronger than that of CO₂ (over 100 years), small changes of CH₄ fluxes have a large effect on the greenhouse gas (GHG) balance of an ecosystem (Forster et al., 2007). Both the ratio of CH₄ and CO₂ fluxes and the GHG balance are important subjects of investigation when considering the contribution of peat areas to the enhanced green house gas effect (Whiting and Chanton, 1993; Drösler et al., 2008).

The factors driving and constraining the exchange of CO₂ between the soil, vegetation and atmosphere are relatively well known (e.g. Davi et al., 2006; Friend et al., 2007; De Boeck et al., 2007; Baldocchi, 2008). How much CO₂ is taken up from, or released to the atmosphere by plant communities depends on the magnitude of photosynthetic inputs and respiration outputs. Both photosynthesis and respiration depend greatly on climate and soil conditions (Davidson et al., 1998; Knapp et al., 2002; De Boeck et al., 2007). Additionally, plant species, species richness and plant characteristics affect plant productivity and thereby CO₂ fluxes (Hooper et al., 2005; Van Ruijven and Berendse, 2005; De Boeck et al., 2007).

The exchange of CH₄ between soil and atmosphere is understood to an increasing extent, however many uncertainties still exist and the relative importance of environmental factors needs to be assessed. Both the microbial processes of CH₄ production and oxidation in the soil as well as the CH₄ gas transport mechanisms are important when analysing CH₄ fluxes (Schlesinger, 1991; Whalen, 2005; Van Huissteden et al., 2005; Hendriks et al., 2009). Most favourable conditions for methanogenesis are water saturated (anaerobic) soils with a high organic content and high temperatures (e.g. Christensen et al., 2003). Also, the availability of easily decomposable organic matter (root exudates and fresh organic matter) and soil acidity affect CH₄ production (Dunfield et al., 1993; Whalen, 2005; Van Huissteden et al., 2005). Plant transport is found to be the most important transport mechanism for CH₄ from soil to atmosphere in ecosystems with vascular plants (e.g. Whiting and Chanton, 1996; Grünfeld and Brix, 1999; Hendriks et al., 2009). However, transport of O₂ into the rhizosphere is enhanced by vascular plants too, creating aerobic conditions and CH₄ oxidation (Roura-Carol and Freeman, 1999; Whalen, 2005). Spatial and temporal variability of CH₄ emissions from peatland and wetland areas have often been attributed to water level (e.g. Moore and Knowles, 1990; Waddington and Roulet, 1996; Van den Pol-van Dasselaar et al., 1999; Waddington and Day, 2007) or temperature (e.g. Schütz et al., 1990; Beckmann and Lloyd, 2001; Rinne et al., 2007). Also, nutrient availability and net carbon uptake were pointed out as driving variables (e.g. Whiting and Chanton, 1993; Christensen et al., 2003; Van Huissteden et al., 2005). Finally, vegetation type was found to be an important driver of spatial and temporal variation of CH₄ fluxes (Hirota et al., 2004; Van Huissteden et al., 2005; Strack et al., 2006; Treat et al., 2007; Pelletier et al., 2007). Plant functioning and vegetation characteristics thus strongly affect the production, fixation and transport of CH₄ and CO₂. Additionally, due to competition for resources (Eppinga et al., 2009) vegetation also

reflects the local climatic and soil conditions that affect carbon fluxes. Vegetation might therefore be a good indicator of CH₄ and CO₂ fluxes, since it reflects and integrates many environmental factors as well as their spatial variation and changes in time.

Changes in management practices or climate affect CH₄ and CO₂ flux patterns directly as well as indirectly through their effects on vegetation. Both changing management practices and climate change often imply hydrological modifications. In many peat areas water table draw down, for the purpose of agriculture or as a result of warming or drying of the climate, alters vegetation from wetland species to species characteristic for dryer areas. Also, the levels of soil respiration increase, while CH₄ emissions decrease (Jacobs et al., 2007; Hendriks et al., 2007; Veenendaal et al., 2007, Drösler et al., 2008). Research on climate change during the Holocene showed that temperature and precipitation changes significantly affected hydrology in peat areas: increasing temperatures and decreasing precipitation caused lowering of water levels (Mauquoy and Yeloff, 2008). As a result peat areas show degradation, implying a change in vegetation patterns and a decrease of aquatic species and species richness in general (Heathwaite, 1993; Poiani et al., 1995; Mulhouse et al., 2005; De Boeck et al., 2007; Eppinga et al., 2009). Also, recent drought studies showed reduced plant productivity, respiration and photosynthetic activity during exceptionally warm years, causing a net decrease of the carbon sink capacity of ecosystems (Reichstein et al., 2007; Ciais et al., 2005). Indirect effects of climate change on the carbon balance (C-balance) are shifts in phenology (e.g. prolonged growing seasons (Marchand et al., 2004)) and shifts in the seasonal timing of precipitation and temperature can also have significant effects on the hydrological situation and vegetation characteristics of wetlands (Poiani et al., 1995). Besides water level manipulation, other management practices affect the C-balance. Fertilization and biomass removal both reduce species richness (Sala et al., 2000; Boers et al., 2007; Prach, 2008) and cause the introduction of plant species that are tolerant to high nutrient levels like *Juncus effusus*, *Glyceria maxima*, *Phragmites australis* and *Typha latifolia* (Smolders et al., 2008; Wei and Chow-Fraser, 2005; Boers and Zedler, 2008). Eutrophication due to fertilization increases plant productivity and microbial activity (Van Dijk et al., 2004; Van Huissteden et al., 2006; Hendriks et al., 2007). On the other hand ecosystem was found to increase with higher species richness due to a more complete use of available resources, increased positive interactions and the higher probability of presence of productive species (Hooper et al., 2005; Van Ruijven en Berendse, 2005). Finally, abandoning and rewetting of managed eutrophic peat areas, although imposed as restoration practice, often leads to internal eutrophication and increased decomposition rates (Van Dijk et al., 2004).

Thorough knowledge of vegetation characteristics and their relation with ecosystems functioning as a whole, might provide a key to estimate CO₂ and CH₄ flux patterns and the GHG balance of peat areas. Also, the response of vegetation to management and climate change might be indicative for changes in CO₂ and CH₄ flux patterns and GHG balances. The aim of this research assessment was to investigate the role of vegetation characteristics in CH₄ and CO₂ flux patterns, net C-balances and GHG balances. First, vegetation patterns and characteristics were analysed as well as soil characteristics, CH₄ fluxes, CO₂ fluxes, net C-balances and GHG balances. Next, the relations between CH₄ fluxes, CO₂ fluxes and vegetation and soil characteristics were assessed both temporally

and spatially, using statistical methods. Also, the significance of CH₄ fluxes with respect to the net GHG balance for different vegetation types was determined. Finally, the implications of the findings with respect to management practices and climate change were elaborated.

6.2 Methods and materials

6.2.1 Site description

The Horstermeer measurement site was located on former agricultural land in a drained natural lake in the central part of the Netherlands (52.144° N, 5.043° E) and was described extensively by Hendriks et al. (2007). The research site has been taken out of agricultural production more than 10 years ago, and has developed into semi-natural grassland. The subsoil consisted of a two meter thick organic layer composed of organic-rich lake deposits on an eutrophic peat, overlying eolian sands of Pleistocene age. After the site was taken out of agricultural production, the ditch water table has been raised to approximately 10 cm below the land surface. The vegetation at the 8250 m² of the research site was transitional, consisted of vascular plants (dominant species: *Holcus lanatus*, *Urtica dioica*, *Glyceria maxima*, *Juncus effusus*, *Phalaris arundinacea*, *Phragmites australis* and *Typha latifolia*) and showed a patchy structure. The Horstermeer polder was situated in a moderate sea climate with an average air temperature of 9.8 °C and an average precipitation of 793 mm yr⁻¹. The growing season starts at the end of March or the beginning of April and ends at the end of August or the beginning of September (Hendriks et al., 2007). However, some plant species remain green annually (e.g. *Holcus lanatus*, *Juncus effusus*).

6.2.2 Measurement and sampling techniques

In March 2006 and April 2007 the vegetation was classified by GIS analysis of aerial photographs and vegetation mapping in the field. Also, distinct assemblages of vegetation species and their surface coverage were determined. The Relevé quadrat method (Jansen, 1967) was used to record the species distribution for distinct assemblages at 9 May 2006 and 9 May 2007. For this purpose quadrants were not chosen randomly, but representative for the vegetation assemblages.

Flux chamber measurements of CH₄ fluxes and CO₂ fluxes (ecosystem respiration, R_{eco}) were made with a Photo Acoustic Field Gas-Monitor (type 1312, Innova AirTech Instruments, Ballerup, Denmark) connected with tubes to closed, dark chambers (Hendriks et al., 2007; Van Huissteden et al., 2005). Every month of the growing seasons of 2006 and 2007 flux measurements were made at seven locations that covered all vegetation assemblages (Fig. 6.1). Additionally, soil water level (WL_{soil}), soil temperature at 0.01 m below the surface (T_{soil}), as well as electrical conductivity (EC) and pH value of the soil water were measured simultaneously with every flux chamber measurement. Additionally, aboveground dead and living biomass (DB and LB), leaf area index (LAI), root mass (RM) and carbon content (C-content), nitrogen content (N-content) and C:N ratio of the soil (CN_{soil}) and the plants (CN_{plant}) were determined.

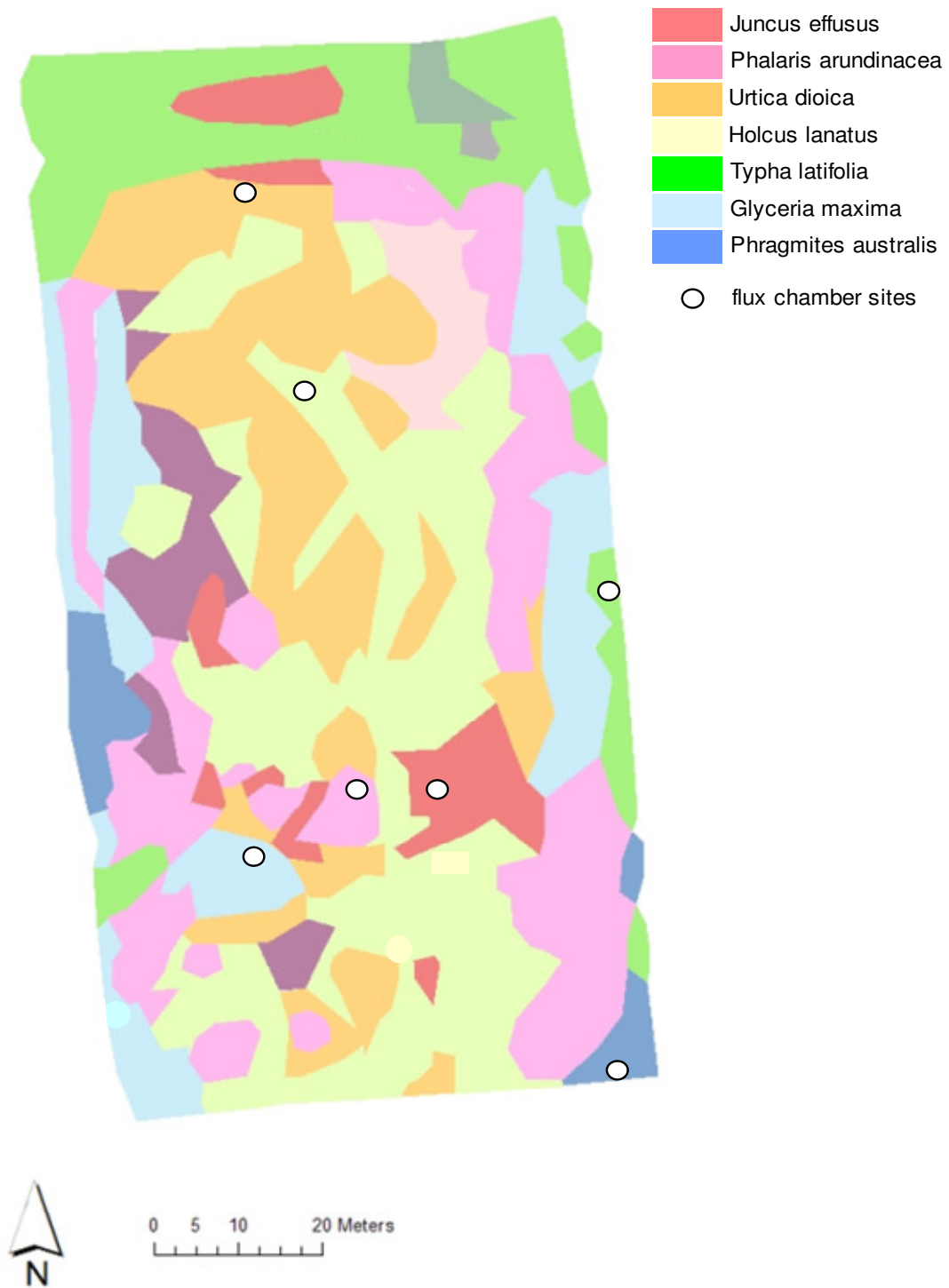


Figure 6.1: Overview of the Horstermeer peat area site with distribution of vegetation types and flux chamber sites.

To determine DB and LB, the vegetation from a 0.16 m² square was clipped, split in dead and living plant material, dried at 105 °C and weighed. The LAI was measured with a SunScan (Delta-T Devices Ltd., Cambridge, England, U.K.), which analysed the leaf density by measuring the intensity of sunlight above and below the vegetation. From this ratio, the LAI was calculated. An average was calculated from three measurement locations per vegetation assemblage. Soil cores of 1.17×10⁻⁴ m³ were cut at two locations and at three depths (0.05–0.10 m, 0.15–0.20 m and 0.25–0.30 m) for each vegetation assemblage. From each core a sub sample of 2.00×10⁻⁶ m³ was taken, which was dried, pulverized and analyzed in duplicate for C- and N-content using a Thermo Gravity Analyser (Flash 1112). Depth integrated averages of C- and N-content were determined per assemblage and C:N ratios were calculated. The remaining part of the cores (1.15×10⁻⁴ m³) was analyzed for RM. The samples were disintegrated with natriumpyrophosphate and sieved to separate the sediment from the roots. Finally, dead plant material was removed manually and the samples were dried at 105°C. The dry RM was weighed and depth integrated averages were determined per vegetation assemblage. All vegetation and soil sampling and analyses were done during the same weeks in which the flux chamber measurements were performed. Sampling locations were representative for the vegetation assemblages and in the vicinity of the corresponding flux chamber site. Additionally, water filled porosity (ϕ) was determined for each of the vegetation assemblages. In June 2007 soil cores of 1.17×10⁻⁴ m³ were cut at two locations and at three depths (0.05–0.10 m, 0.15–0.20 m and 0.25–0.30 m) near each flux chamber sites. From the difference in weight between the cores in saturated state and dry state ϕ was determined.

6.2.3 Statistical analyses and comparison with models

When determining site averages of carbon fluxes, soil variables and vegetation variables, the fractions of the areas covered with the various vegetation types were taken into account. Pearson product-moment correlation coefficient analyses were applied to determine correlation coefficients between variables (ρ) as well as the significance of the correlation (p). Basic R mode factor analysis with varimax rotation was performed to decrease the amount variables and detect the driving forces of the ecosystem and its carbon fluxes. Factor analysis returned a reduced set of new independent variables (factors), factor loadings of each original variable on the factor axes, eigen values, (cumulative) percent trace, scores of all data points on the factor axes and communalities. Also, regressions analyses were performed and were evaluated by ANOVA tests to determine the significance (p) of the model fit (R^2) as well as the regression equation. The statistical analyses described above were performed with the computer programmes Matlab 7.6.0 for Windows and SPSS 14.0 for Windows.

6.3 Results

6.3.1 Vegetation mapping and counting of species

In total 21 plant species occurred at the research site (Table 6.1), most of which were vascular plants typical for eutrophic conditions. Dominant plant species could be divided in two groups: species typical for moist nutrient rich areas (*Urtica dioica*, *Holcus lanatus*,

Phalaris arundinacea, *Agrostis stolonifera*, *Equisetum palustre*, *Glyceria maxima*, *Ranunculus repens* and *Cirsium arvense*) and species typical for eutrophic wetlands and marshes (*Typha latifolia*, *Juncus effusus* and *Phragmites australis*). Part of these species have been described in literature as invasive species (*Glyceria maxima*, *Typha latifolia*, *Juncus effusus* and *Urtica dioica*), that repress species of less eutrophic environments in disturbed ecosystems (Wei and Chow-Fraser, 2005; Smolders et al., 2008; Prach, 2008; Boers and Zedler, 2008).

vegetation type: year	Glyceria type		Holcus type		Juncus type		Phalaris type		Phragmites type		Typha type		Urtica type	
	2006	2007	2006	2007	2006	2007	2006	2007	2006	2007	2006	2007	2006	2007
area covered by veg. type (%)	11.7	12.7	27.8	15.5	5.3	4.7	19.3	21.0	2.8	4.3	15.3	15.3	17.8	26.5
bare soil (%)	5	0	0	0	0	5	0	0	5	5	5	0	20	0
boverage by litter (%)	45	30	15	5	5	15	30	10	45	15	80	70	0	0
boverage by vegetation (%)	50	70	85	95	95	80	70	90	50	80	15	30	80	100
species richness (S)	4	5	7	7	9	8	6	5	6	5	6	9	7	4
shannon's index (H')	0.79	0.99	1.58	1.40	1.66	1.39	0.99	0.95	1.49	1.26	1.78	1.82	1.48	0.71
Species (%)														
<i>Agrostis stolonifera</i>	-	-	35	15	25	10	-	-	-	-	-	-	-	-
<i>Cardamine flexuosa</i>	-	-	-	-	-	-	-	-	10	5	-	-	-	-
<i>Chamerion angustifolium</i>	-	-	6	-	-	-	<1	-	-	-	5	-	-	-
<i>Cirsium averse</i>	-	<1	-	3	1	1	5	10	5	-	5	-	<1	15
<i>Elytrigia repens</i>	-	-	-	-	1	5	-	-	-	-	-	-	6	-
<i>Equisetum palustre</i>	<1	10	6	15	1	4	<1	3	5	10	5	5	6	5
<i>Equisetum fluviatile</i>	-	<1	-	-	-	-	-	-	-	-	-	-	-	-
<i>Galeopsis tetrahit</i>	-	-	-	-	-	-	<1	-	-	-	-	-	<1	-
<i>Galium aparine</i>	<1	-	-	-	-	-	-	-	-	5	-	-	6	-
<i>Glyceria fluitans</i>	-	-	6	-	1	-	-	-	-	-	-	-	-	-
<i>Glyceria maxima</i>	50	30	-	-	-	-	-	-	-	-	35	10	-	15
<i>Holcus lanatus</i>	-	-	35	50	25	5	-	2	-	-	-	-	-	8
<i>Juncus effusus</i>	-	-	-	-	25	60	-	-	-	-	-	-	-	-
<i>Phalaris arundinacea</i>	-	-	-	-	-	-	45	70	-	-	5	-	-	-
<i>Phragmites australis</i>	-	-	-	-	-	-	-	-	35	45	-	-	-	-
<i>Poa trivialis</i>	-	-	6	-	5	-	-	-	-	-	-	-	-	2
<i>Ranunculus repens</i>	-	-	6	15	-	5	-	-	-	-	-	-	-	5
<i>Taraxacum officinales</i>	-	-	-	-	-	-	-	-	-	-	-	-	-	5
<i>Typha latifolia</i>	-	-	-	-	-	-	-	-	-	-	40	80	-	-
<i>Urtica dioica</i>	50	60	-	2	15	10	50	15	35	35	5	5	80	40
<i>Valeriana officinalis</i>	-	-	-	-	-	-	-	-	10	-	-	-	-	5

Table 6.1: Overview of all vegetation species per vegetation type recorded with the Relevé method in May 2006 and May 2007. Also, the area of the Horstermeer site covered by the vegetation types as well as percentage of bare soil, litter and vegetation coverage, S and H' per vegetation type are listed.

From the GIS analysis and vegetation mapping in the field, a patchy distribution of vegetation was observed (Fig. 6.1). Based on this finding the ecosystem was subdivided in seven main types of vegetation assemblages, which were named after the genus of its most abundant vegetation species: the Glyceria type, the Holcus type, the Juncus type, the Phalaris type, the Phragmites type, the Typha type and the Urtica type. This was an ad-hoc classification, adjusted to the site conditions, without reference to other phytosociological classifications. An overview of the assemblages of plant species that comprised the various vegetation types at 9 May 2006 and at 9 May 2007 was listed in Table 6.1. The Typha type, the Phragmites type and the Glyceria type bordered the ditches where the soil was saturated permanently. The Glyceria type, the Phragmites type and the Juncus type

were also found at relatively wet, but not permanently saturated, locations of the site farther from the ditches. The *Holcus* type, the *Phalaris* type and the *Urtica* type were found at the driest locations of the site. The largest part of the site was covered by the latter group of vegetation types (*Holcus* type, *Phalaris* type and *Urtica* type), each covering app. 20% of the area. The *Juncus* type and *Phragmites* type covered the smallest areas: each app. 5% of the site (Fig. 6.1 and Table 6.1). The most obvious difference between 2006 and 2007 was the decrease of the *Holcus* type and the increase of the *Urtica* type. Additionally, an increase of the *Glyceria* type, the *Phalaris* type and the *Phragmites* type and a slight decrease of the *Juncus* type were observed. The surface area covered with the *Typha* type remained stable.

Since it was stated in literature that S and H' affect productivity of an ecosystem and its carbon fluxes, the influence of these vegetation parameters on the carbon fluxes at the Horstermeer site was assessed. S and Shannon's diversity index H' (North et al., 2005) were determined for all vegetation types. S was defined as the amount of vegetation species occurring within the vegetation type and H' was calculated according to eq. 6.1:

$$H' = -\sum_{i=1}^S (p_i \ln(p_i)) \quad (6.1)$$

where p_i is the fraction of the total amount of individuals consisting of one species. Theoretically, H' is maximized when species are present in equal numbers, while in case H' is low, one or two species dominate the ecosystem. At the Horstermeer site both S and H' were low compared to other peat land and grass land ecosystems (Prach, 2008). Lowest S and H' at the Horstermeer site were both found for the *Glyceria* type, while highest S was observed for the *Juncus* type and highest H' for the *Typha* type (Table 6.1).

6.3.2 Soil and vegetation characteristics

First the trends in soil and vegetation characteristics over the two growing seasons were analysed to detect the temporal variability and the differences between the two measurement years. Also, spatial differences in soil and vegetation characteristics were evaluated to detect differences between the vegetation types.

Soil variables

T_{soil} increased during both growing seasons with highest values in June, while the average was relatively low in 2007 (Table 6.2 and Fig. 6.2). T_{soil} was on average highest at the *Typha* type and lowest at the *Phalaris* type. WL_{soil} decreased during the growing season of 2006, while in 2007 WL_{soil} was more stable and shallow. At the *Typha* type and the *Glyceria* type WL_{soil} was relatively high, while at the *Urtica* type lowest WL_{soil} was observed. The maximum difference between the lowest and the highest WL_{soil} (WL_{diff}) was smallest at the *Typha* type and largest at the *Holcus* type and the *Juncus* type. In both years the observed pH values decreased during the growing season from app. 7.5 down to app. 6. Highest pH values were observed at the *Urtica* type, while at the *Phalaris* type the soil was most acidic. For all vegetation types EC increased during the growing season of

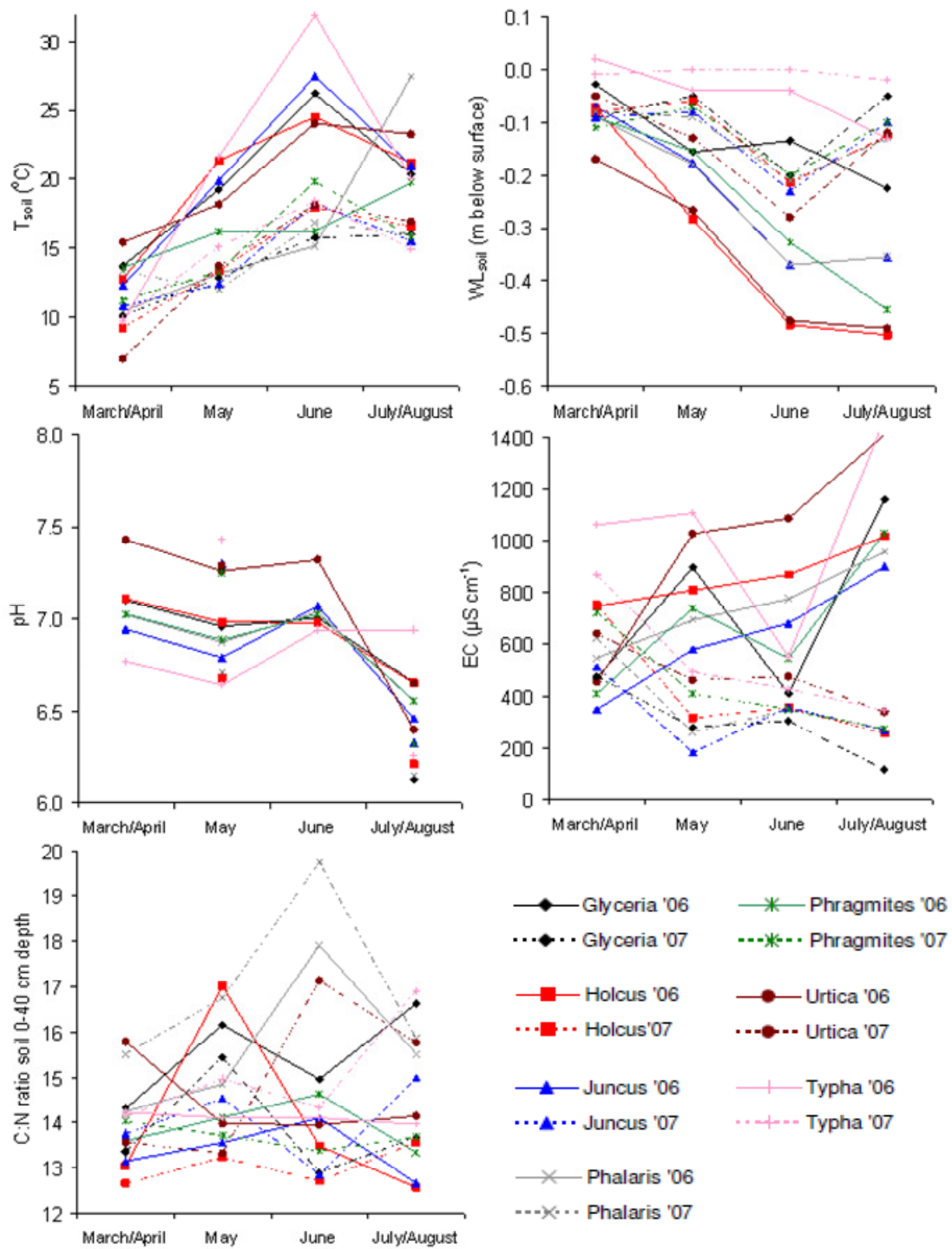


Figure 6.2: Results of all measurements and analyses of soil variables for all vegetation types during the growing seasons of 2006 and 2007.

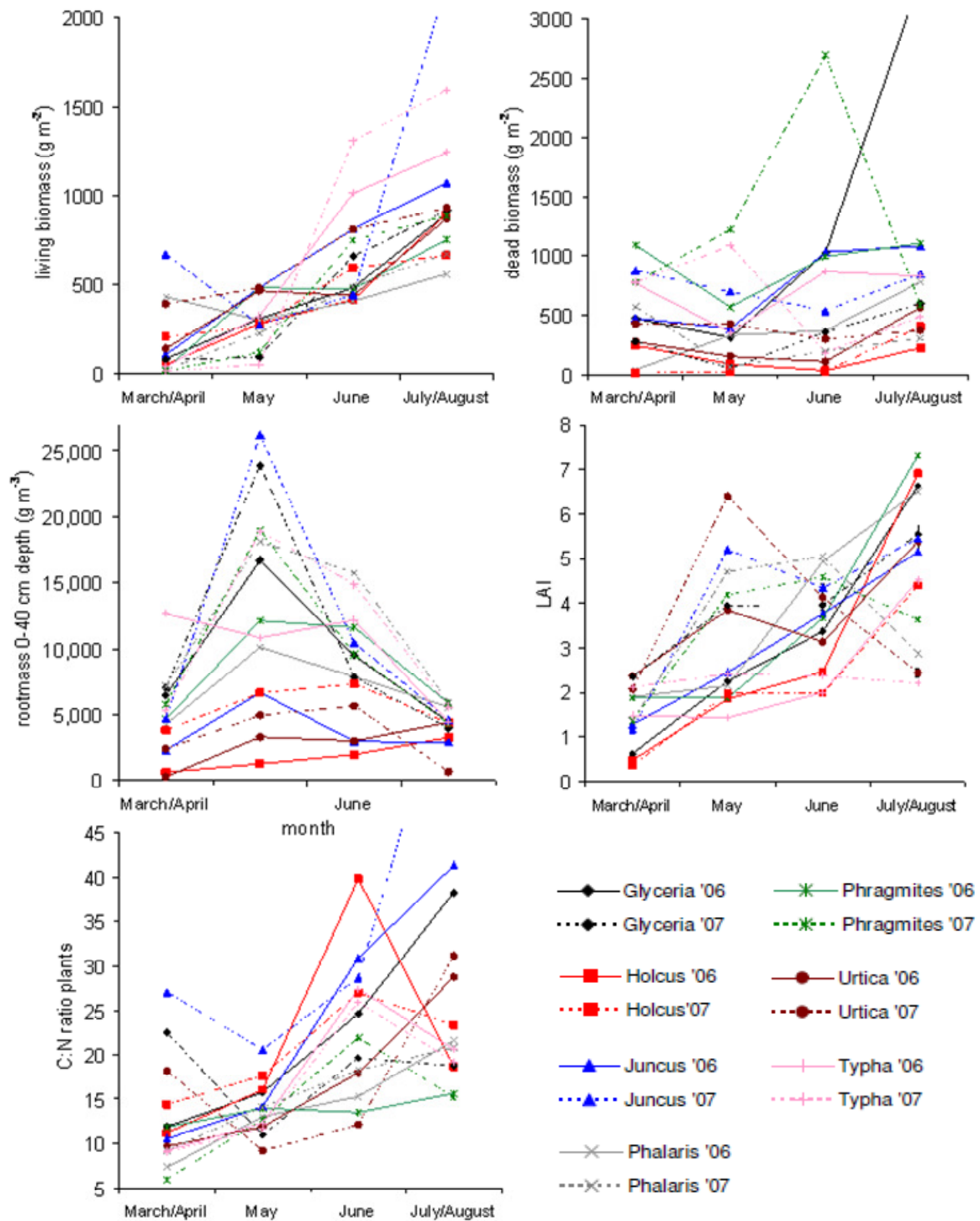


Figure 6.3: Results of all measurements and analyses of vegetation variables for all vegetation types during the growing seasons of 2006 and 2007.

2006 and decreased during the growing season of 2007. Highest EC values were observed at the Typha type and the Urtica type, while at the Juncus type EC was lowest on average. The CN_{soil} was highly variable, but on averaged increased slightly during the course of the growing season, was highest at the Phalaris type and lowest at the Holcus type. The Glyceria type showed the highest ϕ , the Urtica type the lowest. For the Typha type ϕ could not be sampled due to the lack of sediment cohesion, which suggested high ϕ .

Vegetation variables

LB increased during both growing seasons, with on average highest amounts at the Juncus type and lowest amounts at the Phalaris type (Table 6.2 and Fig. 6.3). The amount of DB was lowest in May and generally increased during the growing season. DB was lowest at the Holcus type and highest at the Phragmites type. The ratio of DB and LB (D/L) was highest at the Phragmites type and the Glyceria type, while it was relatively low at the Holcus type. Further, D/L was highest at the start of the growing season and it was relatively high in 2006 compared to 2007. RM amounts were on average highest in May and decreased towards the end of the growing season. Highest RM was observed at the Typha type and lowest RM at the Holcus type. *Juncus effusus*, *Phragmites australis* and *Typha latifolia* are known for their deep rooting system with rooting depths (RD) up to -0.70 m to -1.00 m. With our sampling technique, however, these deep roots could not be quantified. LAI clearly increased during the growing season of 2006, while this pattern was less clear in 2007. Highest LAI values were found at the Urtica type and lowest values at the Typha type. In 2007 CN_{plant} showed an increase until June and a decrease at the end of the growing season, while in 2006 most types showed an increase of CN_{plant} over the whole growing season. Highest CN_{plant} values were found at the Juncus type and lowest ratio's at the Phragmites type.

	T _{soil} (°C)	WL _{soil} (m)	WL _{diff} (m)	EC ($\mu\text{S cm}^{-1}$)	pH	ϕ (%)	CN _{soil}	DB (g m ⁻²)	LB (g m ⁻²)	D/L	LAI	RM (g m ⁻²)	RD (m)	CN _{plant}	R _{eco} (mg C m ⁻² hr ⁻¹)	CH ₄ flux (%)	F _{CH₄}
average per vegetation type																	
Glyceria	16.78	-0.12	0.20	515	6.85	76.6	14.68	802	441	1.82	3.59	2499	0.50	20.29	330	2.41	0.72
Holcus	17.12	-0.23	0.44	640	6.77	72.9	13.54	131	424	0.31	2.55	147	0.20	21.01	528	1.35	0.26
Juncus	17.21	-0.18	0.30	479	6.82	68.2	13.70	740	757	0.98	3.60	7618	1.00	29.81	449	1.54	0.34
Phalaris	15.56	-0.19	0.29	561	6.73	77.3	16.30	331	391	0.85	3.69	843	0.30	14.95	189	0.36	0.19
Phragmites	15.75	-0.19	0.39	560	6.84	71.9	13.82	1129	440	2.56	3.56	9138	1.00	13.83	146	0.90	0.61
Typha	17.72	-0.03	0.15	791	6.83	-	14.60	668	700	0.96	2.32	10621	1.00	16.93	327	21.82	6.26
Urtica	17.33	-0.26	0.44	777	6.98	71.0	14.56	334	628	0.53	3.92	140	0.20	18.46	302	0.59	0.20
weighed average per period																	
March/April	11.42	-0.07	0.19	654	7.09	73	14.02	407	166	2.45	1.48	2430	-	12.34	166	4.02	2.36
May	15.89	-0.14	0.28	616	7.02	73	14.94	314	301	1.04	3.28	8071	-	13.38	262	2.15	0.82
June	20.15	-0.27	0.48	580	7.05	73	15.21	386	644	0.60	3.46	5209	-	23.14	461	3.59	0.77
July/August	19.33	-0.23	0.48	717	6.47	73	14.68	678	940	0.72	4.73	2065	-	25.01	460	7.21	1.55
weighed average per year																	
2006	19.14	-0.25	-	858	6.93	-	14.57	486	479	1.01	3.22	3120	-	18.74	432	3.58	0.82
2007	14.26	-0.11	-	425	6.71	-	14.86	407	546	0.74	3.26	4444	-	18.19	242	4.90	1.99

Table 6.2: Overview of all soil and vegetation variables and flux chamber measurements (CH₄ fluxes and R_{eco}): average values per vegetation type and weighed averages per month and per growing season.

6.3.3 Flux chamber measurements: CH₄ fluxes and R_{eco}

Significant spatial variability of CH₄ fluxes and R_{eco} at the Horstermeer site was found by Hendriks et al. (2009). The flux chamber measurements presented in this paper showed

similar spatial variability (Fig. 6.4 and Table 6.2). On average, the Phalaris type, the Urtica type, and the Phragmites type showed a low CH_4 emission, while the Holcus type, the Juncus type, and the Glyceria type showed intermediate CH_4 emission. By far highest were the emissions at the Typha type which were approximately ten times higher than that at the other vegetation types. R_{eco} was highest at the Holcus type and the Juncus type, while at the Phalaris type and the Phragmites type R_{eco} was lowest. Large temporal variability during the year and between the measurement years was observed. Generally, CH_4 fluxes and R_{eco} increased over the course of the growing season. This trend was however not consistent, and variations were found between the vegetation types. At all types, except the Typha type, the average CH_4 emission was relatively low in 2007. R_{eco} was relatively high in 2006 at all types except at the Phalaris type and the Phragmites type. The weighed average CH_4 emission of 2007 was higher than that of 2006, while for R_{eco} the opposite was observed.

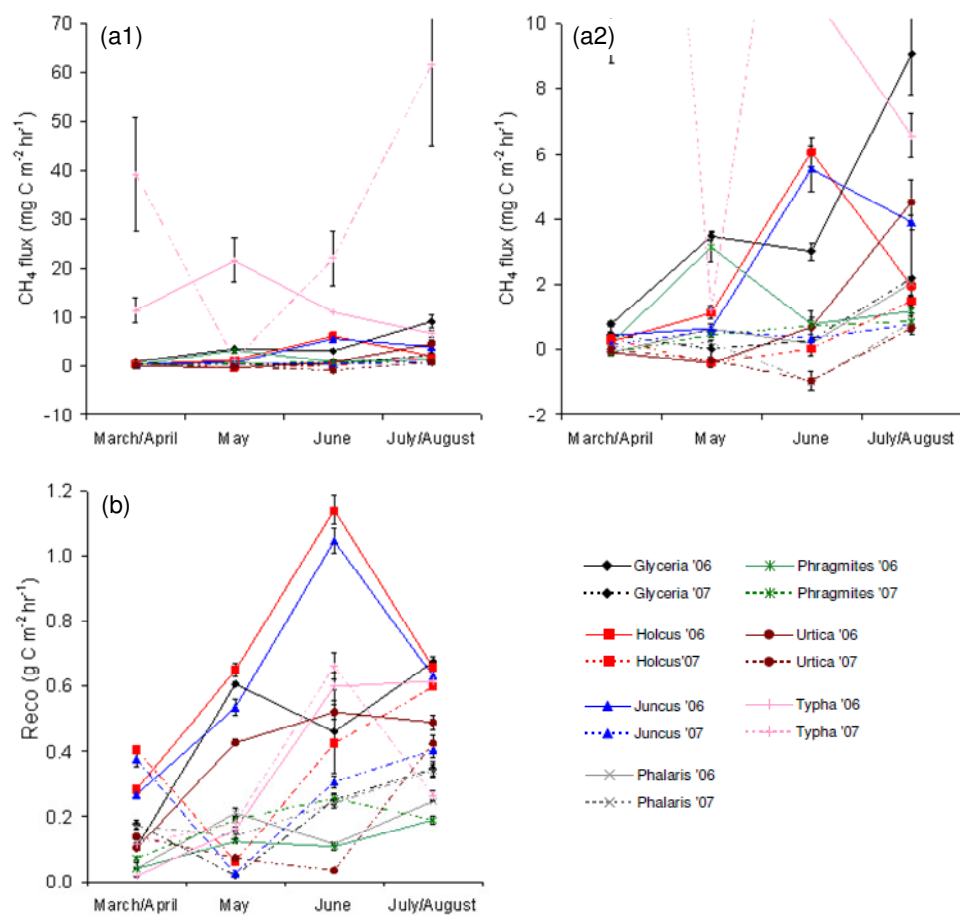


Figure 6.4: Results of the measurements of (a) CH_4 fluxes (in $\text{mg C m}^{-2} \text{hr}^{-1}$) and (b) R_{eco} (in $\text{g C m}^{-2} \text{hr}^{-1}$) for all vegetation types over the growing seasons of 2006 and 2007. In graph (a2) CH_4 fluxes are plotted on a smaller scale to clarify the variability of the other vegetation types than the Typha type. Error bars indicate the statistical measurement error.

To detect where and when organic carbon was effectively subjected to methanogenesis and emitted as CH₄ instead of being oxidized and emitted as CO₂, the fraction of carbon that was emitted as CH₄ (F_{CH₄}) was determined according to eq. 6.2:

$$F_{CH_4} = f_{CH_4} / (f_{CH_4} + R_{cco}) \quad (6.2)$$

where f_{CH_4} was the CH₄ flux (Table 6.2). Considering the averages per vegetation type, F_{CH₄} was highest at the Typha type (6.26%), while at the Glyceria type and the Phragmites type F_{CH₄} was respectively 0.72% and 0.61% and at the other types F_{CH₄} was less than 0.35%. During the growing season of the relatively wet and cold year 2007 F_{CH₄} was on average higher than the relatively dry and warm year 2006. Also, F_{CH₄} was relatively high at the start and at the end of the growing season compared to May and June.

6.3.4 Carbon pools and net carbon exchange

To obtain a comprehensive overview of the pathways of carbon at the different vegetation types, the various carbon pools of the ecosystem (RM carbon, LB carbon, DB carbon and soil carbon) were assessed. For all vegetation types their relative importance was determined over the two growing seasons. From the biomass and soil analyses, the amounts of carbon stored in or released from the carbon pools RM, LB, soil and DB over the growing season could be determined per vegetation type. The amount of carbon stored in LB and in RM was determined by multiplying the amount of LB and RM with the fraction of carbon in the plant tissue. The top layer of the soil profile consisted mainly of DB; therefore this carbon pool was included in the soil carbon pool. The amount of carbon in the soil plus the amount of carbon in DB was determined by multiplying the depth integrated fraction of carbon in the soil with the dry soil density. The net carbon exchange over the growing season in RM (ΔRM), soil plus DB (ΔCS) and LB (ΔLB) was determined by subtracting the amount of carbon stored at the end of the growing season from the amount that was stored at the start of the growing season and was expressed as gC m⁻² d⁻¹ (Fig. 6.5).

It was expected that vegetation types growing under the most anaerobic conditions (Typha type and Glyceria type, and to a smaller extend Juncus type and Phragmites type) would accumulate carbon over the growing season. Vegetation types with a relative thick aerobic top soil layer on the other hand (Urtica type, Holcus type, Phalaris type), were expected to loose carbon from their soil profile due to relatively high levels of oxidation. Also, the relatively wet and cold year 2007 was expected to show a relatively high net carbon uptake compared to the relatively dry and warm year 2006. First, the two-year average ΔRM , ΔCS and ΔLB per vegetation type were considered (Fig. 6.5). Opposed to the other vegetation types the Glyceria type and the Typha type showed a positive ΔRM , suggesting that a large part of the RM was turned into labile soil carbon during the growing season, stimulating CH₄ production. The Juncus type, the Phragmites type and the Typha type showed a positive ΔCS (loss of soil carbon), while the other vegetation types showed a negative ΔCS . This indicated that oxidation of soil organic material was higher than the amount of carbon stored in the soil during the growing season. The three vegetation types

showing the high ΔCS also had relatively deep root systems, which might explain the high loss of soil carbon: through the deep rooting systems, a mechanism to transport CH_4 and CO_2 produced in the deeper soil layers to the atmosphere was provided by the deep rooting plants. Also, oxygen could enter into deep soil layers thereby enhancing oxidation of organic material in deeper layers. The *Juncus* type and the *Typha* type showed relatively high uptake of carbon in LB over the growing season. Large amounts of LB increased the possibility of gas transport through plant aerenchyma from vascular plants, potentially resulting in higher emissions. Additionally, large amounts of LB provided high amounts of easily decomposable DB and soil carbon later during the growing season and in the following years (Fig. 6.3).

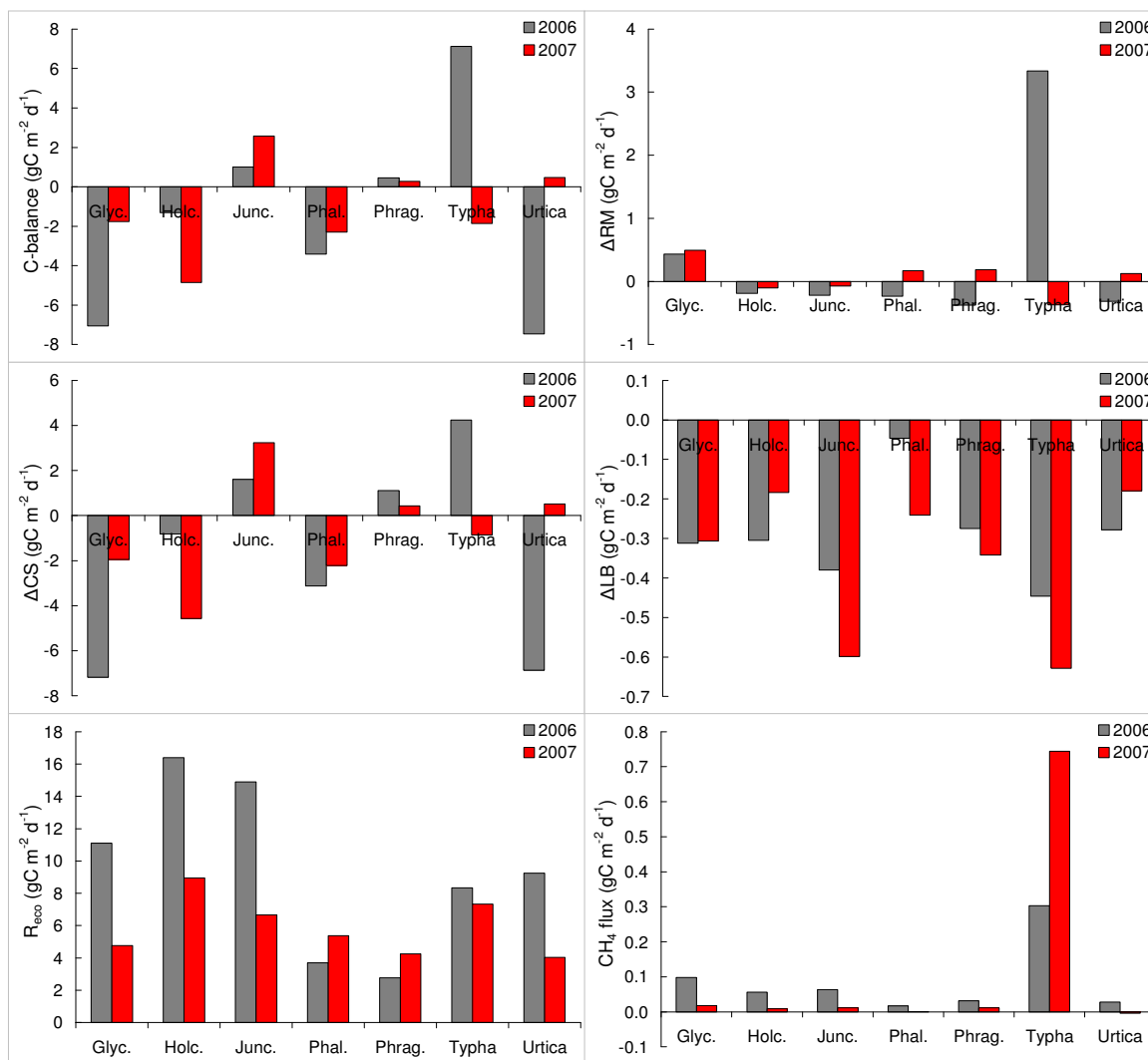


Figure 6.5: Overview of C-balance, ΔRM , ΔCS , ΔLB , R_{eco} and CH_4 flux in $gC\ m^{-2}\ d^{-1}$ for all vegetation types per growing season. Note that the scales of the y-axes vary.

Next, the differences in ΔRM , ΔCS and ΔLB between the two growing seasons were considered. Over the growing season of 2006 on average more carbon was released from RM. However, this difference was mainly due to the large difference at the Typha type from a positive ΔRM in 2006 to a negative ΔRM in 2007. However, the sampling and analysis techniques of RM hold relative large uncertainties and no definite conclusions could be drawn from small differences in RM. The Phalaris type, the Phragmites type and the Urtica type showed a shift in the opposite direction. Over the growing season of 2006 on average more soil carbon was accumulated. However, the vegetation types showed varying differences in ΔCS between the two years. At the Holcus type, the Phragmites type and the Typha type ΔCS was higher in 2006, while for the Glyceria type, the Juncus type, the Phalaris type and the Urtica type ΔCS was lower in 2006. On average slightly more carbon was stored in LB over the growing season of 2007. For the Glyceria type ΔLB was stable over the two years, while for the Holcus type and the Urtica type ΔLB higher (less uptake) and for the other vegetation types ΔLB was lower (more uptake) in 2007.

6.3.5 Carbon balances and green house gas balances

The net change of carbon over the growing season (C-balance) per vegetation type could be determined from changes in the carbon pools (eq. 6.3):

$$\text{C-balance} = \Delta RM + \Delta LB + \Delta CS \quad (6.3)$$

where all components were expressed as $\text{gC m}^{-2} \text{d}^{-1}$. Also, the GHG balance of the different vegetation types could be determined. In general, the GHG balance is closely related to the C-balance, but reflects the combined radiative forcing of all GHG's emitted or taken up in an area. The GHG balance was calculated in CO_2 -equivalents from the C-balance and the CH_4 flux using global warming potentials (GWP). The GWP of CH_4 expressed as CO_2 -equivalents was 25 (over 100 years: 1 kg CH_4 = 25 kg CO_2) while that of CO_2 is by definition 1 (Forster et al., 2007). Emissions of N_2O , another important GHG often found in peat areas, were not found at the Horstermeer site (Hendriks et al., 2007).

The GHG balances per year and per vegetation type were plotted versus the corresponding C-balance (Fig. 6.6). Most data points were located on or near the 1:1 line, indicating that the GHG balance was of most vegetation types was for the largest part determined by CO_2 exchange. In 2006 the Typha type, the Glyceria type, the Holcus type and the Juncus type deviated significantly from the 1:1 line in the plot, indicating a rise in the GHG balance due to high CH_4 emissions at these vegetation types. In 2007 only the Typha type deviated significantly from the 1:1 line in the plot, indicating that only here the CH_4 emission significantly increased the GHG balance. Also, the Typha type showed a larger deviation from the 1:1 line in 2007, indicating that the effect of the CH_4 emission on the GHG balance was relatively high that year. Moreover, the C-balance of the Typha type was negative in 2007, indicating that the net emission of GHG was caused fully by the high CH_4 emissions. Overall, the ecosystem was a small sink of carbon and had a small

negative GHG balance over the growing seasons of both 2006 ($-2.02 \text{ gC m}^{-2} \text{ d}^{-1}$; $-1.32 \text{ gCO}_2\text{-equiv. m}^{-2} \text{ d}^{-1}$) and 2007 ($-1.49 \text{ gC m}^{-2} \text{ d}^{-1}$; $-0.53 \text{ gCO}_2\text{-equiv. m}^{-2} \text{ d}^{-1}$).

Considering the spatial variability of the C-balances and GHG balances (Fig. 6.6), the Typha type, the Juncus type and the Phragmites type were sources of carbon and net emitters of GHG's. Especially the Typha type had a highly positive GHG balance. At the Typha type and the Juncus type, the positive climate effect was due to a combination of high CH_4 emissions and a positive C-balance. At the Phragmites type the positive climate effect was solely due to a positive C-balance. The other vegetation types were carbon sinks and were net sinks of GHG's. The seven vegetation types showed varying changes in C-balance and GHG balance between the years. The C-balance and the GHG balance of the Glyceria type, the Juncus type, the Phalaris type and the Urtica type were relatively high during the wet and cold year 2007. The C-balance and the GHG balance of the Typha type, the Phragmites type and the Holcus type were relatively high during the dry and warm year 2006.

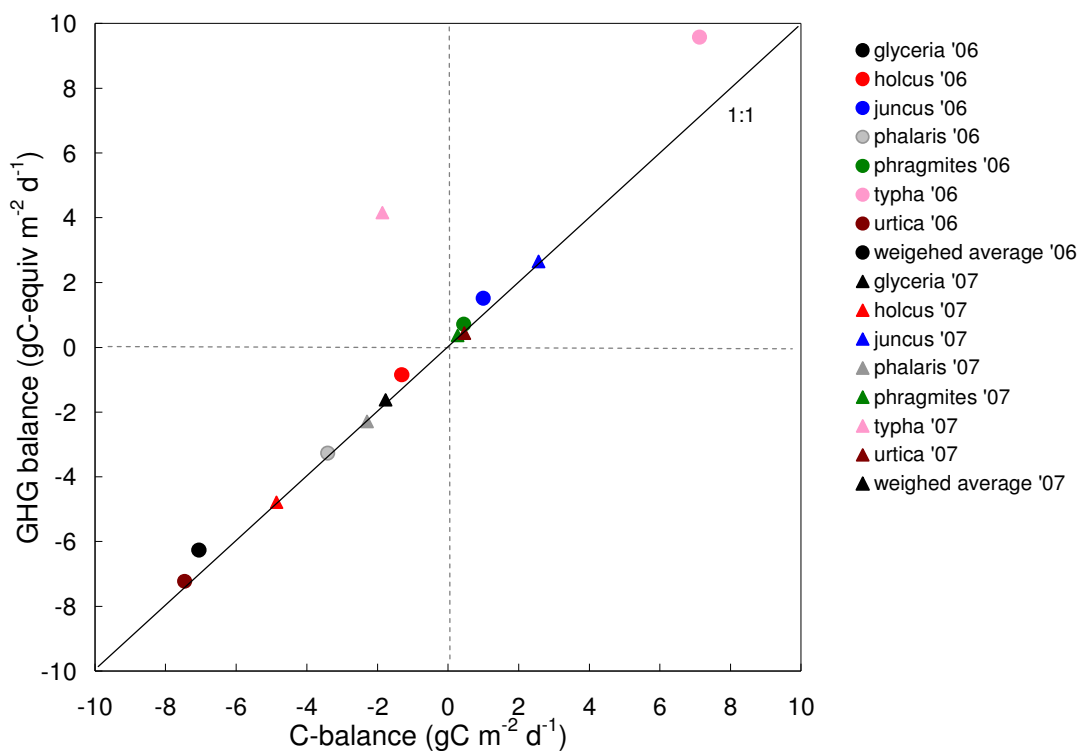


Figure 6.6: C-balance versus GHG balance of all vegetation types for both growing seasons. Positive values indicate respectively C losses and net GHG emission.

6.3.6 Statistical analyses

The influence of all vegetation and soil variables on CH_4 fluxes were analysed separately as well as the ecosystem functioning as a whole and the synergy between soil and vegetation characteristics with respect to the CH_4 fluxes. For this purpose correlation coefficient analyses, factor analyses and regression analyses were performed. The CH_4

emissions from the *Typha* type were an order of magnitude higher than that of the other vegetation types. When analysing the data, this large difference concealed smaller variations in the dataset. In order to analyse these smaller variations, all statistical analyses were done with and without the data from the *Typha* type. When the *Typha* type was present in the analyses, the highest correlation coefficients were found between soil and vegetation variables and the natural logarithm of the CH₄ flux ($\log(\text{CH}_4)$). When the *Typha* type was excluded highest correlation coefficients were found between soil and vegetation variables and the untransformed CH₄ flux. To distinguish between temporal and spatial variability of CH₄ fluxes, correlation coefficient analyses were done for single data points (Table 6.3) and for weighed average values per vegetation type (Table 6.4).

Driving variables of CH₄ flux and F_{CH4}

In case the *Typha* type was included, temporal variability of $\log(\text{CH}_4)$ was best explained by R_{eco}, while also T_{soil}, WL_{diff}, pH and CN_{plant} showed significant correlation coefficients. Spatial variability of $\log(\text{CH}_4)$ was mainly explained by ΔRM , but significant correlation coefficients were also found for ΔLB and LAI (negative correlation). The temporal variability of F_{CH4} was related to D/L, while the spatial variability of F_{CH4} was best explained by ΔRM and was also significantly related to WL_{soil} and negatively to LAI. In case the *Typha* type was excluded, temporal variability of the CH₄ flux was best explained by R_{eco}, while also T_{soil}, WL_{soil}, EC, DB and CN_{plant} showed significant correlation coefficients. Spatial variability of the CH₄ flux was best explained by WL_{diff}. The temporal variability of F_{CH4} best explained by RM, while the spatial variability of F_{CH4} was best explained by D/L and was also significantly related to WL_{soil} and DB. When only the *Typha* type was used in the correlation coefficient analyses, the variability of $\log(\text{CH}_4)$ was almost entirely explained by pH (negative correlation). DB and RM were significantly related to $\log(\text{CH}_4)$ too, however both these vegetation variables themselves were strongly affected by pH. The variability of F_{CH4} at the *Typha* type was best explained by CN_{plant} and was also significantly related to T_{soil} and CN_{soil}. Additionally, in none of the analyses significant correlations between the CH₄ flux or $\log(\text{CH}_4)$ and *S* or *H'* were found.

Driving variables of C-balance and net greenhouse gas balance

Spatial differences in C-balance and GHG balance were expected to be related to soil and vegetation variables and changes in carbon pools. Correlation coefficient analysis pointed out that C-balance was best explained by ΔCS , but was also significantly related to RM, RD and ΔLB (negative correlation) (Table 6.4). The GHG balance was best explained by C-balance and ΔCS , but was also related to RM, RD, T_{soil}, CH₄ flux, F_{CH4} and ΔLB (negative correlation). Important here was also that ΔCS and ΔLB both showed highest correlation coefficients with RM and RD. Additionally, no significant correlations between any of the carbon pools, the C-balance or GHG balance and *S* or *H'* were found.

Relations between vegetation and soil variables

The variability of CH₄ flux, C-balance and GHG balance could thus be explained by both vegetation and soil characteristics. Additionally, vegetation variables were strongly affected by soil variables, indicating that the effect of soil variables on CH₄ fluxes was, at

(a) all vegetation types included

for $p \leq 0.01$, ρ is bold	T_{soil}	WL_{soil}	EC	pH	CN_{soil}	DB	LB	D/L	LAI	RM	CN_{plant}	R_{eco}	$\log(\text{CH}_4)$	F_{CH_4}
T_{soil}	1.00	-0.57	0.33	-0.09	0.06	0.19	0.39	-0.33	0.35	-0.06	0.41	0.66	0.34	-0.19
WL_{soil}		1.00	-0.47	0.03	0.00	-0.02	-0.18	0.29	-0.52	0.35	-0.27	-0.45	-0.03	0.31
EC			1.00	0.07	-0.07	0.14	-0.01	0.07	0.10	-0.19	-0.01	0.32	0.24	0.23
pH				1.00	0.00	-0.08	-0.61	0.25	-0.27	0.31	-0.41	-0.16	-0.41	-0.16
CN_{soil}					1.00	-0.01	0.06	-0.06	0.13	-0.01	-0.04	-0.12	-0.14	0.02
DB						1.00	0.19	0.20	0.34	0.24	0.27	0.08	0.29	0.06
LB							1.00	-0.43	0.43	-0.10	0.71	0.42	0.27	-0.07
D/L								1.00	-0.28	0.15	-0.33	-0.32	-0.02	0.38
LAI									1.00	0.01	0.33	0.12	0.02	-0.21
RM										1.00	-0.09	-0.24	0.27	0.24
CN_{plant}											1.00	0.59	0.34	-0.16
R_{eco}												1.00	0.43	-0.18
$\log(\text{CH}_4)$													1.00	0.36
F_{CH_4}														1.00

(b) Typha type excluded

for $p \leq 0.01$, ρ is bold	T_{soil}	WL_{soil}	EC	pH	CN_{soil}	DB	LB	D/L	LAI	RM	CN_{plant}	R_{eco}	CH_4 flux	F_{CH_4}
T_{soil}	1.00	-0.74	0.45	-0.14	0.10	0.23	0.37	-0.25	0.43	-0.15	0.39	0.66	0.59	0.16
WL_{soil}		1.00	-0.69	0.03	-0.03	-0.05	-0.29	0.23	-0.47	0.21	-0.25	-0.52	-0.41	-0.05
EC			1.00	0.07	-0.01	0.13	0.03	-0.01	0.15	-0.30	0.06	0.41	0.50	0.18
pH				1.00	0.07	-0.15	-0.64	0.00	-0.34	0.27	-0.45	-0.20	-0.36	-0.09
CN_{soil}					1.00	0.00	0.00	-0.06	0.15	-0.02	-0.05	-0.11	-0.02	-0.16
DB						1.00	0.28	0.19	0.37	0.25	0.31	0.10	0.50	0.32
LB							1.00	-0.37	0.54	-0.15	0.77	0.35	0.30	0.02
D/L								1.00	-0.28	0.10	-0.28	-0.27	-0.13	-0.02
LAI									1.00	0.16	0.32	0.09	0.28	0.12
RM										1.00	-0.07	-0.30	-0.06	0.45
CN_{plant}											1.00	0.56	0.51	0.20
R_{eco}												1.00	0.70	0.17
CH_4 flux													1.00	0.52
F_{CH_4}														1.00

(c) only Typha type

for $p \leq 0.1$, ρ is bold	T_{soil}	WL_{soil}	EC	pH	CN_{soil}	DB	LB	D/L	LAI	RM	CN_{plant}	R_{eco}	$\log(\text{CH}_4)$	F_{CH_4}
T_{soil}	1.00	-0.46	-0.07	0.10	-0.23	-0.04	0.44	-0.64	0.11	0.11	0.74	0.68	-0.12	-0.69
WL_{soil}		1.00	-0.60	-0.01	0.22	-0.12	-0.43	0.39	-0.80	0.56	-0.35	-0.54	0.10	0.50
EC			1.00	0.06	-0.60	0.15	-0.26	0.07	0.39	-0.43	-0.33	-0.10	-0.12	0.18
pH				1.00	-0.50	0.86	-0.54	0.71	0.25	0.70	-0.12	0.13	-0.99	-0.49
CN_{soil}					1.00	-0.13	0.43	-0.19	-0.09	-0.14	0.05	-0.17	0.29	-0.64
DB						1.00	-0.43	0.42	0.25	0.11	-0.29	-0.21	-0.68	-0.43
LB							1.00	-0.72	0.45	-0.34	0.84	0.76	0.35	-0.51
D/L								1.00	-0.20	-0.09	-0.69	-0.60	0.01	0.49
LAI									1.00	-0.38	0.34	0.58	-0.29	-0.24
RM										1.00	0.01	-0.04	-0.63	0.09
CN_{plant}											1.00	0.93	0.10	-0.74
R_{eco}												1.00	-0.04	0.36
$\log(\text{CH}_4)$													1.00	0.43
F_{CH_4}														1.00

Table 6.3: Results of the correlation coefficient analysis performed with data from: (a) all vegetation types, (b) all vegetation types except Typha type and (c) the Typha type. Correlation coefficients are significant if $p \leq 0.01$ for (a) and (b) and if $p \leq 0.1$ for (c) and are printed bold.

(a) all vegetation types included

for $p \leq 0.1$, ρ is bold	T_{soil}	WL_{soil}	WL_{diff}	EC	pH	ϕ	CN_{soil}	DB	LB	D/L	LAI	RM	RD	CN_{plant}	ΔRM	ΔCS	ΔLB	R_{eco}	$\log(CH_4)$	F_{CH_4}	C- balance	GHG- balance
T_{soil}	1.00	0.27	0.71	0.54	0.44	-0.21	-0.44	-0.24	0.73	-0.51	-0.48	0.13	0.08	0.51	0.46	0.18	-0.61	0.70	0.65	0.49	0.24	0.38
WL_{soil}		1.00	0.00	0.13	-0.20	0.57	0.14	0.42	0.28	0.26	-0.53	0.66	0.59	-0.09	0.92	0.37	-0.69	-0.07	0.87	0.86	0.52	0.70
WL_{diff}			1.00	0.90	0.62	0.15	0.42	0.44	0.59	0.65	0.55	0.28	0.29	0.97	0.82	0.10	0.09	0.03	0.65	0.19	0.45	0.45
EC				1.00	0.46	0.19	0.05	-0.38	0.30	-0.45	-0.43	-0.01	-0.19	-0.38	0.49	-0.02	-0.10	0.02	0.38	0.58	0.08	0.28
pH					1.00	-0.38	-0.25	0.14	0.42	0.05	0.36	-0.02	-0.04	0.03	0.02	-0.11	-0.11	-0.08	0.02	0.00	-0.11	-0.08
ϕ						1.00	0.68	-0.11	-0.46	0.06	-0.32	-0.10	-0.19	-0.61	0.61	-0.39	0.18	-0.33	0.30	0.45	-0.24	0.00
CN_{soil}							1.00	-0.25	-0.31	-0.11	0.29	-0.32	-0.34	-0.48	0.17	-0.38	0.44	-0.55	-0.25	0.04	-0.31	-0.21
CN_{plant}								1.00	0.13	0.92	0.20	0.76	0.81	-0.07	0.19	0.48	-0.48	-0.47	0.25	0.17	0.48	0.39
LB									1.00	-0.27	-0.11	0.50	0.50	0.57	0.33	0.65	-0.79	0.33	0.48	0.45	0.66	0.66
L/B										1.00	0.29	0.51	0.56	-0.32	0.04	0.18	-0.12	-0.61	0.03	-0.03	0.17	0.09
LAI											1.00	-0.31	-0.18	0.04	-0.61	-0.28	0.44	-0.46	-0.74	-0.70	-0.38	-0.56
RM												1.00	0.98	0.02	0.52	0.87	-0.83	-0.20	0.63	0.64	0.92	0.89
RD													1.00	0.16	0.40	0.87	-0.82	-0.17	0.54	0.50	0.89	0.82
CN_{plant}														1.00	-0.22	0.26	-0.44	0.76	0.09	-0.21	0.18	0.07
ΔRM															1.00	0.24	-0.61	-0.04	0.90	0.95	0.42	0.67
ΔCS																1.00	-0.77	0.01	0.43	0.46	0.98	0.88
ΔLB																	1.00	-0.29	-0.82	-0.69	-0.83	-0.87
R_{eco}																		1.00	0.28	-0.01	-0.01	0.01
$\log(CH_4)$																			1.00	0.91	0.57	0.76
F_{CH_4}																				1.00	0.61	0.83
C-balance																					1.00	0.95
GHG-balance																						1.00

(b) Typha type excluded

for $p \leq 0.1$, ρ is bold	T_{soil}	WL_{soil}	WL_{diff}	EC	pH	ϕ	CN_{soil}	DB	LB	D/L	LAI	RM	RD	CN_{plant}	ΔRM	ΔCS	ΔLB	R_{eco}	CH_4 flux	F_{CH_4}	C- balance	GHG- balance
T_{soil}	1.00	-0.28	0.67	0.33	0.51	-0.55	-0.55	-0.33	0.64	-0.53	-0.19	-0.25	-0.20	0.72	-0.05	-0.07	-0.43	0.81	0.41	-0.19	-0.10	-0.07
WL_{soil}		1.00	0.01	-0.84	-0.33	0.42	0.15	0.59	-0.20	0.60	0.14	0.36	0.43	0.13	0.77	-0.02	-0.34	-0.14	0.70	0.77	0.03	0.08
WL_{diff}			1.00	0.08	0.57	0.34	0.41	0.47	0.89	0.48	0.52	0.78	0.63	0.71	0.79	0.24	0.44	0.08	0.81	0.66	0.89	0.89
EC				1.00	0.60	-0.11	0.01	-0.56	0.01	-0.49	0.02	-0.60	-0.67	-0.33	-0.32	-0.43	0.54	0.01	-0.51	-0.53	-0.47	-0.51
pH					1.00	-0.42	-0.25	0.15	0.48	0.05	0.50	-0.02	-0.05	0.03	0.07	-0.12	-0.15	-0.08	0.00	0.08	-0.13	-0.13
ϕ						1.00	0.73	-0.17	-0.83	0.11	-0.02	-0.49	-0.49	-0.59	0.63	-0.74	0.70	-0.37	0.05	0.19	-0.71	-0.71
CN_{soil}							1.00	-0.26	-0.38	-0.11	0.48	-0.45	-0.42	-0.47	0.29	-0.47	0.66	-0.55	-0.40	-0.25	-0.45	-0.47
CN_{plant}								1.00	0.09	0.94	0.39	0.88	0.87	-0.05	0.28	0.49	-0.55	-0.47	0.32	0.81	0.53	0.55
LB									1.00	-0.25	0.36	0.31	0.37	0.76	-0.33	0.55	-0.72	0.36	0.07	-0.23	0.53	0.54
L/B										1.00	0.30	0.72	0.69	-0.35	0.39	0.25	-0.26	-0.62	0.26	0.86	0.30	0.32
LAI											1.00	0.20	0.23	-0.14	0.20	0.07	-0.06	-0.65	-0.24	0.08	0.09	0.08
RM												1.00	0.99	0.18	-0.16	0.84	-0.72	-0.26	0.15	0.52	0.87	0.88
RD													1.00	0.28	-0.09	0.84	-0.78	-0.20	0.23	0.53	0.87	0.89
CN_{plant}														1.00	-0.09	0.40	-0.79	0.78	0.51	-0.09	0.39	0.43
ΔRM															1.00	-0.59	0.04	-0.13	0.68	0.69	-0.55	-0.51
ΔCS																1.00	-0.70	0.01	-0.13	0.00	1.00	0.99
ΔLB																	1.00	-0.38	-0.55	-0.37	-0.71	-0.75
R_{eco}																		1.00	0.48	-0.24	-0.02	0.01
$\log(CH_4)$																			1.00	0.69	-0.10	-0.04
F_{CH_4}																				1.00	0.06	0.10
C-balance																					1.00	1.00
GHG-balance																						1.00

Table 6.4: Results of the correlation coefficient analysis performed with average values from: (a) all vegetation types and (b) all vegetation types except the Typha type. Correlation coefficients are significant if $p \leq 0.1$ and are printed bold.

least partly, manifested through vegetation variables. R_{eco} , which showed the highest correlation to the temporal variability of CH_4 fluxes, was in fact the sum of autotrophic and heterotrophic respiration and therefore reflected both soil and vegetation conditions. Accordingly, the statistical analyses pointed out that R_{eco} was significantly related to soil variables (T_{soil} , WL_{soil} and EC) and to vegetation variables (CN_{plant} and LB). Also, other vegetation variables that affected the CH_4 fluxes were significantly related to soil variables: CN_{plant} was related to T_{soil} and pH; D/L was related to by T_{soil} and WL_{diff} ; and RM, RD, ΔRM and ΔCS were related to WL_{soil} and WL_{diff} . ΔLB and DB on the other hand, were not related with any of the soil variables, suggesting that these were relatively independent vegetation variables that were not constrained by any soil characteristic at the Horstermeer site.

Integrated approach to small scale CH₄ flux variability

The results presented indicated that the CH₄ flux was related to various vegetation and soil characteristics, while also the soil and vegetation characteristics among one another showed significant correlation coefficients. To increase the understanding of the ecosystem functioning as a whole and the synergy between soil and vegetation characteristics factor analyses were performed. A factor analysis including all vegetation types indicated that three independent factors explained most of the variability in the ecosystem (Table 6.5): an a-biotic soil factor with high factor loadings of T_{soil}, WL_{soil}, EC and R_{eco}; an aboveground biotic factor with high factor loadings of LB, CN_{plant} and pH; and a belowground biotic factor with high factor loadings of DB, RM and CN_{soil} (Fig. 6.7). A correlation coefficient analysis pointed out that log(CH₄) was significantly correlated with the scores on the first (a-biotic) and second (aboveground biotic) factor axes. These correlation coefficients were higher than the correlation coefficients with the original soil and vegetation variables (Table 6.5). When the Typha type was excluded, three similar factors explained most of the variability within the ecosystem. Also, a correlation coefficient analysis pointed out that the CH₄ flux was significantly correlated with the scores on the first (a-biotic) and second (aboveground biotic) factor axes and that these correlation coefficients were higher than the correlation coefficients with the original soil and vegetation variables (Table 6.5). These findings indicated that CH₄ fluxes were determined mostly by a-biotic soil characteristics and aboveground biotic characteristics and that the CH₄ fluxes were the result of the interplay of soil and vegetation characteristics rather than from a single soil or vegetation characteristic.

In order to find out which combination of variables best explained the CH₄ fluxes, multiple linear regression analyses were performed. Based on the results of the correlation coefficient analyses and the factor analyses various combinations of variables were tested. Combinations of variables that all had significant correlations with CH₄ fluxes and showed high loadings on different factor axes, were expected to be most complementary and result in regression equations with high model fits. When all vegetation types were combined, a regression equation with pH and T_{soil} showed highest model fit explaining 30.2% of the variability of log(CH₄) (Table 6.6). When the Typha type was excluded, a regression equation with R_{eco} and DB showed the highest model fit explaining 56.8% of the variability of the CH₄ flux. In this regression model R_{eco} represented mainly the a-biotic and aboveground biomass factors (gas transport through plant aerenchyma and temperature effects on microbial activity), while DB represented availability of easily decomposable organic material. When modelling the CH₄ fluxes for the Typha type, no multiple regression equation modelled the variability of log(CH₄) better than a single regression equation with pH, which explained 91% of the variability. Apparently, under permanently saturated conditions, the CH₄ flux was almost entirely determined by the variation in subsoil CH₄ production. Since carbon and nutrient were abundant at the Horstermeer site, their availability did not limit CH₄ production; pH was therefore the only variable affecting CH₄ production under water saturated conditions.

(a) all vegetation types included				(a) Typha type excluded			
factor	eigen values	percent trace	cumulative percent trace	factor	eigen values	percent trace	cumulative percent trace
1	3.56	35.62	35.62	1	3.76	37.60	37.60
2	1.79	17.90	53.52	2	1.94	19.40	56.99
3	1.24	12.42	65.94	3	1.28	12.83	69.82
4	0.90	9.00	74.94	4	0.86	8.58	78.39
5	0.75	7.54	82.47	5	0.69	6.86	85.26
6	0.54	5.43	87.91	6	0.58	5.75	91.01
7	0.42	4.24	92.14	7	0.43	4.34	95.35
8	0.35	3.54	95.68	8	0.28	2.80	98.15
9	0.28	2.80	98.48	9	0.11	1.10	99.24
10	0.15	1.52	100.00	10	0.08	0.76	100.00

corr. scores and log(CH ₄)			corr. scores and CH ₄ flux		
factor	ρ	p	factor	ρ	p
1	0.47	0.002	1	0.683	<0.001
2	-0.49	0.001	2	-0.583	<0.001
3	0.13	0.41	3	0.096	0.578

Table 6.5: Results of the factor analyses and the correlation coefficient analyses of the scores on the respective axes with corresponding CH₄ fluxes. (a) all vegetation types included; (b) Typha type not included.

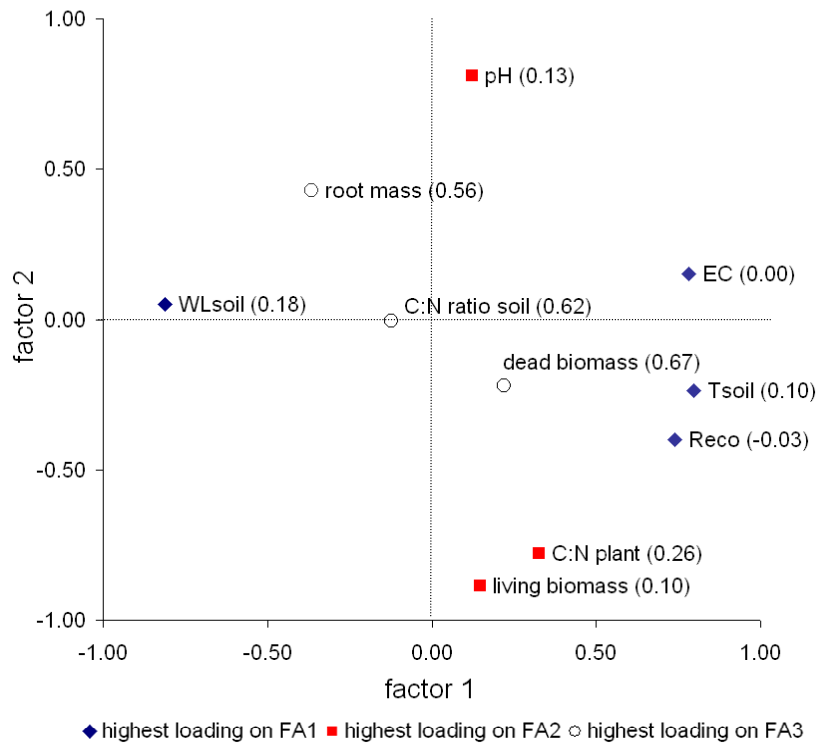


Figure 6.7: Factor loadings of the soil and vegetation variables on the three important factor axes. Loadings on third axis between brackets; symbols indicate the axis of highest loading for each variable.

dependent variable	independent variable x1	independent variable x2	n	R ²	p	regression type	a	b1	b2	p1	p2
all sites											
CH ₄ flux	pH	T _{soil}	42	0.302	0.001	exp(a + b1x1+ b2x2)	20.703	-3.852	0.271	0.008	0.008
no Typha sites											
CH ₄ flux	R _{eco}	DB	36	0.586	<0.001	a + b1x1+ b2x2	-1.162	4.469E-03	1.441E-03	<0.001	<0.001
only Typha site											
CH ₄ flux	pH		6	0.912	<0.001	exp(a + b1x1)	13.416	-1.849		0.011	

Table 6.6: Results of the regression analyses with the CH₄ flux as dependent variable. Symbols: independent variables (x1 and x2), sample number (n), model fit (R²), significance model fit (p), regression equation type, regression constants (a, b1 and b2) and significance of constants (p1 and p2).

6.4 Discussion

6.4.1 Eutrophic conditions and vegetation patterns

Despite the abandonment of the site almost 15 years ago, the soil conditions at the Horstermeer site remained eutrophic and pH had increased to approximately 7 due to internal eutrophication (Van Dijk et al., 2004). The nutrient rich conditions generated high plant productivity and microbial activity, resulting in high carbon fluxes. Also, the eutrophic conditions and the mowing/grazing activities before the abandonment resulted in low *S* and *H'*. The vegetation distribution was patchy and could be subdivided in seven vegetation types. Eutrophic wetland plants covered 36% of the area and occurred bordering the ditches and in other relatively wet areas. Grasses and forbs typical for eutrophic, moist conditions occurred at the dryer parts of the site and covered 64% of the area. Several of the plants species (*Typha latifolia*, *Juncus effusus*, *Phragmites australis*) have been described in literature as invasive in disturbed, eutrophic ecosystems (Wei and Chow-Fraser, 2005; Smolders et al., 2008; Prach, 2008; Boers and Zedler, 2008).

6.4.2 Highest CH₄ emissions at wetland vegetation

Significant spatial variability of CH₄ fluxes was found between the vegetation types. CH₄ emission was on average low at the Phalaris type, the Urtica type, and the Phragmites type, while the Holcus type, the Juncus type, and the Glyceria type showed intermediate CH₄ emission. By far highest were the emissions at the Typha type which were approximately ten times higher than that at the other vegetation types. Similar CH₄ emissions from *Typha latifolia* were found by Whiting and Chanton (1996). In previous research wetland plants like *Phragmites australis* and *Juncus effusus* also have been reported to have high CH₄ emissions (Grünfeld and Brix, 1999; Brix et al., 1996; Roura-Carol and Freeman, 1999). Grünfeld and Brix (1999) however showed that CH₄ emissions from organic soils vegetated with *Phragmites australis* were significantly lower with a low WL_{soil}, similar to that of the Phragmites type and the Juncus type at the Horstermeer site. According to these previous findings, these vegetation types are therefore expected to generate CH₄ emissions in the order of magnitude of the Typha type in case of a further rise of water levels. CH₄ fluxes from the other vegetation types were consistent with

values found in previous research (Best et al., 1997; Strack et al., 2006; Moore and Knowless, 1990, Van den Pol-Van Dasselaar et al., 1999).

The spatial variability of CH₄ fluxes was mainly explained by ΔRM and WL_{soil} , while WL_{soil} and ΔRM were also strongly related: the *Typha* type and the *Glyceria* type had high WL_{soil} , showed a net loss of RM carbon over the growing season and had highest CH₄ emissions. This was in agreement with previous research that attributed high CH₄ emissions to a combination of WL_{soil} and root characteristics (Hirota et al. 2004; Hendriks et al., 2009), while other research solely pointed at anaerobic conditions induced by high WL_{soil} (e.g. Moore and Knowles, 1990; Waddington and Roulet, 1996; Van den Pol-van Dasselaar et al., 1999; Waddington and Day, 2007). Roots are an important source of easily decomposable organic material for methanogens (Whalen, 2005; Van Huissteden et al., 2005), which might explain the relation between a decrease in RM carbon and high CH₄ emissions. Additionally, roots play an important role in transporting CH₄ from the subsoil to the atmosphere, leading to relatively high CH₄ emissions (Schlesinger, 1991; Walter and Heimann, 2000; Christensen et al., 2003; Whalen, 2005, Van Huissteden et al., 2006). In agreement with previous research (Whiting and Chanton, 1993; Hirota et al., 2007) ΔLB carbon was also related to the spatial variability of CH₄ emissions. In addition to the CH₄ plant transport being enhanced by the deep roots, the CH₄ transport was enhanced by relatively high amounts of aboveground LB. Apparently contradictory, a negative relation existed between LAI and CH₄ fluxes. However, as was shown by Nouchi et al. (1990) and Whiting and Chanton (1993) CH₄ was released from plants stems or culms rather than from leaves and large amounts of leaves inhibited the CH₄ gas transport through the stems and culms. Wetland plants species like *Typha latifolia*, *Phragmites australis* and *Juncus effusus* have optimal characteristics for high CH₄ emissions: deep root systems, large RM, anaerobic soil conditions, large amounts of LB, but low LAI. Finally, F_{CH_4} was relatively high at the deep rooting plants (*Typha* type, *Glyceria* type, *Phragmites* type), suggesting that deep root systems enhanced CH₄ emissions more than oxidation and R_{eco} . This was in accordance with previous findings by Ding et al. (2005), who observed a significant decrease in CH₄ emissions after clipping aboveground vegetation stems, while oxidation levels and CH₄ concentration in the subsoil were only slightly affected.

6.4.3 Temporal variability of CH₄ fluxes due to interaction of variables

Clear short term variability of CH₄ fluxes and R_{eco} during the year was observed. In general CH₄ emissions were relatively high at the start and the end of the growing season, R_{eco} increased over the course of the growing season but stabilized in summer and F_{CH_4} was relatively high at the start and at the end of the growing season. For all vegetation types except the *Typha* type, a regression analysis showed that a multiple linear regression with R_{eco} and DB explained 59% of the variability in CH₄ fluxes, which was the highest possible model fit. R_{eco} was in fact the sum of autotrophic and heterotrophic respiration and therefore reflected both soil and vegetation conditions. Accordingly, R_{eco} was related to various soil and vegetation variables, most of which were significantly related to CH₄ fluxes. Previous research also pointed out that temporal variability of CH₄ and CO₂ fluxes is affected by fluctuations in gas transport through plants (Brix et al., 1992; Thomas et al.,

1996; Hendriks et al., 2009). Overall, since R_{eco} was strongly related to plant transport and reflected the amounts of soil carbon as well as temperature and moisture conditions it was a good predictor of CH_4 fluxes. DB formed an important source of easily decomposable organic matter for methanogens (Whalen, 2005; Van Huissteden et al., 2006) and was relatively independent from R_{eco} . Especially at the start and end of the growing season CH_4 emissions were probably increased due to high amounts of DB and litter.

At the Typha type, pH explained 92% of the variance in the CH_4 fluxes. Apparently, the Typha type, with its permanently saturated soil and well developed capacity to transport CH_4 through aerenchyma (Brix et al., 1996), the magnitude of the CH_4 emission was mainly determined by the production of CH_4 in the soil. Since other factors related to CH_4 production, e.g. nutrient and carbon availability did not create limitations, pH was the major constraining variable. As stated in literature the production of CH_4 is strongly dependent on pH, with an optimum at approximately 6 (Dunfield et al., 1993; Van Huissteden et al., 2006). At the Horstermeer site, pH values of 6 and higher were observed and CH_4 fluxes decreased with increasing pH.

Previous research at the Horstermeer site showed that at a combination of W_{Lsoil} and T_{soil} at 0.40 m depth, representing both plant transport mechanisms and soil conditions best explained CH_4 fluxes. This result was however obtained using daily averages of landscape scale data acquired with eddy covariance, which have a significantly different spatial scale compared to the point measurements obtained with the flux chamber technique. Also, despite the apparent contradiction both analyses pointed out that CH_4 fluxes are determined rather by a combination of environmental variables than by one single variable. Both analyses showed that plant transport mechanisms and soil conditions are important determinants of CH_4 fluxes.

6.4.4 Highest carbon emissions and positive greenhouse gas balances at wetland vegetation

Significant spatial variability of carbon fluxes and GHG balances was found between the vegetation types. Surprisingly, wetland vegetation types Typha, Juncus and Phragmites were net emitters of carbon and GHG's despite the relative anaerobic soil conditions. Another wetland vegetation type, the Glyceria type, showed relatively high carbon uptake; this was in line with expectations. The GHG balances were almost entirely determined by the C-balances, except for the Typha type where CH_4 emissions took up an important part of the GHG balance. Both the C-balance and net GHG balances were closely related to ΔCS , which showed largest changes over the growing season compared to the other carbon pools (LB and RM). The spatial variability of ΔCS , C-balance and GHG balance was best explained by vegetation variables RM and RD: deep-rooting wetland vegetation types having relatively high carbon emissions. This finding was supported by previous research which stated that root systems enhance the transport of O_2 into the anaerobic soil layers, thereby stimulating the oxidation of soil organic material. Also, the deep roots created a shortcut for transport of CH_4 and CO_2 to the atmosphere through the plant aerenchyma (Roura Carol and Freeman, 1999; Whalen, 2005).

6.4.5 No effect of S and H' on carbon fluxes

No significant relations between S or H' and any of the carbon fluxes were found, indicating the effect of S and H' on plant productivity described in literature was subordinate to other vegetation and soil characteristics at the Horstermeer site. Probably the positive effect of the nutrient rich conditions on the occurrence of plant species, plant productivity and microbial activity was dominant. As stated by Hooper et al. (2005) characteristics of specific species can strongly influence ecosystem properties by influencing pathways of energy and material flows, thereby outweighing the effects of S and H' . Additionally, non-biotic factors, like climatic changes, could have overruled the effects of S and H' as was found previously by De Boeck et al. (2007).

6.4.6 Total ecosystem is sink of carbon and greenhouse gases

Despite the significant CH_4 and CO_2 emissions at some vegetation types, the ecosystem was on average a small sink of carbon and had a small negative GHG balance over the growing season. This was in agreement with previous findings by Hendriks et al. (2007) and comparable to other natural and restored peat areas (Whiting and Chanton, 2001; Friborg et al., 2003; Drösler et al., 2008), while managed peat areas have been reported as net carbon sources (Lloyd et al., 2006; Veenendaal et al., 2007; Drösler et al., 2008). Carbon emissions at the Horstermeer site (CH_4 emissions and R_{eco}) were however similar to managed eutrophic peat areas (Best et al., 1997; Van den Pol-Van Dasselaar et al., 1999; Lloyd et al., 2006; Veenendaal et al., 2007), indicating that the gross uptake of carbon in the area was relatively high.

6.4.7 Comparison dry and wet year

The carbon fluxes at the vegetation types responded differently to the climatic differences between the two years. At the Typha type, with its' permanently anaerobic soil conditions, CH_4 fluxes were most sensitive to the differences in WL_{soil} between the years. This was in agreement with a wealth of studies (e.g. Moore and Knowles, 1990; Waddington and Roulet, 1996; Van den Pol-van Dasselaar et al., 1999; Waddington and Day, 2007). However, in the dryer areas CH_4 fluxes were sensitive to differences in T_{soil} between the years, which was in agreement with the temperature dependency of CH_4 fluxes that has also been established by a wealth of studies (e.g. Schütz et al., 1990; Beckmann and Lloyd, 2001; Rinne et al., 2007). The average CH_4 emission of the relatively wet and cold year 2007 was 37% higher than that of 2006 and F_{CH_4} was over twice as high in 2007 compared to 2006. This was however fully due to the high CH_4 emission at the Typha type, while all other vegetation types showed relatively high CH_4 emissions and F_{CH_4} during the relatively dry and warm year 2006. Bubier et al. (2005) found a 60% increase of CH_4 fluxes from boreal wetlands during a relatively wet and warm year. This suggested that CH_4 emissions at the Horstermeer site might be higher in years with both wet and warm conditions, which was in agreement with previous CH_4 flux measurements at the Horstermeer site in the relatively warm and wet year 2005.

The C-balance was relatively high at the Typha type, the Phragmites type and the Holcus type during the warm and dry year 2006, which was probably mainly due to reduced soil

carbon uptake resulting from reduced photosynthetic activity and higher R_{eco} during the dry conditions. The *Glyceria* type, the *Juncus* type, the *Phalaris* type and the *Urtica* type had a relatively high C-balance during the cold and wet year 2007, the wet and cold conditions were probably less favourable for these vegetation types to take up carbon in LB and to store carbon in the soil. In general it is assumed that net carbon uptake is reduced under warm and dry conditions (Knapp et al., 2002; Reichstein, 2007; Ciais et al., 2005; De Boeck et al., 2007), however also extremely high moisture contents might damage certain plants species through suffocation of the roots thereby reducing the carbon uptake.

6.4.8 Effects of changes in management and climate

At eutrophic peat areas like the Horstermeer site CH_4 and CO_2 emissions probably increase in case of further rewetting, due to the higher CH_4 emissions from wetland plants and due to expansion of deep-rooting wetland plants which have positive C-balances and GHG balances. In case rewetting is combined with climate warming, C-balances and GHG balances will increase even more, due to increased microbial activity. On the other hand, warming without rewetting will lead to lowering of water levels. Initially, C-balance and GHG balance will decrease due to loss of wetland plants and decreased CH_4 emissions. Continued warming will however lead to thick aerobic peat layers and high R_{eco} . As a result the areas will turn into sources of carbon and GHG's. In agreement with previous research (Hirota et al., 2004; Strack et al., 2006; Treat et al., 2007; Parmentier et al., 2008) this assessment showed that water level changes due to management or climate change do not directly cause the expected effect on CH_4 fluxes, C-balance and GHG balance. Only when the changes are persistent over multiple years and the vegetation has adapted to the new hydrological situation, the effect will be fully reflected by CH_4 fluxes, C-balance and GHG balance. Short term climate or management changes might lead to counter-intuitive carbon fluxes: e.g. high WL_{soil} leads to high CH_4 emissions solely in areas dominated by wetland plants, while at other vegetation types CH_4 emissions are inhibited by the unfavourable conditions for plant growth.

6.4.9 Mitigation through management

Successful decrease of C-fluxes and reduction of CH_4 emissions in peat areas can only be realized, when the nutrient level is reduced. In this manner plant productivity and microbial activity will be suppressed and the peat areas will become more acidic. Accordingly, restoration of diverse, species-rich vegetation types can be realized in abandoned peat areas (e.g. *Carex* associations (mesotroph) or *Sphagnum* associations (oligotroph)). Due to the anaerobic soil condition and nutrient poor conditions, R_{eco} will be reduced strongly. Nutrient poor conditions and acidic conditions also reduce the production of CH_4 production, and in case of oligotrophic conditions with *Sphagnum* species CH_4 emissions will be inhibited due to limited plant gas transport and anaerobic oxidation of CH_4 (Raghoebarsing et al., 2006; Thauer and Shima, 2006).

Solely abandoning an area and raising water levels will however not lead to nutrient reduction in peat areas due to processes of internal eutrophication (Van Dijk et al., 2004). More thorough management interventions will be inevitable (Bakker and Oloff, 1995;

Smolders et al., 2008), like topsoil removal, mowing or grazing. Restoration of diverse, species-rich vegetation types by these practices is however questionable, because open patches are created which will be primarily colonized by the unwanted species like *Juncus effusus*, *Typha latifolia* and *Phragmites australis* (Smolders et al., 2008). Additionally, mowing and grazing will not generate the wanted result before many years of practice. Liming, as additional measure, prevents acidification of soils and has been shown to effectively diminish unwanted species and increase S and H' (Smolders et al., 2008). Finally, long periods of management might have depleted species diversity and seed banks over large areas. Artificial introduction of preferred species might accelerate the development towards a mesotrophic or oligotrophic ecosystem with high S and H' and without vegetation types that are net GHG sources.

Water management might provide limited possibilities of reducing or stabilizing the GHG emissions from eutrophic peat areas. Keeping WL_{soil} just below the soil surface, for instance by replacing ditches by belowground drainage systems, might repress extremely high CH_4 emissions from deep-rooted wetland plants and prevents the expansion of these vegetation type. However, WL_{soil} should be lowered carefully, because R_{eco} will increase dramatically when WL_{soil} is lower than to -0.10 to -0.15 m below the surface (Jungkunst and Fiedler, 2007). Due to the continued nutrient rich conditions the area will remain a potential big source of GHG's.

6.5 Conclusions

This research assessment resulted in several conclusions regarding the application of vegetation as indicator for CH_4 emissions, CO_2 fluxes and GHG balances from peat areas as well as regarding the effect of vegetation on carbon fluxes. Also, the effect of climate and management on vegetation, CH_4 and CO_2 fluxes and GHG balances in peat areas was clarified. Below, the most important findings are listed:

- The persisting eutrophic conditions of the abandoned and rewetted peat area affected both vegetation and caused high carbon fluxes;
- Vegetation types and vegetation characteristics were found to be good indicators of CH_4 flux, C-balance and the GHG balance;
- Variability of CH_4 fluxes was caused interaction of vegetation and soil characteristics rather than one single variable;
- Deep-rooting wetland vegetation types showed net carbon emission, CH_4 emissions and were net GHG sources, while other vegetation types were carbon sinks and net GHG sinks;
- Temporal variability of CH_4 fluxes was best explained by R_{eco} combined with DB. However, for saturated conditions pH explained the CH_4 fluxes almost entirely;
- S and H' did not show an effect on the carbon fluxes;
- Currently, the area was on average a carbon sink and a net GHG sink, despite the significant CH_4 emissions.; Persistent changes in climate or management can however

dramatically increase CH₄ emissions or R_{eco} and turn the area into a source of carbon and GHG's;

- Nutrient reduction is an indispensable component of GHG mitigation management and for improvement of ecological values in abandoned peat areas.

Acknowledgements

This research project is performed in the framework of the European research programme Carbo Europe (contract number GOCE-CT2003-505572) and the Dutch National Research Programme Climate Changes Spatial Planning (www.klimaatvoorimte.nl). We would like to thank nature organisation “Natuur Monumenten” for providing the possibility of the measurement location in the Horstermeer polder. Also, we would like to thank Martin Konert and Martine Hagen for their cooperation in the laboratories. Finally, we would like to thank the MSc students Monica Jiménez Díaz and Cristina Ruiz Martinez and the BSc students Jelmer Panman, Jan Martijn Roetman, Pieter Pauw, Maarten Slot and Marlène van den Bos for their contribution in the fieldwork campaigns, laboratory work and interesting discussions.

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