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# Variability of annual CO<sub>2</sub> exchange from Dutch Grasslands

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**BGD**

4, 1499–1534, 2007

## Variability of annual CO<sub>2</sub> exchange from Dutch Grasslands

C. M. J. Jacobs et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

**EGU**

## Abstract

An intercomparison is made of the Net Ecosystem Exchange of CO<sub>2</sub>, *NEE*, for eight Dutch grassland sites; four natural grasslands, two production grasslands and two meteorological stations within a rotational grassland region. At all sites the *NEE* was determined during at least 10 months per site, using the eddy-covariance (EC) technique, but in different years. The photosynthesis-light response analysis technique is used along with the respiration-temperature response technique to partition *NEE* among Gross Primary Production (*GPP*) and Ecosystem Respiration (*R<sub>e</sub>*) and to obtain the eco-physiological characteristics of the sites at the field scale. Annual sums of *NEE*, *GPP* and *R<sub>e</sub>* are then estimated using the fitted response curves with observed radiation and air temperature from a meteorological site in the centre of The Netherlands as drivers. These calculations are carried out for four years (2002–2005). The estimated annual *R<sub>e</sub>* for all individual sites is more or less constant per site and the average for all sites amounts to 1390±30 gC m<sup>-2</sup> a<sup>-1</sup>. The narrow uncertainty band (±2%) reflects the small differences in the mean annual air temperature. The mean annual *GPP* was estimated to be 1325 gC m<sup>-2</sup> a<sup>-1</sup>, and displays a much higher standard deviation, of ±100 gC m<sup>-2</sup> a<sup>-1</sup> (8%), which reflects the relatively large variation in annual solar radiation. The mean annual *NEE* amounts to -65±85 gC m<sup>-2</sup> a<sup>-1</sup>, which implies that on average the grasslands act as a source, with a relatively large standard deviation. From two sites, four-year records of CO<sub>2</sub> flux were available and analyzed (2002–2005). Using the weather record of 2005 with optimizations from the other years, standard deviation of annual *GPP* was estimated to be 171–206 gC m<sup>-2</sup> a<sup>-1</sup> (8–14%), of annual *R<sub>e</sub>* 227–247 gC m<sup>-2</sup> a<sup>-1</sup> (14–16%) and of annual *NEE* 176–276 gC m<sup>-2</sup> a<sup>-1</sup>. The inter-site standard deviation was higher for *GPP* and *R<sub>e</sub>*, 534 gC m<sup>-2</sup> a<sup>-1</sup> (37.3%) and 486 gC m<sup>-2</sup> a<sup>-1</sup> (34.8%), respectively. However, the inter-site standard deviation of *NEE* was similar to the interannual one, amounting to 207 gC m<sup>-2</sup> a<sup>-1</sup>. Large differences occur due to soil type. The grasslands on organic (peat) soils show a mean net release of CO<sub>2</sub> of 220±90 gC m<sup>-2</sup> a<sup>-1</sup> while the grasslands on mineral (clay and sand)

**BGD**

4, 1499–1534, 2007

### Variability of annual CO<sub>2</sub> exchange from Dutch Grasslands

C. M. J. Jacobs et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

**EGU**

soils show a mean net uptake of CO<sub>2</sub> of 90±90 g C m<sup>-2</sup> a<sup>-1</sup>. If a weighing with the fraction of grassland on organic (20%) and mineral soils (80%) is applied, an average *NEE* of 28±90 g C m<sup>-2</sup> a<sup>-1</sup> is found, which means that on average the Dutch grasslands behave like a small sink for CO<sub>2</sub>. The results from the analysis illustrate the need for regionally specific and spatially explicit CO<sub>2</sub> emission estimates from grassland.

## 1 Introduction

Grasslands cover about 20% of the world's land area (Hadley, 1993) and about 22% of the EU-25 land area (EEA, 2005). They not only constitute an important socio-economic and environmental resource, but they also affect the atmospheric energy, water and carbon budgets. As such, grassland areas contribute significantly to the terrestrial greenhouse gas (GHG) balance (Soussana et al., 2007b). Thus, realistic estimates of greenhouse gas budgets require reliable estimates of emissions from grasslands. Currently, it is suggested that grasslands demonstrate the same CO<sub>2</sub> accumulation rates as forests (Hu et al., 2001). If this is correct on a long-term basis, this is of great interest in light of the discussions on global warming. For these reasons and because of the relatively unexplored potential for grassland soils to store carbon the interest in the carbon cycles of these ecosystems has increased (Van Ginkel et al., 1999; Soussana et al., 2007b).

In national inventory reports such as required under the Kyoto Protocol by the United Nations Framework Convention on Climate Change (UNFCCC) all grasslands are usually shared under one so-called source/removal category with one emission factor (IPCC, 2003). Similarly, in global or regional carbon budget models land cover is often prescribed in terms of biomes such as “temperate grassland” with only one set of vegetation parameters (see, e.g., Friedlingstein et al., 2006). However, even within relatively small regions with uniform climatic conditions large variability in emissions from grasslands may be expected due to differences in soil type and water- and land-management practice (Ammann et al., 2007; Gilmanov et al., 2007; Soussana et al., 2007a). In order

### Variability of annual CO<sub>2</sub> exchange from Dutch Grasslands

C. M. J. Jacobs et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

to obtain more realistic GHG balance estimates and proper uncertainty assessments differences in grassland emission factors depending upon such influences should be accounted for.

Emission variability analysis requires continuous observations of GHG exchange during prolonged periods of time and for various sites to address both spatial as well as temporal variability of emission factors. Thanks to the gradually increasing number of sites with long-term flux observations based on the eddy covariance (EC) technique (Baldocchi et al, 2001) such analyses are now within reach for carbon dioxide (CO<sub>2</sub>).

The large variability of CO<sub>2</sub> exchange of grasslands has recently been investigated on a European scale by Gilmanov et al. (2007). These authors compared data from 20 European grasslands, covering a large range of ecophysiological and climatic conditions. Their datasets each represent 1–2 years of flux observations. Annual net ecosystem CO<sub>2</sub> exchange (*NEE*) was found to vary between net uptake of 655 gC m<sup>-2</sup> and a release of 164 gC m<sup>-2</sup>. Net release was observed in 4 cases, associated with organic soils, grazing and heat stress.

In this paper we focus on the CO<sub>2</sub> emission variability of grasslands in The Netherlands. About 50% of the agricultural land in the Netherlands consists of grassland, where rotational grazing is the most common land use (CBS, 2007). Wetlands and grassland on organic soils play a special role in the GHG budget from land sources in The Netherlands. A relatively large fraction of about 20% of the production grasslands in The Netherlands is located on peat soils (CBS, 2007). These areas have been drained to maximize agricultural production, which resulted in subsidence of the peat surface due to changes in physical conditions and oxidation of organic material. During oxidation CO<sub>2</sub> is released from the soil resulting in yearly net CO<sub>2</sub> emissions, as has been confirmed in estimates from long-term EC observations (e.g., Nieveen et al., 2005; Lloyd, 2006). Some of these areas have now been taken out of agricultural production in order to restore a (semi-) natural grassland. In addition, a number of peat bog areas with natural grassland are located in The Netherlands. In (semi-) natural wetland areas CO<sub>2</sub> emission due to oxidation is minimized or may even be reversed.

**Variability of annual  
CO<sub>2</sub> exchange from  
Dutch Grasslands**

C. M. J. Jacobs et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

In the national inventory report of The Netherlands grassland is defined as all managed grasslands, natural grasslands and grasslands for recreation. The contribution of grassland to the national greenhouse gas budget is expressed by means of a simple emission factor, amounting to  $518 \text{ g C m}^{-2} \text{ a}^{-1}$ . The emission factor has been derived from belowground carbon stock changes in organic soils as influenced by water management (Brandes et al., 2006). Clearly, this emission factor is much larger than the maximum yearly emission reported by Gilmanov et al. (2007) for organic soils. Moreover, it neglects the possible uptake of  $\text{CO}_2$  by grasslands on mineral soils and in waterlogged areas.

In the present study eight datasets of quasi-continuous  $\text{CO}_2$  flux measurements covering at least 10 months are analysed. The datasets are all obtained in the past decade, using the EC technique. They represent contrasting grassland sites in The Netherlands, ranging from managed grassland to natural grassland. In contrast with Gilmanov et al. (2007), there is much less variation in the climatic conditions among the sites.

We first investigate ecophysiological differences between the grasslands. The analysis is based on the construction of ecosystem response curves, notably the photosynthesis-light and the respiration-temperature response characteristics. The contributions from ecosystem respiration  $R_e$  and photosynthesis (gross primary production,  $GPP$ ) can then be distinguished. To date, this approach is commonly used to analyse the net ecosystem exchange of  $\text{CO}_2$  and has proven to offer a valuable analysis tool for the detection of ecophysiological differences among different locations (Gilmanov et al., 2007). We then estimated annual emissions using data from a meteorological station in the centre of The Netherlands to drive the fitted ecosystem responses of the sites. This methodology may be viewed as a normalisation of the annual  $\text{CO}_2$  budget with respect to climatic conditions. It allowed us to better assess the influence of ecophysiological differences between the grasslands, in particular the difference between organic and mineral soils.

Datasets from two extensively managed grassland sites covered a period of four

## Variability of annual $\text{CO}_2$ exchange from Dutch Grasslands

C. M. J. Jacobs et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

consecutive years. Based on these data, we also estimated the interannual variability relative to ecophysiological differences.

Like Gilmanov et al. (2007), the present analysis is restricted to CO<sub>2</sub> exchange of grassland sites. We recognize the potentially significant role of nitrous oxide and methane in the total greenhouse gas budget of grasslands as well as of farm practice and management. However, long-term micrometeorological observations of N<sub>2</sub>O and CH<sub>4</sub> exchange similar to those of CO<sub>2</sub> are not yet available in The Netherlands. Moreover, *NEE* is usually the largest term in the surface-atmosphere exchange of GHG at the field scale, and is the starting point for the construction of more complete GHG balances at the farm level (Soussana et al., 2007a; also see Brandes et al., 2006).

## 2 Materials and methods

### 2.1 Study sites

The Netherlands, a midlatitude coastal country, has a high frequency of rain events that are more or less evenly distributed during the year. The long-term mean precipitation ranges between 730 mm a<sup>-1</sup> (South West) and 750 mm a<sup>-1</sup> (East) and occurs during 190±26 days a year (Jacobs et al., 2006). The long-term mean annual temperature ranges between 8.9°C (North) and 9.5°C (South) and the long-term mean incoming solar radiation ranges between 3400 MJ m<sup>-2</sup> a<sup>-1</sup> (Centre) and 3850 MJ m<sup>-2</sup> a<sup>-1</sup> (West).

CO<sub>2</sub> exchange of 8 grassland sites distributed over the Netherlands is analyzed. The geographical locations of these sites are shown in Fig. 1. All sites have a so-called long potential growing season (above 260 days), in which the mean air temperature is above 5°C. For example, the most eastern and coldest grassland site had a potential growing season of 305±12 days in the years 2002–2005, which is the period analyzed here.

In order to measure the CO<sub>2</sub> fluxes, all stations are equipped with EC systems, consisting of a fast response sonic anemometer and a fast response CO<sub>2</sub>–H<sub>2</sub>O analyzer.

## Variability of annual CO<sub>2</sub> exchange from Dutch Grasslands

C. M. J. Jacobs et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

General principles of the EC flux measurement methodology as well as processing of the data required to obtain high-quality flux estimates are described by Aubinet et al. (2000, 2003). For all sites included in this study, data treatment and quality control closely followed the guidelines in these papers.

In addition to the EC devices at each site a weather station is installed, which provides 30-min averages of global radiation ( $R_{in}$ ), net radiation, air temperature ( $T_a$ ), vapour pressure, wind speed, wind direction and precipitation. The agro-meteorological station “Haarweg” in the centre of the Netherlands is equipped with an independent double meteorological measurement system in order to avoid gaps in the data. This makes the meteorological data from this station suitable to estimate annual CO<sub>2</sub> budgets from the ecosystem responses (see Sects. 2.2 and 2.3).

Below a brief description is given of the various grassland sites included here. Moreover, the main characteristics of the sites are listed in Table 1. For more detailed information on the EC measurements, the reader is referred to the cited literature.

### 2.1.1 Haarweg station

The meteorological observatory of the Wageningen University, Haarweg Station, is located in the centre of the Netherlands (lat. 51°58' N, long. 5°38' E, altitude +7 m a.s.l.; www.met.wau.nl). The dominating plant species in this perennial grassland area are rye grass (*Lolium perenne*) and rough blue grass (*Poa trivialis*). The soil at the site is predominantly heavy clay resulting from the back-swamps of the river Rhine. The one-sided Leaf Area Index, LAI, of the terrain is kept constant as good as possible and has a numerical value of 2.9±0.3. About monthly the LAI is measured by a plant analyzer (CID-Inc. model CI-110). During the growing season (1 May–1 November), the grass cover is mowed weekly. With a special grass height meter (Eijkelkamp, model NMI), the mean grass height (about 10 cm) is checked daily. There is a unique relation between the grass height and LAI (Keuning, 1988). If the LAI as derived from the observed grass height exceeds the maximum value of 3.2 within a week, the grass is mowed more frequently. At the measurement site the mowed grass is not removed but

Variability of annual  
CO<sub>2</sub> exchange from  
Dutch Grasslands

C. M. J. Jacobs et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

evenly spread over the area. CO<sub>2</sub> flux measurements from the period 2002–2005 are analyzed here. More details about the site can be found in Jacobs et al. (2003b).

2.1.2 Fochteloërveen

The Fochteloërveen area is a disturbed raised bog in the north of the Netherlands (lat. 53°00' N, long. 6°24' E, altitude +11 m a.s.l.). The vegetation is a natural tussock grassland, with an average height of approximately 0.4 m. A layer of 0.1 m of dead organic material from the previous growing seasons covered the tussocks and the hollows in between. The dominating plant species is *Molina caerulea* (>75%) but also species like *Eriophorum vaginatum*, *Calluna vulgaris* and *Erica tetralix* could be found. The green LAI has a maximum of about 1.7 in August. Throughout the seasons, the water table depth varied, depending on the weather, from 0 to 0.2 m below the tussock soil interface but the soil remained saturated. CO<sub>2</sub> fluxes were measured between June 1994 and October 1995. More details about this site can be found in Nieveen et al. (1998) and Jacobs et al. (2003a).

2.1.3 Cabauw

The Cabauw site is located on grassland in the centre of the Netherlands (lat. 51°57' N, long. 4°54' E, altitude -0.7 m a.s.l.). The dominating plant species in this perennial grassland area are *Lolium perenne* (40%), *Poa trivialis* (20%) and *Alopecurus geniculatus* (10%). The grass is maintained by grazing of sheep and the mean LAI is about 3. The soil is a 0.7 m thick clay layer on peat. Ditches occupy 10% of the aerial surface. The water level in the ditches is kept constant during the winter half year and the summer half year respectively. Horizontal transport of water from the grassland to the ditches is limited. This results in considerable changes in ground water level at the central parts of the grassland throughout the year.

CO<sub>2</sub> fluxes from four consecutive years (2002–2005) are analysed here. With westerly wind, the footprint of the flux observation is partly over a neighbouring field which

Variability of annual CO<sub>2</sub> exchange from Dutch Grasslands

C. M. J. Jacobs et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



is bare soil in winter and maize during summer. Results from the wind direction from this area, between 177 and 317 degrees, are therefore ignored in the present study. More details about this site can be found in Beljaars and Bosveld (1997).

2.1.4 Horstermeer

5 The Horstermeer site is a grassland/wetland polder of a former agricultural land in a drained natural lake in the centre of the Netherlands (lat. 52°02' N, long. 5°04' E, altitude -2.2 m a.s.l.). The site has been taken out of agricultural production more than 10 years ago, and has developed into semi-natural grassland. The two meter thick soil consists of peat, overlain with organic-rich lake deposits and is overlying eolian  
10 sands of Pleistocene age. After the site has been taken out of agricultural production, the ditch water table has been raised to approximately 10 cm below the land surface. Large parts of the Horstermeer polder are subject to strong groundwater seepage from surrounding lake areas and Pleistocene ice pushed ridges. At the measurement location seepage is largely reduced and even infiltration occurs as a result of the high water  
15 table. The surface of the research area consists for 10% of ditches, for 20% of land that is saturated year-round (mostly alongside the ditches) and for 70% of relatively dry land with a fluctuating water table (between 0 to 40 cm below the soil surface) and an aerated top-layer. Management consists only of regulation of the ditch water table; no cattle grazing or harvesting takes place, the only removal of vegetation consists of sporadic  
20 grazing by roe deer. Vegetation consists of different types of grasses (dominant species *Holcus lanatus*, *Phalaris arundinacea*, *Glyceria fluitans*), horsetail (*Equisetum palustre*, *fluviatile*) reeds (*Phragmites australis*, *Typha latifolia*) and high forbs (*Urtica dioica*, *Cirsium arvense*, *palustre*). Measurements of CO<sub>2</sub> fluxes from the year 2005 are included in the present study. More details about this site can be found in Hendriks  
25 et al. (2007).

Variability of annual CO<sub>2</sub> exchange from Dutch Grasslands

C. M. J. Jacobs et al.

Title Page

AbstractIntroduction

ConclusionsReferences

TablesFigures

◀▶

◀▶

BackClose

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

2.1.5 Haastrecht

The Haastrecht site is a grassland polder in the centre of the Netherlands (lat. 52°00' N, long. 4°48' E, altitude -1.4 m a.s.l.). The dominating plant species in this perennial grassland area are *Lolium perenne* and *Poa trivialis*, with an averaged LAI of about 3. The soil at the site is predominantly a peat soil. The water table is kept constant with a level of -1.6 m during the summer season and -1.8 m during the winter season. The grass at the measurement site is maintained by grazing of sheep. The direct surroundings of the measurement site are agricultural grasslands with rotational grazing by cows and sheep. CO<sub>2</sub> flux measurements were performed from July 2003 until May 2004.

2.1.6 Stein

The Stein site is a polder in the west of the Netherlands (lat. 52°01' N, long. 4°46' E, altitude -1.6 m a.s.l.). The polder was used as grass production land and during the past 20 years the area has gradually become a meadow bird reserve. The dominating plant species in this perennial grassland area are *Lolium perenne* and *Poa trivialis*. Vernal grass (*Anthoxantum odoratum*) and sour dock (*Rumex acetosa*), however, are becoming more abundant. The soil at the site is a clayey peat or peaty clay of about 25 cm thickness on a 12 m thick peat layer. About 15% of the area is open water (ditches or low parts in the landscape). CO<sub>2</sub> flux measurements were conducted from 2004 onwards. More details about this site can be found in Veenendaal et al. (2007)<sup>1</sup>.

<sup>1</sup>Veenendaal, E. M., Kolle, O., Leffelaar, P., Schrier, A., Van Huissteden, K., Van Walsum, J., Moller, F., and Berendse, F.: Land use dependent CO<sub>2</sub> exchange and carbon balance in two grassland sites on eutropic drained peat soils, Biogeosci. Discuss., submitted, 2007.

Variability of annual CO<sub>2</sub> exchange from Dutch Grasslands

C. M. J. Jacobs et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

2.1.7 Oukoop

The Oukoop site is a grassland polder in the west of the Netherlands (lat. 52°02' N, long. 4°47' E, altitude −1.8 m a.s.l.). The grassland site is part of an intensive dairy farm with rotational grazing during the summer period (mid-May–mid-September). The dominating plant species in this perennial grassland area are *Lolium perenne* and *Poa trivialis*. Manure and fertilizers are applied two or three times a year, but not during winter time. The area is about 4 km South-West of the Stein location and has the same soil characteristics. CO<sub>2</sub> flux measurements started in 2004. More details about this site can be found in Veenendaal et al. (2007)<sup>1</sup>.

2.1.8 Lelystad

The Lelystad site is a grassland site in the centre of the Netherlands (lat. 52°31' N, long. 5°35' E, altitude 0 m a.s.l.). The site is located in the Flevopolder, an area reclaimed from Lake IJssel in 1965. The soil consists of young sea clay. The groundwater table is maintained at about 1 m below the ground surface, but it can be higher during periods of rain. The grassland site is part of an experimental farm “De Waiboerhoeve” with intensive management with 5–6 harvests a year. Grass was removed from the field either by cutting or by grazing. The farm has a total number of 400 cows and 500 sheep. Manure and fertilizers are applied about six times a year, but not during winter time. CO<sub>2</sub> flux observations from the period July 2003 until June 2004 are analyzed here. More details about this site can be found in Gilmanov et al. (2007).

2.2 Net Ecosystem Exchange of CO<sub>2</sub> (*NEE*) and respiration

The net ecosystem exchange of CO<sub>2</sub>, *NEE*, is the result of photosynthetic uptake, *GPP*, and the ecosystem respiration, *R<sub>e</sub>*. Using the ecological sign convention with photosynthetic uptake defined positive, we have:

$$NEE = GPP - R_e$$

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

During nighttime, only respiration occurs which enables analyses based on a distinction between daytime (downward solar radiation  $R_{in} > 0$ ) and nighttime ( $R_{in} = 0$ ) fluxes. For nighttime Eq. (1) reduces to:

$$NEE = -R_e = -R_{\text{night}} \quad (2)$$

- 5 Temperature is an important driving variable of respiration. This relation is usually expressed by means of, for example, an Arrhenius-type relation. Here, we apply the following equation to analyse the response of respiration to temperature (Lloyd and Taylor, 1994):

$$NEE = R_e = R_o \exp(E_a(\frac{1}{T_o - T_{\text{ref}}} - \frac{1}{T - T_{\text{ref}}})) \quad (3)$$

- 10 where  $R_o$  ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ ) is the reference respiration at  $T = T_o = 10^\circ\text{C}$  (or  $T_o = 283.15 \text{ K}$ ),  $T$  ( $^\circ\text{C}$ ) is temperature and  $E_a$  ( $\text{K}^{-1}$ ) is a the so-called ecosystem activation energy or sensitivity coefficient,  $T_{\text{ref}} = 227.13 \text{ K}$  is a second reference temperature denoting the temperature below which there is no respiration anymore. Temperature  $T$  in (3) may be soil temperature  $T_s$  or air temperature  $T_a$ . Because  $R_e$  originates from the soil and the vegetation,  $T_s$  would be a logical choice to use in (3). However, this temperature is not always available at all sites. Using half-hourly or hourly fluxes from eddy correlation measurements the fraction of variance explained by (3) does usually not differ much and for forest in particular, a slightly better correlation may even be obtained using  $T_a$  (Reichstein et al., 2005; Ruppert et al, 2006). Moreover, Van Dijk and Dolman (2004) suggested that using  $T_a$  gives much more consistent results in inter-site comparisons, which is probably due to problems and inconsistencies in the measurement of  $T_s$ . Therefore, and because we aim at a similar analysis for all sites, we use  $T_a$ , instead of  $T_s$ .

- 25 From the nighttime flux data we excluded those obtained during precipitation events. Furthermore, it was required that friction velocity  $u_* > 0.1 \text{ m s}^{-1}$ . During relatively calm stable nights turbulence is suppressed and the eddy-covariances become ill-defined

**BGD**

4, 1499–1534, 2007

## Variability of annual $\text{CO}_2$ exchange from Dutch Grasslands

C. M. J. Jacobs et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

**EGU**

since these conditions are non-stationary and non-homogeneous. It appears that the criterion  $u_* \leq 0.1 \text{ m s}^{-1}$  is an appropriate threshold for not applying the eddy-covariance technique (Van de Wiel et al., 2003). Indeed, analysis of the Haarweg data showed that the uncertainty in  $R_e$  due to uncertainty in the fitted parameters was less than 3% for 3 out of 4 years as long as if  $u_* > 0.1 \text{ m s}^{-1}$  but only increased to about 7% in one case (2003).

To determine the responses of  $R_e$  to temperature, the data from one entire year were averaged in  $T_a$  bins with an equal number of data. Equation (3) was then fitted to the bin averages, by optimizing the reference respiration,  $R_o$  as well as  $E_a$  (Ruppert et al., 2006). Annual sums of the respiration are then estimated by applying Eq. (3), with observed  $T_a$  from Haarweg as the driving variable.

The base respiration  $R_o$  and sensitivity coefficient  $E_a$  are probably influenced by soil moisture as well (Reichstein et al., 2005). Similarly, changes in ecosystem characteristics may affect  $R_e$ . To deal with these effects, the optimization may be carried out for separate, shorter periods of time. Tests with separate optimizations per period of half a month for the year 2005 showed that the effect on the annual sums on  $R_e$  varies from minor ( $48 \text{ gC m}^{-2} \text{ a}^{-1}$  or 3% in the case of Cabauw) to considerable ( $205 \text{ gC m}^{-2} \text{ a}^{-1}$  or 22% in the case of Lelystad). However, the numbers are then based on sometimes meaningless fits, with negative or very low correlations between model and data, with sometimes spurious behavior of  $R_o$ . Furthermore, for some sites gaps of a few months per year occurred, which implies additional uncertainty in inter-site comparisons, with results that cannot be compared anymore. Considering our goal, that is, to provide an estimate of the differences at an annual basis, it may therefore be argued that such a refined analysis does not necessarily imply a more reliable result. Therefore, it was decided to stick to the analysis in periods of one entire year.

Variability of annual  
CO<sub>2</sub> exchange from  
Dutch Grasslands

C. M. J. Jacobs et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

## 2.3 Parameterization photosynthetic uptake

There are two major light-use efficiency characteristics used in literature; the physiological one and the ecological one. Here we use the ecological light-use efficiency because these characteristics matches the scale of our analysis (Gilmanov et al., 2007).

- 5 The daytime data ( $R_{in} > 0$ ) are used to make an assessment of the light-response curves at the ecosystem scale. Again, data during episodes of precipitation are discarded. The data were stratified in  $T_a$  classes of 5°C and per temperature class the data were binned into 10 light intensity classes of equal numbers of data. Light response curves were then fitted to the light-bin averages, using the rectangular hyperbola (Goudriaan and Van Laar, 1994):
- 10

$$NEE + R_{eco} = GPP = \frac{\alpha R_{in} GPP_{max}}{\alpha R_{in} + GPP_{max}} \quad (4)$$

where  $R_{in}$  ( $W m^{-2}$ ) is the incoming short wave radiation,  $\alpha$  ( $\mu mol J^{-1}$ ) is the actual light conversion factor and  $GPP_{max}$  ( $\mu mol m^{-2} s^{-1}$ ) is the maximum gross assimilation rate.

- The stratification in temperature classes accounts for the effect of temperature on the photosynthesis. In addition photosynthesis may be affected by the humidity of the air, due to stomatal closure under dry atmospheric conditions. However, humidity deficit and temperature are strongly correlated in particular at the upper temperature ranges above the photosynthetic temperature optimum. Consequently, at the ecosystem scale, accounting for humidity differences as well has only a small effect on the annual sums in practice, in particular if the temperature bins are reduced. Similarly, as suggested
- 15
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- 25
- by Ruppert et al. (2006) ecosystem characteristics affecting the light response, such as LAI (Veenendaal et al., 2007<sup>1</sup>), may be correlated with temperature at seasonal timescales. Tests were performed with temperature bins reduced to 2 K. The scatter in the fitted parameters increased, but differences of <1% ( $\sim 15 gC m^{-2} a^{-1}$ ) were found with respect to the annual sums of  $GPP$ . Therefore, it was decided to only stratify the data into  $T_a$  bins of 5 K.

**BGD**

4, 1499–1534, 2007

### Variability of annual $CO_2$ exchange from Dutch Grasslands

C. M. J. Jacobs et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

**EGU**

### 3 Results and discussion

#### 3.1 Respiration characteristics

First, the nighttime fluxes of all grassland stations are analyzed in order to obtain the reference respiration,  $R_o$ , and the activation energy,  $E_a$ . Figure 2 shows the results from this analysis for the individual sites, as well as the mean parameter value from all the sites. In the case of Haarweg and Cabauw, the mean of 4 years has been plotted. Error bars denote the standard deviation.

It can be seen that the Stein and Oukoop locations behave more or less similar in their respiration characteristics. Both stations are situated in the same area and have nearly the same history. Only during the past 20 years the Stein site is gradually subjected to a different management regime, from intensively managed grassland into a meadow bird reserve. Apparently, this change has hardly affected the respiration characteristics until today. Second, we infer from Fig. 2 that the Fochteloërveen and Horstermeer grassland/wetland locations deviate most from all other locations. The Fochteloërveen area is a natural bog area. In summertime only, there is green vegetation with a very low LAI (about 1.7) and with a relatively high water table ranging between  $-0.0$  m (wintertime) and  $-0.2$  m (summertime) below the tussock soil interface. The Horstermeer area is a grassland/wetland area that is taken out of production for more than 10 years and has been developed into a semi-natural grassland/wetland. Also here the water table is relatively high and ranges between  $-0.4$  (summertime) and  $-0.0$  m (wintertime). As a consequence, at both locations the aeration of the uppermost soil layer is probably reduced, which then limits the respiration. In peat areas where the water table is usually close to the ground surface, this phenomenon may then result in a close relation between the water table depth and respiration (Lloyd, 2006). In places with a less direct coupling between soil moisture content of the upper layer and the depth of the groundwater table, such a relation may be very weak or absent (Lafleur et al., 2005; Nieveen et al., 2005).

For the Haarweg and Cabauw sites, observations from four complete years (2002–

**BGD**

4, 1499–1534, 2007

#### Variability of annual CO<sub>2</sub> exchange from Dutch Grasslands

C. M. J. Jacobs et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

**EGU**

2005) are available. To get insight into the interannual variation of  $R_o$  and  $E_a$ , their standard deviations have been calculated for both sites and plotted in Fig. 2 as well. These standard deviations can then be compared with the standard deviation from the average of all sites. In the case of Haarweg, the standard deviation in  $R_o$  amounts to  $0.66 \mu\text{mol m}^{-2} \text{s}^{-1}$  (15% of the average from four years), while it is  $39 \text{K}^{-1}$  in  $E_a$  (18%). For Cabauw, the standard deviations are  $0.46 \mu\text{mol m}^{-2} \text{s}^{-1}$  (14%) and  $39 \text{K}^{-1}$  (13%), respectively. This is much less than the standard deviations from all sites:  $1.37 \mu\text{mol m}^{-2} \text{s}^{-1}$  for  $R_o$  (31%) and  $125 \text{K}^{-1}$  (41%) for  $E_a$ , respectively. Assuming similar variability characteristics for all sites, these estimates of interannual variability imply an error of  $\sim 15\%$  in estimates of annual respiration if we apply the respiration characteristics calculated from one year of observations to all other years (also see Sect. 3.3).

To have some idea of the mutual respiration differences between all eight grasslands, the fitted respiration curves of all sites have been plotted in Fig. 3 as function of the air temperature along with the averaged temperature dependency and their standard deviations. Clearly, it can be inferred from Fig. 3 that both grassland/wetland locations reveal relatively low respiration rates at low temperatures, but their high temperature sensitivity compensates for the lower base respiration at the higher temperatures. Considering the response curves over the entire range, these two sites cause the relatively large standard deviations from the mean value. Moreover, from Fig. 3 it can be observed that the Haastrecht site shows a relatively high base respiration rate. The Haastrecht site is a peat soil area and has a lower water table than the Fochteloërveen and Horstermeer sites which ranges between  $-0.2$  (summertime) and  $-0.4 \text{ m}$  (wintertime). Probably both reasons (peat soil and lower water table) are responsible for the relatively high base respiration rate at the Haastrecht site. However, the temperature sensitivity is much less than at Horstermeer and Fochteloërveen, which tends to reduce the overall respiration rate at the higher temperatures. The Lelystad site reveals a similar low temperature sensitivity. However, in this case the base respiration is much like the average one, resulting in relatively large deviations from the average at higher temperatures.

# Variability of annual $\text{CO}_2$ exchange from Dutch Grasslands

C. M. J. Jacobs et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## 3.2 Light responses

Figure 4 depicts the characteristics of the light response curves of all eight grassland sites as a function of the temperature. The temperature taken is central in the 5-degrees temperature bins defined in the analysis. This is very close to the bin-averaged temperature. In the case of Cabauw and Haarweg, the values from 2005 have been plotted. The variability of the parameters during the period 2002–2005 will be further investigated below.

In the top panel of Fig. 4, all the light conversion factors  $\alpha$  are plotted along with the average from all sites and the standard deviations per temperature bin. It can clearly be seen that on average  $\alpha$  is nearly a constant for all temperature classes, with a value somewhat below  $0.1 \mu\text{mol J}^{-1}$ . The Fochteloöerveen area has a very low LAI, especially during the start and the end of the growing season ( $\text{LAI} < 1$ ). It must be expected that this is the reason for a relatively low light conversion factor for this area in particular for the low temperature classes. On the other hand,  $\alpha$  at the Haastrecht site is rather high at higher temperatures. This causes the largest part of the standard deviation in the temperature classes  $> 20^\circ\text{C}$ . Since the Haastrecht site generally also shows the highest values of the gross maximum assimilation rate (see below) this may be an effect of a high LAI in this area. Effects of LAI on the light conversion factor and on the assimilation rate at saturating light intensity has been demonstrated at the Oukoop and Stein sites by Veenendaal et al. (2007)<sup>1</sup>. However, note that part of the large standard deviation at high temperatures is due to uncertainty in the fits caused by low numbers of data in these temperature classes.

The bottom panel of Fig. 4 contains a measure for the gross assimilation rate at a solar light intensity of  $R_{in} = 1000 \text{ W m}^{-2}$ ,  $GPP_{1000}$ . The maximum gross assimilation rate  $GPP_{\text{max}}$  is an asymptotic value for the rectangular hyperbolic light response function (see Eq. 4), which varies during the seasons and for different ecosystems. However, it often does not saturate within a realistic range of radiation intensities, especially in cases where the response tends to be linear, or if no observations are available beyond

**BGD**

4, 1499–1534, 2007

### Variability of annual $\text{CO}_2$ exchange from Dutch Grasslands

C. M. J. Jacobs et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

**EGU**

the quasi-linear section of the curves. In such cases, the fitted  $GPP_{\max}$  is not a realistic measure of maximum gross assimilation rates. Therefore, in order to obtain a more realistic comparison between different sites we follow Ammann et al. (2007) and use  $GPP_{1000}$  instead. As such,  $GPP_{1000}$  can be interpreted as a measure for the so-called light saturation point for the various ecosystems.

It must be expected that for an ecosystem with a low LAI, the light saturation is reached at lower irradiances than for an ecosystem with a high LAI (Goudriaan and Van Laar, 1994) but  $GPP_{1000}$  will be higher for ecosystems with higher LAI. Figure 4 clearly reflects that for the Fochteloërveen site, which has the lowest maximum LAI ( $LAI_{\max} \approx 1.7$ ). Similarly, Haastrecht presumably has the highest LAI. Although there are no direct observations, at locations near the Haastrecht site LAI values up to about 10 have been observed.

Observations from four complete years (2002–2005) at Haarweg and Cabauw are further analyzed to get insight into the interannual variation of  $\alpha$  and  $GPP_{1000}$ , relative to the variation between sites. We consider the temperature classes between 5 and 25°C because the fits in these classes are most reliable and are available for all years. These variations can then be compared with the standard deviation from the average of all sites. Figure 5 shows as a function of the middle temperature of the bins the coefficient of variation (CV, standard deviation relative to the mean value) of  $\alpha$  and  $GPP_{1000}$  for the Haarweg and Cabauw averages in the period 2002–2005, and for the individual years of all sites (2005 in the case of Haarweg and Cabauw). The interannual variability of  $\alpha$  is comparable or even larger than the inter-site variability, with CV values between 18 and 63%. In contrast, the interannual variability of  $GPP_{1000}$  is clearly less than the inter-site variability. CV values range between 12 and 35% for the interannual variability, and between 34 and 59% for the inter-site variability. At the lower and higher  $T_a$  classes, the uncertainty tends to be larger because there are less data in the bins. Also, because temperature and irradiation are correlated, high  $R_{in}$  is underrepresented at low  $T_a$  and the reverse.

Because the values of  $\alpha$  and  $GPP_{\max}$  (or  $GPP_{1000}$ ) from the fits tend to be anti-

## Variability of annual $CO_2$ exchange from Dutch Grasslands

C. M. J. Jacobs et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

correlated, the estimated variability in the annual *GPP* is much less. Based on the observed meteorological conditions at Haarweg in the year 2005, the CV of annual *GPP* amounts to about 9 and 14% for Haarweg and Cabauw, respectively, while it is nearly 38% for the inter-site variability. Thus, again assuming similar variability characteristics for all sites, these estimates imply an error of ~15% in estimates of annual *GPP* if we apply the light-response characteristics calculated from 1 year of observations to all other years (also see Sect. 3.3).

### 3.3 Annual CO<sub>2</sub> exchange

Figure 6 contains the individual annual sums of *R<sub>a</sub>*, *GPP* and *NEE* for the eight different locations and the four selected years. The sums have been computed using the observed meteorological conditions (*T<sub>a</sub>* and *R<sub>in</sub>*) at Haarweg as driver of the response functions. Because the response functions used are the same in each year, the interannual variability revealed in Fig. 6 reflects differences in the main climatological drivers.

The respiration does not show large interannual differences for all eight individual sites. This is to be expected because the driving variable of the respiration model is *T<sub>a</sub>*, that does not vary much on the annual timescale, in the period considered here. For example, at the Haarweg site the long-term mean annual air temperature is 9.4±0.7°C (Jacobs et al., 2006). The mean annual respiration is 1450±25 gC m<sup>-2</sup> a<sup>-1</sup>. The average *GPP* for all sites amounts to 1400±110 gC m<sup>-2</sup> a<sup>-1</sup>, which displays a much higher variability (8%) than the respiration (2%). *GPP* depends on *R<sub>in</sub>* in combination with *T<sub>a</sub>*. In particular *R<sub>in</sub>* can vary much between the years. For example, the long-term *R<sub>in</sub>* for the Haarweg site is 3400±300 MJ m<sup>-2</sup> a<sup>-1</sup>.

Obviously, the *NEE* shows a much larger variation (see Fig. 6c). On average, the annual *NEE* amounts to -65±85 gC m<sup>-2</sup> a<sup>-1</sup>, which means that on average our grasslands act as a source with a relatively large standard deviation.

We next assess the interannual variation of the carbon exchange components due to eco-physiological differences (see Sects. 3.1 and 3.2). To this end, annual sums

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

are computed for the Cabauw and Haarweg sites for the year 2005, using the fits of each individual year in the period investigated. The average of the four sums and the standard deviation are then compared with the average and standard deviation from all sites, using the respective model fits of the specific year of the observations (2005 in the case of Cabauw and Haarweg), again driven with  $T_a$  and  $R_{in}$  from Haarweg in 2005. Results are shown in Table 2. It can be seen that the absolute and relative variation in  $GPP$  and  $R_d$  due to the interannual differences in ecophysiological characteristics are much smaller than the intersite variation (10–15% versus 35–37%, respectively). However, the standard deviation of the site-average  $NEE$  is similar to the one of the period-average (207 versus 176–276 gC m<sup>-2</sup> a<sup>-1</sup>). Note that the CV of  $NEE$  given in the table shows a spurious behavior due to the small averages.

From former research it must be expected that grasslands on organic soils (e.g. peat) are sources for carbon dioxide (Nieveen et al., 1998; Nieveen et al., 2005; Lloyd, 2006; Veenendaal et al., 2007<sup>1</sup>), while grasslands on mineral soils (for example, clay and sand) are sinks for carbon dioxide (Gilmanov et al., 2007). Clearly it can be observed that the Fochteloërveen, Haastrecht, Oukoop and Stein sites follow this rule for organic soils and the Haarweg and Horstermeer sites for mineral soils. An exception appears to be the Cabauw site, which has a clay soil but sometimes behaves as a source (2002, 2003, 2004) and sometimes as a sink for CO<sub>2</sub> (2005).

To make a distinction between both soil types, the sums of the annual carbon fluxes are plotted separately for both soil types in Fig. 7 along with their standard deviations. From Fig. 7 we conclude that the annual standard deviations for all fluxes of the organic soils are much higher than those for the mineral soils. In our case this larger standard deviation is mainly caused by the Fochteloërveen bog site, which behaves quite differently from the other organic grassland sites. Second, we conclude that for both soil types the interannual differences in  $R_d$  are small in comparison to the interannual differences in  $GPP$  and as a consequence the interannual differences in  $NEE$  are large as well. This also can be concluded from Table 3 where for both soil types the mean of the whole selected period have been given.

## Variability of annual CO<sub>2</sub> exchange from Dutch Grasslands

C. M. J. Jacobs et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

On average we conclude from Table 3 that the annual *NEE* amounts  $90\pm90\text{ gC m}^{-2}\text{ a}^{-1}$  for the mineral soils and  $-220\pm90\text{ gC m}^{-2}\text{ a}^{-1}$  for the organic soils. As stated earlier, about 80% of the Dutch grasslands are on mineral soils and about 20% on organic soils. Do we take the weighed mean for the Dutch grasslands we find on average  $28\pm90\text{ gC m}^{-2}\text{ a}^{-1}$  which means that on average the Dutch grasslands behave like a sink for  $\text{CO}_2$ .

Our results suggest that within small regions with relatively uniform climatic conditions the variability may be similar to the one observed at much larger scales with a large range of climatic conditions. At the European scale, Gilmanov et al. (2007) found the annual *GPP* to vary between 464 and  $1881\text{ gC m}^{-2}\text{ a}^{-1}$ ,  $R_e$  between 572 and  $1636\text{ gC m}^{-2}\text{ a}^{-1}$  and *NEE* between an uptake of  $655\text{ gC m}^{-2}\text{ a}^{-1}$  and a release of  $164\text{ gC m}^{-2}\text{ a}^{-1}$ . These numbers are based on gapfilled timeseries of observations. Our ranges in *GPP* and  $R_e$  are similar to the one reported by Gilmanov et al. (2007): annual *GPP* varies between 391 and  $2109\text{ gC m}^{-2}\text{ a}^{-1}$ , and  $R_e$  between 560 and  $2047\text{ gC m}^{-2}\text{ a}^{-1}$ . We find the *NEE* to vary between a net uptake of  $307\text{ gC m}^{-2}\text{ a}^{-1}$  and a release of  $250\text{ gC m}^{-2}\text{ a}^{-1}$ . Our results are based on ecosystem characteristics derived from on-site quality-controlled observations, extrapolated using response functions at the yearly timescale to the climatological conditions of one site. We feel that this method works satisfactorily for intersite-comparison and enables estimates of the relative contribution of climatological and ecophysiological conditions to the variability of  $\text{CO}_2$  exchanges of grassland.

Finally, comparing the ranges in annual  $\text{CO}_2$  exchange at the European and National (Dutch) scale, it may be concluded that emission factors should be derived at the scale of application, and cannot simply be interpolated from larger to smaller regions. Moreover, there is a need for regionally specific and spatially explicit  $\text{CO}_2$  emission factors at the field scale.

## Variability of annual $\text{CO}_2$ exchange from Dutch Grasslands

C. M. J. Jacobs et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

## 4 Summary and conclusions

For eight Dutch grassland sites, CO<sub>2</sub> fluxes were determined using the Eddy Covariance technique during periods of at least 10 months per site. The measurement sites, four natural grasslands, two production grasslands and two meteorological stations within a rotational grassland region, are more or less distributed over the grassland areas in The Netherlands. The photosynthesis-light response analysis technique is used along with the respiration-temperature response technique to partition *NEE* among Gross Primary Production (*GPP*) and Ecosystem Respiration (*R<sub>e</sub>*) and to obtain the eco-physiological characteristics of the sites at the field scale. To assess annual sums of *NEE*, *R<sub>0</sub>*, *GPP* and their variability, calculations using the fitted response curves were then carried out for four years (2002–2005). Air temperature and solar radiation observed at the Haarweg meteorological station in the centre of The Netherlands were used as drivers of the response models. The main conclusions of this study are summarized as follows:

1. The annual *NEE* is estimated to be  $-65 \pm 85 \text{ gC m}^{-2} \text{ a}^{-1}$ . This means that on average the grasslands act as a source, with a relatively large standard deviation. However, a distinction can be made between the grasslands on mineral soils, with a mean net uptake of  $90 \pm 90 \text{ gC m}^{-2} \text{ a}^{-1}$ , and those on organic soils with a mean net release of  $220 \pm 90 \text{ gC m}^{-2} \text{ a}^{-1}$ . The mean *NEE* weighed with the fraction of grasslands on organic (20%) and mineral soils (80%) is  $28 \pm 90 \text{ gC m}^{-2} \text{ a}^{-1}$ , implying that on average the Dutch grasslands behave like small sink for CO<sub>2</sub>.
2. The main characteristics of the respiration-temperature response curves, *R<sub>0</sub>* and *E<sub>a</sub>*, of individual sites show an interannual variability which is much lower than the inter-site variability, with a variability coefficient of ~15% versus ~35%, respectively. The resulting corresponding variabilities in annual *R<sub>e</sub>* are similar. The variability due to differences in climatological factors is much smaller, ~2%.
3. The light conversion factor,  $\alpha$ , is more or less a constant for all analyzed ecosystems.

**BGD**

4, 1499–1534, 2007

### Variability of annual CO<sub>2</sub> exchange from Dutch Grasslands

C. M. J. Jacobs et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

**EGU**

## Variability of annual CO<sub>2</sub> exchange from Dutch Grasslands

C. M. J. Jacobs et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

tems and for all temperature classes, while  $GPP$  and the light saturation point,  $GPP_{1000}$ , differs for all analyzed ecosystems and temperature classes. It must be expected that  $GPP_{1000}$  is a function of the leaf area index. Interannual variability of  $\alpha$  ranges from  $\sim 20$  to  $\sim 60$  %, depending on the air temperature, and is similar to the intersite variability. The standard deviation of  $GPP_{1000}$  is  $\sim 10$  to  $\sim 40$  % of the four-year averages and  $\sim 40$  to  $\sim 60$  % of the means from all sites, again depending on the air temperature. The corresponding coefficients of variation for annual GPP are  $\sim 10$  to  $15$  % and  $\sim 37$  %, respectively. Variability due to climatology is assessed to be  $\sim 8$  %.

4. The standard deviation of annual  $NEE$  due to interannual and intersite variability of ecophysiological differences is estimated to be  $176$ – $276$   $\text{gC m}^{-2} \text{a}^{-1}$  both cases, as compared to  $85$   $\text{gC m}^{-2} \text{a}^{-1}$  for climatologically driven variability.
5. Our variability estimates are similar to those on a much larger, European scale. It may be concluded that emission factors should be derived at the scale of application, and cannot simply be interpolated from larger to smaller regions. There is a need for regionally specific and spatially explicit CO<sub>2</sub> emission factors at the field scale.

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**BGD**

4, 1499–1534, 2007

## Variability of annual CO<sub>2</sub> exchange from Dutch Grasslands

C. M. J. Jacobs et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

**EGU**



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**BGD**

4, 1499–1534, 2007

## Variability of annual CO<sub>2</sub> exchange from Dutch Grasslands

C. M. J. Jacobs et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

**EGU**

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**BGD**

4, 1499–1534, 2007

## Variability of annual CO<sub>2</sub> exchange from Dutch Grasslands

C. M. J. Jacobs et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

**EGU**

# Variability of annual CO<sub>2</sub> exchange from Dutch Grasslands

C. M. J. Jacobs et al.

**Table 1.** Site characteristics of the eight Dutch grassland sites.

Name	Type	Soil (FAO)	Fertilizer Use	Land Use	Year
Haarweg	WMO-Grassland	Eutric gleyic Fluvisol	No	Mowing	2002–2005
Cabauw	WMO-Grassland	Eutric Fluvisol	No	Grazing sheep	2002–2005
Horstermeer	Grassland/Wetland	Eutric Histosol	No	Semi-natural permanent grassland	2005
Fochterlooërveen	Natural Grassland	Eutric Histosol	No	Natural grassland	1994–1995
Haastrecht	Production Grassland	Eutric Fibric Histosol	Yes	Intensively managed permanent grassland	2003(July)–2004(May)
Oukoop	Production Grassland	Fibric Eutric Histosol	Yes	Intensively managed permanent grassland	2005
Stein	Meadow Bird Reserve	Fibric Eutric Histosol	No	Natural grassland	2005
Lelystad	Production Grassland	Calcaric Eutric Fluvisol	Yes (6 times a year)	Intensively managed permanent grassland	2004

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

## Variability of annual CO<sub>2</sub> exchange from Dutch Grasslands

C. M. J. Jacobs et al.

**Table 2.** Estimated mean and standard deviation of annual *GPP*, *R<sub>e</sub>* and *NEE* for all sites in the year 2005 and for Haarweg and Cabauw over the period 2002–2005.

	<i>R<sub>e</sub></i> (gC m <sup>-2</sup> a <sup>-1</sup> )	<i>σR<sub>e</sub></i> (gC m <sup>-2</sup> a <sup>-1</sup> )	<i>GPP</i> (gC m <sup>-2</sup> a <sup>-1</sup> )	<i>σGPP</i> (gC m <sup>-2</sup> a <sup>-1</sup> )	<i>NEE</i> (gC m <sup>-2</sup> a <sup>-1</sup> )	<i>σNEE</i> (gC m <sup>-2</sup> a <sup>-1</sup> )
Cabauw (2002–2005)	1458	227 (15.6%)	1466	206 (14.1%)	8	276 (3422%)
Haarweg (2002–2005)	1803	247 (13.7%)	2011	171 (8.5%)	208	176 (84.8%)
All sites (2005)	1396	486 (34.8%)	1432	534 (37.7%)	36	207 (575%)

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[◀](#)
[▶](#)
[◀](#)
[▶](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)

## Variability of annual CO<sub>2</sub> exchange from Dutch Grasslands

C. M. J. Jacobs et al.

**Table 3.** The mean annual sums of  $R_d$ , Gross Primary Production,  $GPP$ , and the net ecosystem exchange,  $NEE$ , for the organic and mineral soil types for 2002 until 2005.

	Organic soils	Mineral soils
$R_d$ (gC m <sup>-2</sup> a <sup>-1</sup> )	1520±30	1250±30
$GPP$ (gC m <sup>-2</sup> a <sup>-1</sup> )	1300±100	1370±100
$NEE$ (gC m <sup>-2</sup> a <sup>-1</sup> )	-220±90	90±90

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[I◀](#)
[▶I](#)
[◀](#)
[▶](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)



**Fig. 1.** Geographical distribution of the Dutch grassland study sites: 1 – Cabauw, 2 – Fochteloöërveen, 3 – Haarweg, 4 – Haastertrecht, 5 – Horstermeer, 6 – Oukoop, 7 – Stein, 8 – Lelystad.

## Variability of annual $\text{CO}_2$ exchange from Dutch Grasslands

C. M. J. Jacobs et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

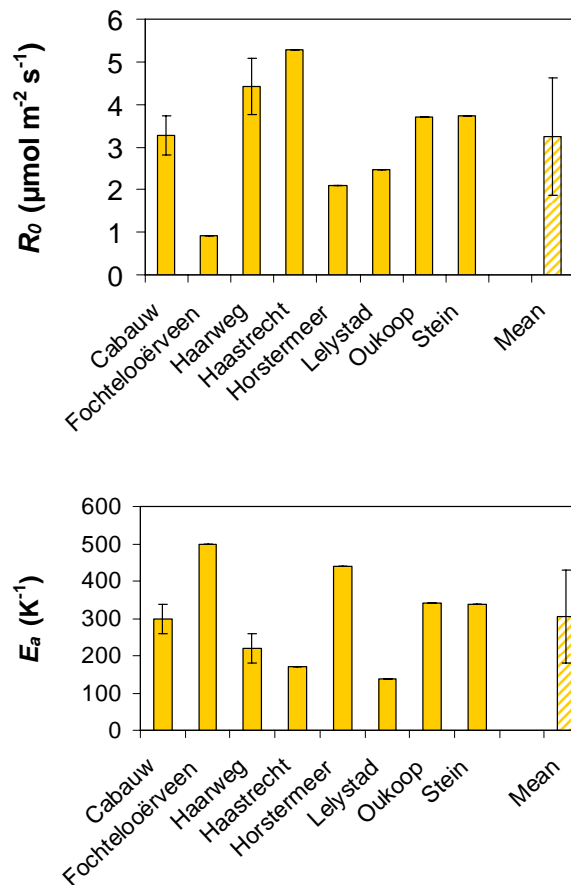
Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**Fig. 2.** The ecosystem activation energy,  $E_a$ , and the reference respiration,  $R_o$ , for the various grassland stations. For the Haarweg and Cabauw sites, the standard deviations have been indicated for the four measurement years.

## Variability of annual $\text{CO}_2$ exchange from Dutch Grasslands

C. M. J. Jacobs et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

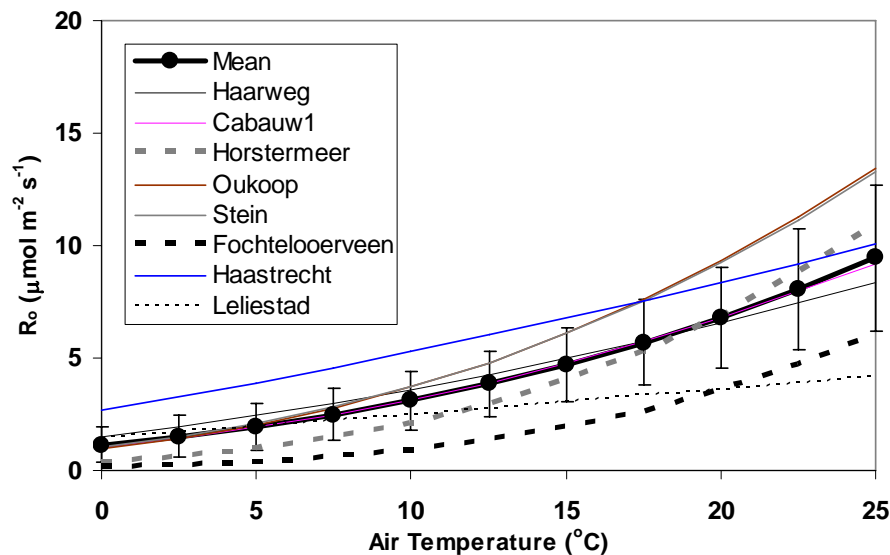
Full Screen / Esc

Printer-friendly Version

Interactive Discussion

**Variability of annual  
CO<sub>2</sub> exchange from  
Dutch Grasslands**

C. M. J. Jacobs et al.



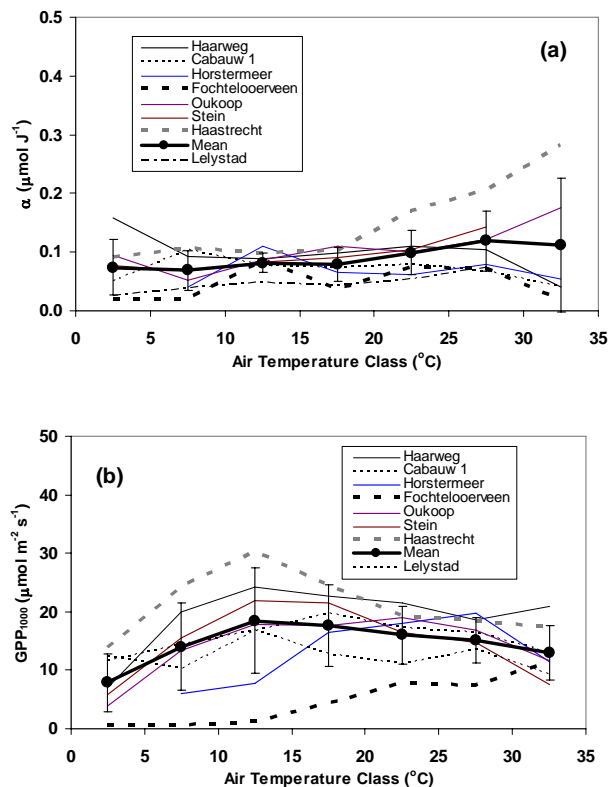
**Fig. 3.** The air temperature dependency of the respiration of all grassland locations along with the averaged values and standard deviations.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)



# Variability of annual CO<sub>2</sub> exchange from Dutch Grasslands

C. M. J. Jacobs et al.



**Fig. 4.** The air temperature dependency of the light conversion factor,  $\alpha$ , (top frame) and gross assimilation rate at an incoming short wave radiation of  $1000 \text{ W m}^{-2}$ ,  $GPP_{1000}$ , (bottom frame) of all grassland locations along with the averaged value and their standard deviations.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

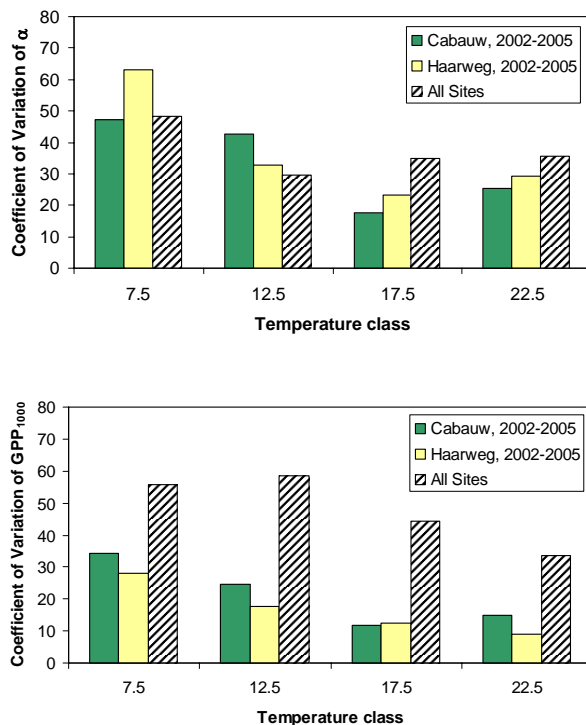
Full Screen / Esc

Printer-friendly Version

Interactive Discussion

**Variability of annual  
CO<sub>2</sub> exchange from  
Dutch Grasslands**

C. M. J. Jacobs et al.

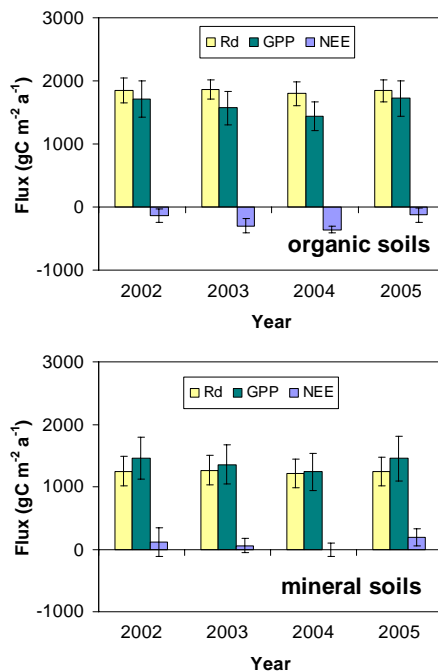


**Fig. 5.** Coefficient of variation per temperature class of  $\alpha$ , (upper frame) and  $GPP_{1000}$  (lower frame). The temperature class is indicated by the middle temperature of the class. The CV from of interannual variability (Haarweg and Cabauw, 2002–2005) is compared to CV from the intersite variability (year 2005).

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

## Variability of annual $\text{CO}_2$ exchange from Dutch Grasslands

C. M. J. Jacobs et al.

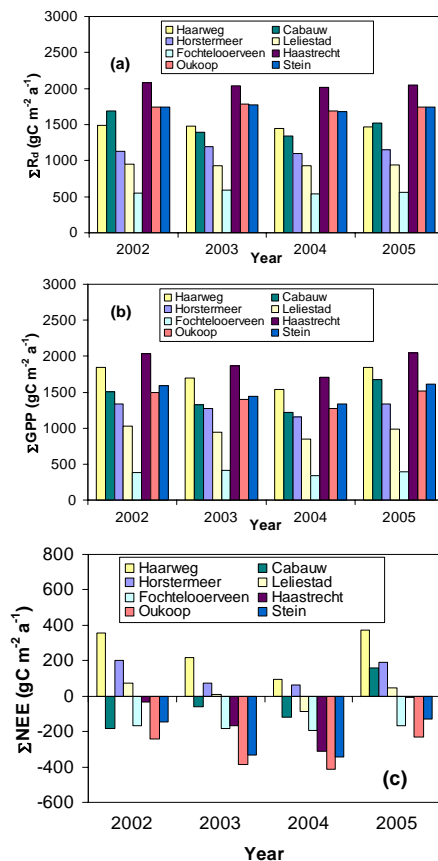


**Fig. 6.** The individual cumulative respiration,  $R_d$ , Gross Primary Production,  $GPP$ , and the net ecosystem exchange,  $NEE$ , of all grassland stations for 2002 until 2005.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

# Variability of annual CO<sub>2</sub> exchange from Dutch Grasslands

C. M. J. Jacobs et al.



**Fig. 7.** The mean annual sums of  $R_d$ , Gross Primary Production,  $GPP$ , and the net ecosystem exchange,  $NEE$ , for the organic and mineral soil types during 2002 until 2005.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion