Earth System Science Group

Internship Earth System Science

A comparative field study of four soil respiration systems



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Preface

The fulfillment of this internship was the last step in completing the requirements for my master degrees. From June to December 2007 this study on the comparison of different soil respiration systems was performed at Alterra, ESS-CC.

I would like to thank Dirk de Kramer for his help during the nightly measurements and Bert Heusinkveld for calculating and providing the eddy correlation data. I also like to thank Eef Velthorst with his help during the fieldwork and to get started with the ADC soil respiration system. Last I want to thank Jan Elbers and Marcel Hoosbeek for their supervision and for answering all my questions.

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1 Introduction

One of the major terrestrial ecosystem fluxes of the global carbon cycle is formed by soil respiration. Soil respiration is the flux of CO_2 from the soil surface to the atmosphere and consists of heterotrophic respiration and autotrophic root respiration (Han et al., 2007). The global soil respiration flux is estimated at 80.4 Pg C yr⁻¹ and is therefore one of the major fluxes of the global carbon cycle (Raich et al., 2002). For comparison; anthropogenic fossil fuel combustion accounts for a flux of 5.5 Gt C yr⁻¹. Small changes in the soil respiration flux can cause large perturbations on the global C cycle. Therefore detailed knowledge on soil respiration and the driving environmental factors is required. Figure 1-1 presents the in- and outputs concerning soil CO_2 effluxes. However, soil respiration measurements form a major source of uncertainty, not in the last place because of the lack of a reference method (Raich & Schlesinger, 1992 in Jensen et al., 1996).

Soil respiration thus consists of soil CO_2 production and transport of CO_2 to the atmosphere (gaseous diffusion and mass flow). The concentration gradient between the soil and atmosphere drives the diffusion of CO_2 to the atmosphere. Mass flow is defined as the pumping of air by atmospheric pressure fluctuations on turbulent scales (Kimball and Lemon, 1971 in Janssens et al., 2000). Several environmental parameters can influence soil respiration (Han et al., 2007): soil temperature, soil moisture, root biomass, NPP, litter input, microbial population, root nitrogen concentrations, soil texture, substrate quantity and substrate quality, see also Figure 1-1. Of these parameters soil temperature and soil moisture are the main influencing factors. Furthermore management practices, like ploughing, irrigation and the addition of fertilizer, can have considerable consequences for the soil CO_2 efflux.

Soil respiration measurements show considerable temporal and spatial variation (Rayment & Jarvis, 1997). The temporal variation is mainly driven by soil temperature and soil moisture, which control the CO₂ production by affecting terrestrial ecosystem productivity and the rate of SOM decomposition (Wiseman and Seiler, 2004). Other factors, like soil porosity, water content and the turtuosity of the soil affect the diffusion of soil CO₂ to the atmosphere (Simunek and Suarez, 1993 in Jensen et al., 1996). Spatial variations can occur over small distances. Rayment and Jarvis (1997) found that soil respiration varied from 0.25 μ mol m⁻² s⁻¹ to 3.6 μ mol m⁻² s⁻¹ over a few meters for a black spruce forest. Han et al. (2007) indicated that within an agricultural ecosystem consisting of maize the spatial variation of soil respiration is correlated with the amount of root biomass i.e. distance from the plant, soil temperature and NPP.





Figure 1-1 A conceptual model of the in- and outputs of the soil CO₂ effux (from Ryan & Law, 2005).

Accurate measurement of CO_2 effluxes is difficult. An appropriate method does not alter the soil respiratory activity and furthermore the concentration and pressure gradient and the air motion near the soil surface should resemble the ambient situation. The lack of a standard reference methodology for the measurement of soil respiration has lead to the use of several types of methods, which are listed below. Each method has its dis- and advantages. Between the different methods often large differences are observed, but these are often strongly correlated (Janssens et al., 2000). Different soil respiration measurement techniques are: 1. Eddy covariance techniques

- 2. Measurement of $[CO_2]$ in soil profile
- 3. Static systems
- 4. Dynamic systems

1. Eddy covariance technique

The eddy covariance technique is based on the concept that gas transport is accomplished by eddies that displace air parcels from the soil to the measurement height (Mosier, 1990 in Janssens et al., 2000). This vertical flux is measured at a reference level, which represents the CO_2 efflux from the soil. One of the major advantages is the soil system remaining undisturbed, while measurements can be done continuously. A second advantage is the measurement of soil CO_2 effluxes from a larger surface area, thus representing (part of) the spatial variability (Janssens et al., 2000). However, for correct measurements of the CO_2 effluxes certain conditions have to be met. It is questioned if these conditions prevail continuously throughout

the measurement period, but often they are assumed to occur (Rayment & Jarvis, 1997). The assumed requirements are:

- Level and homogeneous upwind fetch.
- Zero mean vertical windspeed, steady-state conditions.
- Absence of sources and sinks between soil and the sensor (like canopy or vegetation cover)

2. Measurement of CO₂ in the soil profile

A second technique for measuring CO_2 fluxes is the measurement of CO_2 in the soil profile. This method is less frequently used due to its practical limitations. To determine the diffusivity of CO_2 knowledge on gas diffusivities is required (Rayment & Jarvis, 1997). However, soil is a very heterogeneous substrate resulting in a highly spatially variable CO_2 diffusion coefficient, making accurate estimates difficult. Furthermore gas sampling with a syringe can cause an overestimation of the CO_2 concentrations as also gas is sucked from other parts of the soil system, due to the suction (Le Dantec et al., 1999).

3. Static systems

In static chambers a volume of atmosphere above the soil surface is sealed for an extended period, preferably 24 hours, to allow gasses to accumulate to a concentration that can be determined by an alkali solution, like soda-lime. The alkali solution traps the CO_2 , thus it is removed from the chamber. Within the chamber no artificially driven air circulation occurs. An advantage of this system is that several different gasses can be measured simultaneously (Norman et al., 1997). Besides, the static chamber technique is relatively inexpensive and easy to use. One of the disadvantages of this enrichment method is the overestimation of the small fluxes and the underestimation of large fluxes (Nay et al., 1994). Furthermore, the atmospheric ambient pressure fluctuations at the soil surface are prevented, thereby reducing the exchange of air between soil and atmosphere (Hutchinson & Mosier, 1981 in Rayment, 2000; Conen & Smith, 1998).

4. Dynamic chambers

Dynamic chambers are characterized by the circulation of air inside the chamber. Dynamic chambers can be divided in: closed (DCC) and open systems. Closed systems have air circulating in a loop between the chamber and an external gas analyzer (Janssens et al., 2000). Pressure equilibration is achieved by a venting tube. In an open system ambient air passes through a chamber. The CO₂ concentration of the in- and outgoing flux is measured, the difference in concentration represents the soil CO₂ efflux. One of the advantages of dynamic chambers is the short sampling period, changes in soil moisture and soil temperature are therefore minimal. A second advantage is the prevention of the build up of a soil boundary layer as the air is mixed in the chamber. This air mixing however does not resemble ambient conditions. Janssens et al. (2000) reports that a viscous layer is build up in the chamber which retards the diffusion rates. The soil [CO₂] will increase, which might lead to lateral diffusion of CO₂ in the soil and thus an underestimation of the flux. However open chambers have the disadvantage of creating pressure differences between the in- and outgoing flux (Rayment & Jarvis, 1997). This pressure difference depends on the windspeed, which again depends on the height of the chamber above the soil surface (Conen & Smith, 1998). Rayment and Jarvis (1997) have designed an open chamber system where the pressure difference between the chamber interior and the ambient pressure is no more than 0.004 Pa.

Comparative studies between different techniques have been done previously (Jensen et al., 1996; Norman et al., 1997; Rochette et al., 1997; Janssens et al., 2000; Butnor et al., 2005; Ngao et al., 2006) often comparing DCC techniques and/or static and EC techniques. However closed chamber techniques and open chambers comparisons are less frequently done and contradicting results are reported (Norman et al., 1997 and Widen and Lindroth, 2003). For this study four different soil respiration measurement systems are used in a field experiment. The four systems (two open chamber systems, a closed dynamic system and an EC system) are all used for local to regional scale research on CO_2 fluxes of the Earth System Science and Climate Change group of Wageningen UR. It is however unknown to what extend these systems show correlations and deviations to each other. To improve the understanding on the measured CO_2 fluxes and to be able to compare CO_2 fluxes from the four systems a comparative experiment is set up at a grassland ecosystem. This *in situ* comparison will thus generate relative differences between the different soil respiration systems. Absolute performances of different soilR systems can only be derived when using controlled CO_2 fluxes.

The objective is to compare these different soil respiration systems and find possible correlations and differences.

Research questions:

- Do the soil respiration measurement techniques show (consistent) differences in diurnal variation?
- To which amount differ the field scales averages of the different techniques?
- To which amount differ the chamber averages of the different techniques?

2 Materials and Methods

2.1 Site description

The field experiment was setup at the Haarweg meteorological observatory of the Meteorology and Air Quality Group of Wageningen University. The location coordinates are: $51^{\circ}58$ 'N and $5^{\circ}38$ 'E, with an altitude of +7 m a.s.l. (Jacobs et al., 2007, [1]). The vegetation consists of perennial grassland with dominating species: rye grass (*Lolium perenne*) and rough blue grass (*Poa trivialis*). The grass is mowed weekly during the growing season (1 May – 1 November) and maintained at a height of about 10 cm. Soil parent material is heavy clay deposited by the river Rhine. Figure 2-1 gives a schematic overview of the Haarweg meteorological site. The dotted circle and star indicate the location of the Eddy correlation system, the dashed oval indicates the location of the other respiration systems.

At the Haarweg site many meteorological measurements are done, some of which are used in this study e.g. soil temperature (5 cm under grass) and radiation.



Figure 2-1 Overview of the Haarweg experiment site ([1]). The * indicates the location of the EC system, The dashed oval indicates the location of the other respiration systems.

2.2 Soil respiration systems

Below follows the description of the different soil respiration systems used during this study. These systems are used like in other field experiments and are not adjusted for a better comparison, it is therefore an in situ comparison which will give relative indications of the differences between the systems.

System 1: Automatic open chamber system

The automatic open chamber system was first designed and described by Rayment & Jarvis (1997). The system consists of a steel ring (diameter 0.243 m, height 0.15 m) with on top a removable flat lid. The ring has a surface area of 464 cm². The ring is inserted in the soil to a depth of 9-10 cm. This was considered deep enough to avoid leakage. To ensure a gas-tight seal upon closure of the chamber a silicon rim is placed around the top of the ring. On top of the lid a tube is fixed, through which ambient air can enter the chamber. The air from the chamber is pumped to the Ciras IRGA analyzer (LI-COR Inc., Lincoln) through the outlet tube at 1.4 dm³ min⁻¹.

On 5 July 2007 (DOY 186) 8 automatic open chambers were installed at the Haarweg meteorological site. Before installation the vegetation (grass) was cut to an approximate length of 2 cm. Measurements starting two weeks after installation were used for analysis, prior measurements were still influenced by disturbances due to installation, like root damage. During week 28 soil moisture and temperature sensors were installed. The chambers close in turn once every hour for about four minutes. The first three minutes are needed to reach equilibrium. During the last minute, the actual CO_2 efflux is measured, this results in 8 CO₂ fluxes measured per hour. Furthermore data are recorded on the variability of the elevated concentration during the measurement, ambient CO₂ concentration, air flow and soil moisture and soil temperature. During the measurement period the grass was cut regularly to maintain 2 cm length. At August 12 (DOY 224) one of the pumps broke down, which was again repaired at the 31st of August (DOY 243). During this period the ambient concentrations measured represented the chamber concentrations due to soil respiration. For this period part of the fluxes could afterwards be calculated, assuming that the Eddy Correlation measurements represented the ambient concentrations. EC ambient concentrations were first compared to ambient open chamber measurements to correct for a possible offset between the two systems.

System 2: EGM-1/4 by PP systems

This soil respiration system consists of the EGM 1 or 4 (PP Systems, Hitchin, UK), the environmental gas monitor (IRGA) and the SRC-1, the soil respiration chamber. This is a closed dynamic system for measuring soil respiration. The soil respiration chamber has a surface area of 78 cm² and has a system volume of 1171 ml. When the SRC-1 is placed on the soil; the air in the chamber is mixed by a fan. The EGM measures the increase in CO_2 concentration every 8 s for 120 s, the rate of increase of CO_2 should be linear. Measurements are also ended when the concentration increased more than 50 ppm. To prevent leakage of CO_2 to the air when the chamber is placed on the grass, collars were installed 25th of July (DOY 206). A rubber ring between the respiration chamber and the

collar was used as a seal. Respiration rates were corrected for the increase of volume of the system. Comparative measurements started 2 weeks after installation of the collars, again to prevent any influence on soil respiration rates by root damage.

System 3: Two chamber ADC

The ADC Soil Respiration Measurement System consists of an ADC2250 differential CO_2 and H_2O infrared gas analyzer with a leaf chamber analyzer (type: LCA4) and a soil respiration hood. This is an open system. The soil respiration hood is supplied with a collar which was inserted in the soil (\pm 6 cm). Furthermore the soil respiration hood is equipped with a fan and a pressure equalization vent. A soil hood with collar has a surface area of 97.5 cm² and a volume, while taking complete collar intrusion into account, of 987 cm³ (Instruction manual soil respiration hood MkII). Soil temperature is measured by a separate soil temperature probe. The soil respiration hood is connected to the leaf chamber analyzer, which is again connected with the ADC 2250 Analyser. The ADC 2250 is an IRGA analyzer, which measures the reference (background) and the sample concentration separately and then calculates the differential [CO₂]. In order to derive a soil respiration rate the mass flow can be set contant. The IRGA analyzer has a measurement range of 0-2000 ppm CO_2 ([2]). To obtain the soil respiration rate for the ADC system, measurements are performed for several minutes (usually 1500 s), with measurements recorded every second, until the difference in CO₂ is stable. From the differential CO₂ concentration, the surface area of the soil hood and the massflow, the soil respiration rate can be calculated according to equation 2.1:

 $F = \frac{\partial CO_2 * u}{A}$ Eq. 2.1 F = Soil respiration flux (µmol m ⁻² s⁻¹) $\partial CO_2 = \text{Differential CO}_2 \text{ concentration (ppm)}$ u = Mass flow (mol s⁻¹) A = Surface area (m²)

System 4: Eddy correlation system

The eddy correlation system at the Haarweg is installed at a height of 4 m. The system includes: a three-dimensional sonic anemometer (3-D Solent Res. Gill Instruments Ltd, model A1012R2), a fine-wire thermocouple (home made) and an open path infrared CO_2 and H_2O gas analyzer (IRGA) (LI-COR Inc., Lincoln, NE, model LI-7500). The 3-D sonic anemometer and the IRGA are placed 0.05 m apart (from Jacobs et al., 2003). The footprint can reach up to several hundred meters. The EC data were corrected for density changes (Webb correction), axis alignment, sensor separation and frequency response of the instruments.

2.3 Complementary measurements

To get a better understanding of the soil respiration, complementary measurements are done for the most influencing factors: soil temperature and soil moisture.

Soil moisture

Soil moisture is measured with the Thetaprobe soil moisture sensor (Type ML2x). It measures the volumetric soil moisture content based on the dielectric constant, which is proportional to the soil moisture content.

Soil temperature

During EGM measurements the STP-1 Soil Temperature Probe by PP systems is used. The temperature probe is a 40 cm stainless steel tube with in the tip the temperature sensor. The probe is inserted in the soil and has a temperature range of 0-50 °C with an accuracy of 0.5 °C ([3]). For the open chamber system, thermo sensors installed at the Haarweg site, 5 cm under grass are used. The thermo sensors of the open chamber system itself did not work properly.

2.4 Methods

This comparative experiment is divided in two parts. In the first part three measurement systems are compared at small scale i.e. chamber level. The automatic open chamber system is chosen as reference to which the EGM and ADC systems are compared. The automatic open chamber system was chosen as it measures continuously and has the largest chamber surface area. In the second part the open chamber system is compared with the EC system, which is a comparison at field scale.

Chamber scale

Figure 2-2 gives a schematic representation of the field site. Adjacent to each open chamber are two PVC collars for EGM measurements. Due to a lack of ADC soil hood collars, ADC soil respiration measurements were only done adjacent to chamber 1 (at DOY 319 measurements were also done adjacent to chambers 2, 3 and 4, these data were only used for modeling response functions). Upon closure of one of the chambers, EGM measurements were done at the two corresponding collars. After each measurement the SRC-1 chamber was held in open air and flushed to refresh the air in the chamber. As the EGM -SRC 1 chamber was placed on a PVC rim during measurement, volume corrections are necessary. Therefore the extra volume was calculated by measuring the height of the PVC rim above the soil surface. The soil respiration rates were averaged (to get a better comparable surface area) and compared with the corresponding open chamber CO_2 efflux.



Figure 2-2 Experimental set-up for the comparison of the EGM-4 and the Automatic Open Chamber System. Distances between the automatic open chambers amounts to approx.2 m.

ADC measurements could not follow the open chamber sequence as there are only two collars and measurements need more time, approximately 20 minutes, to reach equilibrium. During ADC respiration measurements the transparent soil hood was covered by a larger non-transparent hood to prevent photosynthesis. In between the measurements the soil hood was placed in open air to refresh the air in the hood. ADC measurements were afterwards compared with the corresponding open chamber measurement in time.

The use of the EGM and ADC systems is limited to dry conditions, no comparisons during precipitation are available. Data correction for the open chamber system was also necessary as system/measurement errors occurred regularly. In case of negative or an observed measurement error (e.g. equipment failure) the data were deleted. The fluxes measured by the open chamber contained several measurement errors i.e. unrealistic fluctuations in the measured flux of up to a difference of several µmol m ⁻² s⁻¹ between sequential measurements. Most of the measurement errors were eliminated based on the recorded data of the variability of the CO2 measurement, i.e. when variability was higher than 20 ppm.

Field scale

Comparison of the open chamber and EC data is limited to nighttime measurements when no photosynthesis takes place. However, during nighttime the lack of incoming radiation limits the amount of turbulence and stable conditions can occur. The stratification of the lower atmosphere prevents free exchange of air parcels, which causes the build up of a layer with high CO₂ concentrations near the soil. For comparison with the open chamber system, only nighttime data are used when there was enough wind i.e. when friction velocity (u*) was >0.1 m/s (pers. comm.. B. Heusinkveld). For comparison with the open chamber system, wind directions from 0-100° were deleted as this area included arable land instead of grasslands. Measurements done during precipitation were also deleted as drops can occur on the lenses of the instrument, yielding unreliable measurements. The same was done for times when the relative humidity was larger than 98% (Thesis Sandra Snel, 2004). Furthermore unrealistic measurements, like negative fluxes during nighttime and extreme high values are left out of the analysis as well. The EC measurements used for the analysis were recorded for every half hour. For the comparison with the open chamber data, the fluxes of chambers 1 to 4 and 5 to 8 were averaged. The average represented the open chamber CO_2 flux measured for half an hour. Half hour open chamber averages based up on one chamber measurement were left out of the analysis.

3 Results

This chapter discusses first the open chamber measurements, followed by the chamber scale and field scale comparison. In the last section the soil respiration data are used to estimate model parameters for two different temperature-soil respiration response curves.

3.1 Open chamber system

In Figure 3-1 the soil respiration, temperature and soil moisture curves are presented for the eight rings of the open chamber system. Measurements analyzed for the system start at DOY 200 (July 19) till 337 (December 3). From DOY 224 to 243 (August 12 to 31) one of the pumps was broken and consequently correct ambient concentration measurements were lacking. As described in section 2.2 EC data were used as ambient [CO₂] to calculate the fluxes. EC data could however not be used for the nights of DOYs 233 and 237 till 242 as stable conditions prevailed ($u^{*}<0.1$). At DOY 310 a fuse broke, which was repaired at DOY 311. The same day however the pump broke, which was not repaired until DOY 325. From DOY 294 to DOY 305 measurements for rings 4 were poor, due to damage to the rubber ring. Correct measurements are also lacking for all rings from DOY 310 to 311 and from DOY 311 to 325.

In Figure 3-1 a diurnal pattern is observed for both temperature and soil respiration, higher daytime temperatures result in higher soil respiration rates. Also large fluctuations in daily temperature, result in large diurnal fluctuations for the soil respiration rates, like for DOYs 223, 224 and 226. In the summer months (until DOY 264) when temperatures are high, soil respiration rates vary around 4-5 μ mol m⁻² s⁻¹. In autumn, temperatures gradually drop as do soil respiration rates to an average flux of $3 \text{ umol m}^{-2} \text{ s}^{-1}$. In November and December a further drop in soil respiration is observed to rates most of the time below 2 μ mol m⁻² s⁻¹. The relation of soil respiration with soil moisture is less obvious in Figure 3-1. For the summer months an increase in soil moisture results in a gradual increase of the soil respiration rates, while for autumn soil respiration rates seem hardly to be influenced by an increase in soil moisture. A possible explanation might be found in the field sites' soil texture as it consists of heavy clay, which implies possible water availability limitations for the vegetation in summer. During the field campaign it was indeed observed that the soil showed signs of drying i.e. shrinkage of the soil, resulting in fissures around the rings. In autumn temperatures drop and evapotranspiration is reduced, leaving the soil with plenty of moisture.



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Results



Figure 3-1 Soil respiration rates for the open chamber system from DOY 200 to 337. Temperature and soil moisture curves are presented on the second and third y-axis.

Figure 3-1 shows that the measurements for the eight different rings give similar soil respiration curves. At a closer look, it is observed that soil respiration rates for ring 4 are often lower than for the other rings. During the field campaign it was observed that for this chamber, vegetation and soil moisture differed. The soil in and around this ring was often very wet or dry compared to the other rings. The vegetation is less dominated by grasses, but by mosses instead. The chamber which records the highest soil respiration rates along the measurement period. In general can be said that ring 1 often records high soil respiration rates, followed by rings 3, 7 and 8. Variability between the chambers, can amount up to 3 μ mol m⁻² s⁻¹, for example on DOY 267 and more regularly up to 2 μ mol m⁻² s⁻¹, for example: DOYs 222, 226, 227 and 252. Taking DOYs 255 till 260 as an example, small scale spatial variability becomes more pronounced with increasing temperature fluctuations. When daily temperature fluctuations are minimal, like for DOYs 305 till 307, spatial variabile role makes the comparison with other soil respiration plays a considerable role makes the comparison with other soil respiration systems more complicated.

Despite the data having been filtered for measurements with high variability. still large fluctuations of several μ mol m⁻² s⁻¹ occur between sequential measurements. Sometimes measurements drop to nearly zero and recover again in the following hour. Often this occurs for more than one ring in the same hour and mainly during night times. During most of these spikes the ambient CO_2 concentration shows an increase, indicating a possible build-up of CO₂ due to lack of turbulence. In Figure 3-2 the wind speed is plotted versus the ambient concentrations of the eight rings. Ambient concentrations have a base-level of around 380 ppm and can rise up to 1200 ppm, which is the maximum for the systems measurement range. When wind speed is low, ambient CO₂ concentrations completely cover this range. This wide range at low wind speed is caused by the accumulation of CO₂ near the soil surface due to the lack of turbulence, which occurs in night times when there is no radiation and no heating of the earth's surface. The high ambient CO₂ concentrations cause measurement problems for the CIRAS gas analyzer, differential concentrations are small and result in the calculation of very small fluxes. During the day there is often more wind, which causes the air to mix and the variance decreases. With increasing wind speed the ambient concentrations decrease and two "legs" are formed. The first leg is found at the CO₂ base-level e.g. the ambient concentrations as found during most days (340 -460 ppm). The other leg is found around 560 ppm. These data are in fact mostly ambient concentrations measured in the early morning when stable conditions start to break up due to increased turbulence.



Figure 3-2 Wind speed versus ambient concentrations for the eight chambers of the open chamber system (non-filtered data).

The accumulation of CO_2 near the soil surface during stable conditions and the excretion of the measured air by the gas analyzer might cause dimished fluxes for chambers 1 and 5 as sucked-in air might have higher CO_2 concentrations. Correlations (Pearson) between wind speed and soil respiration rates were in the order of 35% and significant at the 0.01 level for all rings, except ring 4. Correlations between ambient [CO_2] and wind speed explained more of the variance, for all chambers in the order of -0.5 and all were significant at the 0.01 level. Correlations for rings 1 and 5 did not differ from the other rings. Thus rings 1 and 5 are located far enough from the datalogger and the IRGA to prevent any influence due to elevated CO_2 concentrations.

3.2 Chamber scale: Open chamber and EGM

Comparative measurements were done at DOYs: 215, 228, 229, 232, 236, 242, 246, 249, 256, 257, 262, 270, 278 and 281. Measurement periods varied from one to 16 hours. In total 380 comparative datapoints are used for the analysis.

All measurements

In Figure 3-3 all the comparative measurements are presented. Measurements vary for the open chamber system from 2 to nearly 10 μ mol m⁻² s⁻¹, fluxes measured by the EGM vary from 2.4 to 8.6 μ mol m⁻² s⁻¹. The measurements show a clustering for the EGM from 3.5 to 5.2 μ mol m⁻² s⁻¹ and for the open chamber system from 3.6 to 6 μ mol m⁻² s⁻¹. Of this cluster most data are located above the 1:1 line, indicating higher measured fluxes for the open chamber system. Outside this cluster most data are found below the 1:1 line, indicating higher soil respiration rates for the EGM system.



Figure 3-3 All comparative data for EGM and Open chamber system. The cluster of data is indicated by the black circle, the line indicates the ideal 1:1 line and the dashed line is the trendline.

The trendline indicates that with increasing fluxes, the difference between the two systems also increases i.e. the trendline deviates farther from the ideal 1:1 line. High EGM respiration rates are more often accompanied by relatively low open chamber respiration rates, but the explanatory value of the trendline is poor (24%). As soil respiration rates vary during the day and between the seasons, a closer look is taken at the various day curves in the following paragraph.

Results

Day curves

The day curves in Figure 3-4 present the measurements for both systems during the day.





Figure 3-4 Soil respiration fluxes for the EGM and open chamber system.

At the start of the field campaign (DOYs 215 till 232) differences between the two systems are on average 2 μ mol m⁻² s⁻¹, with the exception of DOY 228, see Table 3-1, with the highest soil respiration fluxes measured by the EGM system. For DOY 215 fluxes are around 6-8 μ mol m⁻² s⁻¹, except before 11 a.m. for the open chamber. A sudden positive shift in the open chamber measurements of about 2 μ mol m⁻² s⁻¹, results in a closer correspondence between the two systems. The cause of this change is unclear. Also for DOYs 228 and 229 the EGM recorded higher fluxes than the open chamber system. At DOY 232 EGM measurements are again higher than the open chamber measurements, but during the measurement period the difference between the two systems becomes smaller. For the first three measurements differences up to

4 μ mol m⁻² s⁻¹ are found, but the difference has diminished to less than 0.5 μ mol m⁻² s⁻¹ at the end. The smaller difference is caused by a general increase of the measured fluxes for the open chamber and a gradual decrease in the measured fluxes during the day by the EGM. For DOY 236 all EGM measurements, except for one, are larger than the open chamber measurements. EGM measurements do show more variation between the different measurements, while the open chamber measurements show a more gradual increase during the day. DOY 242 shows again higher fluxes for the EGM, but for both systems there is considerable variation. For the EGM this varies from 4.6 to 6.5 μ mol m⁻ 2 s⁻¹, for the open chamber system from 3.1 to 4.9 µmol m⁻² s⁻¹. For DOY 246 the open chamber system shows a large amount of variation, without a conclusive pattern, measurements vary from 2.0 to $6.6 \,\mu\text{mol}\,\text{m}^{-2}\,\text{s}^{-1}$ and for the EGM from 4.3 to 7.4 μ mol m⁻² s⁻¹. For DOY 249 measurements by both systems are nearly equal, all around 6 μ mol m⁻² s⁻¹. The pattern is however the opposite, when soil respiration rates for the EGM increases, it decreases for the open chamber system and vice versa. DOY 256 shows a similar pattern as DOY 249, with respiration fluxes around 7 µmol m 2 s⁻¹. On DOY 257 the open chamber system measured slightly higher fluxes, with the exception of 10-11 a.m. when there is a sudden drop in the measured respiratory fluxes by the open chamber system. DOY 262 the highest respiratory fluxes are found for the open chamber system. However this system also shows the most variation during the measurement period. For DOY 270 the open chamber system records the higher fluxes, but also the differences between successive measurements are larger than for the EGM of which the measurements show a more gradual daily pattern. The amount of variation between the measurements of the open chamber system is also higher for DOY 278. But on this day the EGM system records again the higher fluxes. DOY 281 is the longest measurement day, which also includes comparative nighttime measurements. In the early morning and evening EGM measurements show higher soil respiratory fluxes than the open chamber system. During the day this difference disappears and fluxes are nearly similar for both systems. The cause of this difference between the system in the early morning and evening is unclear. Despite EGM measurements being done by three different persons, no clear relation with the increase in variation could be found i.e. the relief of persons does not coincide with the time variation. Possibly stable conditions caused measurement problems for the EGM, during some hours friction velocity (u*) was smaller than 0.1 m/s.

In general there seems to be a trend where in August (DOYs 215-242) the EGM system records the highest respiratory fluxes, with average differences reaching up to 2.5 μ mol m⁻² s⁻¹ (Table 3-1). DOYs 246-257 form a transition period where differences decrease to around 1 μ mol m⁻² s⁻¹. For DOYs 262 and 270 clearly higher soil respiratory fluxes are recorded for the open chamber system, while for DOYs 278 and 281 (with the exception of the early morning and evening) both systems record nearly the same fluxes. In summer, the average difference between the two measurement systems is in general higher than in autumn, as is the variance, with the exception of DOY 228. This corresponds with the observations for Figure 3-3.

Results

	Average		Duration
DOY	difference	Variance	(h)
215	2.192	1.427	3
228	1.174	0.133	1
229	2.495	1.155	1
232	1.940	2.226	1:45
236	2.009	1.155	3:45
242	1.233	0.325	3
246	1.647	2.668	3
249	0.874	0.257	2
256	0.799	0.240	2
257	1.096	0.796	6
262	0.794	0.484	3
270	1.117	0.409	5
279	1.172	1.351	2:30
281	0.827	0.735	16:15

Table 3-1 Average differences and variance for the measurement days.

Spatial variability

The interpretation of soil respiration measurements is complicated by the large spatial variability. It is reported that the variation in soil respiration chamber measurements is at the scale of centimeters (Davidson et al., 2002). In Figure 3-5 the comparative measurements are plotted per open chamber ring.



Figure 3-5 Comparative measurements plotted per ring.

For ring 1 most datapoints are found along the 1:1 line, indicating nearly similar results for both systems. For ring 2 most datapoints are found around or below the 1:1 line, indicating higher soil respiration rates for the EGM system. For rings 3 and 4 most datapoints are found around and below the 1:1 line, again indicating higher comparative fluxes for the EGM measurements. For rings 5 and 6 most data are found in a narrow

band along the 1:1 line. Measurements for ring 7 show a considerable spread, the data points are found just above the 1:1 line or below, again indicating higher comparative measurements for the EGM system. For ring 8 measurements were found on both sides of the 1:1 line, for both systems higher comparative measurements were found during measurement period.

The variation between comparative measurements can reach up to several μ mol m⁻² s⁻¹, especially for rings 2, 3, 4, 7 and 8. For rings 1, 5 and 6 comparative measurements show less variation and system results are better comparable. Ring 4 is the exception with always higher EGM measurements, except for five datapoints, which are located almost on top of the 1:1 line. Spatial variability, like already observed for the open chamber system, is also observed for the EGM rings in comparison with the open chamber rings. Spatial variation in the order of several μ mol m⁻² s⁻¹ occurs within a distance of a few decimeters.

3.3 Chamber scale: Open chamber and ADC

For the two open chamber systems comparative measurements were done for 7 days during the field campaign (DOYs: 236 (6 comparative datapoints), 242 (6), 246 (4), 249 (4), 257 (14), 270 (9), 281 (21)). First all comparative measurements are presented, followed by the comparative data for the different measurement days.



Figure 3-6 All comparative data for ADC and open chamber system. The bold line indicates the 1:1 line.

Figure 3-6 presents the data for both open systems. Measurements for DOYs 236 and 246 have nearly similar results for both systems. All measurements for DOY 242 have higher respiratory fluxes for the ADC system, with differences between the systems reaching up to 2.8 umol/m^2 /s. Also for DOY 249 all measurements show clearly higher respiration rates for the ADC system. For the three following measurement days more measurements

Results

were done, which show more variation. These measurements are presented against time in the figures below to observe system differences during the day.

In the table below the average absolute difference between the two measurements and the corresponding variance is presented.

DOY	Average	Variance	
236	0.487	0.123	
242	2.448	1.834	
246	0.618	0.378	
249	1.834	0.306	
257	0.814	0.672	
270	0.951	0.218	
281	1.373	1.175	

Table 3-2 Average differences and variances for the measurement days

As was described above, measurements for both systems are nearly the same for DOYs 236 and 246, see Figure 3-7. For DOY 242 the ADC system gives higher soil respiratory fluxes than the open chamber system. The differences between the comparative measurements differ however. ADC measurements from the left ring have smaller differences with the open chamber measurements than the ADC right ring measurements. For DOY 249 this difference is not observed. ADC fluxes are again higher (around 8 μ mol m⁻² s⁻¹) than those measured by the open chamber system (around 6 μ mol m⁻² s⁻¹), but differences for the left and right ADC ring are similar. For DOY 257 more measurements are available. ADC measurements vary from 4 to 6 μ mol m⁻² s⁻¹ during the day. The open chamber measurements show a different pattern, the first six measurements show a gradual increase in soil respiration rates

from 3.6 to 5.4 μ mol m² s⁻¹. After 10 a.m. soil respiration rates drop suddenly to values varying from 2.6 to 3.5 μ mol m⁻² s⁻¹ and increase again after 12 o'clock to levels similar as for the ADC measurements (5.8 to 6.9 μ mol m⁻² s⁻¹). No explanation could be found for this sudden drop in soil respiration rates between 10 and 12 a.m. (see also for the comparison with the EGM). Comparing both systems shows that (with the exception of 10 to 12 a.m.) measurements lie close to each other, with in the early morning somewhat more variation. There is no trend observed for one system measuring constant higher soil respiration rates. However there is a consistent difference between the right and left ADC collar. For the right collar higher soil respiration rates are measured than for the left collar, for the first measurements this difference is over 1 μ mol m⁻² s⁻¹. For DOY 270 both systems show a gradual increase in measured soil respiration rates during the measurement period. For the ADC this increase starts at 4.2 to 5.1 μ mol m⁻² s⁻¹, for the open chamber from 3.3 to 6.3 μ mol m⁻² s⁻¹. For 8 out of 10 measurements the ADC system measured lower respiration rates than the open chamber system. Also during these measurements for the ADC right collar measured soil respiration rates were higher than for the left collar. In Figure 3-8 can be seen that differences in soil respiration rates between collars are again in the same order of magnitude as the differences in soil respiration rates between the two systems.





Figure 3-7 Soil respiration fluxes for the ADC and open chamber systems.

At DOY 281 a full day of comparative measurements was done, starting at 5 a.m. Unfortunately the ADC could not record the CO₂ concentrations until after 9 a.m. Concentrations were outside the measurement range, however the open chamber system and the EGM-4 did not have problems recording the high concentrations. Probably the ADC is quite sensitive for moist conditions, limiting the measurement performance. Measurements for the open chamber system are quite stable for the first hours, all measurements are around 4 µmol m⁻² s⁻¹ and increase gradually after mid-day to about 5 to 6 µmol m⁻² s⁻¹. After 4 p.m. soil respiration rates decrease again to soil respiration rates between 3 and 4 µmol m⁻² s⁻¹ for the left collar to about a.4.5 µmol m⁻² s⁻¹ for the right collar. After two o'clock the rates for the left collar show a drop of 1 µmol m⁻² s⁻¹ compared to the previous hours. From 4 p.m. onwards soil respiration rates increase for both collars to rates of more than 7 µmol m⁻² s⁻¹ for the right collar and more than 5 µmol m⁻² s⁻¹ for the left collar. Measurements from the right collar are always higher than from the left collar.

The above comparative measurements show that spatial differences between measurement plots for the same system are of the same size as the differences in soil respiration rates between systems.

3.4 Field scale: Open chamber vs EC

Comparative data were available for DOY 195 to 304. After data selection as described in section 2.4, 618 half hour measurements were left for analysis.



Figure 3-8 Data comparison of the eddy correlation system and the open chamber system.

Open chamber measurements range from 0.8 to 9.58 μ mol m⁻² s⁻¹, while eddy correlation measurements show a range from 0.41 to 9.97 μ mol m⁻² s⁻¹, indicating similar measurement ranges for both systems. Most data are concentrated in the range of 2 to

5 μ mol m⁻² s⁻¹ for the open chamber system and from 1 to 7 μ mol m⁻² s⁻¹ for the EC system. In case of relatively small fluxes most data are just below the 1:1 line and variance is limited to a few outliers. When the CO₂ effluxes increase i.e. becomes larger than 5 μ mol m⁻² s⁻¹ for one of the systems, the variance between the two systems increases as well, data clustering becomes less prominent and for most data the EC system gives higher fluxes. As the amount of CO₂ production in the soil mainly depends on soil temperature and thus has seasonal variation, a closer look was taken at the nights during the measurement season for which several successive hours of data were available. Comparison of these nights distinguished three different periods as indicated in Figure 3-8. The first period, until DOY 249 (beginning of September) is characterized by relatively high soil respiration fluxes, but also by a lot of variation between the two systems. In the following period (DOY 249 to 296) soil respiration fluxes drop and gradually differences between the two systems diminish. However, still most data comparisons show higher fluxes for the EC system. After DOY 296 soil respiration fluxes decrease to levels around 2.5 μ mol m⁻² s⁻¹, system differences diminish even further and the highest soil respiration fluxes are found for the open chamber system.



Figure 3-9 Temperature, soilR EC and open chamber data. Note that the data are not sequential as only comparativer data are used.

Figure 3-9 shows the EC and open chamber comparative data as well as the temperature versus time. In the first period differences between the two systems are sometimes larger than $2 \mu \text{mol m}^{-2} \text{ s}^{-1}$, in the next period in general differences become smaller. Occasionally a night occurs where differences between the systems are large. In the last period the whole picture changes. Soil respiration fluxes from both systems differ only little and the open chamber fluxes are most of the times larger than the EC fluxes. The higher EC fluxes in the first period can be explained by more biomass present at the footprint of the EC system. In the open chamber rings, the grass is maintained at a few centimeters length, while the grass at the rest of the field and the surrounding grasslands is longer i.e. more biomass resulting in more respiration and thus higher fluxes. Later in the season respiratory activity declines and the differences in amount of biomass become less pronounced and the differences between the systems decrease.

3.5 Modeling soil temperature response curves

In literature many equations are found that describe the temperature dependence of soil respiration. There is still an ongoing discussion about the exact form of this relationship. The most commonly used relationship is an exponential function (Lloyd & Taylor, 1994; Tuomi et al., 2007). In this section a few simple exponential relationships are fitted on the soil respiration data of the different systems. In case of the open chamber system the hourly averaged measurements were used for modeling. Using the hourly measurements from a single chamber would induce quite some spatial variation as differences between the chambers can be considerable, see section 3.1. In Figure 3-10 the datalogger temperature is plotted versus the hourly averaged soil respiration rates for the open chamber system. An exponential growth curve (Equation 3-1) is fitted through the data:

$$SoilR(T) = ae^{bSoilT}$$

Eq. 3-1

Where:



Figure 3-10A: Temperature versus hourly averaged soil respiration rates for the open chamber system. B: 1:1 The residuals plotted versus temperature.

Besides a fit with datalogger temperatures also other temperature records were plotted against soil respiration rates. In Table 3-3 the results of these fits are presented, the corresponding figures can be found in Appendix 1. The best exponential fit is found for the datalogger and air temperature records with respectively R squared values of 56.6% and 54.5%. Despite the reasonable fit still nearly 50% of the variance is unexplained, which is illustrated by the large scatter of datapoints around the curve. For a temperature of for example 20°C, respiration fluxes of just above 1 μ mol m⁻² s⁻¹ to 8 μ mol m⁻² s⁻¹ were measured. For the air temperature record at 150 cm similar results are found. However, the relation between soil temperature under grass at 5 cm versus soil respiration fluxes is not as well described by an exponential curve. For all plotted

temperature records variance increases with increasing temperature, but for the soil temperature record this increase in variance is even larger, which results in a small explanatory value for the exponential curve. It would be expected that soil respiration responds to changes in soil temperature. The fact that better correspondence is found with air temperature records might indicate that most respiration takes places in the upper few centimeters of the soil. A possible reason for this can be the high groundwater levels during a large part of the year.

In Figure 3-10B residuals of the measured minus the predicted values are plotted. At low temperatures the function can underestimate the fluxes considerable, but also some small overestimations occur. The variance increases with increasing temperature. For the range of 10 to 25°C both over- and underestimations are found, from 25°C onwards more underestimations occur.

 Table 3-3 Fitted parameters for the different soil respiration temperature response curves.

Temperature	a	b	\mathbf{R}^2
T datalogger (80 cm in	1.6856	0.0527	0.566
cabinet)			
Tsoil 5 cm under grass	1.426	0.0667	0.255
T 150 cm	1.6515	0.0648	0.545

Another frequently used model to describe the temperature dependence of soil respiration is the Arrhenius equation (Tuomi et al. 2007):

$$SoilR(T) = ae^{bT^{-1}}$$
 Eq. 3-2

Where the parameters are defined as for equation 3-1.

$$SoilR(T) = 11.9947e^{-16.6996SoilT^{-1}}$$
 Eq. 3-3

In Figure 3-11A the Arrhenius function is plotted for the datalogger temperature versus the soil respiration rates. This function performs better in describing the higher respiration rates, but for the low respiration rates the observed variance is poorly described. This is also seen in Figure 3-11B, the Arrhenius function shows an overestimation of the small soil respiration fluxes for temperatures below 8°C. For temperatures varying from 8 to 27°C both under- and overestimation are found. For temperatures higher than 27°C the Arrhenius function show considerable overestimations.



Figure 3-11A Modeling the Arrhenius equation for the hourly averaged open chamber measurements. B: The residuals plotted versus temperature.

EGM

For the EGM data the same two functions were fitted as for the open chamber data as can be seen in Figure 3-12. A few data with incorrect temperature readings i.e. T>100°C were not used for the analysis. For the group of measurements at T<5°C, temperature recordings were missing. Based on the time of measurement the 10 minute Haarweg soil temperature recordings of 5cm under grass vegetation were used instead. However these data do not always match entirely with the EGM soil temperature recordings. The response function for the EGM resulted in the following estimations for parameters a and b, the R² of this function is 0.634 (n=380):

$$SoilR = 1.2089e^{0.0932 soil1}$$

Eq. 3-4



Figure 3-12A SoilT versus EGM soil respiration fluxes. B: The residuals plotted versus temperature.

Figure 3-12A shows that a few odd flux measurements, fluxes of around 10 μ mol m⁻² s⁻¹ exist, which do not fall within the trend observed for the other data. In Figure 3-12B the residuals shows that for low temperatures fluxes are underestimated. However the number of data for low temperatures is limited. For temperatures in between 10 and 22°C both under- and overestimations occur. High temperature recording are unfortunately lacking. The residuals found at 14°C and having values of 5-8 are most likely not correct.

The Arrhenius equation for the EGM (Eq.3-5) is shown in Figure 3-13A, the explanatory value is only 44%. Part B of the figure shows no obvious over or underestimations for certain temperature ranges.



Figure 3-13A Modeling the Arrhenius equation for the EGM measurements. B: The residuals plotted versus temperature.

ADC

As the soil temperature probe of the ADC system did not work properly, the matching EGM soil temperature recordings were used. The number of ADC measurements is limited (n=70), however the exponential fit (Equation 3-6) still has an R^2 of 56%. Due to the limited number of datapoints determining over- and underestimations is quite difficult, however at low temperatures soil respiration rates seem to be underestimated, which seems also the case for respiration rates at temperatures >17°C. Most probably, when also taking the models for the previous two systems into account, the over- and underestimations for temperatures from 10 to 20°C fall within the normal variance.

 $SoilR(T) = 1.5437e^{0.0793SoilT}$

Eq. 3-6



Figure 3-14A SoilT versus ADC soil respiration fluxes. B: The residuals plotted versus temperature.

Equation 3-7 presents the modeled Arrhenius function for the ADC data. Here soil respiration rates are overestimated for low temperatures. In comparison to the exponential curve the variance is more evenly distributed.



Figure 3-15A Modeling the Arrhenius equation for the ADC measurements. B: The residuals plotted versus temperature.

Modeling temperature dependence of soil respiration while using the exponential or Arrhenius equations leads to the conclusion that for all systems the explained variance by the modeled curve is around 50%, leaving thus half of the variance unexplained. For the modeled systems it was observed that for temperatures from 10 to 25 °C a lot of variance occurs, but that none of the curves for none of the systems show under- or overestimations. In case of low temperatures most often underestimations are reported. Measurements at high temperatures are only available for the open chamber system, the two models show contradicting estimations for high temperatures.

EC

For the eddy correlation measurements an exponential curve was fitted on the data according to equations 3-8. The explained variance is very low, the scatter of data is too large to derive reliable estimates of soil respiration rates.

 $SoilR(T) = 3.2973e^{0.0385T}$

Eq. 3-8





Figure 3-16A Air temperature versus EC soil respiration fluxes. B: The residuals plotted versus temperature.

Plotting the residuals of the exponential function, as can be seen in Figure 3-16B, shows the same pattern: a lot of scatter. Due to the high amount of variation in the data, parameters for the Arrhenius function were not estimated.

Soil moisture

In section 3-1 it was already observed that soil respiration was only influenced by soil moisture limitations in summer. Correlating soil respiration rates of the open chamber system with the soil moisture measurements result in a negative correlation of 0.128 (Pearson correlation, significant at 0.01 level, n=2474). In Figure 3-17 soil moisture versus the hourly soil respiration measurements is plotted. The measurements show a wide spread, for low respiration fluxes the soil moisture recordings vary from 0.48 to 0.65, for high respiration fluxes the range becomes only slightly narrower: 0.48 to 0.60. There is no obvious trend observed between the soil moisture content and soil respiration fluxes.



Figure 3-17 Soil moisture (m³/m³) versus hourly averaged soil respiration fluxes.

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4 Discussion

In literature many articles can be found on the comparison of different soil respiration systems. Comparative studies have been done in the field, as well as under laboratory conditions. Laboratory studies have the advantage that spatial and temporal heterogeneities are eliminated. Results from a laboratory study by Nay et al. (2004) support the observation by Norman et al. (1997) that closed chamber systems underestimate the soil CO₂ efflux by around 10%. However, Widen and Lindroth (2003) found the opposite relationship, also while using simulated and repeatable soil CO₂ effluxes. They reported that the open system always overestimated the CO_2 efflux, while the closed system showed both underestimations of 19% and overestimations to 21%. Contradicting results from comparative experiments are already reported under laboratory conditions. Moving the experiment to the field introduces more variables, which makes the comparison of different systems even more complicated. In Butnor et al., 2005 it is reported that soil respiration is influenced by several field factors: Physical heterogeneity, turtuosity of the diffusion pathway, soil-air content, soil moisture status, pressure differentials and boundary layer resistance (Kimball and Lemon 1971; Freijer and Bouton, 1991; Rayment and Jarvis 1997; Fang and Moncrieff 1998; Le Dantec et al 1999; Conen and Smith 2000; Rayment 2000; Welles et al 2001; Butnor and Johnsen 2004 in Butnor et al., 2005). Pumpanen et al. (2004) demonstrated the influence of soil texture and soil moisture differences in a comparative laboratory study in which the EGM/SRC1 and the automated open chamber system from Norman et al. (1997) were used. The chambers were tested on quartz sand with different textures and moisture contents, through which constant CO_2 fluxes were generated by a calibration tank. The different tested closed dynamic chambers yielded contradictory results. For PP systems, the EGM3 with SRC1 and EGM4 with SRC1 overestimated fluxes by as much as 33%, when collars were used. On wet fine sand, fluxes were underestimated by 6%. The open chamber system overestimated fluxes by 9% on wet fine sand. On dry fine sand there was an underestimation of 4%. On coarse sand fluxes were overestimated by 3-5%. Butnor et al. (2005) reports the opposite for the EGM3 under laboratory conditions, on sand the EGM shows an underestimation, while on a pebble medium flux rates are overestimated.

For this field study no systematic differences between the open chamber systems and the closed system were observed, system differences seemed however to vary with time/season. For both the EGM and EC system differences with the open system showed a temporal change i.e. in summer EGM and EC measurements recorded higher fluxes. When fluxes decreased to around $4 \mu mol m^{-2}s^{-1}$, the systems showed similar measurements. A further decrease of soil respiration rates leads to higher measured fluxes by the open chamber system compared to the other two systems. The fact that system differences seem to change with the season might indicate that the EGM and EC overestimate at higher fluxes and underestimate at low fluxes or in the opposite way for the open chamber system. Comparing systems in this type of field study does not make it possible to judge which system is more correct, especially not when the open chamber systems, despite the smaller amount of comparable data, seems better.

Only for DOYs 242 and 249 large differences are observed. For the other measurement days systems are in the same range. However the differences observed between the systems fall within the observed spatial variability. This field study does support the observations by Davidson at al., 2002 that soil respiration fluxes can vary over small distances. This was demonstrated by the differences between the different system rings. For example the left ADC ring often recorded considerable lower fluxes than the right ring. Also ring 4 from the open chamber system deviated regularly from the other rings by several μ mol m⁻²s⁻¹.

Eddy correlation systems allow for the integration of soil respiration from a larger surface area and thus for the integration of small scale spatial variability. In this study it is reported that EC measurements are in general higher than open chamber measurements, but also here there seems to be a seasonal trend. Kabwe et al (2005) compared three different systems (DCC, SCC and EC) on a waste-rock pile, which has the advantage of being texturally uniform, had no plant cover or soil development and had a large and level surface area (important for the EC). DCC results showed that the CO₂ efflux was relatively uniform, both spatially and temporally. EC CO₂ fluxes were about 12% lower than those calculated from the chamber data. Underestimation of fluxes by EC method compared to chamber methods is widely reported in literature.

Besides technique performance is one aspect, but the feasibility of a technique for field conditions is another. The ADC proved to be quite a challenge due to its size. Furthermore, it was hardly possible to read from the ADC display screen. The EGM was far more practical. However, manual chambers have the advantage of covering a larger spatial resolution compared to automated chambers. On the other hand, nighttime measurements are far easier obtained by automated systems, which do require power (Burrow et al., 2005).

Discussions also still exist on the modeling of temperature -soil respiration response curves. There is an ongoing-debate on the different functions that can be used for modeling. In this study hardly any response of soil respiration rates on soil moisture was found, only for the first days of the measurement period soil moisture might have limited soil respiration. Exploratory modeling of the soil temperature response proved that underestimations of fluxes at low temperatures were frequently observed for all the systems for both the Arrhenius and exponential functions. This agrees with the observations reported by Lloyd & Taylor (1994) for both the Arrhenius and exponential functions. They concluded that both functions underestimated soil respiration rates at low temperatures and overestimated at high temperatures. Poor fits were also reported by Tuomi et al. (2007)for the exponential and Arrhenius functions.

5 Conclusions

- Spatial variation between the different rings of the open chamber system can be considerable.
- Measurements of the open chamber system regularly show spikes. Part of these fluctuations can be explained by the occurrence of high [CO₂] during stable conditions.
- Measurement differences between the systems fall within the range of spatial variation for the field site.

EGM and open chamber

- Comparative measurements show a lot of variation, both spatial and between the systems.
- Most often the highest fluxes are recorded for the EGM system.
- There might be a seasonal trend: In August highest respiratory fluxes were recorded for the EGM system, in autumn comparative measurements were often nearly similar or higher fluxes were recorded for the open chamber system.
- During nighttime the EGM records the highest fluxes.

ADC and open chamber

- For the first four DOYs the ADC system measured higher fluxes, afterwards measurements became more similar.
- During nighttime the ADC records the highest fluxes
- The ADC system experiences measurement problems when $\{CO_2\}$ is high or when humidity is high.

EC and open chamber

- In general higher fluxes are measured by the EC system.
- A seasonal trend might be present: DOY 195-249 a lot of variance and higher fluxes for the EC, 249-296 better resemblance of the measurements, but still EC fluxes most of the times larger than open chamber fluxes. DOY 296-304 open chamber fluxes are higher than EC fluxes.

Modeling

- For all systems (except EC) the explanatory value of both the exponential and the Arrhenius function lies between 40 and 60%.
- For all systems (except EC) and for both functions low fluxes are overestimated and high fluxes underestimated. The turning point of the trend is found around 4 $5 \mu mol m^{-2}s^{-1}$

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References

Literature

- Burrows, E.H., J.L. Bubier, A. Mosedale, G.W. Cobb & P.M. Crill, 2005. Net ecosystem exchange of carbon dioxide in a temperate poor fen: a comparison of automated and manual chamber techniques. Biogeochemistry **76**: 21-45.
- Butnor, J.R., K.H. Johnsen & C.A. Maier, 2005. Soil properties differently influence estimates of soil CO₂ efflux from three chamber-based measurement systems. Biogeochemistry **73**: 283-301.
- Conen, F. & K.A. Smith, 1998. A re-examination of closed flux chamber methods for the measurement of trace gas emissions from soils to the atmosphere. European Journal of Soil Science **49**: 701-707.
- Davidson, E.A., K. Savage, L.V. Verchot & R. Navarro (2002). *Minimizing artifacts and biases in chamber-based measurements of soil respiration*. Agricultural and Forest Meteorology **113**: 21-37.
- Fang, C. & J.B. Moncrieff, 2001. *The dependence of soil CO*₂ *efflux on temperature*. Soil Biology and Biochemistry **33**: 155-165.
- Han, G., G. Zhou, Z. Xu, Y. Yang, J. Liu & K. Shi, 2007. Soil temperature and biotic factors drive the seasonal variation of soil respiration in a maize (Zea mays L.) agricultural ecosystem. Plant and Soil **291**: 15-26.
- Jacobs, A.F.G., B.G. Heusinkveld & A.A.M. Holtslag, 2003. *Carbon dioxide and water vapour flux densities over a grassland area in the Netherlands*. International Journal of Climatology **23**: 1663-1675.
- Jacobs, C.M.J., A.F.G. Jacobs, F.C. Bosveld, D.M.D. Hendriks, A. Hensen, P.S. Kroon, E.J. Moors, L. Nol, A. Schrier-Uijl & E.M. Veenendaal, 2007. Variability of annual CO₂ exchange from Dutch Grasslands. Biogeosciences Discuss 4: 1499-1534.
- Janssens, I.A., A.S. Kowalski, B. Longdoz & R. Ceulemans, 2000. *Assessing forest soil CO₂ efflux: an in situ comparison of four techniques.* Three Physiology **20**: 23-32.
- Jensen, L.S., T. Mueller, K.R. Tate, D.J. Ross, J. Magid & N.E. Nielsen, 1996. Soil surface CO₂ flux as an index of soil respiration in situ: a comparison of two chamber methods. Soil Biology and Biochemistry **28**: 1297-1306.
- Kabwe, L.K., R.E. Farrell, S.K. Carey, M.J. Hendry & G.W. Wilson, 2005. *Characterizing spatial and temporal variations in CO₂ fluxes from ground surface using three complimentary measurement techniques.* Journal of Hydrology **311**: 80-90.
- Le Dantec, V., D. Epron & E. Dufrene, 1999. Soil CO₂ efflux in a beech forest:comparison of wo closed dynamic systems. Plant and Soil 214: 125-132.
- Lloyd, J. & J.A. Taylor, 1994. On the temperature dependence of soil respiration. Functional Ecology 8: 315-323.
- Nay, M.S., K.G. Mattson & B.T. Bormann, 1994. Biases of chamber methods for measuring soil CO₂ efflux demonstrated with a laboratory apparatus. Ecology 75: 2460-2463.

References

- Ngao, J., B. Longdoz, D. Perrin, G. Vincent, D. Epron, V. Le Dantec, K. Soudani, M. Aubinet, F. Willm & A. Granier, 2006. *Cross-calibration functions for soil CO*₂ *efflux measurement systems*. Annals of Forest Science 63: 477-484.
- Norman, J.M., C.J. Kucharik, S.T. Gower, D.D. Baldocchi, P.M. Crill, M.B. Rayment, K. Savage & R.G. Striegl, 1997. *A comparison of six methods for measuring soil surface carbon dioxide fluxes*. Journal of Geophysical Research Atmospheres **102**: 28771-28777.
- Pumpanen, J., P. Kolari, H. Ilvesniemi, K. Minkkinen, T. Vesala, S. Niinistö, A. Lohila, T. Larmola, M. Morero, M. Pihlatie, I. Janssens, J.C. Yuste, J.M. Grünzweig, S. Reth, J.A. Subke, K. Savage, W. Kutsch, G. Ostreng, W. Ziegler, P. Anthoni, A. Lindroth & P. Hari, 2004. *Comparison of different chamber techniques for measuring soil CO₂ efflux.* Agricultural and Forest Meteorology 123: 159-176.
- Raich, J.W., C.S. Potter & D. Bhagawati, 2002. *Interannual variability in global soil respiration*, 1980-94. Global Change Biology **8**: 800-812.
- Rayment, M.B. & P.G. Jarvis, 1997. An improved open chamber system for measuring soil CO₂ effluxes in the field. Journal of Geophysical Research Atmospheres **102**: 28779-28784.
- Rayment, M.B., 2000. *Closed chamber systems underestimate soil CO*₂ *efflux.* European Journal of Soil Science **51**: 107-110.
- Rochette, P., B. Ellert, E.G. Gregorich, R.L. Desjardins, E. Pattey, R. Lessard & B.G. Johnson, 1997. *Description of a dynamic closed chamber for measuring soil respiration and its comparison with other techniques*. Canadian journal of soil science **77**: 195-203.
- Ryan, M.G. & B.E. Law, 2005. Interpreting, measuring and modeling soil respiration. Biogeochemistry 73: 3-27.
- Schimel, D.S., 1995. *Terrestrial ecosystems and the carbon cycle*. Global Change Biology **1**: 77-91.
- Snel, S., 2004. *Soil-atmosphere exchange of CO*₂. Thesis Wageningen University, Wageningen, 41 pp.
- Tuomia, M., P. Vanhalaa, K. Karhua, H. Fritzec & J. Liski, 2007. *Heterotrophic soil respiration- Comparison of different models describing its temperature dependence*. Ecological Modeling ??:??
- Widén, B. & A. Lindroth, 2003. A Calibration System for Soil Carbon Dioxide-Efflux Measurement Chambers: Description and Application. Soil Science Society of America Journal **67**: 327-334.
- Wiseman, P.E. & J.R. Seiler, 2004. Soil CO₂ efflux across four age classes of plantation loblolly pine (Pinus teada L.) on the Virginia Piedmont. Forest Ecology and Management **192**: 297-311.

Websites

- [1] <u>www.met.wau.nl</u> accessed July 2007.
- [2] www.adc.co.uk/products-76.html accessed at 23th of July.
- [3] <u>www.ppsystems.com/Literature/EDSEGM4.pdf accessed July 2007</u>.

A comparative field study of four soil respiration systems

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Appendix 1 Response curve fitting

In Figure 1 the temperature at 150 cm response curves for the soil respiration data are plotted as well as the residuals. The corresponding exponential function is:

 $SoilR = 1.6515e^{0.0648T}$

In Figure 2 similar plots are made, but then for the temperature 5 cm under grass. The corresponding function is:

 $SoilR = 1.426e^{0.0667 SoilT}$



Figure 1A:Temperature at 150 cm versus the hourly averaged soil respiration fluxes with exponential curve fitting B: The temperature at 150 cm versus the residuals (measured – predicted respiration rates).



Figure 2A Soil temperature at 5 cm under grass versus the hourly averaged soil respiration fluxes with exponential curve fitting. B: The temperature at 5 cm under grass versus the residuals (measured – predicted respiration rates).