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On the spatial variation of soil rhizospheric and heterotrophic respiration in a winter wheat stand

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ABSTRACT

Field-scale soil respiration reveals a tremendous variability in space. In order to quantify the spatial variability originating from the heterotrophic and the rhizospheric contribution to total soil respiration, the root exclusion method was applied. At 61 locations within a 50 m × 50 m plot in a winter wheat stand, 7 cm-collars and 50 cm-collars were inserted prior to the root growth to simultaneously measure total respiration and heterotrophic respiration. The rhizospheric component was determined as the difference between the flux measurements of total and heterotrophic respiration. During the vegetation period 2009, in total 18 repeated measurements, including soil temperature and moisture, were carried out.

The highest spatial variability in terms of standard deviation up to 2.9 μmol CO_2 m^{-2} s^{-1} was detected for the rhizospheric respiration during the period of massive plant growth. Compared to the heterotrophic contribution the coefficient of variation in space was constantly higher for the rhizospheric contribution. Variogram analyses revealed an almost completely random spatial distribution of heterotrophic respiration, whereas the rhizospheric respiration showed a clear spatial autocorrelation. The spatial pattern of total respiration mainly resembles the pattern of the rhizospheric component and is characterized by an average spatial correlation length of 18 m.

The results indicate that the sampling design for chamber-based measurements of soil respiration in agro-ecosystems should account for the high spatial variability during plant growth and collars should be separated by a distance larger than the spatial correlation range to ensure uncorrelated samples and thus unbiased representative flux estimates.

1. Introduction

Soil respiration is a major component of the global carbon cycle (Raich and Schlesinger, 1992). Depending on terrestrial ecosystem type, the average soil respiration varies between 1.4 and 2.6 μmol m^{-2} s^{-1} (Chen et al., 2010). Precise measurements of soil respiration are prerequisite for the quantification of annual balances and carbon sequestration in soils particularly in highly managed systems like agricultural fields (Janssens et al., 2003).

The most commonly applied measurement approach is the dynamic chamber technique (e.g. Janssens et al., 2000). Chamber-based spatially distributed measurements of soil respiration reveal a tremendous variability even at plot scale for agricultural sites (Camporese et al., 2008; Panosso et al., 2009; Fiener et al., 2012; Allaire et al., 2012; Herbst et al., 2012), grasslands (Foti et al., 2008) and forests (Rayment and Jarvis, 2000; Khomik et al., 2006; Kosugi et al., 2007; Konda et al., 2008; Ohashi et al., 2008). In order to capture this variability in space for the determination of representative average fluxes, a large number of simultaneous local measurements would be required (Yim et al., 2003; Rodeghiero and Cescatti, 2008; Herbst et al., 2009). The source of this small-scale spatial variation that hampers the measurement of effective fluxes is not clearly identified (van den Pol-van Dasselaar et al. 1998; La Scala Jr. et al. (2000); Ngao et al., 2012; Piotrowska and Dlugosz, 2012). Apart from technical issues, this could partly be attributed to the fact that soil respiration is a mixed signal of two major processes: rhizospheric respiration and heterotrophic respiration. Soil heterotrophic respiration is the product of the microbial decomposition of soil carbon, known to be highly sensitive to soil temperature and moisture (Davidson and Janssens, 2006; Moyano et al., 2013). Soil rhizospheric respiration originates from the growth and the activity of plant roots, including the easily decomposable root exudates (Hanson et al., 2000; Moyano et al., 2007). The rhizospheric respiration is also known to be affected

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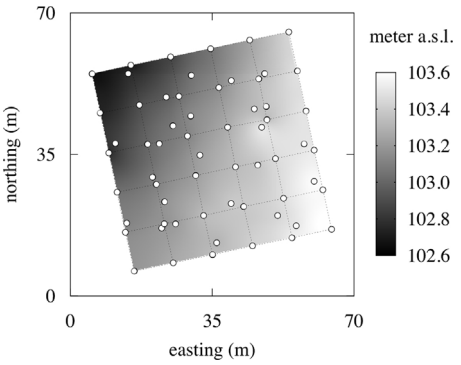

Fig. 1. Spatial sampling design and terrain elevation of the test site.

by soil temperature and soil moisture; however, the respective sensitivity functions probably look different from those of heterotrophic respiration sensitivity (Baggs, 2006; Suleau et al., 2011). Additionally the plant growth and development strongly influences rhizospheric respiration, which adds a strongly time-dependent component, particularly in agricultural systems (Moureaux et al., 2008; Suleau et al., 2011).

The question arises whether the spatial pattern of rhizospheric respiration differs from the spatial pattern of heterotrophic respiration, and how both underlying patterns determine the overall spatial pattern of total soil respiration. This study had three main goals: (i) to determine the differences in the spatial patterns of rhizospheric versus heterotrophic respiration, (ii) to determine the spatial autocorrelation lengths of the patterns and (iii) to identify the process with the biggest influence on the spatial pattern of total soil respiration.

To achieve these goals, soil respiration measurements were made at 61 locations within a 50 m × 50 m winter wheat plot. The root exclusion method was used to separate total respiration into its rhizospheric and heterotrophic components, respectively. Since a strong temporal effect was expected, especially for the rhizospheric contribution, 18 repeated measurement campaigns of the patterns were carried out between April and August 2009.

2. Materials and methods

2.1. Experimental data

Experimental data were gathered in an agricultural field cultivated with winter wheat (*Triticum aestivum* L.), harvested at 27 July 2009. The plant density was about 260 seedlings m^{-2}, resulting in an average distance of 6.3 cm between each plant. The 'Selhausen' test site (50°52′11″ N, 6°26′57″ E, 103 m a.s.l.) is located about 30 km west of Cologne, Germany. With mean annual temperature of 9.9 °C and mean precipitation of 698 mm $year^{-1}$, the test site is characterized by a temperate climate. According to the World Reference Base for Soil Resources (IUSS Working Group WRB, 2006) soil type is Haplic Luvisol containing 1.2% organic carbon in the upper 33 cm. The soil is classified as a silt loam with clay content of 18%, 67% silt and 15% sand.

Simultaneous measurements of CO_2 fluxes, soil temperature and water content were carried out for 36 sampling locations on a regular 10 m grid refined with 25 additional sampling locations randomly placed within each of the 10 m blocks (see Fig. 1). This ensured spatial coverage and an adequate number of small sampling distances required for the geostatistical analyses.

Soil respiration was measured with a closed dynamic chamber system (LI 8100-103, LI-COR Biosciences, Lincoln, NE, USA). Each measurement took 3 min, including 1 min for opening, relocation and automatic closure of the chamber and 2 min closure time, the first 30 s of which were routinely omitted as adaption period. Each of the 61 sampling locations was equipped with a 7 cm and 50 cm long soil collar (20 cm diameter), installed into the soil in such a way that the collar protruded 2 cm above the soil surface. Root exclusion using the 50-cm collars allowed to measure the heterotrophic contribution to soil respiration R_h (Bowden et al., 1993; Hanson et al., 2000; Tang et al., 2005; Baggs, 2006; Subke et al., 2006; Moyano et al., 2007), whereas the commonly applied 7-cm collars allowed the measurement of total soil respiration R_s (e.g. Khomik et al., 2006; Graf et al., 2011). Accordingly, the rhizospheric contribution to soil respiration R_r was calculated as the difference ($R_s - R_h$).

To minimize any disturbance effects, the collars were installed at the beginning of March, about 1 month before the first measurement campaign and significant root growth. After the measurements, all collars were removed and the 50-cm collars were checked for roots grown into the collars from underneath. This however did not occur.

To allow for simultaneous measurement of soil water content without disturbance, time domain reflectometry (TDR) probes with a rod length of 20 cm were installed horizontally at 6 cm depth within the soil collars. Similarly, thermocouples were permanently installed at the same depth to measure soil temperature. Further, green and brown leaf area index were measured bi-weekly with a portable leaf area meter (LI-3000A, LI-COR Biosciences, Lincoln, NE, USA) at three locations and averaged.

2.2. Data processing

Three steps were involved in the processing prior to the geostatistical analyses: (i) correction for soil water content in the 50-cm collars; (ii) temporal and spatial de-trending; (iii) spatial outlier detection. Between steps one and two the CO_2 fluxes were log-transformed to ensure normal distribution of the data. This is commonly applied to CO_2 fluxes (e.g. Konda et al., 2008; Ohashi et al., 2008).

Step one was required since the 50-cm collars inhibited the growth of roots inside the collars. Thus, root water uptake did not occur in those collars, resulting in higher water contents compared to the 7-cm collars. We therefore corrected the 61 heterotrophic respiration measurements of each sampling campaign according to the water content of the 7-cm collars. Since a correlation of 0.53 ($p < 0.02$) between the respiration and the soil water content measured at the 50-cm collars θ_{50} was given, a quadratic function was fitted to the data. The root mean square error of this correction function (Eq. (1)) was 0.30 μmol m^{-2} s^{-1}.

$$f(\theta) = 1.07 + 16.8\theta_{50}^2 \quad (1)$$

In the next step, the respiration of the 50-cm collars was corrected according to the water content of the 7-cm collars θ_7:

$$R_{corr} = R_{orig} + f(\theta_7) - f(\theta_{50}) \quad (2)$$

where R_{orig} is the uncorrected value and R_{corr} is the corrected heterotrophic respiration.

This procedure only influenced the field average of heterotrophic respiration for each measurement campaign. Due to the log-transform directly after step (i), this did not affect the point-to-point differences.

The second step involved spatial and temporal de-trending. Since the measurement campaigns started at morning and it took about 3 h to sample the 61 locations a slight and almost linear temporal trend was observed. Thus, the fluxes were de-trended to the time of the first measurement at morning. As a result of the gentle slope (Fig. 1), a small spatial trend existed in the data, which was removed by linear de-trending to the same elevation. This was necessary to remove the small deterministic part of the spatial