



Soil moisture induced changes on fine-scale spatial pattern of soil respiration in a semi-arid sandy grassland



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ABSTRACT

High variability of soil respiration measured at fine spatial scale increases the uncertainty when trying to determine the representative average soil respiration (R_s) flux. A possible way to decrease the uncertainty, while also optimising measurement effort, could be the calculation of required number of R_s measurements (N_{opt}) together with the optimisation of their spatial arrangement. The goals of this study were to find explanatory variables of the structural parameters of fine-scale R_s spatial pattern and of N_{opt} for sampling optimisation. We conducted field R_s , soil temperature (T_s) and soil water content (SWC) measurements in a Hungarian sandy pasture over several years along circular transects of 75 evenly spaced (20 cm distance) sampling positions. Structural parameters of patterns of R_s and the covariates were determined from variograms. Ranges of spatial autocorrelation varied between 0 and 3.6 m for R_s , 0 and 3 m for SWC and 0 and 2.9 m for T_s . Patch size of R_s depended negatively on transect average SWC. To understand and quantify the spatial dependence of variables, cross-variograms were calculated. R_s proved to be positively spatially correlated to SWC at low water supply, while T_s – R_s and SWC– T_s spatial correlations were mostly negative, both due the direct effect of evaporative cooling on T_s . We found that spatial patchiness became less robust and the correlations generally decreased as soil moisture content was high. We found that explanatory variable of N_{opt} was also SWC, with negative correlation between them. We conclude that sampling could be optimized on the basis of the easily measurable actual SWC, which determines both the optimal number of R_s measurements and the minimum distances between individual samples in semi-arid ecosystems.

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1. Introduction

Soils contain more carbon than the living biomass and atmosphere together (Schmidt et al., 2011) and this pool is highly sensitive to changes in climate or land use. Soil respiration (R_s) is the second largest CO₂ flux in most ecosystems following photosynthesis (Kuzyakov, 2006) and accounts for 60–90% of total ecosystem respiration (Raich and Schlesinger, 1992) or 40–60% of gross primary production (Janssens et al., 2001).

Abbreviations: a, range; c, structural variance; CV, coefficient of variation; N_{opt} , optimal sample size for estimating patch scale means; R_s , soil respiration; SOM, soil organic matter; SWC, soil water content; T_s , soil temperature; y_0 , nugget variance.

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In dry grasslands, abiotic drivers of R_s , such as soil temperature (T_s) and soil moisture (SWC) account for 40–80% of variability in R_s (Balogh et al., 2011; Mäkiranta et al., 2008). Both are therefore fundamental explanatory variables used in R_s models. Soil water availability limits R_s at high and low water contents (Chen et al., 2010; Walle et al., 2007) due to the contrary effects of substrate and oxygen availability (Davidson et al., 2012; Moyano et al., 2013). A significant part of the variability in R_s can be explained by photosynthetic activity with proper time lags (Balogh et al., 2011; Graf et al., 2010; Högberg et al., 2001) between the CO₂ uptake of the canopy and CO₂ efflux from the soil.

A major component of R_s is heterotrophic respiration, originating from a number of components, such as the microbial decomposition of litter, soil organic matter (SOM), root exudates and rhizodeposits. SOM derived CO₂ emission can be also dependent on carbon supply, but is supposed to be mostly temperature driven (Craine et al., 2010). Seasonal fluctuations in the ratio of autotrophic to heterotrophic components follow the courses of temperature, soil moisture, plant biomass and litter fall (Epron, 2009), whereas diurnal fluctuations in the autotrophic to

heterotrophic ratio can follow the daily CO₂ uptake course (Heinemeyer et al., 2012; Kuzyakov and Gavrichkova, 2010). Larger precipitation events increase soil respiration (Xu and Luo, 2012) by inducing microbial activity despite of a decreased gas phase conductance for CO₂ in the soil profile (Nagy et al., 2011).

Together with temporal variability, R_s and its main abiotic drivers, SWC and T_s, show substantial spatial heterogeneity and patchiness (Dale, 1999; Huenneke et al., 2001; Parker et al., 2012; Saiz et al., 2006). Although recent studies showed that the small-scale spatial pattern of R_s depends on soil water content (Chen et al., 2010; Fóti et al., 2008; Graf et al., 2012; Herbst et al., 2009, 2012; Kosugi et al., 2007), the question about how exactly SWC influences the structural parameters of the respiration pattern was not clarified yet.

At the same time, spatial variability of R_s may also depend on plant canopy microclimate (Chatterjee and Jenerette, 2011), litter and soil characteristics (Ohashi and Gyokusen, 2007; Walle et al., 2007) all affected by land use (Petroni et al., 2008). Confounding effects of spatially and temporally variable processes and the interaction of explanatory variables for the patch structure of R_s point to the relevance of spatial studies (Allaire et al., 2012).

Spatial heterogeneity may cause serious flux uncertainty even in eddy-covariance studies (Kosugi et al., 2007). Scaling up from punctual (chamber) samples to the level of the eddy-covariance measurements is inevitable for flux partitioning (Subke et al., 2009). It seems however, that the commonly used number of samples (cf. Supplementary material) is less than the calculated optimum (N_{opt}) (eg. Herbst et al., 2009; Rodeghiero and Cescatti, 2008). A possible solution to decrease the uncertainty of large scale estimates, while also optimising measurement effort, could be the calculation of required number of R_s measurements (Knohl et al., 2008) together with the optimisation of their spatial arrangement (Ohashi and Gyokusen, 2007). Although several studies stated that N_{opt} depends on the variability of the measured fluxes (Adachi et al., 2005; Almagro et al., 2009; Knohl et al., 2008), and calculated different N_{opt}-s e.g. for different seasons, the causes of this variability were not explained. On the other hand, the autocorrelation range should be known for proper sample arrangement to get spatially independent samples, but the influencing factor of the spatial range is neither fully understood.

Within this study, we measured T_s and SWC simultaneously with R_s along transects in a Hungarian sandy pasture covering a period of several years. We hypothesized that SWC is the main explanatory variable that determines the patch structure of R_s, and therefore may influence design and required number of R_s sampling in a dry grassland ecosystem. Temporal aspects of R_s measurement in this ecosystem have already been investigated extensively (Balogh et al., 2011; Nagy et al., 2011). Our aim was to investigate the fine-scale spatial patterns of R_s and its driving variables with the following specific goals: (1) to study the dependency between the patch structure of R_s and the corresponding structures of T_s and SWC, and (2) to provide estimation of N_{opt} and optimal sampling design for R_s measurements based on explanatory variables for a wide range of vegetation phases and climatic variables.

2. Materials and methods

2.1. Study site

The vegetation at the Bugac site (46.69 N, 19.6 E, 114 m a.s.l.) is semi-arid sandy grassland dominated by *Festuca pseudovina* Hack. ex Wiesb., *Carex stenophylla* Wahlbg. and *Cynodon dactylon* L. Pers. The average annual precipitation is 562 mm and annual mean temperature is 10.4 °C. According to the FAO classification (Driessen et al., 2001) soiltype is a chernozem with a rather high organic carbon content of 51.5 g kg⁻¹ for the 0–10 cm topsoil (Balogh et al., 2011). Soil texture is a sandy loam. The study site is part of the Kiskunság National Park and has been under extensive management (grazing) for the last 20 years. Grazing intensity was 0.3–0.65 animal ha⁻¹ during the measurement

period 2004–2012. The grassland may potentially turn into a source of carbon in drought years (Nagy et al., 2007), with annual C-balances ranging from –171 (sink) to +96 (source) g C m⁻² (Pinter et al., 2010).

2.2. Sampling

Fine-scale measurements were conducted along circular transects of 15 m length (~4.7 m diameter) at every 20 cm giving 75 sample positions. Our sampling strategy originates from the classical micro-coenological studies, where investigations focus on the fine-scale compositional heterogeneity within plant communities and look for the related characteristic scales (spatial range) (Bartha et al., 2004; Juhász-Nagy and Podani, 1983). The advantages of this sampling design are the efficient work flow and the low disturbance level.

Circular transects were placed randomly in a plot of 70 × 70 m in the vicinity of an eddy covariance station (Nagy et al., 2007) at each sampling occasion. The 70 × 70 m sampling plot was a flat area, the difference was less than 1 m between the highest and lowest point. There was no apparent elevation difference within the transects. In total 22 transects were measured during the vegetation periods between 2004 and 2012 (2004: one transect in May; 2007: 6 transects in April, August and October; 2010: 7 transects in March, June and August; 2011: 5 transects in June, July and August; 2012: 3 transects in May and June). Sampling campaigns were scheduled with the aim to cover all development stages of the vegetation under various environmental conditions. However, we intended to avoid measuring short-term effects of precipitation, direct impact of temperature changes and effects due to apparent differences of the vegetation structure within a particular transect, because the main goal was the description of fine-scale spatial aspects in R_s under temporally stationary measuring conditions.

R_s was measured using the LICOR 6400 (Li-Cor, Lincoln, NE, USA) system equipped with the 6400-09 soil chamber. Each gas-exchange measuring occasion started at about noon and for one transect lasted ~1.5 h (there were 6 occasions when two transects were measured on the same day which lasted ~2.5–3 h). The soil gas exchange chamber was used without collar to minimize disturbance and to avoid disruption of the assimilate supply to the roots (Davidson et al., 2002; Wang et al., 2005). The sandy surface, the litter layer and the weight of the chamber ensured non-leaky conditions. We cut the green vegetation 1.5 h before starting the soil respiration measurements. This delay was enough to allow for the dissipation of direct disturbance effects, as measured during pilot investigations.

We measured volumetric soil water content and soil temperature simultaneously with the R_s measurements, both in the main rooting zone, which clearly provides the dominant contribution to the total efflux (Nagy et al., 2011). Previous measurements did not reveal consistent time lags between the soil temperature and CO₂ efflux (Balogh et al., 2011).

SWC was measured by time domain reflectometry (ML2, Delta-T Devices Co., Cambridge, UK; FieldScout TDR300 Soil Moisture Meter, Spectrum Technologies, IL-USA) in the 0–6 cm soil layer. T_s was determined at 5 cm depth by a digital soil thermometer.

2.3. Statistical and geostatistical analysis

First, we analysed raw datasets for correlation between drivers and R_s separately for each measurement campaign. As several datasets were non-normally distributed, Spearman rank-correlation was calculated between SWC-R_s, T_s-R_s and SWC-T_s for each occasion. Bonferroni correction was applied to avoid Type I error increase when calculating correlations between autocorrelated datasets (Dale and Fortin, 2002; Henebry, 1993), and because the compared datasets were not necessarily independent. We set the level of significance test to $\alpha = 0.05/3 =$

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