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# Dependence of soil respiration on soil moisture, clay content, soil organic matter, and $CO_2$ uptake in dry grasslands

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ABSTRACT

The effects of abiotic and biotic drivers on soil respiration ($R_s$) were studied in four grassland and one forest sites in Hungary in field measurement campaigns (duration of studies by sites 2–7 years) between 2000 and 2008. The sites are within a 100 km distance of each other, with nearly the same climate, but with different soils and vegetation. Soil respiration model with soil temperature ($T_s$) and soil water content (SWC) as independent variables explained larger part of variance (range 0.47–0.81) than the Lloyd and Taylor model (explained variance: 0.31–0.76). Direct effect of SWC on $R_s$ at much smaller temporal and spatial scale (1.5 h, and a few meters, respectively) was verified.

Soil water content optimal for $R_s$ ($SWC_{opt}$) was shown to significantly (positively) depend on soil clay content, while parameter related to activation energy ($E_0$) was significantly (negatively) correlated to the total organic carbon content (TOC) in the upper 10 cm soil layer. Dependence of model parameters on soil properties could easily be utilized in models of soil respiration. The effect of current (a few hours earlier) assimilation rates on soil respiration after removing the effect of abiotic covariates (i.e. temperature and water supply) is shown. The correlation maximum between the $R_s$ residuals ($R_{s\_res}$, from the $R_s$ (SWC, $T_s$) model) and net ecosystem exchange (NEE) was found at 13.5 h time lag at the sandy grassland. Incorporating the time-lagged effect of NEE on $R_s$ into the model of soil respiration improved the agreement between the simulated vs. measured $R_s$ data. Use of $SWC_{opt}$ and $E_0$ parameters and consideration of current assimilation in soil respiration models are proposed.



## 1. Introduction

In the last decades, a strong interest has arisen in soil respiration, due to widely used eddy flux studies and its problems on partitioning NEE. Eddy flux partition methods require simple but effective models in which main abiotic and biotic drivers of $R_s$ are both taken into account.

At an annual scale, soil respiration ($R_s$) contributes 60–80% of ecosystem respiration ($R_{eco}$, Raich and Schlesinger, 1992) or 40–60% of gross primary production (GPP, Janssens et al., 2002). As a biochemical process, respiration is governed by temperature, and has been studied and described extensively (Lloyd and Taylor, 1994; Fang and Moncrieff, 2001). The dependence of soil respiration on temperature is generally utilized when partitioning $R_{eco}$ (Campbell et al., 2004; Bahn et al., 2008). However, temperature dependence of $R_{eco}$ has been shown to be strongly different between active and inactive periods due to the higher overall (active leaves and fine roots) activity of the vegetation in active periods (Reichstein et al., 2005). In other cases $R_{eco}$ was shown to be connected only weakly to temperature, leading to problems with eddy data gap filling (Falge et al., 2001). These uncertainties in $R_{eco}$ could arise from uncertainties in the estimation of soil respiration.

In addition to the temperature response, $R_s$ was proven to be significantly limited both by low (Wan et al., 2007) and high (Davidson et al., 1998; Byrne et al., 2005; Saiz et al., 2007) soil water contents (SWC). Taking SWC into account is important when modeling the process of soil respiration in water limited ecosystems (Xu and Baldocchi, 2004; Jia et al., 2007; Nagy et al., 2007; Li et al., 2008). Simultaneous use of soil temperature ($T_s$) and SWC as independent driving variables in empirical models (Bahn et al., 2008) is straightforward in water limited cases (Wu et al., 2010). The importance of water filled pore space and tortuosity has already been elucidated in studies investigating physical soil properties and diffusion of solutes and gases in the soil (Moldrup et al., 1999; Jassal et al., 2004; Reth et al., 2008). One of the most difficult modeling tasks is the estimation of the effect of temporal

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precipitation distribution on $R_s$ (Reth et al., 2008). On the one hand, greater ratio of microbial respiration and enhanced root death after prolonged drought stress have been reported (Harper et al., 2005), on the other hand, enhanced vegetation activity (root growth and germination) after larger precipitation events (Baldocchi et al., 2006) has been observed.

Temporally integrative biotic factors including leaf area index (Suyker and Verma, 2001), absolute growth rate (Jia and Zhou, 2009) and root biomass (Han et al., 2007) have also been considered as factors that strongly influence soil respiration rates and are thus used for modeling. Plant diversity may also affect $R_s$ through increased productivity and C-input into the soil. Dias et al. (2010) reported positive relationship between diversity and soil respiration.

Photosynthesis stimulates $R_s$ after translocation of the recent photosynthate to the roots and root-associated soil microbes (Moyano et al., 2007), with a few hours of time lag between the two processes (Tang et al., 2005; Bahn et al., 2009). However, based on numerous studies, different time lags have been documented in grasses and in trees, hours of time lag in the first and days of time lag in the latter (Kuzyakov and Gavrichkova, 2010). This above effect decouples soil respiration from temperature (Tang et al., 2005). The magnitude of this effect and the fast response (short time lags) clearly show why it is important to consider recent photosynthesis in soil respiration modeling and carbon balance studies. The diurnal $CO_2$ exchange data sets are available at eddy-covariance sites, therefore they can be easily used in $R_s$ estimations.

One aim of the present study was to describe the dependence of $R_s$ on both SWC and $T_s$ in different soils. The study has been conducted on five sites with soils strongly differing in soil total organic carbon (TOC) content and soil mechanical composition (clay content). These two parameters are usually available for most sites, thus we have also investigated their applicability as parameters in soil respiration models.

Another objective of the study was to separate the influence of recent photosynthesis on $R_s$ from covariate effect of abiotic factors. This separation has been achieved at one study site where parallel eddy covariance and soil respiration data were available. These methods are expected to provide information which can be utilized to improve soil and ecosystem respiration models used in eddy flux studies.

## 2. Materials and methods

### 2.1. Site descriptions

Soil respiration measurements were undertaken within the framework of research projects that estimate the C-balance of Hungarian grasslands. The sites include four Festuca grasslands and one deciduous woodland which have evolved under nearly the same climate, yet differ in vegetation composition and soil structure. Two of the Festuca grasslands (Bugac and Mátra) are eddy-covariance sites. The sites' main characteristics are shown in Table 1.

The vegetation at site Bugac (B) is semi-arid sandy grassland dominated by *Festuca pseudovina* Hack. ex Wiesb., *Carex stenophylla* Wahlbg. and *Salvia pratensis* L. The study site is a part of the Kiskunság National Park and has been under extensive management (grazing) for the last 20 years. Grazing pressure was about 0.75 animal $ha^{-1}$ during the study. $CO_2$ flux measurements (eddy covariance) have been started in 2002. The grassland can turn into a source of carbon in dry years (Nagy et al., 2007), with annual sums of NEE between −186 and +105 gC $m^{-2}$.

The Mátra site (M) is situated at the edge of the Mátra Mountains. The site has a slight (<1%) slope exposed to west. The climate is characterized by a slightly higher than average annual precipitation sum (Table 1). Dominant species in the grassland include *Festuca rupicola* Heuff., other frequent species are *Arrhenaterum elatius* L., *Poa pratensis* L., *Plantago lanceolata* L. $CO_2$ flux measurements (eddy covariance) have been started in 2003, yearly sum of NEE ranged between −133 and +64 gC $m^{-2}$ (Pintér et al., 2008).

The Isaszeg (I) site is an abandoned pasture situated on a hill with a slope (about 20%) exposed to the west. The grassland is vertically well structured (60–80 cm height), species-rich, with several exhibiting broad-leaved dicotyledonous. This grassland is dominated by *F. rupicola* Heuff., *Bromus inermis* Leyss. and *Brachypodium rupestre* (Host.) Roem. et Schult. Other characteristic taxa were *Salvia nemorosa* L., *Euphorbia pannonica* Pall., *Seseli osseum* Cr. and *Galium verum* L. Modeled NEE based on chamber measurements (Balogh et al., 2005b) and measured variability in soil respiration (Fóti et al., 2008) suggest the highest carbon exchange rates of the investigated grasslands.

**Table 1**
Site characteristics.

| Site | B (Bugac) | M (Mátra) | I (Isaszeg) | V (Vácrátót) | G (Gödöllő) |
|---|---|---|---|---|---|
| Location | 46.69 N, 19.6 E | 47.50 N, 19.43 E | 47.34 N, 19.2 E | 47.16 N, 19.16 E | 47.36 N, 19.26 E |
| Altitude, asl., (m) | 114 | 300 | 230 | 180 | 220 |
| Annual precipitation (mm) | 562 | 622 | 550 | 507 | 550 |
| Mean annual temperature (°C) | 10.4 | 10.2 | 9.1 | 10.5 | 11 |
| Vegetation | Sand grassland | Mountain pasture | Loess grassland | Open sand grassland | Maple-oak forest |
| Soil type | Chernozem type sandy soil; (FAO: chernozem) | Brown soil with high clay content (FAO: vertisol) | Chernozem type loess soil. (FAO: chernozem) | Sandy soil (FAO: arenosol) | Brown forest soil with high clay content (FAO: cambisol) |
| Soil texture[a] | Sandy loam | Silty clay loam | Loam | Loamy sand | Clay loam |
| Soil $pH_{KCl}$[a] | 7.3 | 6.2 | 7.6 | 7.6 | 6.9 |
| Bulk density (g $cm^{-3}$)[a] | 0.99 | 1.3 | 0.97 | 1.29 | 0.8 |
| Clay content (g $kg^{-1}$)[a] | 128 | 346 | 184 | 17 | 311 |
| TOC (g $kg^{-1}$)[a] | 51.5 | 15.4 | 24.6 | 17.7 | 35.6 |
| TN (g $kg^{-1}$)[a] | 3.8 | 1.5 | 2.1 | 0.7 | 2.5 |
| SWC (vol%)[b] | 2.2–29 | 14.6–42 | 4.1–39.6 | 3.1–11.7 | 11.4–40 |
| $T_s$ (°C)[b] | −1.4–31.5 | −1.6–34.8 | −1.14–28.6 | 7.7–24.7 | −1–20.5 |
| $R_s$ (μmol $CO_2$ $m^{-2}$ $s^{-1}$)[b] (measurement dates) | 0.17–18.6 (20/2/2006, 27/6/2008) | 0.101–14.7 (11/8/2004, 1/8/2008) | 0.24–15.6 (3/3/2006, 27//2008) | 0.226–2.59 (4/4/2001, 3/5/2004) | 2.44–10.56 (3/4/2008, 16/7/2008) |
| Land use | Extensive grazing Natural reserve | Extensive pasture | Abandoned (grazed ~10 years before) | Natural reserve | Natural reserve |
| Number of measurement years | 7 | 3 | 3 | 3 | 2 |

[a] Values given are representative for 0–10 cm soil depth.
[b] Measured maximum and minimum of SWC, $T_s$ and $R_s$ respectively, during the experimental period.