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Spatial and temporal variability of soil gas diffusivity, its scaling and relevance for soil respiration under different tillage

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ABSTRACT

Soils are an important source and sink for carbon. Soil management such as reduced or no-tillage management has been reported to increase soil organic matter budgets, probably due to a hampered microbial mineralization of organic components. While soil respiration is mainly controlled by temperature and soil moisture, it can be also limited by the soil pore system facilitating diffusive gas fluxes between the soil and the atmosphere. However, soil gas diffusivity as a controlling factor for soil respiration has not been assessed under different soil management. Moreover, no adequate methods have been developed yet that facilitate the description of spatial or temporal variations of the highly non-linear soil gas diffusivity functions. Therefore, the objectives of this study were to deduce and apply a scaling rule for gas diffusivity, and to observe and analyze spatio-temporal variations of soil respiration and gas diffusivity under conventional tillage (CT) and no-tillage (NT). We measured soil respiration rates and gas diffusivities along a transect on an arable field in Hollabrunn (Lower Austria) within the 2014 vegetation period. We also determined the soil hydraulic properties and gas diffusivities as a function of air-filled porosity. By adopting the similar media approach of Miller and Miller we facilitated scaling of spatially variable gas diffusivity model functions. The scaling performed well to derive representative mean parameters while preserving the spatial variability in the scaling factors. The comparison of scaling factors for soil water retention, hydraulic conductivity, and gas diffusivity revealed that flow pathways were not the same for water and gases. This finding was explained by the continuity of pores that are accessible for water or gas movement. Compared to NT, the CT plot was characterized by greater soil respiration rates, gas diffusivities, total porosities, and unsaturated hydraulic conductivities, while soil water retention, observed volumetric water contents, and the spatial variability of these properties were smaller. Soil respiration rates were mainly changing with time as a result of soil temperature and soil water content. However, we also found that the diffusive soil properties slightly influenced CO_2 efflux rates.

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1. Introduction

Soil management practices affect the physical soil properties dynamically in space and time with consequences for the storage and movement of water, nutrients and pollutants, and the gas exchange within the soil–plant–atmosphere continuum (Strudley et al., 2008). It is well known that for given climatic conditions and a particular soil–plant system, the soil management system considerably controls soil structure development (Messing and Jarvis, 1993). Consequently, the impacts of different soil management techniques (i.e. soil tillage methods) on soil physical and hydraulic properties have been frequently studied in recent decades (e.g., Buczko et al., 2006; Sauer et al., 1990; Strudley et al., 2008). Despite a considerable spatial and temporal variability, most publications reported averaged comparisons between different tillage practices and did not account for spatio-temporal dynamics (Schwen et al., 2011; Strudley et al., 2008). Recently, a series of studies addressed both the temporal and management-induced changes in soil hydraulic properties (Alletto and Coquet, 2009; Bormann and Klaassen, 2008; Cameira et al., 2003; Daraghmeh et al., 2008; Hu et al., 2009; Moret and Arrue, 2007; Mubarak et al., 2009; Schwen et al., 2011). These studies helped to improve our understanding of the dynamic impacts of soil management on physical and hydraulic soil properties.

Despite some site-specific differences, the above listed studies revealed controversial implications of no-tillage (NT) management practices on physical and hydraulic soil properties. Compared to conventionally tilled systems (CT), soils under NT tend to have a better developed macropore network and a temporally more stable soil structure. This results in an increased saturated hydraulic conductivity

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Abbreviations: CT, conventional tillage; GHG, greenhouse gas; NT, no-tillage.
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K_s. At the same time, soils under NT are often more compacted and thus characterized by higher bulk densities ρ_b and a less porous soil matrix, especially in the subsoil. Consequently, soil water retention $\theta(h)$ can be increased under NT, while unsaturated hydraulic conductivity $K(h)$ through smaller pores (micro- to mesopores) can be reduced (Schwen et al., 2011). The studies also reported a higher spatial variability of the macropore network under NT as a result of undisturbed biological activity, while plowing operations were found to homogenize the structural pore network under CT.

Other studies analyzed management impacts on soil carbon pools and greenhouse gas (GHG) emissions. It was reported that NT cropping systems inhibit an increased content of organic carbon, while emissions of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are diminished (Six et al., 2004; Triplett and Dick, 2008; Yonemura et al., 2014). However, Arshad et al. (2004) noted that physical soil properties and GHG emissions may not always be improved under NT. Moreover, Nakajima and Lal (2014) stressed the need for more comprehensive studies on management impacts on GHG emissions and physical soil properties that control these emissions.

Since now, the emission of GHG from soils has been mainly studied from a soil-ecological or microbiological perspective. It is well known that carbon transformation and respiration are strongly influenced by nutrient availability, soil type, soil water content, and soil temperature (Heimann and Reichstein, 2008; Kreba et al., 2013; Raich and Tufekcioglu, 2000). Scott-Denton et al. (2003) studied seasonal changes in soil respiration rates and their variances to identify possible covariates (soil temperature, soil water content, soil C) for upscaling respiration measurements. The authors concluded that variation in temperature was the primary temporal control within a season, while soil water content was the primary temporal control interannually. On the other hand, good soil aeration conditions are also essential to alleviating pore-space-related constraints and to moderate GHG emissions (Allaire et al., 2008; Pingintha et al., 2010). Plant roots and soil biota require sufficient amounts of oxygen (O_2) for respiration, while soil-born CO_2 needs to be transported from the place of production to the atmosphere. Mordhorst et al. (2014) analyzed respiration rates for differently textured soils after application of different mechanical loadings. The study revealed that soil compaction significantly reduced CO_2 efflux by reducing the functionality of the pore system. The authors also stressed the need to conduct studies that analyze physical impacts on CO_2 fluxes in structured soils.

The movement of gases in the vadose zone is mainly driven by gaseous diffusion (Jin and Jury, 1996). As described by the law of Fick, gas diffusion in soil is controlled by the concentration gradient and the soil diffusion coefficient D_s that basically depends on the size and continuity of the air-filled pore network (Moldrup et al., 2013; Rolston and Moldrup, 2002). Ball et al. (1997) noted that gas diffusion depends on the continuity of the pore network more directly than any other soil physical property. Thus, it has been suggested as a fingerprint for soil structure quality (Moldrup et al., 2013). As favorable diffusivity conditions are essential for the gas exchange within the soil–atmosphere continuum, threshold values for critically low aeration conditions have been proposed (Schjønning et al., 2003).

Despite its relevance, only a few studies exist that analyzed management effects on soil gas diffusivity. Schjønning and Rasmussen (2000) studied soil pore characteristics as reflected by gas diffusivity for NT and CT systems. Nakajima and Lal (2014) studied the effects of tillage and drainage on the water retention and gas diffusivity of a silt loam soil. The authors reported higher diffusivities under NT compared to CT. However, both studies did not account for spatio-temporal variations and its linkage to soil respiration. Thus, there is a lack of comprehensive studies that analyze impacts of soil management on the hydraulic properties, gas diffusivity, and soil respiration with respect to its spatial and temporal variation.

As stated before, a major challenge in the proper description of physical soil properties is the considerable variability across spatial and temporal scales. Moreover, variations of highly-nonlinear relationships such as the hydraulic conductivity or gas diffusivity functions require methods that provide representative mean sets of parameters while preserving the information about the spatial or temporal variation. To facilitate the analysis of spatial soil hydraulic property variations, the scaling approach of Miller and Miller (1956) has been widely applied in soil hydrological studies (Vereecken et al., 2007). This technique enables the description of spatial variations by a set of scale factors, while relating the soil water retention and hydraulic conductivity data at each location to a representative mean. By this, the obtained scaling factors preserve the spatial variability of the individual measurements and can be used as a measure for the spatial or temporal variability of the analyzed observation series. Several methods have been developed to derive scaling factors and the corresponding representative mean parameters (Tillotson and Nielsen, 1984; Vereecken et al., 2007). For instance, Schwen et al. (2014) used the scaling method to analyze vertical variations of hydraulic properties within two soil profiles. Recently, scaling rules were also derived to describe spatial variations of heavy metal sorption isotherms in soils (Xiao et al., 2015). However, spatial or temporal variations of gas diffusivity have not been subject to scaling yet. This is likely due to a lack of sufficient measurement data and scaling rules.

Our main hypothesis for this study was that CT and NT management result in different spatial and temporal patterns of hydraulic properties and gas diffusivities. We hypothesized that NT management could result in a denser soil matrix hampering soil respiration rates under unfavorable moisture conditions by a limited gas diffusivity. To test this hypothesis, the objectives of this study were (i) to reveal spatial variations of hydraulic properties and gas diffusivities along a transect across an agricultural field under CT and NT management, (ii) to deduce and apply scaling rules for soil gas diffusivities to evaluate spatial relations, and (iii) to reveal spatio-temporal variations and correlations of gas diffusivity, soil respiration, soil water content, and soil temperature within a cropping season under CT and NT management. By this, the study aimed to comprehensively assess the influence of soil management and gas diffusivity on the CO_2 efflux.

2. Theory: scaling of soil gas diffusivities

Diffusive flux of gas in free air F depends on the gas concentration gradient and the specific diffusion coefficient $D_{0,\text{air}}$ ($L^2\,T^{-1}$) as described by Fick's first law:

$$F = -D_{0,air} \cdot \frac{dC_G}{dz} \tag{1}$$

where C_G ($L^3\,L^{-3}$) is the concentration of the gas and z (L) denotes a distance. In soils, gas transport is reduced by the pore geometry as well as liquid and solid barriers, and is described by the apparent diffusion coefficient D_s ($L^2\,T^{-1}$) (Jin and Jury, 1996). D_s is often normalized by D_0 and termed the relative apparent diffusion coefficient D_s/D_0 (−), or simply gas diffusivity. Assuming simple porous media with pores of uniform radius, D_s/D_0 is related to air-filled porosity ε by (Currie, 1960):

$$\frac{D_s}{D_0} = \left(\frac{l}{l_P}\right)^2 \varepsilon \tag{2}$$

where l and l_P are the apparent length (L) (e.g., length of a soil column) and real length of a tortuous pore (L). Despite of other definitions (Caron and Nkongolo, 2004) we define true pore continuity κ (−) as:

$$\kappa = \frac{l}{l_P} \tag{3}$$

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