Influence of mechanical loading on static and dynamic CO_2 efflux on differently textured and managed Luvisols

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ABSTRACT

Mechanical disturbance of soil structure is commonly related to altered physical changes in pore systems, which control CO_2 effluxes e.g. by changes in gas transport properties and in microbial activity. Soil compaction mostly leads to reduced CO_2 fluxes. In contrast, structured soils can also release physically entrapped CO_2 or give access to protected carbon sources inside aggregates due to aggregate breakdown by disruptive forces. In this study it was investigated how far arable soil management affects structure- and compaction-related CO_2-releases using incubation experiments and CO_2 gas analysis under standard matric potentials (-6 kPa). CO_2 efflux was analyzed before, during and after mechanical loading using the alkali trap method (static efflux) and a gas flow compaction device (GaFloCoD, dynamic efflux). Intact soil cores (236 and 471 cm^3) were collected from a Stagnic Luvisol with loamy sand (conservation and conventional tillage systems) and a Haplic Luvisol with clayey silt (under different fodder crops) from the topsoil (10–15 cm) and subsoil (35–45 cm). Mechanical stability was reflected by the pre-compression stress value (P_c) and by the tensile strength of aggregates (12–20 mm). Changes in pore systems were described by air conductivity as well as air capacity and total porosity. While CO_2-releases varied highly during the compaction process (GaFloCoD) for different stress magnitudes, soil depths and management systems, basal respiration rates were generally reduced after mechanical loading by almost half of the initial rates irrespective of soil management. For both methods (dynamic and static efflux) restriction in gas transport functionality was proved to have major influence on inhibition of CO_2 efflux due to mechanical loading. GaFloCoD experiments demonstrated that decreases in CO_2 efflux were linked to structural degradation of pore systems by exceeding internal soil strength (P_c). Otherwise, re-equilibrating matric potentials to -6 kPa and re-incubating offset inhibition of soil respiration suggest a re-enhancement of microbial activity. At this state, physical influences were apparently overlapped by biological effects due to higher energy supply to microbes, which could be offered by spatial distribution changes of microorganisms and organic substrates within a given soil structure. This implies the susceptibility of physical protection mechanism for carbon by disruption of soil structure. In future, special focus should be given on a clear distinction between physical and microbiological effects controlling CO_2 fluxes in structured soils.

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1. Introduction

Carbon sequestration of agricultural soils is strongly affected by management practices and often linked to mechanical disturbing effects. Field traffic and tillage practices permanently modify physical (Ball and Robertson, 1994; Frey et al., 2009; Weisskopf et al., 2010) and biological (Frey et al., 2009; Kladivko, 2001; Santrucková et al., 1993; Whalley et al., 1995) soil properties with consequences on CO_2 effluxes (Morell et al., 2010; Rovira and Greacen, 1957; Watts et al., 1999). Mostly increases in CO_2 effluxes after tillage operations were explained by enlargement of soil surface area and porosity (Reicosky,

1997) which enhanced oxygen supply to microbial decomposers, and by breakdown of aggregates making previously occluded organic substrates available for decomposition (Denef et al., 2001; Rovira and Greacen, 1957; Six et al., 1998). Partly opposite processes occurred in compacted soils, where physical changes in pore system commonly led to less favorable conditions for microorganisms. This was mainly attributed to restriction of gas/water fluxes and lower aeration status due to reduced porosity (Beylich et al., 2010; Jensen et al., 1996; Otten et al., 2000; Torbert and Wood, 1992; Whalley et al., 1995), refinement of pores and disconnection of transport path ways by soil compaction (Doran and Linn, 1984; Pengthamkeerati et al., 2011). Hence, it was suggested that microbial processes take place under more anaerobic conditions in compacted soils (Torbert and Wood, 1992; Whalley et al., 1995) documented by lower oxygen diffusion rate (Czyz, 2004; Jensen et al., 1996; Schjønning et al., 1999). Since aeration status depends on the actual water status of the soil, Doran and Linn (1984)

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demonstrated direct relations between physical parameters expressed by critical water filled pore spaces and microbial activity for disturbed soils (sieved to <2 mm).

With respect to spatial redistribution of energy sources, microorganism and soil water the heterogeneity of habitable pore space and its variation in space and time became crucial in understanding microbial CO_2 production in structured soils (Pierret et al., 2007; Young and Ritz, 2000). Therefore, high variability of microbial activity was observed for structured soils, particularly with the presence of interaggregate-pores (Schjønning et al., 1999) and even strongly pronounced for the subsoil (Salomé et al., 2010). Image analyzes demonstrated how heterogeneous in size, abundance and connectivity pore structure became under specific soil management which was linked to differences in carbon turnover for intra-aggregate pores (Ananyeva et al., 2013). Special focus was given to biopore channels generated by plant roots or earthworms, acting as microbial hotspots and providing preferentially transport paths for microorganisms and soluble carbon (Bundt et al., 2001; Chabbi et al., 2009). Since convective transport mechanisms are strongly dependent on pore radius (Ball, 1981), high aeration promotes fast decomposition of organic material in the surroundings of biopores. Furthermore, their distance to other hot-spot zones of microbial activity also controls exchange processes by diffusion (Ball, 2013). While the latter is of high significance for gas transport processes as it is driven by CO_2 concentration changes by respiration (Gliński and Stępniewski, 1985) the actual loss of microbially produced gasses to the atmosphere is determined by the presence of a continuous pore such as biopores (Ball, 2013).

However, the loss of highly aerated macro-pores by mechanical disturbance strongly affects gas emissions (Blagodatsky and Smith, 2012), which is either explained by changes in microbial activity or by direct release of CO_2. The latter was previously stored in these voids (Maier et al., 2011) resulting in a short-time degassing effect (Rochette and Angers, 1999). Both depend on former carbon storage ability linked to management practices and vary highly for different soil texture and climate conditions (Brussaard and van Faassen, 1994; Morell et al., 2010; Rochette and Angers, 1999; Weisskopf et al., 2010). Conservation management practices such as reduced and zero-tillage supported physical protection of carbon in aggregates compared to conventional ploughing (Álvaro-Fuentes et al., 2007; Beare et al., 1994; Paustian et al., 2000; Six et al., 1998). However, mechanical impacts which exceed the internal soil strength offset the ability of physical protection inducing aggregate breakdown (Beare et al., 1994; Wiesmeier et al., 2012). Thus, the amount of released CO_2 from disrupted aggregates depends on the intensity of disturbance or cultivation history (Whalley et al., 1995). Only few direct methods for determining the relations between biological (CO_2) and mechanical processes are available. Compaction (Baumgartl et al., 2001; Horn et al., 2009; Jasinska et al., 2006; Otten et al., 2000; Watts et al., 1999) and shearing tests (Otten et al., 2000; Watts et al., 1999) confirmed close linkages between a load-dependent degradation of pore functionality, changes in microbial activity and hence CO_2 efflux. Nevertheless, compaction-induced effects on C-mineralization were realized to be highly variable impeding reliable predictions for microbial changes from physical parameters (Beylich et al., 2010; Otten et al., 2000; Santrucková et al., 1993; Shestak and Busse, 2005).

Using a mechanical–biological approach we aimed at studying the influence of mechanical loading on carbon effluxes in structured soils. To achieve this, we conducted mechanical loading tests in combination with static (basal respiration) and dynamic CO_2 efflux measurements (GaFloCoD) under controlled laboratory conditions. It was hypothesized that soils with different SOC levels as well structural and mechanical properties are differently susceptible against mechanical load applications. How far carbon dynamics are controlled by these structural and mechanical properties was tested for different management systems: (1) differentiated tillage systems represented by conservation tillage practices like shallow harrowing and no-tillage compared to conventional

tillage on a loamy sand and (2) different pre-crops with various root architecture and morphology on a clayey silt (2).

Although carbon turnover processes take place on a microscale level, intact soil cores (236 and 471 cm^3) were investigated to display the impact of pore network characteristics and their mechanical strength on CO_2 efflux. Young and Ritz (2000) pointed out the relevance of understanding carbon dynamics on larger scales referring to structural units as components of the whole soil matrix. In this way, interactive processes according to field conditions were considered which were otherwise neglected on most common carbon researches on small aggregate scales (Schjønning et al., 1999).

2. Material and methods

2.1. Soil sampling

Undisturbed soil cores (236 and 471 cm^3) were taken vertically from topsoil (10–15 cm) and subsoil layers (35–45 cm) of two experimental field sites under different soil management (Table 1).

- S1: Flakkebjerg (South-Denmark): Loamy sand plots were subjected to no-tillage (NT), conventional tillage (ploughing to 25 cm depth, CT) and reduced tillage to 8–10 cm depth (harrowed with disc cultivators; CONS) since 2002. Sampling was done in inter-traffic line zones. The soil type is a Stagnic Luvisol (FAO, 2006) derived from glacial till and the mean annual temperature (1961–1990) at Flakkebjerg is 7.7 °C with an annual rainfall of 558 mm (Olesen, 1993, cited in Hansen et al., 2010).
- S2: Klein-Altendorf (North-Western Germany): Clayey silt plots were cultivated with three perennial pre-crops, which differ markedly in root architecture and morphology. We analyzed the processes for allorhizous root systems of alfalfa (*Medicago sativa*, ALFA) and chicory (*Cichorium intybus*, CHIC) as well as for homorhizous root system of tall fescue (*Festuca arundinacea*, FESC). Plots were ploughed before seeding and sampling was done after 2 years of plant growth. The soil type is a Haplic Luvisol derived from loess (FAO, 2006), mean annual temperature is 9.6 °C and mean annual rainfall is 625 mm (Uteau et al., 2013).

2.2. Standard laboratory methods

For both sites and sampling depths basic soil characteristics (Table 1) were analyzed on disturbed, <2 mm sieved, air-dried soil material. Particle size distribution was determined by sieve and pipette technique according to Hartge and Horn (2009). Soil organic carbon concentration (SOC) was analyzed by determining total carbon concentration by dry combustion at 1200 °C (Coulomat 702, Fa Ströhlein instruments) reduced by the inorganic carbon concentration. pH values were determined in $CaCl_2$ solution and total Kjeldahl nitrogen was measured photometrically using a Flow-Injection Analyzer (Blume et al., 2010).

2.3. CO_2 efflux in a static flow system

a) CO_2-measurement: Intact soil cores (236 cm^3, diameter = 10 cm, height = 3 cm) were capillary-saturated and drained on a sandbox to field capacity (−6 kPa) for 7 days and subsequently incubated under controlled climatic conditions at 22 °C in a dark climate chamber for 14 days (INITIAL state). After 14 days a potential initial CO_2 flush occurring from incubation should already have passed and equilibrium conditions have been reached (Pell et al., 2006). During incubation each soil core was located in individual, approximately 800 cm^3 air tight respiration chambers. A moistened sponge was used as a water reservoir to avoid evaporation losses keeping the matric potential constant. The amount of CO_2 evolved from each soil core was determined using an alkali trap inside the respiration