CO_2 flush rates after soil crumbling as related to soil carbon pools and soil fragmentation characteristics

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Abstract

Sensible use of tillage requires knowledge about different aspects of soil crumbling. Decisions of best management practices must be based on complex considerations regarding e.g. effective tractor use, long-term soil health, etc. Research on soil carbon fluxes in tilled soils is an area of investigation which has received much attention recently, but ideally it should be approached in a combined bio-physical manner. We conducted studies on respiration from freshly fragmented clay soil in different aggregate size fractions with help of a multi-channel respirometer. The fragmented soil was characterized in terms of different soil carbon pools. The physical fragmentation itself was characterized in a manner that should be relevant to the three existing ways of relating use of a specific tool configuration to physical outcome of the operation, namely soil mechanical tillage experiments in situ, tests in soil bins and computational soil mechanics. Linear regressions showed that higher specific aggregate surface area, more free organic C per dry soil and more occluded C per dry soil led to higher soil respiration rates.

Key words: carbon mineralization, soil biomechanics, tillage

Introduction

Sensible use of tillage requires knowledge about different aspects of soil crumbling. Decisions of best management practices must be based on complex considerations regarding e.g. effective tractor use, long-term soil health, etc. Research on soil carbon fluxes in tilled soils is an area of investigation which has received much attention recently, but ideally it should be approached in a combined bio-physical manner. Investigations conducted within this research area should therefore include not only relevant characterization of different soil carbon pools but also characterization of used cultivation practices in terms of effects on soil fragmentation. Such an approach has been applied earlier in this type of investigations, but there are still knowledge gaps.

Previously conducted long-term investigations have often included relevant characterization of several aspects as outlined above. Physical effects of the used management practices on soil crumbling must in these cases be estimated retrospectively based on a generic understanding of different types of tillage. Chivenge et al. (2007) studied two soils, sandy and clay, which had been subjected to different tillage practices during 9 years and found significantly higher organic C content in all particle size fractions of the clay soil in the tied ridging treatment (reduced tillage) compared to the conventional tillage treatment (at the most, 147% higher in the fine sand fraction). They attributed this to reduced stabilization of C within micro-aggregates after disturbance. Such differences are interesting regarding soil carbon sequestration, but have not always been found. Murage et al. (2007) studied effects of conventional tillage and no-till in two cultivation regimes in a sandy soil field (12% clay and silt), namely a shift from C_3 plants to C_4 plants 11 years before soil sampling on one hand, and no shift on the other. They estimated amounts of C_4 carbon in the shifted regime by measuring ^{13}C abundance in the samples and comparing with the other regime. They divided the organic carbon in three different fractions – 'free light fraction' and 'occluded light fraction', which were separated by flotation in a 1.8 g/ml solution after centrifugation and after ultrasonic disruption, respectively, and the remaining mineral-associated 'heavy fraction'. They found no significant differences in amounts of C_4 carbon or total carbon between tillage treatments in either fraction of organic matter in the upper 20 cm of soil in the shifted regime.

Incubation studies have so far lacked either discrimination between different fractions of organic matter or physical characterization of the soil fragmentation or both. Chen et al. (2007) noted an increased decomposition of added maize residue and of native soil organic matter after intensive mixing of soil (19% clay) during an incubation study. They credited the increased CO_2 production to aeration and to destruction of aggregates. Chevallier et al. (2004) pressed soil clods through sieves and measured respiration in a 325 days incubation. After 21 days, the accumulated respiration from soil pressed through a 0.2 mm sieve was 1.6–2.3 times higher compared to intact clods, and the increase was significant for six out of six different treatments. After 325 days, the respiration was 0.9–1.6 times higher, with significant increase for three out of six treatments and significant decrease for one of six. Goebel et al. (2009) conducted respiration measurements on crushed and intact soil aggregates coming from seven different soils and found lower carbon mineralization rates in the intact aggregates for three soils and no differences between treatments for the other soils. Dexter et al. (2000) found that mean basal respiration rates from intact soil aggregates was linearly correlated with organic C content. They interpreted the intercept with the x-axis (respiration at zero) as a measure of the physically protected organic C, which do not contribute to the basal respiration. They compared this value with values from similar experiments and concluded that more clay content in soil gives more physically protected organic C. The aggregates they used came from the 0–24 cm layer of a field which in turn had been subjected to different treatments for 22 years. They found no significant differences in basal respiration from aggregates coming from the conventional tillage treatment compared to from the ploughless tillage treatment. They also measured the effect of energy input on respiration from aggregates by using a falling-weight apparatus, and they found that 90 J kg-1 input to soil (equivalent to cultivation by a mouldboard plough) had no significant effect on basal respiration, but that 450 J kg^{-1} input increased the basal respiration significantly.

There are three different ways to relate use of a specific tool configuration to physical outcome of the operation, namely in situ experiments (Hadas and Wolf 1983), tests in soil bins (Wang and Gee-Clough 1993) and computer-aided soil mechanics (Asaf et al. 2007). Characterizations of physical soil fragmentation should be relevant to all these types of tests. A promising approach was used by Perfect et al. (1993), who measured tensile strength distributions within aggregate size classes. However, they dried the aggregates after collecting, and they were not collected from a specific volumetric part of the tilled soil.

We conducted studies on respiration from freshly fragmented clay soil in different aggregate size fractions with help of a multi-channel respirometer (Nordgren 1988). The fragmented soil was characterized in terms of different soil carbon pools. The physical fragmentation itself was characterized in a manner that should be relevant to soil mechanical tillage experiments in situ, tests in soil bins as well as computational soil mechanics.

Materials and methods

Respiration measurements

Clay soil was collected in undisturbed cylinders from an arable field nearby the Ultuna long-term field experiment (Kirchmann et al. 1994; Mårtensson and Carlgren 1994), outside Uppsala, Sweden. Both topsoil samples (10 cm below surface, %C=2.135, %N=0.228) and subsoil samples (40 cm below surface, %C=0.6953, %N=0,0966) were used. Before tillage simulation, they were adjusted to the same water potential (1 m) using sand-beds and hanging columns. As a systematic means of laboratory soil crumbling, the soil was pressed out of some of the cylinders and then pressed through sieves (2, 4, 8, 16 mm) in order to get aggregates in various sizes. A dry sieving apparatus (2, 4, 8 mm) was used for sorting into size fractions and for providing energy (10 min.). The crumbled soil was put immediately in cans with lids, so the moisture content would not decrease. Respiration from different size fractions was then measured during 490 hours at 20°C with the method described by Nordgren (1988), including some undisturbed samples in cylinders. After the incubation, the water contents in the samples were measured by drying. Finally, organic C fractions were determined with a LECO CN-2000 analyzer.

For sake of simplicity, the free organic matter was separated from the dried soil by flotation in water, after which the rewetted but still intact aggregates were analyzed for occluded C content. The drying itself was also a departure from the standard procedure. Among others, Dubeux Jr. et al. (2006) used decantation with water to separate organic matter from soil, instead of following the strict procedure of, e.g., Murage et al. (2007), who separated the free light fraction in 1.8 mg NaI solution. Similarly, Chivenge et al.

(2007) measured total organic matter in courser particle size fractions via floatation in water after dispersion of the soil.

Some reference samples were used for determination of gravimetric water content after water potential adjustment, and some were used for C measurements directly after collection. The undisturbed samples used in the incubation were similarly analyzed for total C.

Cumulative CO_2 emissions after management simulation were analyzed for statistical differences between treatments. Based on the factorial design a multiple regression was made with initial or cumulative respiration per dry soil as dependent variable and free organic matter per dry soil, occluded C per dry soil, specific aggregate surface area and water content as factors.

Soil carbon model

We used a two-compartment model for the labile soil carbon:

$$resp.rate = A_0 k_1 e^{-k_1 t} + B_0 k_2 e^{-k_2 t}$$

which was fitted to the CO_2 production curves from the respirometer (mg CO_2-C h^{-1}) in a log-lin graph (negative values ignored). In this model, $C_0 = A_0 + B_0$ is the labile soil carbon fraction at t_0, and the total carbon C_{tot} equals $C_{inert} + C_0$ at t_0.

Fragmentation characterization

As characterization of the tillage simulation, aggregate size distributions were calculated. Aggregate volumes were estimated from size fractions assuming spherical aggregates:

$$\cancel{V}_i = \frac{\pi}{6}\left(\frac{\phi_i + \phi_{i+1}}{2}\right)^3,$$

where $\cancel{V}_i$ is mean aggregate volume in size fraction i between the sieves with openings ϕ_i and ϕ_{i+1}. These volumes are also relevant in a computational soil mechanics context, since average soil tensile strength can be defined like this:

$$\int_V \int_V \frac{1}{V^2} f(\boldsymbol{x}, \boldsymbol{y}) d\boldsymbol{x} d\boldsymbol{y},$$

where $\boldsymbol{x}, \boldsymbol{y} \in R^3$, volume V is the soil volume under consideration and $f(\boldsymbol{x}, \boldsymbol{y})$ measures tensile strength between two points in the soil (Pa). For a non-sticky soil, the aggregate size distribution within a certain soil volume and also the distribution of aggregate tensile strengths within these size classes can be measured and then the average soil tensile strength can be calculated. Some methods for determination of tensile strength of soil aggregates (not single mineral grains) were described by Dexter and Kroesberger (1985).

If V_1, …, V_n are the volumes of the individual aggregates, which in turn have the individual tensile strengths σ_1, …, σ_n, respectively, then it is reasonable to calculate average soil tensile strength according to:

$$\int_V \int_V \frac{1}{V^2} f(\boldsymbol{x},\boldsymbol{y}) d\boldsymbol{x} d\boldsymbol{y} = \frac{\sum_{z=1}^{n} \left(\sigma_z \cdot V_z^{\,2} \right)}{V^2},$$

where V is the soil volume under consideration. This formula follows from the very definition of integrals, under the assumption that the aggregates a_1, …, a_n are volumetric sub-sets of V and that $f(\boldsymbol{x},\boldsymbol{y})=\sigma_z$ if $\boldsymbol{x},\boldsymbol{y} \in a_z$, and otherwise $f(\boldsymbol{x},\boldsymbol{y})=0$. Given this assumption, function $f(\boldsymbol{x},\boldsymbol{y})$ becomes a step function, and integrals are classically defined in terms of step functions, summation and limits. With the soil mechanical model of Asaf et al. (2007) it is possible to calculate the average tensile strength after computer simulation.

For the purpose of our study, we instead used a dummy variable such that $f(\boldsymbol{x},\boldsymbol{y})=1$ if $\boldsymbol{x},\boldsymbol{y} \in a_z$, and otherwise $f(\boldsymbol{x},\boldsymbol{y})=0$, and thus let the double integral express the soil fragmentation in a single unit-less value between 0 and 1. The soil volume under consideration V was approximated with the soil volume before fragmentation.

Results

The soil fragmentation was calculated to 0.000243 and 0.000218 for subsoil and topsoil, respectively. Main results for both layers are shown in Tables 1-2.

Table 1. Subsoil mass, carbon content and emission. Sample standard deviation is stated ±*s*

Fraction	Total mass (g dry soil)	Free org C (mg C g^{-1} dry soil)	Occl org C (mg C g^{-1} dry soil)	Acc resp (mg C g^{-1} dry soil)	R^2	Initial resp (mg C g^{-1} dry soil hour $^{-1}$)	$A_0 + B_0$ (mg C g^{-1} dry soil)	Half-time(t_0) of hourly resp (hours)
0-2	253	0,0516	6,499	0,0371 ±0,0034 a	0,97	0,000565	0,0481	25,1
2-4	477	0,0060	6,4615	0,0336 ±0,0061 ab	0,92	0,000427	0,0540	27,5
4-8	287	0,00017	6,701	0,0276 ±0,0005 bc	0,92	0,000469	0,0358	19,3
8-16	290	0,00000	6,539	0,0243 ±0,0024 c	0,96	0,000401	0,0325	22,1
Undist.	343			0,0247 ±0,0039 c	0,94	0,000182	0,0361	54,3

Table 2. Topsoil mass, carbon content and emission. Sample standard deviation is stated ±*s*

Fraction	Total mass (g dry soil)	Free org C (mg C g^{-1} dry soil)	Occl org C (mg C g^{-1} dry soil)	Acc resp (mg C g^{-1} dry soil)	R^2	Initial resp (mg C g^{-1} dry soil hour $^{-1}$)	$A_0 + B_0$ (mg C g^{-1} dry soil)	Half-time(t_0) of hourly resp (hours)
0-2	247	0,545	20,06	0,0844 ±0,0025 a	0,97	0,000796	0,140	34,1
2-4	436	0,150	19,69	0,0635 ±0,0053 b	0,97	0,000574	0,113	34,3
4-8	358	0,0089	20,305	0,0513 ±0,0022 c	0,95	0,000426	0,110	32,2
8-16	249	0,0072	19,51	0,0502 ±0,0068 c	0,93	0,000338	0,115	46,0
Undist.	344			0,0481 ±0,0069 c	0,89	0,000191	0,173	199,6

The total C for the undisturbed samples was 6.778 and 21.16 mg C g^{-1} dry soil for subsoil and topsoil, respectively. There were some small mass losses during the crumbling (compare 4·undist.). It can be seen that $C_0 = A_0+B_0$ are fairly similar for both topsoil and subsoil respectively, and that soil crumbling reduced the initial halftimes of the hourly respiration (Tables 1 and 2).

A linear regression analysis was made with accumulated respiration (*F5*) (mg C g^{-1} dry soil) as dependent variable and specific aggregate surface area (*F1*) (mm^{-1}), free organic C per dry soil (*F2*) (mg C g^{-1} dry soil), occluded C per dry soil (*F3*) (mg C g^{-1} dry soil), and gravimetric water content (*F4*) (g/g) as factors (Table 3). The resulting equation was:

$$F5 = 0.085 + 0.00084F1 + 0.051F2 + 0.0017F3 - 0.26F4$$

Table 3. Detected influence of aggregate area (F1), carbon pools (F2-F3) and water (F4) on accumulated respiration. Level of significance is $P<0.05$. R^2=95.4%. R^2(adj)=94.8%

Statistic	Constant	F1	F2	F3	F4
P-value	0.284	0.417	0.000	0.000	0.372

Another linear regression analysis was made with initial respiration rate (*F6*) (mg C g^{-1} dry soil $hour^{-1}$) as dependent variable and specific aggregate surface area (*F1*) (mm^{-1}), free organic C per dry soil (*F2*) (mg C g^{-1} dry soil), occluded C per dry soil (*F3*) (mg C g^{-1} dry soil), and gravimetric water content (*F4*) (g/g) as factors (Table 4). The initial respiration rate was calculated as $A_0k_1+B_0k_2$ and the resulting equation was:

$$F6 = -0.0014 + 0.000047F1 + 0.00032F2 + 0.0000028F3 + 0.0066F4$$

Table 4. Detected influence of aggregate area (F1), carbon pools (F2-F3) and water (F4) on initial respiration. Level of significance is $P<0.05$. R^2=82.4%. R^2(adj)=79.7%

Statistic	Constant	F1	F2	F3	F4
P-value	0.257	0.006	0.053	0.321	0.155

Discussion

The aim to approach research on soil carbon fluxes in tilled soils in a bio-physical manner led us, on the one hand, to characterize the soil fragmentation physically, and on the other hand, to characterize different soil carbon pools. When a selection of these properties subsequently were used as factors in linear regressions on the results from the incubation, the regressions showed that higher specific aggregate surface area, more free organic C per dry soil and more occluded C per dry soil led to higher soil respiration rates. Apart from the obvious difference in respiration rates between topsoil and subsoil, it is possible that the soil organic matter that allegedly becomes exposed to microorganisms after soil disturbance (Chen et al. 2007; La Scala Jr. et al. 2008) is composed partly of free organic matter not attached to soil aggregates and partly of micro-organic matter that is situated on fresh aggregate surfaces.

Regarding the model adaptions, La Scala Jr. et al. (2008) made a similar analysis, although on 25 days of field data from tilled and no-till plots. They used a one-compartment model for the labile soil carbon and found that tillage increased the decay constant, expressing the change with parameter values and associating different parameter values with different types of tillage (stating also the tillage depths). They attributed the increased turnover rates to improved oxygen, temperature and moisture for decomposition via increased total porosity. By analogy, if we would have used a one-compartment model with decay constant k for crude curve fitting in our study, the general halftime of the hourly respiration had been the same as the initial halftime. Furthermore, the halftime of the labile C pool had been the same as the halftime of the hourly respiration, and a reduced halftime of this C pool (after soil crumbling) implies an increased decay constant.

Measuring free organic matter the way we did is easier compared to measuring the free light fraction according to the strict procedure, which if nothing else has a pedagogic value. Regarding the two modes of explanation recognized above, it is also likely that the free light fraction would be associated with increased turnover rates after tillage rather than changed carbon pool sizes. In our study, this role is played by the labile pool $C_0 = A_0+B_0$, calculated through the model adaptions.

Translation of modeling results from incubation to field situations or from short-term to long-term situations should not be made carelessly (Lomander et al. 1998). On the other hand, the same mode of physical characterization of soil crumbling used here could without reservation also be used in field studies. Many studies have been published, in which recalculations were made from aggregate size distribution after tillage to some kind of fractal measure (see e.g. Perfect et al. 1993; Eghball et al. 1993; Filgueira et al. 1999). However, fractals might not be the best alternative as basis for soil engineering generally, or as part of a soil biomechanical approach suited for research on effects of tillage.

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