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Effects of soil compaction, rain exposure and their interaction on soil carbon dioxide emission

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ABSTRACT: Soils release more carbon, primarily as carbon dioxide (CO_2), per annum than current global anthropogenic emissions. Soils emit CO_2 through mineralization and decomposition of organic matter and respiration of roots and soil organisms. Given this, the evaluation of the effects of abiotic factors on microbial activity is of major importance when considering the mitigation of greenhouse gases emissions. Previous studies demonstrate that soil CO_2 emission is significantly affected by temperature and soil water content. A limited number of studies have illustrated the importance of bulk density and soil surface characteristics as a result of exposure to rain on CO_2 emission, however, none examine their relative importance. Therefore, this study investigated the effects of soil compaction and exposure of the soil surface to rainfall and their interaction on CO_2 release. We conducted a factorial laboratory experiment with three soil types after sieving (clay, silt and sand soil), three different bulk densities ($1{\cdot}1$ g cm^{-3}, $1{\cdot}3$ g cm^{-3}, $1{\cdot}5$ g cm^{-3}) and three different exposures to rainfall (no rain, 30 minutes and 90 minutes of rainfall). The results demonstrated CO_2 release varied significantly with bulk density, exposure to rain and time. The relationship between rain exposure and CO_2 is positive: CO_2 emission was 53% and 42% greater for the 90 minutes and 30 minutes rainfall exposure, respectively, compared to those not exposed to rain. Bulk density exhibited a negative relationship with CO_2 emission: soil compacted to a bulk density of $1{\cdot}1$ g cm^{-3} emitted 32% more CO_2 than soil compacted to $1{\cdot}5$ g cm^{-3}. Furthermore we found that the magnitude of CO_2 effluxes depended on the interaction of these two abiotic factors. Given these results, understanding the influence of soil compaction and raindrop impact on CO_2 emission could lead to modified soil management practices which promote carbon sequestration. Copyright © 2012 John Wiley & Sons, Ltd.

KEYWORDS: soil carbon dioxide flux; rain exposure; soil compaction

Introduction

The total global emission of carbon dioxide (CO_2) from soils is 68–75 Pg CO_2-C yr^{-1} (Mosier, 1998). This is one of the largest fluxes in the global carbon (C) cycle and small changes in the magnitude of soil CO_2 flux can have a major influence on atmospheric CO_2 levels (Schlesinger and Andrews, 2000). Soils, with microbial catabolism, release more C per annum than current global anthropogenic emissions (Luo and Zhou, 2006) and therefore could play a key role in mitigating greenhouse gas (GHG) emissions. Soils emit CO_2 through mineralization and decomposition of organic matter and respiration of roots and soil organisms (Houghton, 2007), but can act as C sinks as they are able to accumulate C. Knowledge of the factors which influence the emission of soil CO_2 is therefore key to understanding the terrestrial C cycle and promoting soil C sequestration.

Many factors influence CO_2 fluxes between the soil and the atmosphere. We divide these into two broad groups: processes which influence the production of CO_2 by influencing soil microbial ecology; and those which influence the physical movement of CO_2 between the soil and atmosphere. Much research has focused on how microbial ecology influences CO_2 efflux (Cavigelli *et al.*, 2005; Nadezhda *et al.*, 2008). However, there has been less research into the role of soil physical properties. Most work in this area has focused on how environmental variables such as, air temperature, photosynthetically active radiation (PAR) and air humidity, interact with the soil physical factors (Smith *et al.*, 2003) and affect ecosystem CO_2 exchange (Lloyd and Taylor, 1994; Davidson *et al.*, 1998; Smith *et al.*, 2003; Liu *et al.*, 2006; Morell *et al.*, 2010). Much of the temporal variation in soil CO_2 efflux can be interpreted by a combination of soil temperature and moisture content (Xu and Qi, 2001). The release of CO_2 from soil organic matter generally increases exponentially with temperature (Anderson, 1973; Edwards, 1975; Ewel *et al.*, 1987; Fang *et al.*, 1998; Longdoz *et al.*, 2000), high soil water contents have been shown to impede the diffusion of CO_2 in soil and thus reduce CO_2 emission (Linn and Doran, 1984; Doran *et al.*, 1990; Skopp *et al.*, 1990) but conversely, a low soil water content can inhibit soil microbial activity and consequently root respiration (Davidson *et al.*, 1998; Xu and Qi, 2001; Curiel *et al.*, 2003).

Soil compaction is widespread in agricultural systems as a result of the use of machinery (Lee *et al.*, 1996; Schäffer *et al.*, 2007; Ampoorter *et al.*, 2010) and the presence of animals (Martínez and Zinck, 2004; Hamza and Anderson, 2005). Soil compaction increases soil bulk density, compressing larger pores to smaller pores, thus decreases soil porosity and the infiltration capacity (Huang *et al.*, 1996). Increased soil bulk density has been shown to affect soil ecology by decreasing the numbers of soil bacteria, fungi and actinomycetes by 26–39% (Li *et al.*, 2002) and reducing the microbial activity, as indicated by changes in soil CO_2 flux (Liebig *et al.*, 1995; Jensen *et al.*, 1996; Pengthamkeerati *et al.*, 2005). However, Shestak and Busse (2005) attributed reduced CO_2 flux in compacted soil to reduced gas diffusivity rather than to any direct influence on the function of the soil microbial community.

Soil compaction is also associated with increased risk of erosion and some studies have linked an increase in CO_2 following rewetting to mineralization of freshly exposed organic matter, and the subsequent mineralization of microbial C (Mikha *et al.*, 2005). Furthermore, the physical breakdown of soil aggregates, which occurs due to compaction and exposure to rainfall has been associated with increased CO_2 (Beare *et al.*, 1994; Denef *et al.*, 2001).

To date there have been no studies which examine the influence of soil bulk density and rain exposure and their interaction on soil CO_2 flux. To fill this gap we undertook laboratory core experiments to investigate the effects of soil compaction and rain exposure on CO_2 flux at constant and variable soil moisture. We hypothesize that soils with different bulk densities and rainfall exposures emit different quantities of CO_2 due to impacts on microbial activity, CO_2 diffusivity, and availability of fresh C due to aggregate breakdown.

Materials and Methods

Controlled laboratory experiments were undertaken using a factorial design with three contrasting soil types which had been under continuous arable cultivation, three bulk densities and three different rain exposures, each was replicated five times resulting in 135 soil cores in total. The three soils used were: a clay (59% clay, 24% silt, 17% sand), a silt (17% clay, 73% silt, 10% sand), and a sand (3% clay, 32% silt, 65% sand) with the same organic matter content (19 g kg^{-1}). The soil was sieved to 5 mm and compacted in 5 mm layers into a 64·5 mm diameter, 60 mm tall plastic pipe with geotextile fixed across the base. Each of the three soils were compacted to 1·1 g cm^{-3}, 1·3 g cm^{-3}, or 1·5 g cm^{-3}, which are bulk densities representative of agricultural soils. Our rain exposures were no rain and 30 minutes or 90 minutes rain under a gravity fed rainfall simulator at 52 mm h^{-1}. The higher than field rainfall intensity was selected as it is difficult to generate reproducible rainfall rates at lower intensities and given the drops will not have reached fall velocity increases in the rainfall rate produces kinetic energies closer to that of natural rain. To minimize differences in moisture content at the beginning of the incubation the difference in water volume between the 90 minute and 30 minute and no exposure rainfall treatments was carefully added to the surface of the no exposure and 30 minute exposure experiments using a syringe. All soil cores were stored in open toped Kilner jars at 22 ± 1 °C for the duration of the incubation.

Soil CO_2 efflux and water content were measured one, two, five, six, nine, and 10 days after the start of the incubation. To collect gas samples a lid with a rubber gas sampling septa was fitted to each of the Kilner jars and 5 ml of gas was extracted using a hypodermic needle immediately after closure, 60 minutes after closure and 120 minutes after closure. The samples were analysed using an infrared gas analyser calibrated with 1% standard CO_2 (IRGA model ADC.225. Mk3, manufacturer Asea Brown Boveri). The rate of CO_2 emission was determined from the three samples and the volume of CO_2 produced from the cores was converted to μg g^{-1} soil min^{-1} using the universal gas law as used by Jassal *et al.* (2004) and Certini *et al.* (2003). Soil moisture was measured gravimetrically.

A second experiment was conducted to study the effect of rain exposure and soil compaction on CO_2 emission under constant soil water content, a known influence on CO_2 emission. We used a Columbus Instruments Micro-Oxymax respirometer, which was set up to maintain temperature at 22 ± 1 °C, to maintain soil moisture and measure CO_2 emissions every 80 minutes. For this experiment we compacted the silt loam soil, in 5 mm layers, into a 22 mm diameter, 90 mm tall plastic pipe to the same bulk densities as the other experiment (1·1 g cm^{-3}, 1·3 g cm^{-3}, 1·5 g cm^{-3}). The cores were either not exposed to rainfall or exposed for 90 minutes. The respirometer was not used for all experiments given the small cores and concerns regarding boundary effects.

Data analysis was conducted using SAS statistical package (SAS Institute, 2001). The data were checked for normality and multivariate analysis of variance (MANOVA) was conducted to test the effects of bulk density, exposure to rainfall and their interactions on CO_2 emission.

Results and Discussion

Incubation at constant temperature with variable water content

Soil water content

Soil water content decreased continuously during the incubation period and was statistically affected by rain exposure ($p < 0{\cdot}001$). The highest decrease in soil water content was in soil not exposed to rainfall, followed by soil exposed for 30 minutes and for 90 minutes. In the clay soil, after 10 days of incubation, the water content decreased by 5·8 ± 1·1%, 6·4 ± 1·2%, 7·9 ± 1·7% for soil exposed to rainfall for 90 minutes, 30 minutes and not exposed, respectively. In the silt soil, the water content reduction was 7·6 ± 0·5%, 7·7 ± 1·2% and 8·4 ± 1·0% for soil exposed to rainfall simulator for 90 minutes, 30 minutes and not exposed, respectively. Smaller differences between rainfall exposure treatments were found in sand soil with values of 6·3 ± 2·0%, 6·5 1·2% and 6·7 ± 0·8% for 90 minutes, 30 minutes and not exposed, respectively. The effect of rainfall exposure on water content is the result of evaporation reduction due to aggregate breakdown and soil seal formation. No statistically significant difference was found between the soil water content of the three soil compaction treatments.

Soil CO_2 emission

Soil CO_2 emission was significantly affected by soil texture, rain exposure and soil bulk density (Table I). The clay soil had a significantly ($p < 0{\cdot}001$) higher average CO_2 emission rate than the other soils: the average CO_2 emission rates were 0·063 0·044 μg CO_2 g^{-1} min^{-1}, 0·017 ± 0·010 μg CO_2 g^{-1} min^{-1} and 0·010 ± 0·004 μg CO_2 g^{-1} min^{-1}, respectively, for the clay, silt and sand soils. Cumulative CO_2 emission over nine days from

Table I. Results of analysis of variance (ANOVA) test for soil carbon dioxide (CO_2) emission rate during incubation at constant temperature

Source of variation	*F*	Prob > *F*
Soil	876·09	<0·0001
Bulk density	16·31	<0·0001
Rain	119·48	<0·0001
Replicates	0·85	0·4947
Soil*bulk density	9·00	<0·0001
Soil*rain	45·99	<0·0001
Soil*rain*bulk density	8·61	<0·0001

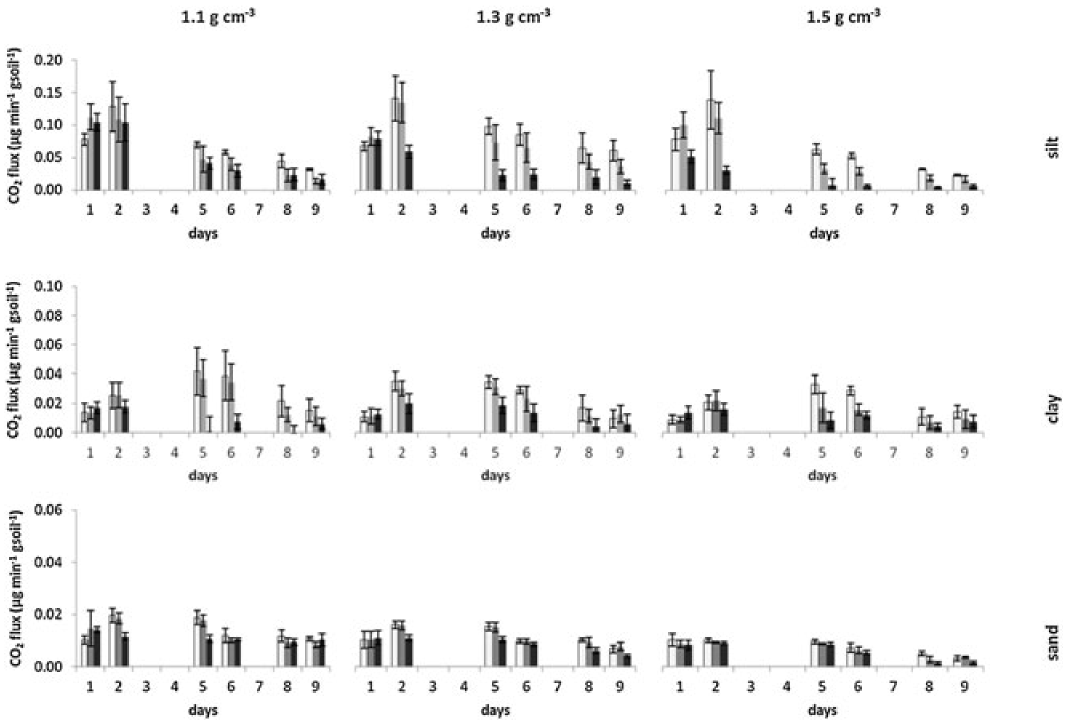

Figure 1. Soil carbon dioxide (CO_2) emission (in µg CO_2 g^{-1} min^{-1}) during incubation at constant temperature. White, grey and black histograms indicate soil exposed to rainfall for 90, 30 and 0 minutes, respectively.

the clay soil was six times greater than for the silt soil and three times greater than for the sand soil. These results concur with Rastogi *et al.* (2002) who observed that CO_2 evolution from fine-textured soil could be approximately twice as high as that from coarse textured soil. This occurs because fine textured soils have higher water holding capacities, which prolong the availability of water in surface layers, thus maintain favourable condition for microbial soil respiration (Feiziene *et al.*, 2010).

Average soil CO_2 efflux significantly decreased ($p < 0{\cdot}001$) with increased soil bulk density. On average soil CO_2 emission rate decreased by 27% and 37% as soil bulk density increased from 1·1 g cm^{-3} to 1·3 g cm^{-3} and 1·5 g cm^{-3}, respectively. Similar observations were also reported by Liebig *et al.* (1995) and Pengthamkeerati *et al.* (2005) who found a significant negative correlation of soil bulk density with soil CO_2 efflux. This occurs as increases in soil bulk density reduce gas diffusivity (Smith *et al.*, 2000) which is linked with oxidation rate (Ball *et al.*, 1997), and consequently rates of soil respiration and CO_2 emission (Van der Linden *et al.*, 1989; Yoo and Wander, 2006). However, examination of the CO_2 emission rate during the nine day incubation period for each soil type shows that emissions decreased with soil compaction for all soils except for the clay soil (Figure 1). In the clay soil the highest average of CO_2 emission rate was from samples compacted to 1·3 g cm^{-3}, followed by 1·1 g cm^{-3} and 1·5 g cm^{-3}. The effect of bulk density on soil CO_2 emission resulted in statistically significant differences only on days 2 ($p < 0{\cdot}01$) and 5 ($p < 0{\cdot}1$) (Figure 2).

Soil CO_2 emission significantly ($p < 0{\cdot}001$) increased with increased rain exposure time on days 1, 2 and 5 (Figure 3). The average CO_2 emission rates over the nine days were $0{\cdot}035 \pm 0$ 014 µg CO_2 g^{-1} min^{-1}, $0{\cdot}030 \pm 0{\cdot}015$ µg CO_2 g^{-1} min^{-1}, $0{\cdot}018 \pm 0{\cdot}012$ µg CO_2 g^{-1} min^{-1} for soil exposed to rainfall for 90 minutes, 30 minutes and not exposed, respectively. We believe there are two mechanisms that produced this effect: first the physical alteration of soil aggregates due to raindrop impact may have increased CO_2 emission by increasing substrate availability and enhancing access to non-biomass labile organic C (Van Gestel *et al.*, 1991, 1993). Secondly, that aggregate breakdown produced surface seals which reduced evaporation, thus maintaining favourable conditions for soil respiration for a longer period, although this may be countered by reduced gas diffusivity (Tackett and Pearson, 1965; Shestak and Busse, 2005). This explains the higher water content after eight days in the soil cores exposed to rain for 90 minutes (Figure 4) and consequently the higher CO_2 emission rates. For all cores there was a rapid and substantial increase in soil respiration on day 1, after the simulated precipitation pulses, followed by a gradual decline. This has been observed in a number of studies (Kieft *et al.*, 1987; Appel, 1998; Fierer and Schimel, 2003; Sponseller, 2007; Chen *et al.*, 2008) and has been attributed to degassing of stored CO_2 from past microbial and plant CO_2 efflux (Liu *et al.*, 2002). However, degassing happens within a few hours of water addition (Smart and Penuelas, 2005). In our study CO_2 emission was measured 24 hours after water addition, and we therefore attribute the increase in CO_2 efflux to an increase in microbial metabolism, in response to great substrate availability following

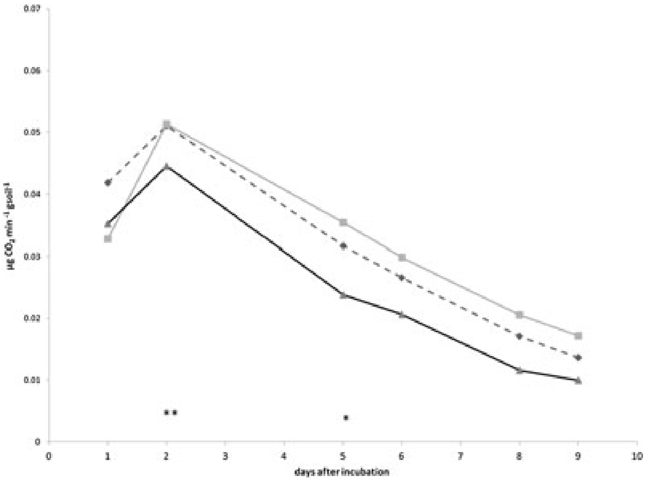

Figure 2. Average of soil carbon dioxide (CO_2) emission rate during incubation period. The black line, the grey line and dotted line indicate soil compacted to 1·5 g cm^{-3}, 1·3 g cm^{-3}, 1·1 g cm^{-3}, respectively (**$p < 0{\cdot}01$; *$p < 0{\cdot}1$).

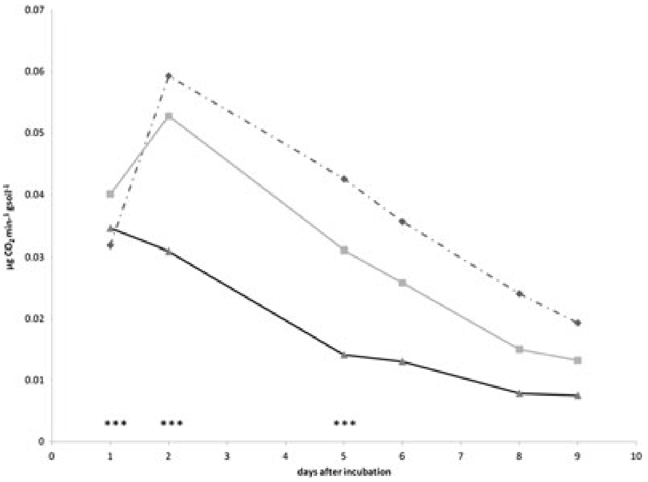

Figure 3. Average of carbon dioxide (CO_2) emission rate during incubation period. The black line, the grey line and dotted line indicate soil exposed to rainfall for 0, 30 and 90 minutes, respectively (***$p < 0{\cdot}001$).

aggregate breakdown, which takes several hours to days to occur (Steenwerth *et al.*, 2005, Chen *et al.*, 2008).

All interactions (soil*bulk density, soil*rain, soil*rain*bulk density) terms were significant (Table I). Soil CO_2 flux rate from soil exposed to rainfall for 90 minutes was 171·7%, 181·5% and 32·3% higher for clay, silt and sand soil, respectively, compared to no rain exposure. The interaction between soil*bulk density was also significant ($p < 0{\cdot}001$) with soil CO_2 efflux for the 1·5 g cm^{-3} bulk density was 17·76%, 20·76% and 41·73% lower for clay, silt and sand soil, respectively, compared to the 1·1 g cm^{-3} treatment.

Soil CO_2 emission during incubation at constant temperature and soil moisture

Soil CO_2 emission rate under constant soil moisture and temperature varied significantly with bulk density, rain exposure and their interaction (Table II). As found in the previous experiments, an increase of soil compaction significantly ($p < 0$ 001) reduced soil CO_2 emission. Average CO_2 emission rates were $0{\cdot}025 \pm 0{\cdot}002$ μg min^{-1} $g_{,}^{-1}$ $0{\cdot}024 \pm 0{\cdot}002$ μg min^{-1} g^{-1} and 0·019 0·004 μg min^{-1} g^{-1}, respectively for soil compacted to 1·1 g cm^{-3}, 1·3 g cm^{-3} and 1·5 g cm^{-3}. Furthermore, as in the constant soil moisture experiments soil CO_2 emission was significantly ($p < 0$ 001) higher for the soil exposed to rainfall (Figure 5).

Cumulative CO_2 emission in soil exposed to rain was 26% more than from the unexposed soil. The average CO_2 emission rates were $0{\cdot}026 \pm 0{\cdot}004$ μg min^{-1} g^{-1} and $0{\cdot}024 \pm 0{\cdot}003$ μg min^{-1} g^{-1}, respectively, for soil exposed to rainfall simulator for 90 minutes and not exposed. Given that the soils had the same moisture content the enhanced CO_2 flux measured from the cores exposed to rainfall must be attributed to aggregate breakdown, due to raindrop impact, exposing previously encapsulated organic C, which then became available for decomposition. This is a substantial impact on CO_2 emissions and corroborates the work of Reicosky (2003) who also attributed an increase in CO_2 emissions from intensively tilled areas to the increase in surface area caused by aggregate breakdown. These results demonstrate the importance of adopting soil management activities which protect soil aggregates from raindrop impact, such as residue management and the use of cover crops.

Table II. Results of analysis of repeated measure variance test for soil carbon dioxide (CO_2) emission rate during incubation at constant temperature and soil moisture

Source	*F*	Prob > *F*
Time	6·65	0·0000
Time*bulk density	1·99	0·0000
Time*rain	4·46	0·0000
Time*rain*bulk density	1·91	0·0000

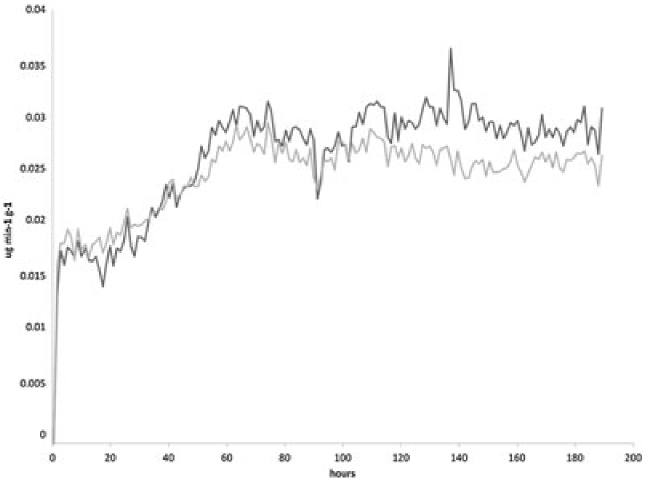

Figure 5. Carbon dioxide rate from soil exposed to rain simulator for 90 minutes (black line) and soil not exposed (grey line).

Finally, the interaction between rain exposure and bulk density was significant with the effect of soil compaction on CO_2 emission rate reduction being greater in soil exposed to rainfall simulator (9%), compared to the no rain exposure treatment (33%).

Conclusion

This study revealed that soil respiration is strongly affected by soil texture, soil compaction, rain exposure, and their interaction.

Figure 4. (a) Soil core exposed under rain simulator for 90 minutes; (b) soil core wetted without the effect of raindrops. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

Our major findings were:

i CO_2 emission from clay-textured soil was six and three times greater than silt and sand soil, respectively;
ii soil compaction results in a decrease in soil CO_2 emission;
iii CO_2 emission is greater in soil exposed to rainfall than soil which was not exposed. This is attributable primarily to soil aggregate breakdown causing exposure of encapsulated organic C.

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