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Relative Importance of Physical Constraints on Decomposition

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ABSTRACT

Soil organic matter (SOM) stability is thought to be dependent almost entirely on temperature, moisture, and microbial dynamics. While soil physical factors are also known determinants of SOM decomposition, proportionally little work has attempted to determine how these factors could regulate future rates of CO_2 release from soils under a changing climate. Here, paired lab-field experiments explore the effects of change in the physical environment and carbon dioxide (CO_2) respiration of SOM in mineral soil from an 80-year old red spruce forest stand in Nova Scotia, Canada. Factors tested were substrate transport, solubilization, oxygen availability, and physical structure, and were performed using the following respective disturbance methodologies: electrokinetics, wetting, air-sparging, and abrasion and compaction. Most treatments drove change in SOM decomposition rates, and the effect of the disturbance usually decayed over several days. Interestingly, laboratory and field results differed strongly, and opposite responses were often observed for a given type of disturbance. Electrokinetics, or the movement of substrates independent of other disturbances, did not produce any change to the soil CO_2 emission regime. Few studies have tackled the importance of physical controls on soil decomposition, but this is new and potentially important work for making accurate future predictions of terrestrial carbon cycling.

Keywords: Respiration, physical environment, soil organic matter, stability, disturbance, flux.

INTRODUCTION

Globally, soils store more than 2000 Pg of carbon (Batjes 1996), and estimates are continually being revised upwards due to improved quantification of northern reserves (Schuur et al. 2008). Respiration from terrestrial ecosystems is one of the dominant fluxes in the carbon cycle and is increasing annually by at least 0.1 Pg as a consequence of climate warming (Bond-Lamberty 2010). Further increases in terrestrial carbon release from increased soil CO_2 production could cause positive feedbacks to climate change (Davidson and Janssens 2006b).

Soil organic matter (SOM) is biochemically heterogeneous and is distributed across microclimatic gradients in the soil profile. Specific environmental and biochemical responses (Buckley and Schmidt 2002; Trumbore 2000) are characteristic of surface soils, and less-studied mineral soils at depth (Jobbagy and Jackson 2000; Fontaine et al. 2007). Overall, SOM decomposition rates and CO_2 production are governed by temperature, moisture, and substrate quality. In a recent review, however, Davidson and Janssens (2006a) suggest that the physical attributes of the soil may also be key in understanding how SOM will react to changing climatic

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factors and thus ecosystem processing (Likens et al. 1996). These physical environmental constraints may complicate the apparent temperature sensitivity of decomposition (Davidson and Janssens 2006a). The four non-thermal physical factors include substrate transport, solubilization, oxygen availability, and physical structure. Figure 1 shows these factors, and the degree of understanding associated with each. Since they often co-vary in both laboratory and field experiments it is difficult to isolate the effect of a given factor and as a result we lack a good understanding of their individual (and synergistic) effects.

The following sections (2.1-2.5) will discuss some of the important limitations on microbial SOM decomposition along with the complexity and intricacy of the physical environment.

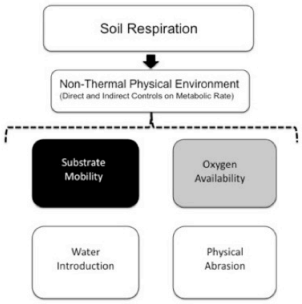

Figure 1: Conceptual diagram that depicts the complex nature of soil respiration and physical limitations to microbial activity. White boxes refer to processes that are generally well understood based on previous literature. Grey-shaded boxes suggest that a fair to fairly poor amount of literature surrounds this topic. Black boxes indicate that very little literature has been published surrounding this process and topic. Arrow colors indicate the interaction between these factors.

Substrate Transport

Respiration may be limited if the microbial community is physically separated from the substrate and therefore protected from decomposition by limited accessibility (Sollins et al. 1996). Crawford and Gosz (1982) have proposed the importance of "fertility islands" within the soil as hot spots for decomposition. Substrate availability varies greatly over time and space, possibly explaining why respiration rates vary so substantially within a relatively small regional area (Davidson and Janssens 2006b). There are various controls on substrate transport including moisture, leaching rate, SOM type, and as outlined by Davidson and Janssens (2006a) environmental constraints. These controls will directly or indirectly affect the concentration of substrate available at the microbial enzymatic reaction sites.

The mobility of substrate and microorganisms via soil is dependent on diffusion within soil pore water, a mechanism controlled by temperature and moisture (Renault and Sierra 1994). In order to separate the role of pore water from substrate diffusion, the impact of pore water movement and substrate diffusion must be evaluated independently for impacts on decomposition, which is challenging and has not yet been done. Unfortunately, the microbial-substrate island effect is largely hypothetical and thus unconfirmed for lack of a suitable experimental procedure that can isolate substrate movement from confounded physical factors such as water movement. The electrokinetics technique (Figure 2) is used to concentrate charged materials resident in pore fluids and spaces, contaminants and/or microbes around electrodes during soil remediation (Acar and Alshawabkeh 1993; Jayasekera and Hall 2007; Alshawabehek and Maillacheruvu 2001; Sequeira and Moffat 1998) without affecting intrinsic soil properties or microbial metabolism (Luo et al. 2005). While electrokinetics offers potential for examining the importance of substrate transport independently from moisture movements, it has not yet been applied to this research area and the role of substrate transport in SOM decomposition remains unconfirmed.

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Solubilization

Water dissolves organic carbon, oxygen, and nutrients thus facilitating the diffusion of these species within soil (Dilly 2006; Buckley and Schmidt 2002). Moisture changes have readily been assessed through the literature (Davidson and Janssens 2006a); however, solubilization is more important on smaller time scales and refers to the introduction of water and its effects on physical structure within the soil (Davidson and Janssens 2006a). Rewetting of soil can cause two distinct or related responses. The initial flush of CO_2 from a system following a wetting event can be attributed to the mineralization of organic matter (OM) exposed by the physical breakdown of soil aggregates (Beare et al. 1994; Appel 1998), or this flush could be due to the release of mineralized carbon from microbes (Halverson et al. 2000; Fierer and Schimel 2003; Mikha et al. 2005). Parts of the microbial community benefit from the osmotic shock of rapid introduction of water to the system as some microorganisms lyse thus providing resistant microbes access to nutrients and substrate (Buckley and Schmidt 2002; Fierer and Schimel 2003).

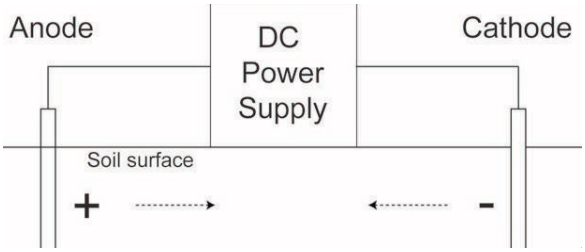

Figure 2: General soil electrokinetic setup in 2D for a typical contamination site. The anode is on the left, cathode on the right facilitating the movement of oppositely charged particles to each electrode. The negatively charged microbes should also move towards the anode.

There is a delicate balance between ample water requirements for optimal aerobic respiration and aeration of the soil (Beare et al. 2009). For aerobic respiration, the optimal water content is between 50-70% of water holding capacity (Orchard and Cook 1983). Decomposition rates will decline with limited water for diffusion because enzymatic processes must occur in water (Davidson and Janssens 2006b). The mineralization process can also be influenced by the physical conditions or compaction of the soil, where uncompacted soils show a decrease in microbial activity with decreased water-filled pore space (WFPS) because lower levels of soil water will hinder the motility of bacteria and the diffusion of solutes (Beare et al. 2009). Wetting and drying cycles are also impacted by soil compaction because this physical constraint will greatly affect the soil microbial activity (Fierer and Schimel 2003). Rewetting can increase the amount of extractable carbon and therefore the availability of the SOM to the microbial community (Fierer and Schimel 2003). Overall, moisture effects on decomposition have been well studied by imposing wetting events and monitoring changes in soil CO_2 efflux.

Oxygen Availability

Efficient aerobic decomposition of SOM requires available oxygen. Soil surfaces that are consistently exposed to wetting events have an altered soil structure forming a seal on the surface of the soil that can inhibit water and nutrient infiltration and gas diffusion (Le Bissonais and Arrouays 1997). Beare et al. (2009) also confirm that this relatively impermeable layer can affect aerobic respiration. Tillage can thus accelerate oxidation rates of carbon to CO_2 by incorporating oxygen into the soil and by exposing previously aggregate-protected OM to microorganisms (Curtin et al. 2000). Oxygen is the preferred electron acceptor for decomposition because oxygen provides the most energy for a specific amount of electron donors; therefore aerobic respiration tends to occur more rapidly than anaerobic (van Cauwenberghe and Roote 1998; Davidson and Janssens 2006a). Oxygen is thermodynamically favored as an electron acceptor and will always be used

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first by aerobic organisms if available (Andrews et al. 2004). Northern ecosystems tend to have very wet soils that generally have low oxygen diffusion (Frolking et al. 2002); this fact along with cryoturbation (Bockheim and Tarnocai 1998) has protected this vast pool of carbon for many years. However, climatic alterations in temperature and hydrologic regimes may alter this pool (Lafleur et al. 2005). Bioremediation is a technique that uses enhanced natural processes such as optimum microbial activity to degrade compounds in situ (Morin 1997; Troquet et al. 2003). When compounds can be more readily degraded aerobically, bioventing is used to deliver oxygen to soil thus enhancing biodegradation by providing the microbial communities with an ample supply of oxygen (Norris et al. 1993).

Physical Structure

A disruption to the physical structure of soil will undoubtedly alter biogeochemical processes occurring within soil. Tillage and compaction are the main processes that alter the physical structure of soil and have been s tudied in regards to aggregate stability and pore space (Tisdall and Oades 1982; Ghani et al. 2003; Cosentino et al. 2006; Unger et al. 1991; Curtin et al. 2000; Beare et al. 2009). The oxidation of organic carbon to CO_2 is accelerated by tillage because the soil becomes aerated, is mixed together improving contact sites between soil particles, and previously aggregate-protected OM is exposed to microorganisms (Beare et al. 1994). Studies on tillage practices have shown that the physical structure, oxygen diffusion, and solubilization of OM are intricately related. Destruction of aggregates through compaction can alter the size and extent of soil pores thus decreasing gas diffusion as well as rates of infiltration (Abid and Lal 2009) and the biological processes that govern biogenic gas production (Beare et al. 2009). The reduction in soil pore space also reduces the evaporation of water to the surface (Unger et al.1991) and this difference in soil moisture can further affect the stability of aggregates (Cosentino et al. 2006). Compaction tends to limit aerobic respiration and thus lower the rates of CO_2 production (Beare et al. 2009). The practice of reduced tillage has been shown to be a very effective method for reducing the flux of CO_2 from agricultural soil to the atmosphere and sequester CO_2 back into the soil (Kern and Johnson 1993). However, highly disturbed soils can only be viewed as a sink for atmospheric CO_2 so long as the soils are not mechanically disturbed yet again (Curtin et al. 2000).

Research Gaps

Research suggests that soil physical factors can have large impacts on SOM decomposition, and exert control landscape carbon balance. Almost all SOM research is, however, preoccupied with temperature and biochemical controls on stability. There is proportionately very little work that helps understand how soil physical factors act individually or synergistically, or how strong they are relative to biochemical determinants - either in laboratory or field settings. Ultimately this understanding limits our ability to predict future SOM decomposition, carbon balance, and (potentially significant new) emissions of CO_2 from soils in a changing climate. Of course, changing climate will not only affect temperature and precipitation patterns, but will have a profound influence on soil physical properties through natural interactions and also via land use changes. While the methodologies exist that would allow us to better understand soil physical factors as determinants of SOM stability, they must be combined and used in experimental research where soil factors can be isolated in both laboratory and field experiments. Here, we do so with paired lab-field experiments, to explore the effect of changes in the physical environment and respiration of SOM in mineral soil from an

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80-year old red spruce forest stand in Nova Scotia, Canada.

METHODS

This study assembles a range of methodologies to test our hypothesis that some physical mechanisms are disproportionately important in determining decomposition rate and SOM CO_2 efflux. The main factors tested included: substrate transport, solubilization of OM, oxygen availability, and physical structure. Each factor was addressed using a different disturbance methodology as outlined below, and the study simply imposed each disturbance and measured the magnitude of each response in soil CO_2 efflux as a proxy of decomposition rate. Each disturbance was designed to be reasonable in magnitude and all disturbance experiments were done separately. The study aimed specifically to develop a broad and comparative understanding. A parallel controlled laboratory and field approach was used; this was important because lab and field experiments can result in different responses (Risk et al. 2008). Although, we hypothesized that lab and field soils would behave similarly and with a universal approach to data analysis the relative importance of each physical mechanism could readily be compared.

Field Site and Laboratory Soils Preparation

The field site, located in the Abrahams Lake area of the Liscomb Game Sanctuary, Nova Scotia, Canada (45 10°N 62 38°W) (Figure 2) is dominated by 80 year-old Red Spruce (*Picea rubens Sarg*.) (Diochon and Kellman 2009). Soils are sandy loam textured orthic hummo-ferric podzols derived from quartzite soil. Mean annual air temperature is 5.8°C with an annual average of 1300 mm of precipitation (Diochon and Kellman 2009). The thick organic litter layer and leached layer were removed to gain access to the mineral soil underneath. The soil used in the laboratory experiments was collected from the same forest stand as the field site. Removing and discarding the litter and leached layers, mineral soil was excavated and placed in bags for transport to the lab. The soil was dried at 45°C in a drying oven for 24 hours and then put through a 2 mm sieve to remove rocks and debris. Soil was then packed into 30 cm diameter plastic receptacles to a depth of 20 cm, layering with distilled water and un-dried sieved soil to inoculate and wet the soil.

Figure 3: Location of field site within the Liscomb Games Sanctuary in Nova Scotia, Canada.

A CO_2 probe and Campbell Scientific 107B Temperature Probe with an accuracy of 0.005°C were installed in each sample and controlled by a Campbell Scientific CR23X datalogger, but the moisture was measured manually with a Campbell Scientific HydroSense 12 cm probe with accuracy of 0.5%.

In both laboratory and field environments, Continuous Timeseries Forced Diffusion (CT-FD) CO_2 probes provided a continuous measuring technique for soil CO_2 efflux measurement, and gave a reading every five minutes (McArthur et al. *submitted*). This methodology allows for extremely high temporal resolution, rare in

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this type of experimental setting. In field experiments supporting data was collected at the same temporal frequency using Campbell Scientific CS616-L50 Water Content Reflectometer moisture probes to an accuracy of 0.005%, Campbell Scientific 107B Temperature Probes buried directly in the mineral layer, accurate to 0.005°C, and all data was logged by a Campbell Scientific CR23X datalogger. Field soil plots were 3 m apart.

Soil Electrokinetics

Soil electrokinetics was used to test the effect of substrate diffusion and was only applied to the laboratory samples. The application of a low power direct current (dc) electric field between at least two electrodes placed in the soil causes the net movement of charged species towards the oppositely charged electrode through electrophoresis (Jayasekera and Hall 2007; Alshawabkeh and Bricka 2000; Dzenitus 1997). As charged species, microbes can be moved by this technique without affecting viability or metabolism (Luo et al. 2005). Eight 20 cm long stainless steel flat electrodes were arranged in a circular formation around the inside perimeter of the plastic soil receptacle with a ninth placed in the middle to act as the oppositely charged electrode. This arrangement was suggested by Virkutyte et al. (2002) to

Solubilization

Wetting was used to test the effects of solubilization on labile water soluble SOM and enzymes. The lab samples were allowed to dry to 12% moisture levels and then the experimental plot was rapidly subjected to a 10 mm simulated rainfall of distilled water. Similarly, the field experimental plot, while not manually dried out, had a simulated 20 mm rainfall of distilled water over a short time period. The simulated rain addition quantities were within reasonable rainfall ranges for the geographic region of the field site.

Oxygen Availability

Like many bioremediation studies, the aim of oxygen addition was to stimulate higher rates of aerobic metabolism in microbial communities in potentially low-redox soil zones through the introduction of atmospheric air to the soil pore space (Norris et al. 1993). In our laboratory sample, atmospheric air was pumped through 3 holes drilled in the bottom of the sample container for a total of 10 minutes at 20 psi. In the field, a 1 cm diameter metal pipe was driven into the ground at a 45° angle to the ground underneath the experimental plot. Atmospheric air was pumped through the pipe for 10 minutes at a pressure of 20 psi.

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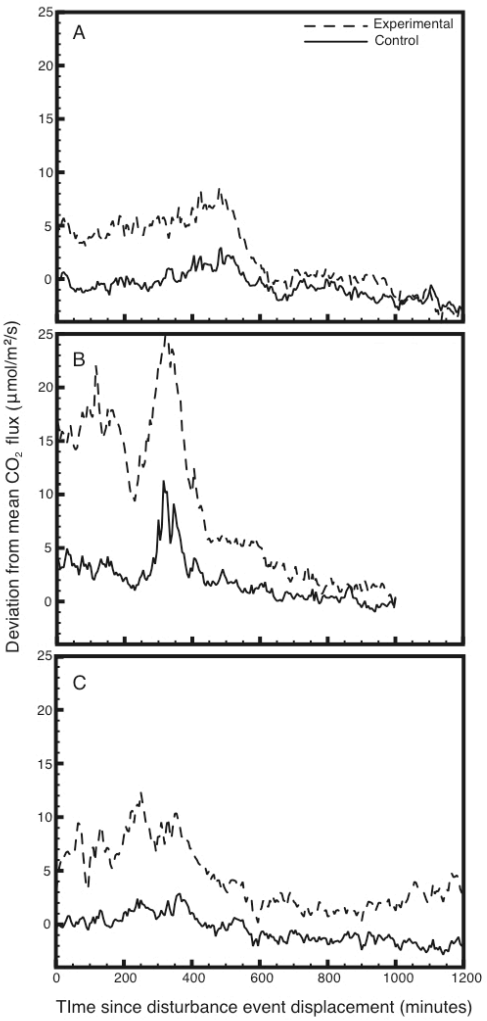

Figure 4: Hourly averaged deviations from the pre-event mean CO_2 flux for laboratory experiments involving electrokinetics (A), wetting (B), air sparging (C), and vibrational compaction (D).

Physical Structure

Physical abrasion and compaction induce changes in soil structure and aggregation, which were hypothesized here to exert changes to SOM decomposition rates. Vibrational compaction events were done in situ in the lab and field soils. Being of smaller scale, the laboratory equivalent of this factor was to use a Campbell Hausfeld TLX103 Air Hammer and vibrate a small 30 cm^2 metal plate on the surface for 6 minutes and then drive 7 pieces of 30 cm stainless steel round rods into the sample. The lab soils were however, already somewhat structurally different than the soil in the field due to the soil preparation procedure described above. In the field, a Pionjar portable drill rig with an x-shaped foot, lengths of 36 cm, was used to vibrate the soil for two minutes in three places around the probes. Finally, seven pieces of rebar were driven into the ground using the force of the Pionjar.

Data Analysis

This study focused on the short- and long-term biological responses to physical factors, and we chose to exclude data from the study associated directly with displacement fluxes that may have occurred as the experimental disturbances were being applied. These displacement fluxes are a result of gas pumping from air introduction and are not indicative of biological processes of interest, which react to the disturbance over longer timescales (hours to days). Post-disturbance fluxes typically stabilized over timescales of minutes to tens of minutes following the disturbance, depending on disturbance type. Uniform treatments between the lab and the field for each factor allowed these results to easily be compared visually, and somewhat quantitatively. The response of soil to each factor in the experimental plots was determined by comparison of CO_2 evolved during and subsequent to the treatments, in comparison to the control plots using a Student's t-test assuming unequal variance. Data was analyzed to a statistical power of 95%.

RESULTS

Throughout the electrical current application, the rate of CO_2 flux from the experimental sample was not altered significantly ($p = 3.222$, $\alpha = 0.05$) (Figure 4A). Temperature was not affected by the low energy of the electrical current ($p = 0.1628$, $\alpha = 0.05$) and the moisture measured before and after the electrical

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event only yielded a decrease in moisture by 1% and was considered normal for the laboratory plots. The tracer test yielded a significant decrease in potassium ions at the

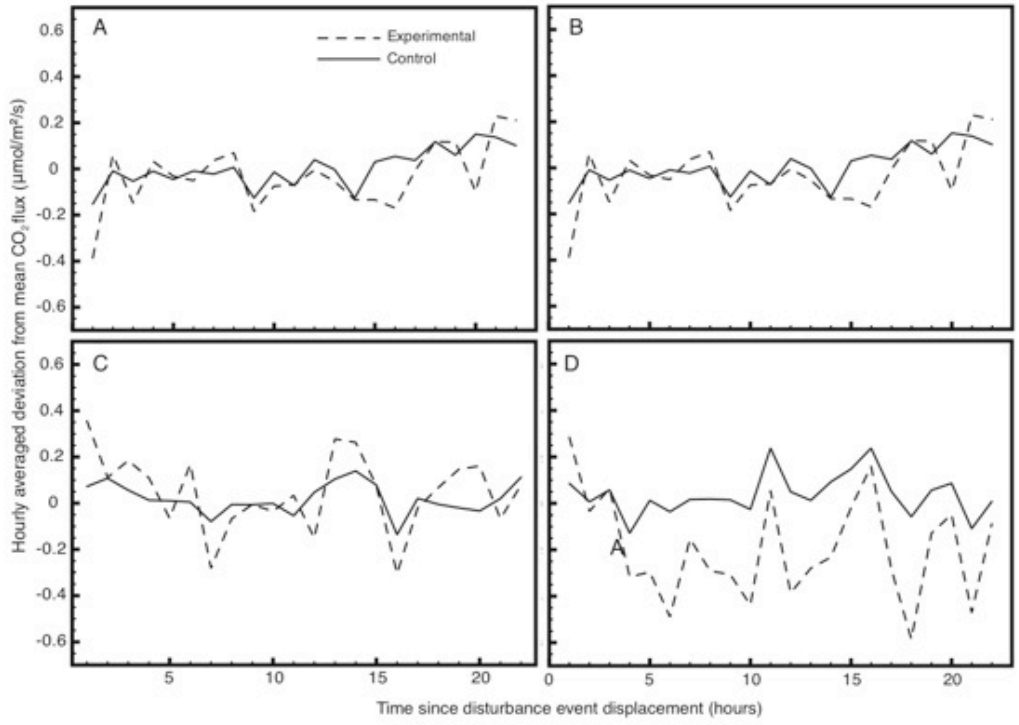

Figure 5: Deviation from the pre-event mean CO_2 flux in field experiments for wetting (A), air sparging (B), vibrational compaction (C).

spiked sites within 42 hours of current application ($p < 0.0001$, $\alpha = 0.05$). A technique for facilitating substrate transport was designed, implemented, and verified by the positive results obtained by the tracer test. Redistribution confirmed by the potassium ion tracer test justifies electrokinetics as a reasonable proxy of low valence ion mobility that extends to living cells, higher valence ions, and SOM, both dissolved and particulate.

Rewetting of soil in the lab showed a significant decrease in CO_2 flux after the initial pulse (Figure 4B). This suggested that the SOM solubilization induced by the wetting was not beneficial to the microbial community ($p = 0.0001$, $\alpha = 0.05$). The simulated rain did not infiltrate immediately, but rather pooled on the surface for several minutes before being absorbed by the soil.

The initial moisture content of 12% was significantly increased to 18% ($p < 0.0001$, $\alpha = 0.05$). When water was introduced in the field there was a significant increase in response of microbial activity and therefore higher fluxes of CO_2 from the soil in the experimental plot compared to the control ($p < 0.0001$, $\alpha = 0.05$) (Figure 5A). There was a significant increase of moisture content from 24.71% to 26.08% following the wetting event ($p < 0.0001$, $\alpha = 0.05$) but no change in temperature. The simulated rain, unlike in the lab, did not pool on the surface of the soil but infiltrated almost immediately upon impact.

Air-sparging caused an initial flush of CO_2 from the laboratory sample, but the

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flux returned to the pre-event rate (Figure 4C). Because there was no change in baseline flux following the flushing event, this soil was not oxygen limited ($p = 0.4899$, $\alpha = 0.05$). Initially the air-sparge event in the field did not change the CO_2 flux but the experimental plot was at an elevated baseline directly before and after the event suggesting that a pre-event factor was controlling the flux ($p < 0.0001$, $\alpha = 0.05$)

Event Disturbance	p-value	Significant?	+/-	Recovery Time (hrs)
Substrate Transport$_{Lab}$	0.3222	no	N/A	N/A
Solubilization$_{Lab}$	0.0001	yes	-	>22
Solubilization$_{Field}$	0.0001	yes	+	10.4
Oxygen Addition$_{Lab}$	0.4899	no	N/A	N/A
Oxygen Addition$_{Field}$	0.0001	yes	+	16.7
Physical Structure$_{Lab}$	0.0001	yes	-	>22
Physical Structure$_{Field}$	0.0001	yes	+	12.4

Table 1: Overall Student's t-test statistics and relative magnitude of each disturbance event ($\alpha = 0.05$).

(Figure 5B). There was no change in temperature or moisture following the flushing of soil pore space with atmospheric air.

Abrasion caused a significant decrease in CO_2 flux from the experimental lab sample following the event ($p < 0.0001$, $\alpha = 0.05$) (Figure 4D). The vibrating foot of the air hammer compacted the soil, particularly at the surface of the sample and formed depressions. The microbial community was negatively affected by this disturbance. The physical abrasion event in the field caused a significant increase in CO_2 flux and an increase in variability ($p < 0.0001$, $\alpha = 0.05$) (Figure 5C). The Pionjar hammer drill vibrated the litter layers around the experimental plot and also compacted the surface layer of soil. An analysis for changes in Q_{10}, or the increase in soil CO_2 emission over a 10°C interval, showed that following this disturbance the Q_{10} became more sensitive.

In the field, diurnal cycles of temperature and moisture were co-variant, and may have, together with other factors, affected post-disturbance recovery rates. A sharp decrease in respiration was typically seen at roughly 1900h. It should also be noted that the field soils contained roots which may have been a significant source of CO_2, whereas the lab soils did not.

DISCUSSION

In the field and lab, CO_2 production and efflux responded in different ways (Table 1). Lack of change in respiration rate during or following the application of electricity suggests that in this soil, substrate transport and the island effect proposed in mineral soil (Crawford and Gosz 1982) was most likely not a main control on SOM stability. That said, the homogenization of the lab soil during the sample preparation may have removed this physical constraint by equally distributing the microorganisms and OM throughout the soil profile. Similar to tillage practices where the mixing of soil layers increases the contact between the microbes and the labile carbon (Ghani et al. 2003), the homogenization process may have removed the importance of substrate transport in this soil. The initial burst of CO_2 following repacking of the soil into the container may have also reduced the available labile carbon.

Electrokinetics and mobilization of carbon compounds within the soil, potentially to microbial sites, was not effective in increasing the soil CO_2 production. Intact cores may have produced a different response to an electric current, and a field trial for this technique could be useful in the future. Also, using a range of moistures may have facilitated a detectable change in net migration of ions throughout the soil since the electroosmotic flow rate is dependent on the medium (Jayasekera and Hall 2007).

Solubilization treatments showed a different response in the lab compared to the field. Any impact of moisture additions must be a result of moisture-microbe or moisture-SOM interactions, and not redistribution, as was suggested by the substrate transport tests. The damped respiration rate following wetting in the lab

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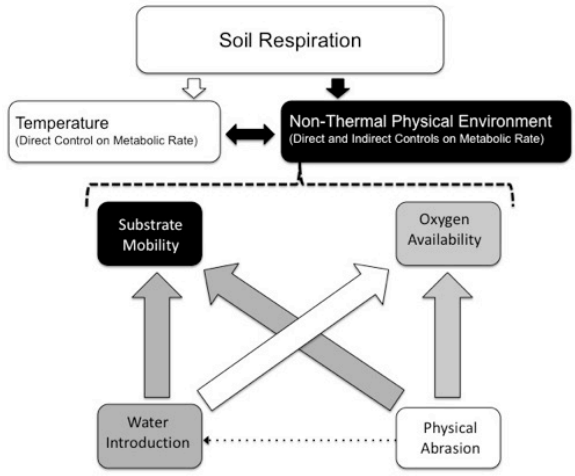
was highly characteristic of results such as from Le Bissonais and Arrouays (1997) where structurally disturbed soils reduced the infiltration of water and gas diffusion, resulting in a lower CO_2 flux from the soil because the gas simply could not escape. Pooling of water observed in the lab upon rewetting has also been reported by Fierer and Schimel (2003) and further supports the idea of limited gas exchange following rewetting. Rigorous physical disruption applied to the soil during the soil preparation may have contributed to this effect. Interestingly, in situ experiments showed a very different response to the addition of water. The microbial community was stimulated in the field following a simulated 20 mm rainfall event. Heightened respiration rates suggest that the solubilization of OM had occurred and thus increased the accessibility of labile carbon compounds to the microbial decomposers (Dilly 2006). The reason for discrepancies between lab and field data is not obvious but is likely related to the difference in soil



structural properties owing to the excision of soil, transport, preparation, and packing for lab trials.

Figure 6: Conceptual Model as presented in Figure 1, but populated with the results of this study. Black, grey and white boxes show where effects were nonexistent, weak, and strong, respectively.

Increased oxygen availability did not increase the rate of respiration in the lab. The microbial community was not oxygen limited and did not benefit or change under more aerated conditions. Field experiments once again showed different results than those observed in the lab where the experimental plot exhibited a much higher rate of respiration. Some confounding effects of natural temporal variation in the field soils may have, however, affected field trials because even before the atmospheric air was introduced, respiration rates in the experimental plot (relative to the control plot) were on the increase. Due to limited field data in the days and hours preceding the oxygen-sparge event, the reason for this difference is not known. We also speculate that the plastic receptacle walls may have created a quick easy transport path for the O_2-rich air out of the soil sample, and that sparge gases may have partially bypassed O_2-poor soil microzones.

In terms of physical structure, decreased respiration rates in the lab suggested that compaction overpowered the vibrational effects of physical abrasion. Physical abrasion should increase the rate of respiration as Beare et al. (1994) pointed out by exposing more OM that was previously protected by aggregation to decomposers (Sollins et al. 1996). Kern and Johnson (1993) found that tillage and breaking up of aggregates produced higher fluxes of CO_2 than less disturbed soils. Compaction of the laboratory soil formed depressions suggesting that the force of the air hammer was large enough to deplete much of the air filled pore space in the sample and thus reduce the rate of diffusion for oxygen and CO_2 (Abid and Lal 2009).

The lab soil emitted less CO_2 after compaction. In the field, however, abrasion and compaction increased the respiration rate. The vibrational effects of this event should have exposed more surface area and thus active sites on the OM for decomposers to attack (Sollins et al. 1996). Beare et al. (1994) noted that disaggregation through

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sonication, grinding, and crushing increased the production rate of CO_2, similar to this study's results. Stemmer et al. (1998) stated that "…crop management, rapid wetting or even raindrop impacts can disrupt macroaggregates and suggested that the physical structure of aggregates in soil may be highly sensitive to abrasion and compaction perturbations…" The importance in aggregate stability for retaining carbon within soils has been explored by Six et al. (2002) who found that the amount of particulate organic matter carbon that is stored within microaggregates in less disturbed sites was significantly greater than in highly disturbed agricultural systems. Our laboratory soil had no microaggregates owing to the soil preparation technique which included sieving, and again these differences in structure may have resulted in the different responses between lab and field. Another explanation for the decreased CO_2 flux in lab versus increased CO_2 flux in field could be due to sample size. In the lab, disturbance was confined to the receptacle, whereas in the field our disturbance was not well-confined and peripherally disturbed soils could have contributed to the observed response.

CONCLUSIONS

The influences of each of the four physical factors investigated here are certainly more complex than previously identified in the literature (Figure 6). The *relative* importance of the various different physical factors was hard to assess given our differing observations in both lab and field settings. We conclude therefore that the response to physical conditions is highly site and soil specific, and that in particular soil structure and aggregation may play an important role in determining the response of the soil microbial community to any given disturbance event. Future studies that allow closer lab mimicry of field conditions, through use of intact cores or mesocosms, may provide more consistent results. In-situ field studies, though difficult, may also be the only way to assess SOM response to changing soils over longer timescales. Many of the appropriate methodologies exist for measuring and monitoring disturbance effects on CO_2 flux from SOM decomposition but researchers in this field increasingly need good collaboration to assemble strong groups who are undertaking parallel (but complimentary) research. Further research could test the methods used within this study in a broader range of soil samples from more geographical locations to better understand the importance of physical environments on soil carbon within different ecosystems.

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