Effects of mechanical energy inputs on soil respiration at the aggregate and field scales

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Abstract

Cultivation machinery applies large amounts of mechanical energy to the soil and often brings about a decrease in soil organic carbon (SOC). New experiments on the effects of mechanical energy inputs on soil respiration are reported and the results discussed. In the laboratory, a specific energy, $K$, of 150 J kg\textsuperscript{-1}, similar to that experienced during typical cultivation operations, was applied to soil aggregates using a falling weight. Respiration (carbon dioxide, CO\textsubscript{2} emission) of the samples was then measured by an electrical conductimetric method. Basal respiration (when $K=0$) measured on Chromic Luvisol aggregates, was found to increase with increasing SOC, from 1.88 mg CO\textsubscript{2} g\textsuperscript{-1} h\textsuperscript{-1} for a permanent fallow soil (SOC=11 g kg\textsuperscript{-1}) to 8.25 mg CO\textsubscript{2} g\textsuperscript{-1} h\textsuperscript{-1} for a permanent grassland soil (SOC=32 g kg\textsuperscript{-1}). Basal respiration of a Calcic Cambisol, more than doubled (2.0–5.2 mg CO\textsubscript{2} g\textsuperscript{-1} h\textsuperscript{-1}) with increasing gravimetric soil water contents. Mechanical energy inputs caused an initial burst of increased respiration, which lasted up to 4 h. Over the following 4–24 h period, arable soils with lower SOC contents, (11–21 g kg\textsuperscript{-1}), respiration rates dropped back to a level, approximately 1.14 times higher than the basal value. However, grassland soils with higher SOC contents (28–32 g kg\textsuperscript{-1}), increases in this longer-term respiration rate following 150 J kg\textsuperscript{-1} of energy, were negligible. A field experiment, in which CO\textsubscript{2} was measured by infra-red absorption, also showed that tillage stimulated increased levels of soil respiration for periods ranging from 12 h to more than one week. The highest respiration rates, 80 mg CO\textsubscript{2} m\textsuperscript{-2} h\textsuperscript{-1} were associated with high energy, powered tillage on clay soils. On the same soil, low energy draught tillage resulted in a respiration rate of approximately half this value. The results of these experiments are discussed in relation to equilibrium levels of soil organic matter. The application of known quantities of mechanical energy to soil aggregates under laboratory conditions, in order to simulate the effect of different cultivation practices, when combined with the subsequent measurement of soil respiration, can provide useful indication of the likely consequences of soil management on SOC. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

For many years, increased intensity of arable cultivation, particularly under wet conditions, has been
linked to a decline in soil physical conditions (Greenland et al., 1975). The increasing difficulty in managing these soils is thought to be partly associated with a reduction in soil organic carbon (SOC). In turn, this has resulted in more intensive cultivations. The depletion of the carbon pool by cultivations thus has significant implications for soil quality and greenhouse gas emission (Kern and Johnson, 1993).

Soil organic carbon has been shown to be very important for many aspects of soil physical quality. For example, greater contents of SOC have been associated with greater stability in water (Oades, 1984), greater porosity and lower bulk density leading to lower dry strength, increased friability (Watts and Dexter, 1998) and a greater resistance to mechanical damage (Watts and Dexter, 1997). Other desirable properties of agricultural soils such as good water holding capacity and good aeration status are also found to be positively correlated with SOC.

For soils in a steady state, the annual loss of carbon (C) is equal to the annual input. The inputs of organic C are usually through photosynthesis by plants and the incorporation of the carbon is thus ‘fixed’ into soil organic matter pools. The greatest route for output from agricultural or forest soils is by respiration of carbon dioxide (CO2) by organisms which are decomposing the compounds containing the SOC. When a system is disturbed, such as by a change in land use, cropping or other management practices including cultivation, it is likely no longer to be in a steady state. Numerous studies have been conducted in the field to evaluate the change in microbial activity as a result of different cultivation systems (Carter, 1992; Chan et al., 1992; Beare et al., 1994; Franzluebbers et al., 1994). These studies also suggest that tillage opens up pores thus exposing previously physically protected SOC to attack by organisms. Other changes likely to influence microbial activity following cultivation include changes to soil climate, water status and aeration.

The mechanical disturbance of soil, by cultivation for example, has been shown to increase the rate of loss of organic C by increasing microbial activity as measured by soil respiration (Rovira and Greacen, 1957; Reicosky et al., 1995; Watts et al., 1999). In general, it has been found that the increasing levels of mechanical energy applied to soil, have produced increased rates of respiration. Such measurements can give a sensitive indication of the short term of changes which take many years to reach new equilibria values.

The energy inputs to soil following different cultivation operations have been measured in long-term experiments by Patterson et al. (1980). Some typical energy values are given in Table 1 for different cultivation systems. In commercial agriculture, total inputs of mechanical energy to soil during primary and secondary cultivation and seeding operations can often approach 300 J kg−1.

In order to obtain a better understanding of the relationship between the application of different amounts of mechanical energy and soil respiration there is a need for controlled laboratory experiments to complement field experiments. In a recent study of the effects of mechanical energy on aggregate stability, Watts et al. (1996a,b) used a simple falling weight to simulate similar energy levels to those used during cultivation operations. In this study, we use the same apparatus to investigate the effects of different mechanical energy inputs on the respiration of collections of aggregates. The aggregates were obtained from soils with long histories of different management

<table>
<thead>
<tr>
<th>Cultivation system</th>
<th>Redbourne, 90 g kg−1 clay (J kg−1)</th>
<th>Silsoe, 510 g kg−1 clay (J kg−1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plough, cultivator drill</td>
<td>68</td>
<td>132</td>
</tr>
<tr>
<td>Chisel plough (2 passes), cultivator drill</td>
<td>124</td>
<td>177</td>
</tr>
<tr>
<td>Shallow plough, combined cultivator drill</td>
<td>82</td>
<td>161</td>
</tr>
<tr>
<td>Spring tine, cultivator (2 passes)</td>
<td>72</td>
<td>90</td>
</tr>
</tbody>
</table>

aData adapted from Patterson et al. (1980).
practices and consequently different SOC contents. Measurements were then made under controlled laboratory conditions at different water contents, but at a constant temperature.

The object of this work was to develop a technique for assessing, under laboratory conditions, the effect of applying to soil aggregates, mechanical energies similar in magnitude to those experienced during cultivation operations, and from this assess the effects on soil respiration. In addition, we measured respiration in the field following cultivation operations of differing intensities.

2. Materials and methods

2.1. Soil

Laboratory experiments were carried out on soils from Highfield and Boot Field sites while field experiments were conducted on Boot Field and Pavilion Fields.

Highfield is one of the ley-arable experiments on Rothamsted Experimental Station. The soil is of the Batcombe Series, (approximate FAO equivalent is the Chromic Luvisol; Avery, 1980), and is defined as fine siltly over clayey drift with siliceous stones (Clayden and Hollis, 1984). The original experiments were conducted to compare contrasting crop rotational systems and to determine their effects on the yields of three arable test crops. These experiments were started in 1949, before which Highfield had been very old permanent grassland. Cultivation, drilling, harvesting and other management practices are described in Johnston (1972). Soil samples were taken from the 0–100 mm horizon of five plots with contrasting management regimes, which have caused different reductions in SOC over 50 years. Some important properties of these samples are given in Table 2.

Boot Field, Silsoe (the site of the first field experiment) had previously grown cereals but had been in set-aside for approximately 18 months prior to this experiment. The soil is a typical calcarious pelosol (Gleyic and Calcic Cambisols, Calcaric Gleysols in the FAO System; Avery, 1980) of the Evesham Series, i.e., swelling-clayey material passing to clay or soft mudstone (Clayden and Hollis, 1984). The texture is classified as clay.

Pavilion Field, Silsoe (the site of the second field experiment) had also been set-aside for 18 months. The soil differs considerably from that in Boot Field. It is a typical brown earth (Dystric and Eutric Cambisols in the FAO System; Avery, 1980) of the Bearsted Series, comprising coarse loamy material passing to sand or soft sandstone (Clayden and Hollis, 1984). The texture is classified as a sandy loam. Compositions of these soils are given in Table 2.

2.2. Sample collection and preparation

For the laboratory experiments, the soil samples were collected from the 0–100 mm horizon, air-dried,
and then sieved. Aggregates which passed a 16 mm sieve but were retained on a 13 mm sieve were selected for the respiration measurements. Up to 200 aggregates of this size were collected from each plot or for each required water content. Aggregates from each treatment were split into four equal batches using a coning and quartering technique. Three of the batches were retained separately for the experiment, while the fourth batch was used to determine the particle size, lower plastic limit and SOC contents (British Standard, 1975). Each of the three sub-samples was further divided into two; those receiving energy and those not. These batches of aggregates were then slowly wet to a water potential of $-10$ hPa, on a tension table. This was done by progressively increasing the water potential from $-50$ to $-20$ hPa and finally to $-10$ hPa. This procedure was adopted to avoid any soil structural changes which might have been caused by rapid wetting (Dexter et al., 1984; Grant and Dexter, 1989). The aggregates were then dried to the water potential required for the respiration experiments ($-30$ hPa unless otherwise stated). Each sub-sample of aggregates was kept in an air tight container for 2 weeks to allow sufficient time for any ‘flush’ of CO$_2$, due to change in water content, to pass (Anderson, 1982). These containers were ventilated each day to prevent a build up of CO$_2$. A small number of aggregates were removed from each of the six sub samples per treatment, and their gravimetric water contents were determined (British Standard, 1975).

The same general soil preparation techniques described above were also used on aggregates collected from Boot Field. However, to obtain different soil water contents required, batches of aggregates were allowed to air dry for different lengths of time, prior to being stored for 2 weeks in air tight containers as described above. Sub sample were taken from each batch to determine their gravimetric water content.

2.3. Mechanical energy inputs

In the laboratory, falling weight apparatus, described by Watts et al. (1996a), was used to apply a known amount of energy input to individual soil aggregates. The apparatus is shown in Fig. 1, and consists of a perspex base and ring of 18 mm inside diameter, a guide tube with the same inside diameter but a length of 120 mm, placed on top of the ring. Within the tube, a brass weight (the falling weight) of 16 mm diameter and 55 mm length is free to fall a maximum of 120 mm. The guide tube has long vertical slots to allow air to escape during the fall of the brass weight. The top of the brass weight is connected to the stem of a linear voltage displacement transducer (LVDT). The combination of the weight and the LVDT stem weigh a total of 1N. The barrel of the LVDT is linked to a rigid frame. The output of the LVDT is converted to give a direct reading of height above the base, to $\pm 0.1$ mm, using a programmable digital voltmeter (DVM). The weight falls with the acceleration of gravity at $g=9.81$ m s$^{-2}$. Tests have shown that friction in the apparatus does not significantly affect this acceleration (Watts et al., 1996a,b).

To apply a known specific energy to the aggregate, previously equilibrated at the desired water potential,
it was first weighed and placed within the base ring. The height of the aggregate \( (h) \) was recorded. The weight was then raised to its dropping position \( (h_2) \), 100 mm above the base, and dropped onto the aggregate. To obtain higher energy inputs, multiple drops \( (n) \) were used, because in previous work, not described here, the effects of multiple drops were found to be linearly additive. The specific energy, \( K \) applied to the aggregate was determined by

\[
K = \frac{mg(h_2 - h)n}{M},
\]

(1)

where \( m \) is the mass of the falling weight (102.4 g), \( g \) the acceleration of the weight \( (9.81 \text{ m s}^{-2}) \), \( h_2 \) the height relative to the base, \( h \) the thickness of the aggregate in the vertical direction, \( n \) the number of drops and \( M \) the mass of the aggregate.

With a dropping height of 100 mm, for aggregates weighing 3 g, \( K \) is approximately 30 J kg\(^{-1}\), similar to, secondary cultivation with tines as shown in Table 1. Three drops would be approximately 90 J kg\(^{-1}\), equivalent to primary cultivation, for example a mouldboard plough. In the experiments reported here, five drops were used which is equivalent to an energy input of approximately 150 J kg\(^{-1}\). This is similar to ploughing followed by two passes with light tines, a typical tillage system on many UK soils.

Field experiments were conducted at Boot and Pavilion Fields at Silsoe, using two different implements. A Bomford Dyna Drive was used to provide a low energy input into the soil. This implement was developed in order to achieve shallow cultivation and a greater degree of soil disturbance than direct drilling (or no till) techniques, at the same time providing a high forward speed and the ability to produce a satisfactory seed bed for cereals in one or two passes (Watts and Patterson, 1984). This machine consists of two rotors with parallel axes and overlapping rotor tines. Power, provided by the forward motion of the tractor, is transmitted from the front soil-driven rotor via chain and sprockets to give an increase in speed of 3:1 to the rear rotor. A parallel-barred crumbler roller is fitted to the rear of the machine for soil consolidation, depth control and further fragmentation. This implement is draught powered, i.e., there is no drive to the rotors from the tractor power take-off (p.t.o.).

A spiked rotor was used to impose a high energy input to the soil in the field experiments. It is fitted with a horizontal rotor made up of radially-mounted spikes, with the drive taken from the tractor p.t.o. Adjustable trailing boards are hinged behind the main hood of the machine to provide additional soil fragmentation and a packer roll at the rear gives depth control and consolidation.

Although energy inputs to the soil from the tillage implements were not measured in this experiment, these have been measured and reported previously (Cope et al., 1991). Measurements of tillage energy were made at the tractor implement interface and so do not include tractor and traction losses. Comparison of the system energy requirements of the above implements shows that one pass with the rotor spike requires approximately the same energy as three passes with the Dyna Drive. For the experiment on Boot Field, four passes with the rotor spike were used for the plot with high energy input and two passes with the Dyna Drive for the one with low energy input. Thus the ratio high energy: low energy input is approximately 6:1. On Pavilion Field, however, both the implements conducted two passes on each plot, respectively, which narrowed the ratio high energy: low energy input to 3:1.

Following each cultivation, a measure of the resulting tilth was made. Using a hollow square frame, 0.71 m \( \times \) 0.35 m and 0.2 m deep, pushed into the soil to the depth of cultivation, the enclosed soil was removed, air dried and passed through a nest of sieves, (19.0, 16.0, 13.2, 11.2, 9.5, 6.7, 4.0, 2.0, 1.0, 0.5, and 0.25 mm). The cumulative weight of soil passing through each sieve was recorded. Mean weight diameter (MWD) was measured for each cultivation treatment and is defined as follows:

\[
\text{MWD} = \sum_{i=1}^{N} X_i W_i,
\]

(2)

where \( X_i \) is the mean diameter of any particular size range of aggregates (determined from the mean size of the sieve containing the aggregates and the one immediately above it), \( W_i \) is the weight of aggregates in that size range, as a fraction of the total sample weight, and \( N \) is the number of size fractions (Van Bavel, 1949). Gravimetric water contents (British Standard, 1975) were determined on soil samples collected from the cultivation depth of each treatment, immediately prior to cultivation and during the subsequent experiment.
2.4. Respiration measurements

The respirometers, used for measuring CO$_2$ emission from soil in the laboratory, are based on the design of Chapman (1971) and subsequently updated by Watts et al. (1999). Each respirometer consists of a perspex tube and base, with a diameter of about 75 mm and an inner height of 155 mm (Fig. 2). An airtight lid contained a conductivity cell into which an alkali solution (potassium hydroxide, KOH) was injected. This reacts with the CO$_2$ emanating from the soil in each cylinder and converts the hydroxide into carbonate

\[
2\text{KOH} + \text{CO}_2 \rightleftharpoons \text{K}_2\text{CO}_3 + \text{H}_2\text{O}.
\]  

(3)

The ionic mobility of carbonate ions is 0.368 of that of hydroxide ions. Therefore, the reaction between CO$_2$ and KOH increases the cell resistance. The concentration of the alkali used restricts the sensitivity of the conductivity cell, the limiting rate of CO$_2$ absorption, and the total amount of CO$_2$ that can be absorbed by the cell (Anderson and Ineson, 1982). The lower the concentration of the alkali, the more sensitively the cell reacts to even small amounts of CO$_2$, but the smaller is the amount of CO$_2$ that it can absorb. In the experiments described here, 5 ml of 0.05 or 0.10 M KOH solution were satisfactory. Cell conductivity was
measured with platinum electrodes connected to a measuring circuit (Fig. 3) using an AC excitation voltage $V_E$ (2.0 V, peak to peak, 300 Hz square wave) and a standard resistor $R_S$ (10 kΩ) provided by a Delta-T DL2 logger. The cell resistance, $R_X$ was determined as follows:

$$ R_X = \frac{V_X R_S}{V_E - V_X}, $$

where $V_X$ was the voltage measured across the respirometer. Twelve similar respirometers were coupled to the logger and readings of $V_X$ were taken every 30 min, initially using a Kiethley 175 autoranging multimeter, and subsequently a Delta T DL2 logger fitted with an AC card. Measurements were made for periods of up to 25 h. Prior to each experiment, each respirometer was calibrated using successive known volumes of a standard (6%) CO$_2$ gas.

The advantages of this conductimetric method for measuring soil respiration are:

1. The possibility of a continuous measurement compared with titrimetric methods which allow a measurement only at the end of an observation period (Chapman, 1971; Anderson and Ineson, 1982).
2. The elimination of the subjectivity involved in the determination of colourmetric end points as is necessary with most titrimetric methods (Chapman, 1971).

A potential disadvantage is the temperature-dependence of the electrical conductivity of the alkali solution. However, this was not a problem in the laboratory where the temperatures was kept at a constant 25°C.

For the laboratory soil respiration measurements, 20 aggregates, were each weighed (typical weight of each was between 2 and 3 g) before being placed in each respirometer. Prior to this, these aggregates had been equilibrated at the desired water potential and had either, no mechanical energy input (control), or had received mechanical energy input from the falling weight apparatus described above. For each treatment, three replicate experiments each using 20 aggregates in three respirometers were done. Most experimental runs used all 12 respirometers. Weighing the aggregates, applying mechanical energy and placing them in the respirometers took around 30 min. Therefore, actual ‘time zero’ in for example, Fig. 6, is uncertain by this amount. However, 30 min is small compared with the time scale of each experimental run, and this error is unlikely to have had any major effect on the experimental results or conclusions obtained. The time each respirometer was closed was logged and was taken as ‘time zero’ for that respirometer data set.

The logged output from each respirometer was plotted as the cumulative amount of CO$_2$ per g of dry soil, over a 24 h period. For basal respiration measurements, this data was essentially a constant increase in CO$_2$ trapped with time. This was represented by a straight line, determined using a linear regression. The gradient of this line represented the respiration rate, and this was normalised by dividing by the oven dry weight of the soil in each respirometer, ($\mu$g CO$_2$ g$^{-1}$ h$^{-1}$). Mean respiration rates for each treatment were determined by averaging three replicates. Following inspection of the data, it was decided that the respirometer outputs containing aggregates subjected to mechanical disturbance would be analysed in two parts. An initial burst of respiration during the 0–4 h period, was characterised separately from the essentially constant respiration rate during the subsequent 4–24 h period. Both were characterised by a linear regression in which the gradients represented the respiration rate.

For measurement of respiration in the field a different approach using respiration chambers (or cover boxes) was used. The design of the respiration chambers was similar to that described by Beyer (1991). Anderson (1982) suggested that this type of cylinder should be at least 300 mm high and 250 mm in diameter. In these experiments, three cylindrical steel chambers with a height of 390 mm and a diameter of 500 mm were used. The end, which was to be driven into the soil, was sharpened for that purpose. The other end was closed except for an opening, which was left unsealed during installation to avoid a pressure increase within the chamber. The chambers were then closed with a self-sealing septum, through which samples of the air inside the chambers was taken.

The three respiration chambers were placed on each plot and driven into the soil a few centimetres. The height of the inner chamber remaining above the earth was measured each time to determine the volume and adjust the data to it later. Samples of the air inside the cylinders was taken every hour with 25 ml gas-tight
syringes during daytime and at the same time every day. After each sampling the cylinders were moved so that two different sites of each energy variant were sampled. Both sites were left covered during the night. From the sixth day onwards of the experiment on Boot Field, samples from each of the alternating sites were taken only twice daily. The CO₂ content of the samples was measured in the laboratory using the infra-red gas analyser (Analytical Development, Type 225). The gas analyser was calibrated with two standard concentrations of CO₂ gas.

The temperature in the soil was recorded at each sampling as even small fluctuations can influence soil respiration (e.g., Ginski and Stepniewski, 1985). For this purpose, thermometers were placed in the soils of both sampling plots of all the three treatments to a depth of approximately 5 cm. Unfortunately, because it was possible to have only duplicates of these measurements, no statistical analyses of the results of these field data were possible.

3. Results and discussion

3.1. Effects of soil organic carbon content

The results in Fig. 4 show that the levels of basal respiration of undisturbed Highfield soil aggregates, at 25°C, and at a matric water potential of \( \psi = -30 \) hPa, increased with increasing quantities of SOC. The basal respiration rate, \( E_0 \), increased almost linearly with SOC content and may be represented by the regression equation,

\[
E_0 = 0.31 \text{SOC} - 1.43, \quad r^2 = 0.91^{**} \quad (\pm 0.03) \quad (\pm 0.81)
\]

where the numbers in parenthesis are the standard errors of the values immediately above them. The respiration rates measured and the magnitudes of these effects are similar to those reported for other soils (e.g., Sommers et al., 1981). Lower respiration rates for aggregates with less SOC, reflect not only less and possibly poorer quality substrate for microbial activity, but also that these soils have been subject to previous mechanical disturbance during cultivation. This has been shown to cause a reduction in active microbial biomass and fungi (Beare et al., 1994). In addition, larger numbers of macro pores were measured in the aggregates with greater amounts of SOC, collected from these plots (Watts and Dexter, 1997). This is likely to have improved their aeration status, easing the movement of gas into, and out of these aggregates.

3.2. Effects of gravimetric soil water content

Fig. 5 shows that respiration of undisturbed Boot Field soil aggregates, measured in the laboratory,
increased with increasing gravimetric water content up to just beyond the soil plastic limit, (British Standard 1377, 1975). This is often taken as the upper limit for most cultivation operations. This soil swells and shrinks normally (i.e., a change in the volume of water in a sample causes a similar change in the total volume of the sample). With such soils the air-filled porosity does not change much with water content. Therefore, the effects shown in Fig. 5 may represent the true effects of water potential on the soil organisms without any confounding effects caused by anaerobic zones at higher water contents.

These data may be represented by a gompertz curve. Assuming respiration is zero at zero water content, then

\[ E_0 = a_1 \exp(-\exp(a_2 - a_3 \theta)), \]  

where \( a_1, a_2, \) and \( a_3 \) are constants and \( \theta \) represents the gravimetric soil water content, g kg\(^{-1}\). For these data the constants are \( a_1 = 5.783 \) (±0.476), \( a_2 = 2.401 \) (±0.700) and \( a_3 = 0.0117 \) (±0.0034). The numbers in brackets represent their standard errors.

### 3.3. Effects of mechanical energy inputs

The structural changes to aggregates, brought about by the falling weight were not measured during these experiments. However, the level of structural damage (in terms of mechanically dispersed clay) to these soils, at this water potential and using this equipment, have been measured previously (Watts and Dexter, 1997). These results showed that the arable soils (SOC 11–21 g kg\(^{-1}\)) yielded up to 10 times the quantity of dispersible clay compared to grassland soils (SOC 28–32 g kg\(^{-1}\)) for a \( K \) of 150 J kg\(^{-1}\). During this experiment, we observed that this level of mechanical energy caused major disruption to the arable aggregates; crushing and changing their shapes. In contrast, the application of energy to aggregates from the grassland soils, just rearranged the very stable 1–2 mm diameter sub aggregates, without appearing to disrupt their internal structure.

Examples of cumulative respiration curves for Highfield soils with and without mechanical energy inputs are shown in Fig. 6. Mean rates of respiration during the 0–4 h \( (E_1) \) and 4–24 period \( (E_2) \) following energy inputs are given separately in Table 3. In all cases, mechanical energy inputs resulted in a greater respiration rates. In the initial period (0–4 h) each of the cumulative CO\(_2\) emission curves increased sharply corresponding to an early burst of respiration. The detailed shape of these respiration peaks was not obtained due to the limited resolution and time response of the respirometers. However, respiration rates during this period, for all five soils, were significantly greater \( (P<0.001) \) than basal respiration rates. \( E_1 \) was on average 1.83 times the \( E_0 \), but the ratio, \( E_1/E_0 \) appears independent of SOC, (Table 3).

Calculations show that this initial burst of respiration was an order of magnitude greater than would have been expected by just stripping CO\(_2\) from the internal air, within the respirometer. Also, there was no obvious initial burst shown in the basal results. This initial burst of respiration probably corresponds to the bursts of respiration observed by Rovira and Greacen (1957), and is consistent with the concept of a temporary increase in metabolic activity of microbes which were already active. Such a constant ratio is unlikely to be the result of exposure of previously physically-protected organic matter, because of the previous work which showed that these soils vary
significantly in their sensitivity to physical disturbance by mechanical energy inputs (Watts and Dexter, 1997).

Analysis of variance of the respirometer results, for all five soils during the 4–24 h period, show no significant difference in respiration rates ($E_2$), following the application of mechanical energy compared with basal values. However, the respiration responses show some variation between treatments. For each of the three arable soils, with the lower SOC contents (1.1–2.1 g kg$^{-1}$), the curves for $K^0$ and for $K^150$ J kg$^{-1}$, continue to diverge until the end of the 24 h experiment, (Fig. 6a). The resulting in respiration ratios ($E_2/E_0$), range from 1.10 and 1.14. These ratios are significantly greater than 1 (Table 3). These results support the concept that at low contents of SOC, mechanical energy input removes some of the physical protection and exposes some of the C compounds to microbial attack.

In contrast, Fig. 6b shows that following mechanical energy inputs on grassland soils, with higher SOC contents (2.8–3.2 g kg$^{-1}$), the increased respiration rate lasted only for the first 4 h or so. During the 4–24 h period, the cumulative CO$_2$ curves for these two soils are essentially parallel, and show no effect of mechanical energy on respiration. For these two soils the mean respiration ratios ($E_2/E_0$) were 1.0 and 1.2 and not significantly different to 1 (Table 3). When the soil has a high SOC content, the physical protection appeared to be better and the soil was better able to resist the mechanical disruption which removed this protection in more susceptible soils.

The results of this experiment are summarized in Table 3 and Fig. 7 which show clearly the greater

![Fig. 7. The influence of SOC on the respiration ratio, $E_2/E_0$, where $E_0$ were the basal respiration rates and $E_2$ were the steady state respiration rates, measured during the period 4–24 h following the application of 150 J kg$^{-1}$ mechanical energy to the soil. Aggregates were from the Highfield site and measurements were made at a water potential, $\psi$ of −30 hPa and a temperature of 25°C. Points marked ‘a’ are from arable plots and points marked ‘g’ were from grassland. Error bars represent standard errors and the detailed levels of statistical significance are given in Table 3.]

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<table>
<thead>
<tr>
<th>Treatment</th>
<th>Permanent fallow</th>
<th>Continuous arable</th>
<th>Ley-arable rotation</th>
<th>Reseeded grass</th>
<th>Permanent grass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basal respiration rate, $E_0$</td>
<td>1.88 (±0.08)</td>
<td>3.86 (±0.31)</td>
<td>3.79 (±0.07)</td>
<td>7.84 (±0.31)</td>
<td>8.25 (±0.03)</td>
</tr>
<tr>
<td>no energy input ($\mu$ CO$_2$ g$^{-1}$ h$^{-1}$)</td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>Respiration rate, $E_1$ (0–4 h after energy input) ($\mu$ CO$_2$ g$^{-1}$ h$^{-1}$)</td>
<td>3.82 (±0.09)</td>
<td>5.57 (±0.09)</td>
<td>7.36 (±0.07)</td>
<td>14.15 (±0.48)</td>
<td>15.88 (±1.44)</td>
</tr>
<tr>
<td>Respiration ratio $E_1/E_0$</td>
<td>2.03 (±0.13)$^b$</td>
<td>1.44 (±0.14)$^b$</td>
<td>1.94 (±0.05)$^b$</td>
<td>1.81 (±0.13)$^b$</td>
<td>1.92 (±0.18)$^b$</td>
</tr>
<tr>
<td>Respiration rate, $E_2$ (5–25 h after energy input) ($\mu$ CO$_2$ g$^{-1}$ h$^{-1}$)</td>
<td>2.06 (±0.07)</td>
<td>4.42 (±0.13)</td>
<td>4.33 (±0.08)</td>
<td>7.98 (±0.18)</td>
<td>8.22 (±0.25)</td>
</tr>
<tr>
<td>Respiration ratio $E_2/E_0$</td>
<td>1.10 (±0.04)$^d$</td>
<td>1.14 (±0.02)$^b$</td>
<td>1.14 (±0.04)$^c$</td>
<td>1.02 (±0.06)$^c$</td>
<td>1.00 (±0.03)$^e$</td>
</tr>
</tbody>
</table>

$^a$ Numbers in brackets represent standard errors.

$^b$ Represent the ratio of significance different from 1.00 at $P<0.01$.

$^c$ Represent the ratio of significance different from 1.00 at $P<0.02$.

$^d$ Represent the ratio of significance different from 1.00 at $P<0.10$.

$^e$ Not significant.
resilience, or ability to resist mechanical energy inputs, of the grass plots. It is not obvious whether this difference is primarily because of higher SOC contents of the grass plots or because they are not mechanically influenced by periodic cultivation. It will be difficult to resolve this question because these two factors are not independent.

3.4. Field measurements

The CO₂ production rates associated with differing cultivation intensities are illustrated in Fig. 8. Elevated respiration rates were measured for periods ranging from 12 h to more than 8 days.

On the Boot Field site (Fig. 8a) high energy cultivation (the p.t.o. powered rotor spike cultivator) stimulated an increase in soil respiration to around 80 mg CO₂ m⁻² h⁻¹ for 5 days followed by a steady decrease to 25 mg CO₂ m⁻² h⁻¹ during the subsequent 3 days. The low energy cultivation system (the draught powered Dyna Drive cultivator) yielded a higher respiration rate than the basal rate, (untilled soil) reaching a maximum value of 46 mg CO₂ m⁻² h⁻¹. Basal respiration rates on this site varied between 15 and 35 mg CO₂ m⁻² h⁻¹ with higher values associated with higher soil temperatures. During the period of these measurements the initial soil water content was 380 g kg⁻¹ reducing to 320 g kg⁻¹ on the untilled soil, 250 g kg⁻¹ on the low energy plot and 240 g kg⁻¹ on the high energy plot.

On the Pavilion Field, cultivation stimulated higher soil respiration during the initial 12 h (Fig. 8b). Subsequently there was no clear or consistent difference between the treatments. Basal respiration on this site was in the 10–20 mg CO₂ m⁻² h⁻¹ band and declined with soil temperature. Following cultivation, the maximum respiration on this site was 34 mg CO₂ m⁻² h⁻¹. Soil water content on this site was very low with an initial value of 75 g kg⁻¹ which decreased to 61 g kg⁻¹ on both tilled plots.

Differences between both sites in terms of elevated respiration rates following cultivation, may be attributed to several factors. The clay soil of Boot Field contains greater SOC than does the sandy loam of Pavilion Field (Table 2). Craswell and Waring (1972) found soil type to be a major influence on SOC decomposition, with clay soils being particularly sensitive to mechanical energy inputs. Physically-protected organic matter depends strongly on the clay content, as biomass adheres mainly to the clay fraction (Rovira and Greacen, 1957; Oades, 1988). The smaller amount of SOC in Pavilion Field contributes to its weaker structure which is more readily broken down by tillage. The tilled produced by the cultivation operations were quantified in terms of mean-weight diameters (MWD). In Boot Field, MWDs of 13.08 and 10.39 mm were produced by the low and high energy treatments respectively, whereas in Pavilion Field, the corresponding values were 4.99 and 3.41 mm. These differences in tilled may influence the soil aeration status and hence respiration although this effect was not investigated separately in these experiments.

Water content at the time of the cultivation was greater in Boot Field, (380 g kg⁻¹) than in Pavilion Field, (75 g kg⁻¹) and this has been shown to increase the effect of cultivation on soil micro structure (McGarry, 1989; Watts et al., 1996a,b). However drying of this site following cultivations may be in...
part responsible for the reduction in respiration rates, particularly days 6, 7 and 8 on the high energy plot. Basal respiration may also have been influenced by changes in soil water content but in general appears to follow the pattern of soil temperatures at both sites. No significant difference was recorded in this experiment between cultivated and uncultivated soil temperatures.

Future field experiments should have a greater level of replication to allow a proper statistical analysis of the results to be done. However, these field experiments clearly show that cultivation stimulates a greater level of soil respiration, but the associated effects of temperature, water content and aeration status are more easily studied separately under controlled laboratory conditions.

Additional research is required to look in detail at the effects of different soil types, different energy levels and different soil water potentials. The implications of these increased rates of C loss for the dynamics of soil organic matter in relation to soil management systems need further study. In future research, it is important that not only the different inputs from the different crops are considered but also the effects of the different tillage systems, in terms of the effects their energy inputs, on C losses by aerobic respiration.

4. Conclusions

1. The falling weight apparatus provided a simple, reliable and repeatable method for applying known inputs of mechanical energy to soil aggregates. The conductimetric respirometers worked well in the laboratory and provided a simple and accurate non-destructive method for monitoring respiration from batches of soil aggregates.

2. Basal respiration measured on Chromic Luvisol aggregates, was found to increase with increasing SOC, from 1.88 μg CO₂ g⁻¹ h⁻¹ for a permanent fallow soil (SOC=11 g kg⁻¹) to 8.25 μg CO₂ g⁻¹ h⁻¹ for a permanent grassland soil (SOC=32 g kg⁻¹).

3. Basal respiration of a Calci C Cambisol, more than doubled from 2.0 to 5.2 μg CO₂ g⁻¹ h⁻¹ with an increase in gravimetric soil water content from 200 to 500 g kg⁻¹. This covers the normal range of water contents for cultivating this soil.

4. At a matric water potential, ψ, of −30 hPa, mechanical energy inputs of about 150 J kg⁻¹ resulted in bursts of respiration which lasted up to 4 h. This burst of respiration was larger by a factor of 1.83 than the basal respiration rate, and this factor was independent of the soil organic carbon content.

5. For the period from 4–24 h after energy input, respiration rate was increased by a factor of around 1.14 following the application of 150 J kg⁻¹ of specific energy for soils with a SOC in the range of 11–21 g kg⁻¹, but were not increased for the two grassed plots (SOC, 28–32 g kg⁻¹).

6. In the field, tillage was found to stimulate increased levels of soil respiration for periods ranging from 12 h to more than 1 week. The highest respiration rates and longest duration were associated with high energy tillage on clay soils. Changes in soil temperature and water content following tillage are likely to have had a major effect on the results.

7. The application of known quantities of mechanical energy to soil aggregates under laboratory conditions, in order to simulate the effect of different cultivation practices, when combined with the subsequent measurement of soil respiration, can provide useful indication of the likely consequences of soil management on SOC.

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