Section 3

Field Measurements of Carbon Loss Due to Ploughing

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3. Field measurements of carbon loss due to ploughing

P.E. Levy, K.J. Hargreaves, R. Milne and T.D. Murray.
CEH Edinburgh, Bush Estate, Penicuik, Midlothian, EH26 0QB
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3.1. Introduction

Globally, it is estimated that around 50 Pg C have been emitted to the atmosphere from soils, following conversion of natural land to cultivated, agricultural land (Paustian *et al.* 2000). The physical basis for this is that disturbance associated with intensive soil tillage increases the turnover of soil aggregates and accelerates the decomposition of aggregate-associated soil organic matter (SOM). However, the number of experimental data quantifying this effect are rather small, and there are no experimental data from the UK. The UK carbon inventory of sources and sinks due to land use change (Milne 2003) requires this information, as it is based on a matrix of transitions between different land use types, and the fluxes arising in these transitions. Grassland soils represent a substantial part of the terrestrial carbon stocks in the UK, and there are potentially large losses when these are cultivated, either for conversion to arable land or for improvement of pasture. Here, our aim was to measure the losses of soil carbon following ploughing of a previously uncultivated grassland.

Whilst the equilibrium soil carbon pool after any given land use conversion will depend on the system to which it is converted, here we focus on the losses which occur in the period of transition. To this end, the system was maintained in a bare state following ploughing by applying herbicide, and so our measurements represent an upper limit to the carbon loss from grassland when it is disturbed by ploughing.

3.2. Methods

Three measurement techniques were used to measure carbon stocks and fluxes at a field site in south west Scotland.

3.2.1. Field site and treatment

The site chosen for the study was at Poldean farm, near Moffat in south west Scotland (grid reference NT 111004 (N55:17:22, W3:24:08), altitude of 196 m). It is a livestock enterprise with extensive permanent pasture receiving fertiliser and manure inputs. The site was chosen on the basis of good meteorological conditions, an appreciable organic layer indicative of a long-term permanent pasture and a cooperative farmer. Further site details can be found in Hargreaves *et al.* 2001.

An area of 200 x 200 m was fenced in November 2000 to exclude sheep and cattle. The experiment had been due to start in February 2001, but was delayed by the outbreak of foot and mouth disease on the farm, which prevented access for several months. By the time foot and mouth restrictions were lifted, winter weather and wet ground conditions delayed work until the following spring.

In April 2002, the fenced experimental area was first treated with glyphosate herbicide to kill existing vegetation. The field was then flailed in May 2002 to break up the surface and make ploughing easier. The site was ploughed, with considerable difficulty, on 5 June 2002, to a depth of 15 cm, although the heavy soil conditions meant that this was quite variable.

Two further treatments of glyphosate were applied on 15 July 2002 and 18 September 2002 to prevent regrowth of the vegetation. In the latter case, the application was delayed for around two weeks owing to heavy rain during the first few days of September, and this allowed some weed growth over the field before the glyphosate became effective.

The following year, a further treatment of glyphosate was applied in May 2003 and the area was cultivated by disking in June 2003. A final treatment of glyphosate was applied in September 2003. As in 2002, this application was delayed by unavailabilty of the contractor at harvest time, and some significant weed growth had taken place before the glyphosate became effective. The experiment was ended in April 2004, when instrumentation was removed and the field prepared for re-seeding. Throughout the period of the experiment, the land adjacent to the experimental area was kept in normal use, as pasture for sheep and cattle, and this is considered as a control area.

3.2.2. Eddy covariance measurements

A micrometeorological approach, eddy covariance, was used to make near-continuous measurements of the surface exchange of carbon dioxide (CO_2) over the experimental area and the control area. The eddy covariance flux measurement system was sited on the NE edge of the experimental area, so that the most common, south-westerly wind direction would allow measurements to be made over the ploughed area. Northerly winds would allow measurements to be made over the control area. Full details of the instrumental techniques may be found in Hargreaves *et al.* 1998,Hargreaves *et al.* 2001, and Hargreaves *et al.* 2003. In brief, the net flux of CO_2, F_c, is given by:

$$F_c = \overline{w'\chi} \qquad [1]$$

where w' is the instantaneous deviation of the vertical windspeed from the mean, and χ is the instantaneous deviation of the CO_2 concentration from the mean. The three components of windspeed were measured at 20 Hz by a Metek ultrasonic anemometer (Model USA1, METEK GmbH, Elmshorn, Germany), mounted at a height of 1.75 m. Air was sampled continuously from a point close to the anemometer down stainless steel tubing (0.25 inch diameter, Dekeron Corp. Illinois, USA) at a flow rate of 5 l /min. CO_2 and H_2O concentrations were measured by an infra-red gas analyser (IRGA)(LI-6262, Licor Corp., Nebraska, USA) with a response time 6.3 Hz. Analogue outputs from the IRGA were passed to the ultrasonic anemometer where they were digitised. A laptop PC, running a LabView software package, logged the data from these instruments and carried out the eddy covariance calculations.

A Campbell 23X datalogger controlled switching of the power supply, and provided remote telemetry via the mobile telephone network. Supporting meteorological measurements included solar radiation, photosynthetically active radiation (PAR), soil and air temperature, relative humidity, soil moisture, and rainfall. Power was supplied by a Rutland model 910-3 Furlmatic wind turbine and four 60W solar panels with a total area of 2 m^2. These charged an array of deep-cycle sealed lead-acid batteries with a total capacity of 700 Ah. The 23X datalogger controlled power consumption by switching off sample pumps and the Licor gas analyser when meteorological conditions were unsuitable for eddy covariance measurements, or battery voltage was too low. Otherwise the system was kept running from May 2002 to April 2004, with occassional breaks for instrument maintenance or lack of power.

In order to produce an estimate of the long-term carbon balance, gaps in the measurement data were filled using standard methodology (Aubinet *et al.* 2000). This involved fitting simple models based on light and temperature responses to the measurement data, and using the fitted models to interpolate the missing values. For daytime values over the control area, data were fitted to the following model:

$$F_{NEE} = F_{RE_{DAY}} - F_{GPP_{OPT}} \left(1 - \exp\left[\frac{a' S_t}{F_{GPP_{OPT}}} \right] \right) \qquad [2]$$

where F_{NEE} is the net ecosystem exchange of CO_2 ,F_{REDay} is the daytime ecosystem respiration rate, F_{GPPopt} is the gross primary production, S_{t} is the solar radiation flux and *a*' is a fitted parameter. Night-time fluxes, and all fluxes over the ploughed area were fittted to the model:

$$F_{NEE} = d \exp(eT_a) \qquad [3]$$

where *d* is a fitted parameter and T_{a} is air or soil temperature. Where linear regression gave a better fit to the data, this was used instead.

3.2.3. Chamber measurements

A static chamber technique was used to measure fluxes of methane (CH_4) and nitrous oxide (N_2O). A plastic cylindrical collar, 30 cm in diameter , was placed in the soil up to a depth of around 2 cm, sufficent to provide an air-tight seal. These were left in place for at least 30 minutes (usually several weeks) before measurements, to remove effects of initial disturbance. At the start of measurements, a lid was sealed on top, and left for around an hour. An air sample was then drawn out of the chamber through a valve, using a gas syringe, and stored in a gas sample bag. A sample of ambient air was also taken, representing the concentration at the start of the measurement. Samples were then analysed in the lab using a tunable diode laser (TDL) to measure CH_4 and N_2O concentrations. Fluxes were calculated from the change in concentration over the measurement period. Measurements were made every month, in both the experimental area and the control area, with two replicates in each.

3.2.4. Soil carbon measurements

Before and after ploughing (in October 2000 and November 2003), soil samples were taken for analysis of carbon content. Nine points in the experimental area were surveyed, and five cores taken at each point, dividing each core into 5cm depth intervals up to 25 cm. The same points were sampled on both occassions. Samples were analysed by CEH Merlewood/Lancaster for organic carbon using Tinsley analysis, total carbon by loss on ignition, and bulk density. More details are provided by Jones *et al.* 2001. Because of the move of CEH Merlewood to Lancaster, chemical laboratory facilities were unavailable for much of 2003, and samples from November 2003 have yet to be analysed. As we do not yet have these data, this method is not discussed further in this report, but the results will go into a manuscript for journal publication within the next year.

3.3. Results

3.3.1. Short-term effect of ploughing on CO2 efflux – 1 month

On the day of ploughing (5 June 2002) micrometeorological measurements of CO_2 exchange were not possible as the wind was blowing from the north-east, thus carrying air over the ploughed area and away from the sensors. However, static chamber measurements were made over a period of 2 to 3 hours immediately following ploughing and although the spatial variability was large the mean emission rate of CO_2 was 5.5 µmol m^{-2} s^{-1} (Figure 3-1). This is approximately three times higher than the mean of pre-ploughing measurements. The first eddy covariance measurements after ploughing also indicate higher than average fluxes, although these tail off towards the end of the month. To represent this phenomenon, gap filling for the month of June 2002 was undertaken by fitting a 4th order polynomial to the measurements.

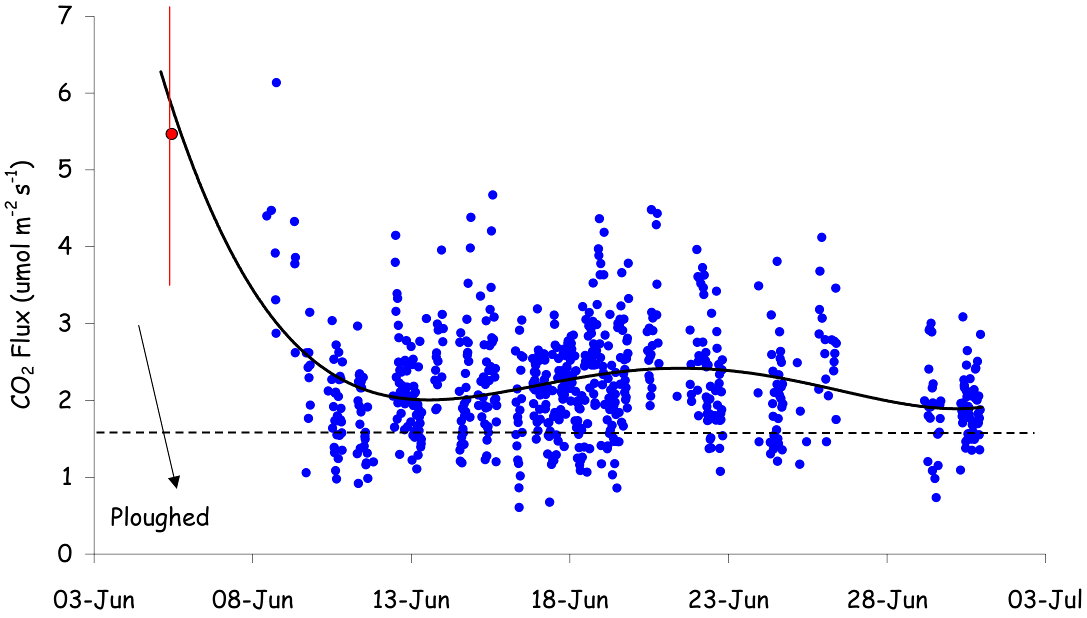


Figure 3-1: Carbon loss from the Poldean field immediately following ploughing. The single data point on 5 June denotes the mean ± 1 SD of chamber measurements of CO_2 release on the day of ploughing. The remainder of the data are from the eddy covariance system. The solid line is a 4th order polynomial fit to all the data. The dotted line shows the mean of all flux measurements before ploughing took place.

3.3.2. Medium-term effect of ploughing on CO2 efflux – 6 months

Figure 3-2 and Figure 3-3 show the loss of carbon in the first six months after ploughing. After the initial pulse immediately after ploughing, efflux rates fell back to lower values, and followed the seasonal time course in temperature, peaking in August and reaching a minimum in December. Over six months, this resulted in loss of almost 0.3 kg C m-2, or 2 % of total carbon in the top 15 cm of soil. Weather patterns were unfortunate in the late summer period, with the prevailing south-westerly winds required to make measurements over the ploughed site were very infrequent (Figure 3-4).

Figure 3-2: The time course of carbon loss from the ploughed Poldean site for the first six months from the date of ploughing (5 June 2002).

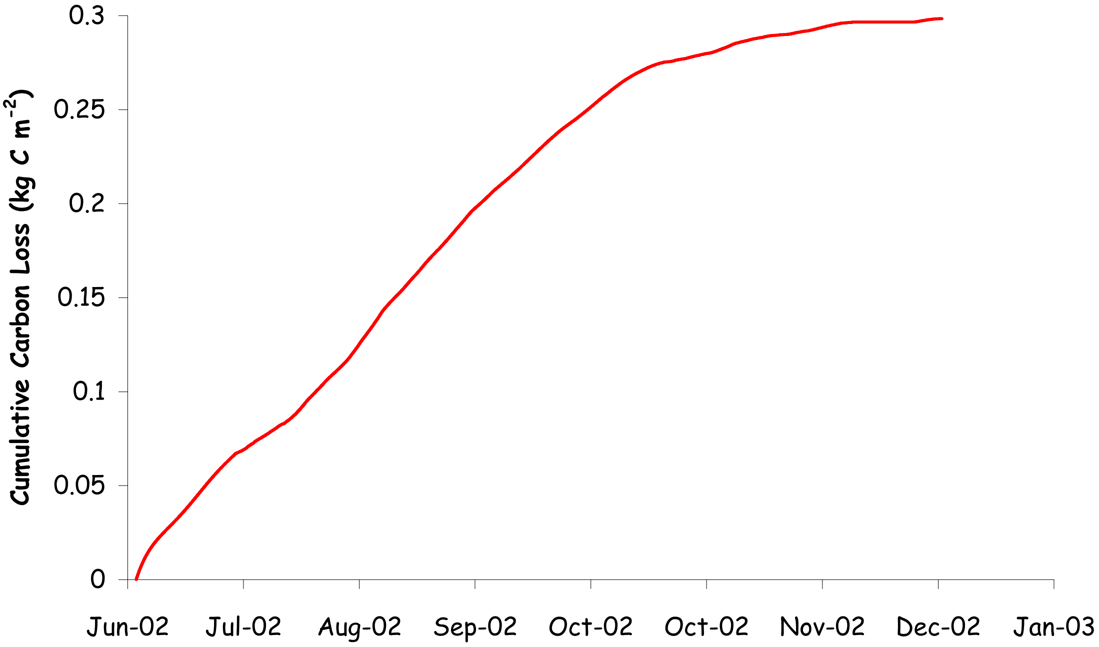
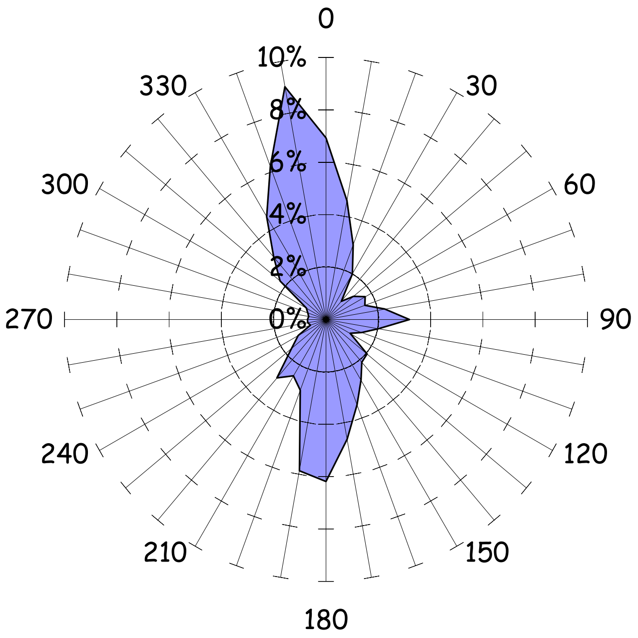


Figure 3-3: Cumulative carbon loss from the ploughed Poldean site for the first six months from the date of ploughing (5 June 2002).

August 2002



September 2002

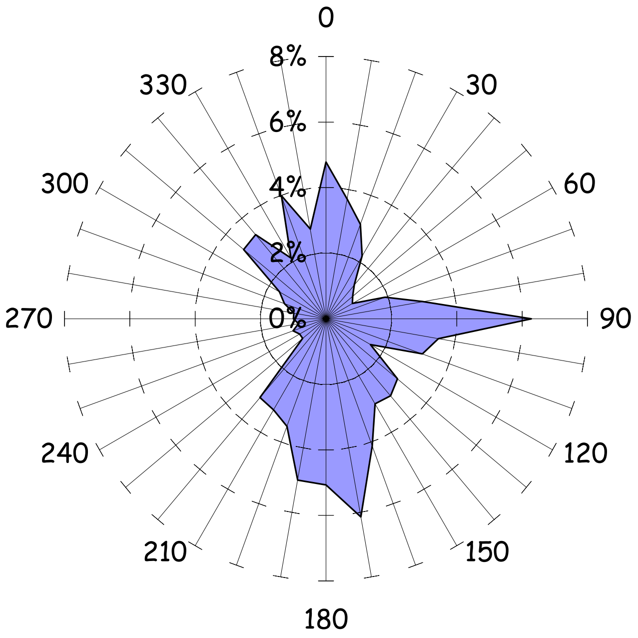


Figure 3-4: Wind roses for August/September 2002 at Poldean. The radial axis denotes the percentage of time wind blew from a particular direction (circumferential axis, degrees from north).

3.3.3. Gap-filling

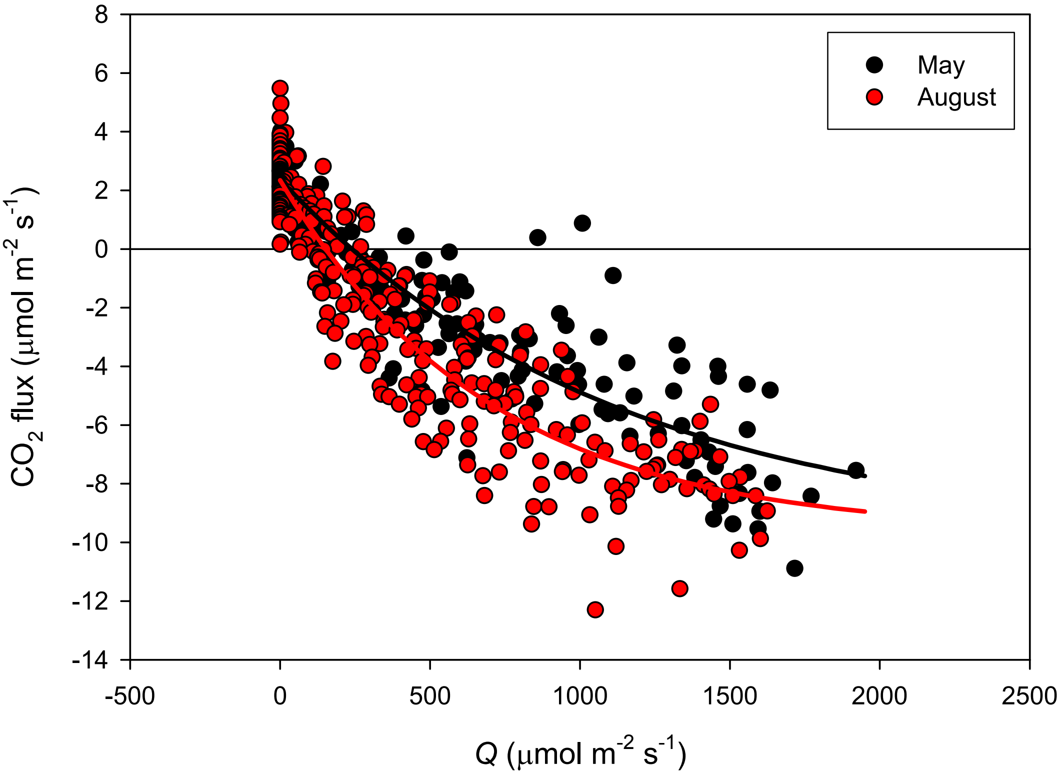


Figure 3-5: Light response curves for May and August 2003 from measurements over the control (unploughed) area. Solid lines show the model fitted to data for each month.

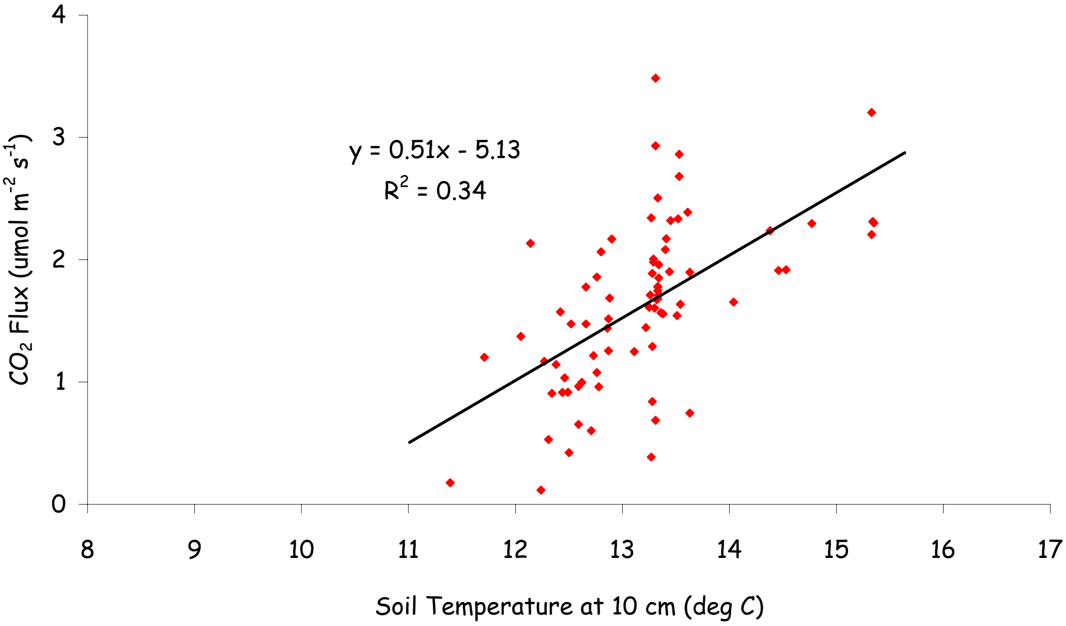


Figure 3-6: The dependence of CO_2 flux over the ploughed field at Poldean on soil temperature, July 2002.

For each month, daytime measurement data over the control area were collated and the parameters of Equation 2 fitted using Genstat statistical software. Figure 3-5 shows fitted light response curves for May and August 2003. The original intention had been to perform the same fitting procedure to data from the ploughed area, using Equation 3. However, the signal-to-noise is much lower in these data because the monthly range in soil temperature is rather small, often only 3-4 degrees (cf. solar radiation, which ranges from zero to near the maximum possible each month). Figure 3-6 shows an example, where temperature explains only 34 % of the variance in the data. Added to this were the reductions in data quantity because of filtering for windspeed, wind direction, and power supply. It was therefore decided to pool these data over the whole annual period and fit Equation 3 to the pooled set. Figure 3-7 shows that efflux rates from the ploughed area tended to be lower than from the unploughed area. This could be a result of the additional respiration of living plants in the unploughed area, or a reduction in soil respiration in the ploughed area after the initial pulse.

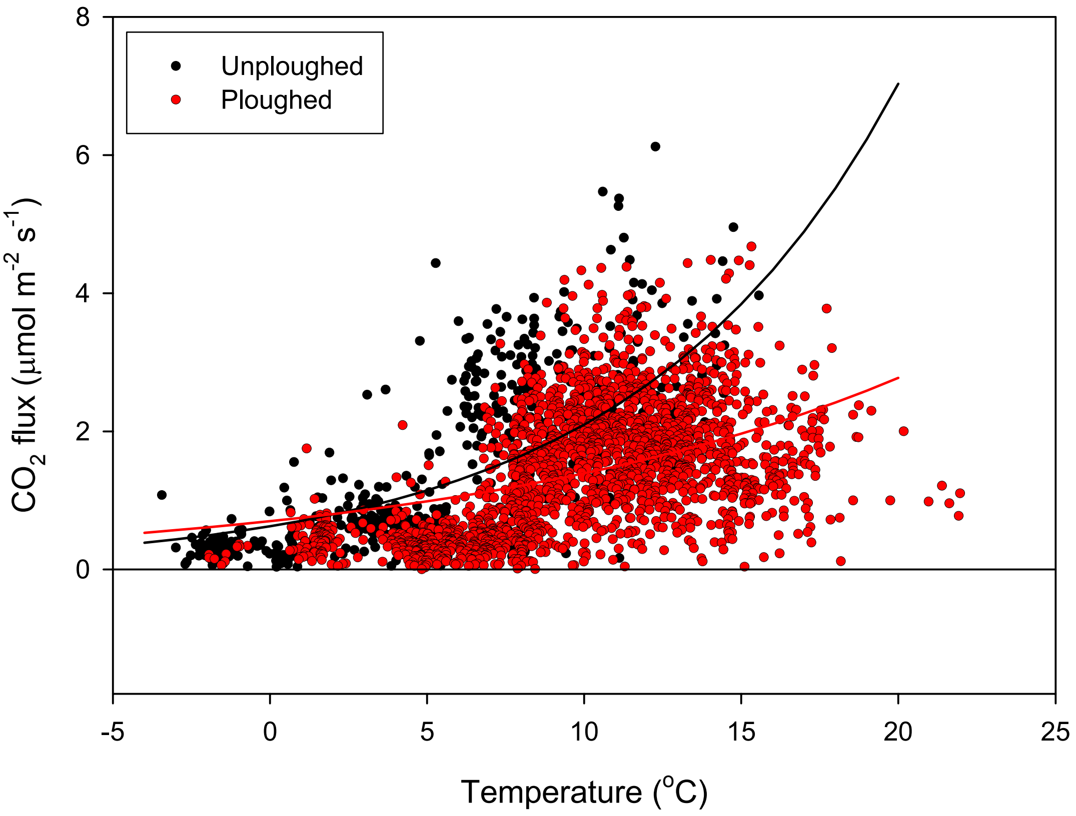


Figure 3-7: Temperature responses of CO_2 efflux from ploughed and unploughed areas. Only nocturnal values for the unploughed area are shown.

3.3.4. Medium to long-term effect of ploughing on CO2 efflux – 12-24 months

Figure 3-8 shows the gap-filled data set for the 20 months following ploughing (the last four months still require re-analysis at the time of writing). Data coverage is somewhat sparse, as it is split over the two plots (so could be maximum of only 50 % over either), as well as filtering out of low windspeeds etc. However, seasonal patterns are visible in both data sets, and the gap-filling models account for a high enough fraction of the variance to give confidence in the estimated long-term cumulative fluxes. Figure 3-9 shows after nearly two years, around 0.8 kg C m^{-2} have been lost from the ploughed area, whilst the unploughed has remained approximately

in balance (a slightly positive source term, but zero is well within the margins of error). The ploughed area has thus lost an average of 3.7 % of the total carbon in the top 15 cm of soil per year.

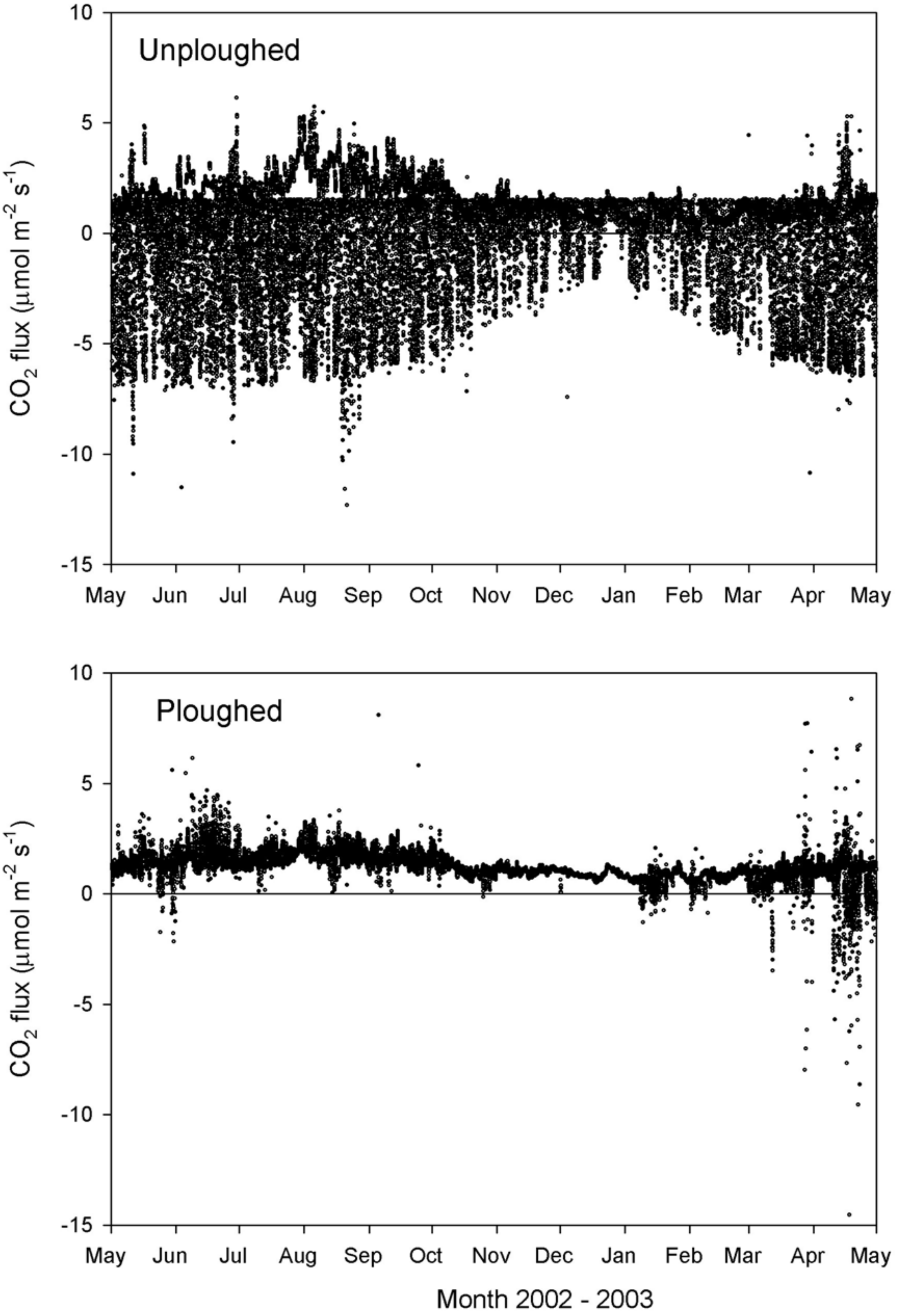


Figure 3-8 : Raw data set from the ploughed and unploughed areas at the Poldean site for 20 months from the date of ploughing

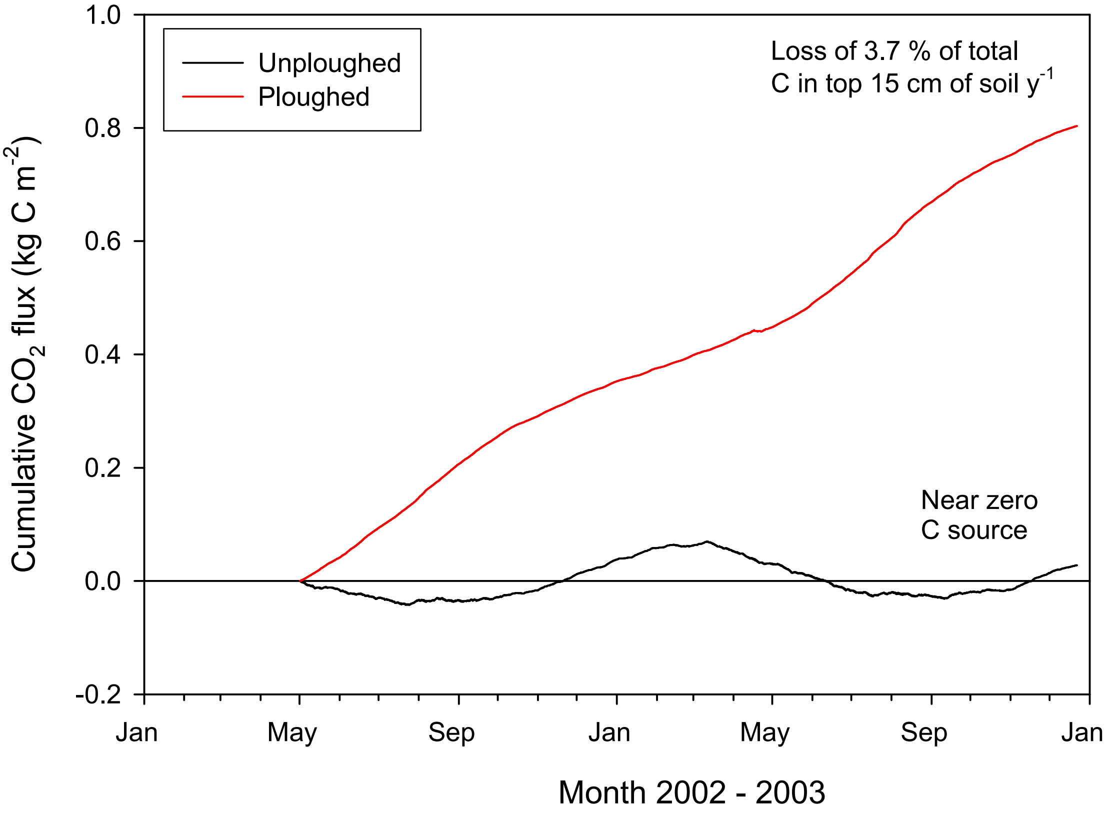
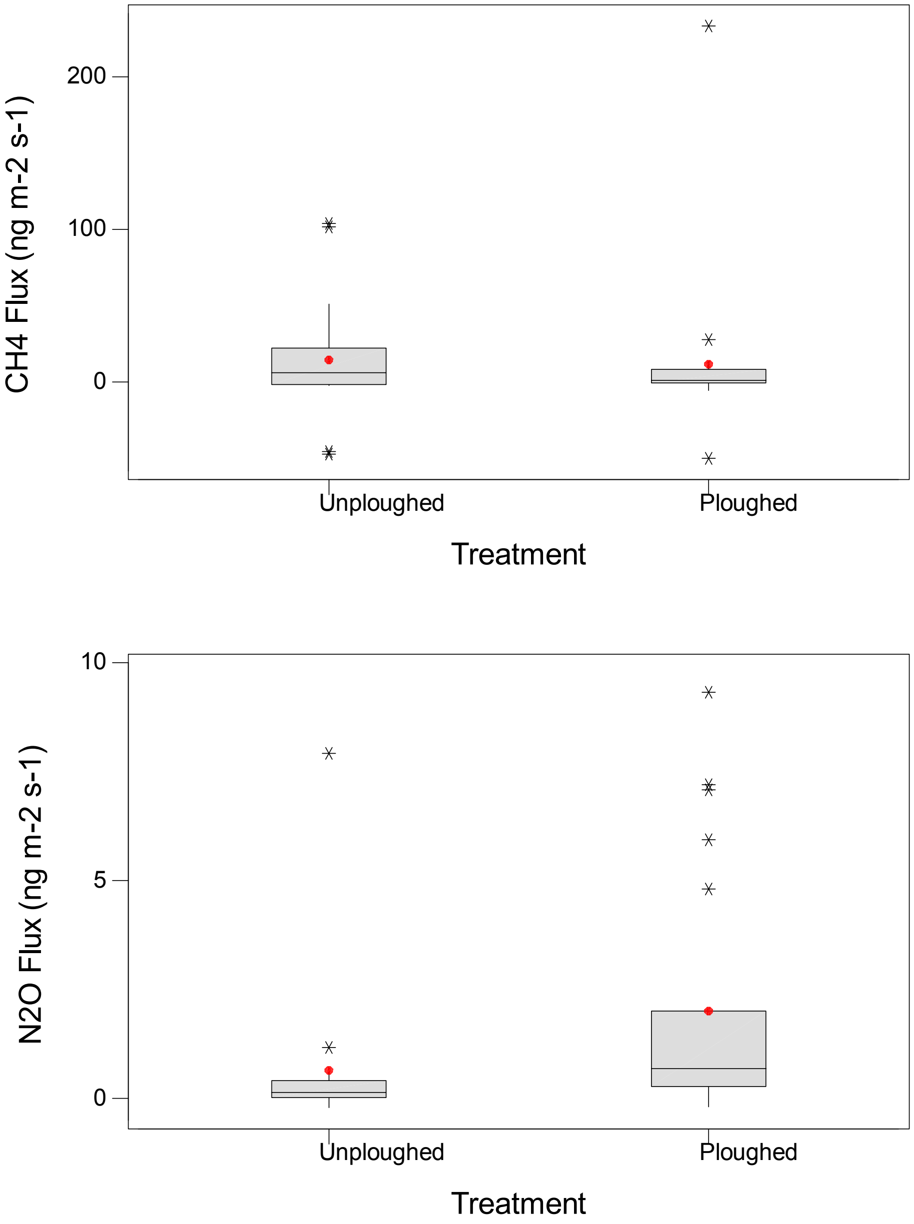


Figure 3-9: Cumulative carbon balance for the ploughed and unploughed areas for 20 months from the date of ploughing

3.4. Chamber measurements

Figure 3-10 shows a comparison of the CH_4 and N_2O fluxes in the ploughed and the unploughed areas. There is considerable variability in the measurements, seemingly caused by small-scale spatial heterogeneity. No clear differences between the treatments is apparent. Treating the data measured in the two areas on the same day as paired samples, to account for temporal variation, does not yield a statistically significant result.



(Boxes show interquartile range. Means are indicated by solid circles, medians by horizontal lines. Asterices show outliers.)

Figure 3-10: Comparison of CH_4 and N_2O fluxes measured using static chambers in the ploughed and the unploughed areas.

3.5. Discussion

Figure 3-1 shows reasonable evidence for a short-term effect of ploughing on soil CO_2 efflux. Within the first few days after ploughing, this may be caused by a purely physical phenomenon, whereby CO_2 stored in the soil is able to diffuse out much more easily (Reicosky *et al.* 1997, Ellert and Janzen 1999, Reicosky *et al.* 1999, Watts *et al.* 2000, La Scala *et al.* 2001, Calderon and Jackson 2002, Wuest *et al.* 2003). Some experiments have found no effect of purely mechanical energy inputs typical of those induced by tillage (Dexter *et al.* 1999). A longer-term phenomenon, lasting a few months has been observed in several other experiments (Dao 1998, Eriksen and Jensen 2001, Kisselle *et al.* 2001), and is most likely to be caused by physical changes affecting the biological processes – improved aeration, breakdown of soil aggregates etc.

Over the medium term, results can be interpreted as the effect of converting to arable, when herbicide would be applied before sowing, and the land would be bare of vegetation for a number of months. The timing and duration of the period when the land is bare would have a substantial effect on the total emission, as respiration rates are higher in the summer than the winter. Over the first six months measured here (June-December), this resulted in loss of almost 0.3 kg C m-2, or 2 % of total carbon in the top 15 cm of soil. The same interpretation cannot be applied to the full two-year data set, as in practice, the land would not be bare for such an extended period. The value of this longer data set is to examine whether the dynamics of soil carbon loss change over the period considered. This is valuable, as most experiment consider fluxes over only relatively short periods. Figure 3-2 and Figure 3-9 suggest that, after the initial elevated efflux of carbon from the soil in the first month, there is no marked change in the behaviour of the system. Other workers have found differences in soil effluxes persisting for many years where treatments have been repeated annually (Franzluebbers and Arshad 1996b, Lee *et al.* 1996, Sanchez *et al.* 2002, Saviozzi *et al.* 2001, Seybold *et al.* 2002, Sparling *et al.* 1992). We note that there are also several experiments which have little difference in long-term soil efflux rates (Franzluebbers and Arshad 1996a), or higher effluxes in unploughed treatements (Kandeler and Bohm 1996, Plante and McGill 2002).

Table 3-1 shows a comparison of the greenhouse warming potential (GWP) of the three gases measured here. In both treatments, CO_2 is the dominant term. CH_4 and N_2O fluxes are only significant when considered as a fraction of the total in the unploughed area, where the CO_2 source is very small, but the absolute numbers are relatively negligible.

Table 3-1: Greenhouse warming potential (GWP) of the three gases measured at Poldean in the ploughed and unploughed areas. GWPs are calculated in terms of CO_2 equivalents, assuming standard IPCC values for the multiplicative factors for N_2O and CH_4.

Unploughed	t CO_2 ha^{-1} yr^{-1}	t N_2O-N ha^{-1} yr^{-1}	t CH_4-C ha^{-1} yr^{-1}	GWP: t C-CO_2 ha^{-1} yr^{-1}
CO_2 Exchange	0.29			0.29
N_2O Exchange		0.0002		0.06
CH_4 Exchange			0.004	0.10
Total GWP				0.45
Ploughed				
CO_2 Exchange	4.45			4.45
N_2O Exchange		0.0006		0.19
CH_4 Exchange			0.003	0.08
Total GWP				4.72

The advantages of our approach are 1. a much more complete temporal set of records, compared with relatively infrequent chamber measurements; 2. a realistic, field-scale experimental treatment, using typical agricultural machinery, and; 3. a relatively long time scale. The main disadvantage of our approach is the lack of further appropriate control treatments. To discern the affect of ploughing *per se*, we would need an unploughed treatment with herbicide. The difference between the flux from this and and the ploughed treatment would allow us to quantify the effect of ploughing independently of the effect of herbicide. However, this would require twice the area of land to be taken out of production for the experiment (to achieve an appropriate fetch for micrometeorological measurements), and be twice as expensive in compensation payments. Given limited funds, we did not have such a treatment, meaning that our results are respresentative of what actually commonly happens in practice (over the first few months), but their interpretation in terms of the effects of ploughing and herbicide is more difficult. A further experiment with this extra control would be useful in aiding the interpretation of these results. This could be at the plot scale, using chambers (static or dynamic) instead of eddy covariance, and be on a small enough scale to require only a small area of land.

Ultimately, the data presented here will be most useful for validating process-based models of soil carbon dynamics. Soils are the major store of carbon within terrestrial ecosystems in the UK, and predicting changes resulting from changes in land use or climate requires a process-based model. Historically, such models have been developed for conditions typically encountered in intensive agricultural systems, such as arable crops and improved pasture, where mineral soils predominate. However, much of the soil carbon within the UK is found in highly organic soils, in upland areas where land management is restricted, and the climate is cool and wet. Existing soil models (such as RothC) fail to capture the dynamics of carbon in these highly organic soils, largely because of differences in soil chemistry, soil fauna and microbial community composition**.** Basic measurements of the model parameters (turnover rates, pool sizes) and variables (carbon fluxes in, out & between pool) necessary for validation are needed. This would be a further direction for future work.

One possible site for these measurements is Moor House, Teesdale, typical of much of the upland peat areas in the UK, where other soil process studies are ongoing. One direct interest here would be to establish whether these peatlands are degrading or agrading, as they have the potential to act as a major source or sink for carbon. Carbon balance of these peatlands will be affected by climate change, elevated CO_2, nitrogen deposition and changes in land use (grazing pressure, management for grouse etc.). The Moor House site is part of the Environmental Change Network, and many long-term monitoring studies have been made on the catchment since the International Biological Programme in the 1970s, and as a flagship site of TIGER in the 1990s. Long-term records are available for meteorology, hydrology, stream water chemistry and vegetation. Mechanistic modelling based on the measurements and the existing records will be used to predict the longer term changes in carbon storage in this area.

3.6. References

Aubinet, M., Grelle, A., Ibrom, A., Rannik, U., Moncrieff, J., Foken, T., Kowalski, A.S., Martin, P.H., Berbigier, P., Bernhofer, C., Clement, R., Elbers, J., Granier, A., Grunwald, T., Morgenstern, K., Pilegaard, K., Rebmann, C., Snijders, W., Valentini, R. and Vesala, T. (2000) Estimates of the annual net carbon and water exchange of forests: The EUROFLUX methodology. *Advances in Ecological Research*, 30, 113-175.

Calderon, F.J. and Jackson, L.E. (2002) Rototillage, disking, and subsequent irrigation: Effects on soil nitrogen dynamics, microbial biomass, and carbon dioxide efflux. *Journal of Environmental Quality*, 31, 752-758.

Dao, T.H. (1998) Tillage and crop residue effects on carbon dioxide evolution and carbon storage in a Paleustoll. *Soil Science Society of America Journal*, 62, 250-256.

Dexter, A.R., Arvidsson, J., Czyz, E.A., Trautner, A. and Stenberg, B. (1999) Respiration rates of soil aggregates in relation to tillage and straw-management practices in the field. *Acta Agriculturae Scandinavica Section B-Soil and Plant Science*, 49, 193-200.

Ellert, B.H. and Janzen, H.H. (1999) Short-term influence of tillage on CO2 fluxes from a semi-arid soil on the Canadian Prairies. *Soil & Tillage Research*, 50, 21-32.

Eriksen, J. and Jensen, L.S. (2001) Soil respiration, nitrogen mineralization and uptake in barley following cultivation of grazed grasslands. *Biology and Fertility of Soils*, 33, 139-145.

Franzluebbers, A.J. and Arshad, M.A. (1996a) Soil organic matter pools during early adoption of conservation tillage in northwestern Canada. *Soil Science Society of America Journal*, 60, 1422-1427.

Franzluebbers, A.J. and Arshad, M.A. (1996b) Soil organic matter pools with conventional and zero tillage in a cold, semiarid climate. *Soil & Tillage Research*, 39, 1-11.

Hargreaves, K.J., Fowler, D. and Storeton-West, R.L. (1998) Long term changes in the carbon balance of afforested peatlands: Part 2. DETR Contract Report EPG 1/1/39, April 1998.

Hargreaves, K.J., Milne, R. and Cannell, M.G.R. (2003) Carbon balance of afforested peatland in Scotland. *Forestry*, 76, 299-317.

Hargreaves, K.J., Murray, T.D. and Nemitz, E. (2001) Field measurements of carbon loss from soil following ploughing. Part 1: Flux measuring methods. DETR Contract Report EPG 1/1/160, April 2001.

Jones, H.E., Garnett, J.S., Hargreaves, K.J., Parrington, J. and Murray, T.D. (2001) Field measurements of carbon loss from soil following ploughing. Part 2: Carbon contents of soils along the proposed flux transect at Poldean Farm prior to ploughing.

Kandeler, E. and Bohm, K.E. (1996) Temporal dynamics of microbial biomass, xylanase activity, N- mineralisation and potential nitrification in different tillage systems. *Applied Soil Ecology*, 4, 181-191.

Kisselle, K.W., Garrett, C.J., Fu, S., Hendrix, P.F., Crossley, D.A., Coleman, D.C. and Potter, R.L. (2001) Budgets for root-derived C and litter-derived C: comparison between conventional tillage and no tillage soils. *Soil Biology & Biochemistry*, 33, 1067-1075.

La Scala, N., Lopes, A., Marques, J. and Pereira, G.T. (2001) Carbon dioxide emissions after application of tillage systems for a dark red latosol in southern Brazil. *Soil & Tillage Research*, 62, 163-166.

Lee, W.J., Wood, C.W., Reeves, D.W., Entry, J.A. and Raper, R.L. (1996) Interactive effects of wheel-traffic and tillage system on soil carbon and nitrogen. *Communications in Soil Science and Plant Analysis*, 27, 3027-3043.

Milne, R. (2003) UK Emissions by Sources and Removals by Sinks due to Land Use, Land Use Change and Forestry Activities. Annual report for Defra Contract EPG1/1/160.

Paustian, K., Six, J., Elliott, E.T. and Hunt, H.W. (2000) Management options for reducing CO2 emissions from agricultural soils. *Biogeochemistry*, 48, 147-163.

Plante, A.F. and McGill, W.B. (2002) Soil aggregate dynamics and the retention of organic matter in laboratory-incubated soil with differing simulated tillage frequencies. *Soil & Tillage Research*, 66, 79-92.

Reicosky, D.C., Dugas, W.A. and Torbert, H.A. (1997) Tillage-induced soil carbon dioxide loss from different cropping systems. *Soil & Tillage Research*, 41, 105-118.

Reicosky, D.C., Reeves, D.W., Prior, S.A., Runion, G.B., Rogers, H.H. and Raper, R.L. (1999) Effects of residue management and controlled traffic on carbon dioxide and water loss. *Soil & Tillage Research*, 52, 153-165.

Sanchez, M.L., Ozores, M.I., Colle, R., Lopez, M.J., De Torre, B., Garcia, M.A. and Perez, I. (2002) Soil CO2 fluxes in cereal land use of the Spanish plateau: influence of conventional and reduced tillage practices. *Chemosphere*, 47, 837-844.

Saviozzi, A., Levi-Minzi, R., Cardelli, R. and Riffaldi, R. (2001) A comparison of soil quality in adjacent cultivated, forest and native grassland soils. *Plant and Soil*, 233, 251-259.

Seybold, C.A., Hubbs, M.D. and Tyler, D.D. (2002) On-farm tests indicate effects of long-term tillage systems on soil quality. *Journal of Sustainable Agriculture*, 19, 61-73.

Sparling, G.P., Shepherd, T.G. and Kettles, H.A. (1992) Changes in Soil Organic-C, Microbial-C and Aggregate Stability under Continuous Maize and Cereal Cropping, and after Restoration to Pasture in Soils from the Manawatu Region, New- Zealand. *Soil & Tillage Research*, 24, 225-241.

Watts, C.W., Eich, S. and Dexter, A.R. (2000) Effects of mechanical energy inputs on soil respiration at the aggregate and field scales. *Soil & Tillage Research*, 53, 231-243.

Wuest, S.B., Durr, D. and Albrecht, S.L. (2003) Carbon dioxide flux measurement during simulated tillage. *Agronomy Journal*, 95, 715-718.

3.7. Acknowledgements

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