Section 10

Field measurements of carbon loss due to ploughing

Table of Contents

10. Field measurements of carbon loss due to ploughing 10-1

10.1. Introduction 10-1
10.2. Methods 10-1
10.2.1. Field site and treatment..10-1
10.2.2. Soil carbon measurements..10-2
10.2.3. Eddy covariance measurements 10-3
10.3. Results 10-4
10.3.1. Soil carbon measurements..10-4
10.3.2. Comparison with eddy covariance measurements 10-6
10.4. Discussion..10-7
10.5. References 10-11
10.6. Acknowledgements..10-11

10. Field measurements of carbon loss due to ploughing

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10.1. 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 at a field site in south west Scotland.

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.

The majority of this work has been reported previously (Levy *et al.*, 2004), but chemical analysis of the final soil samples was delayed by the move of CEH Merlewood to Lancaster, and were not available until October 2004. These samples were used to measure carbon stocks, and infer fluxes from the change over time. Here, we present the results of this method and compare it with the eddy covariance method.

10.2. Methods

Details of the field site and eddy covariance method are repeated here for convenience, but further details are given in Hargreaves *et al.*, 2001 and Levy *et al.*, 2004.

10.2.1. 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.

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.

10.2.2. Soil carbon measurements

Before and after ploughing (in October 2000 and November 2003), soil samples were taken for analysis of carbon content. Eight sample plots were located in the experimental area, so as to be representative of the fetch area sampled by the eddy covariance measurements (Figure 10-1). Five cores were taken in each plot, and divided into 5cm depth intervals, up to 25 cm depth if possble. The same plots were sampled on both occasions. Samples were analysed at 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.

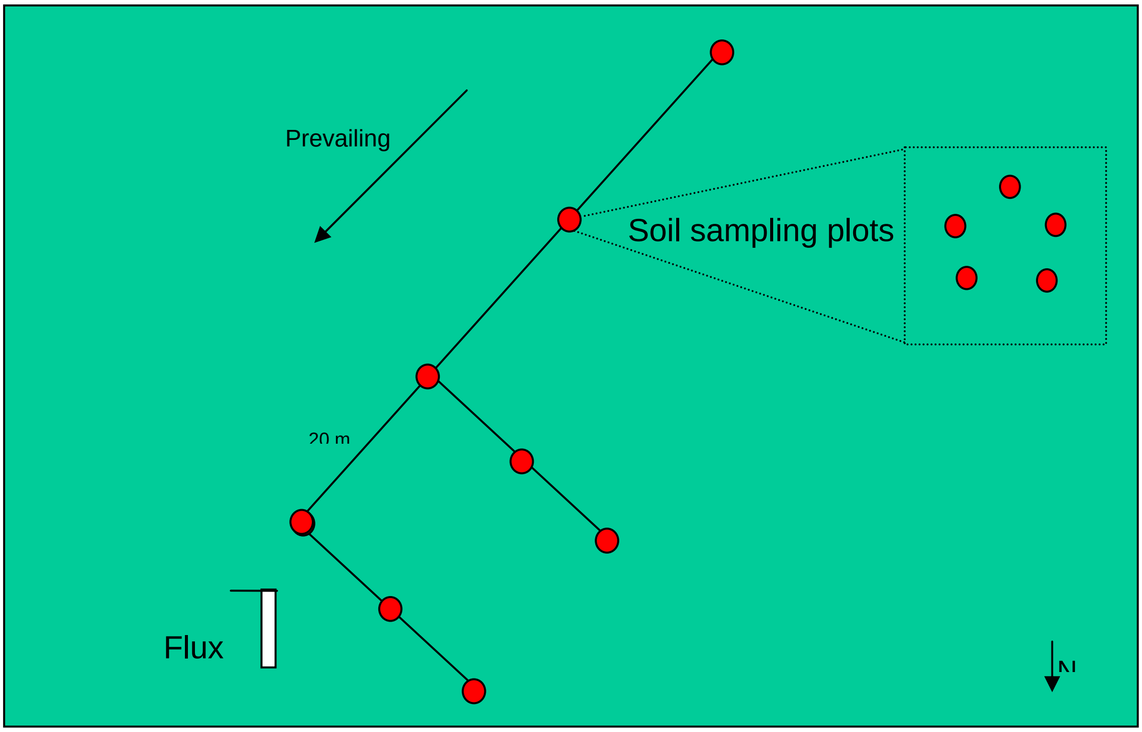

Figure 10-1 Layout of soil sampling points within the experimental area at Poldean Farm. Points were arranged to be in the prevailing upwind direction of the eddy covariance flux tower, and clustered near the tower, so as to be representative of the fetch area sampled by the eddy covariance measurements.

10.2.3. 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:

$$F_c = \overline{w' \chi} \qquad \text{eq 10-1}$$

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 occasional 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:

$$F_{NEE} = F_{RE_{DAY}} - F_{GPP_{OPT}} \left(1 - \exp\left[\frac{a' S_t}{F_{GPP_{OPT}}} \right] \right) \qquad \text{eq 10-2}$$

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 fitted to the model:

$$F_{NEE} = d \exp(eT_a) \qquad \text{eq 10-3}$$

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.

10.3. Results

10.3.1. Soil carbon measurements

All the points in Figure 10-2 fall below the 1:1 line, indicating a clear decrease in soil carbon after ploughing. Figure 10-2 also shows that there is considerable spatial (between-plot) variability, which is consistent over time. This was therefore accounted for statistically by including ‘plot’ as a factor in an analysis of variance.

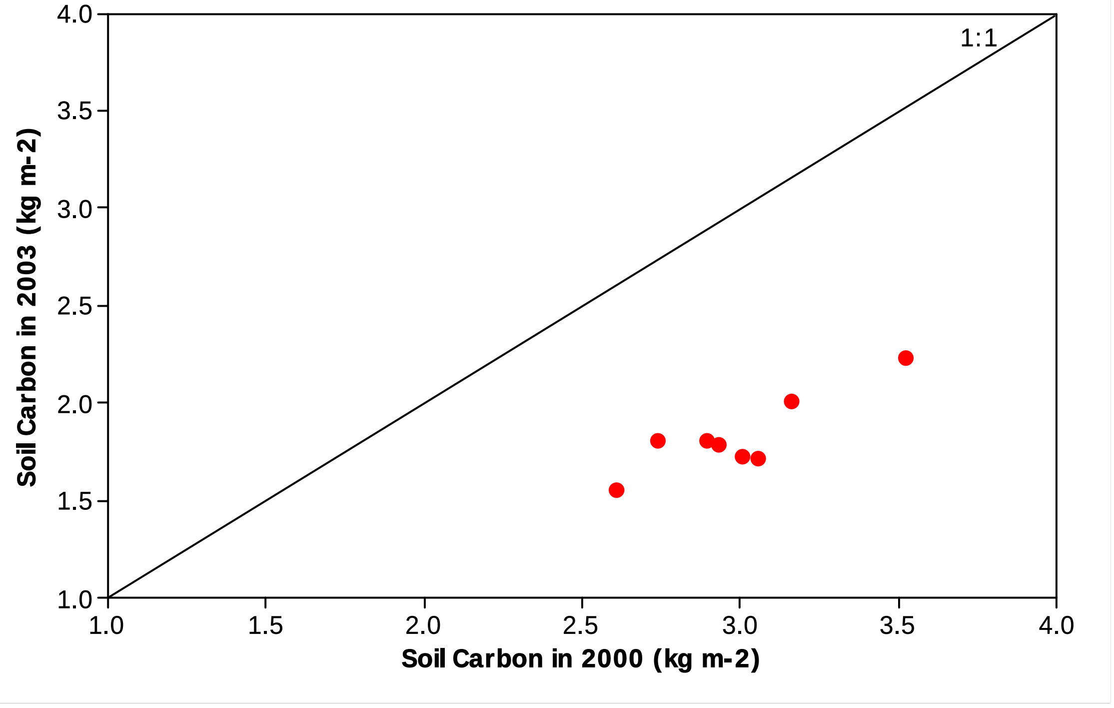

Figure 10-2. Scatter plot of soil carbon measured before ploughing in October 2000 versus values measured after ploughing in November 2003, at the eight sampling plots. Points are the mean of the five cores within each plot.

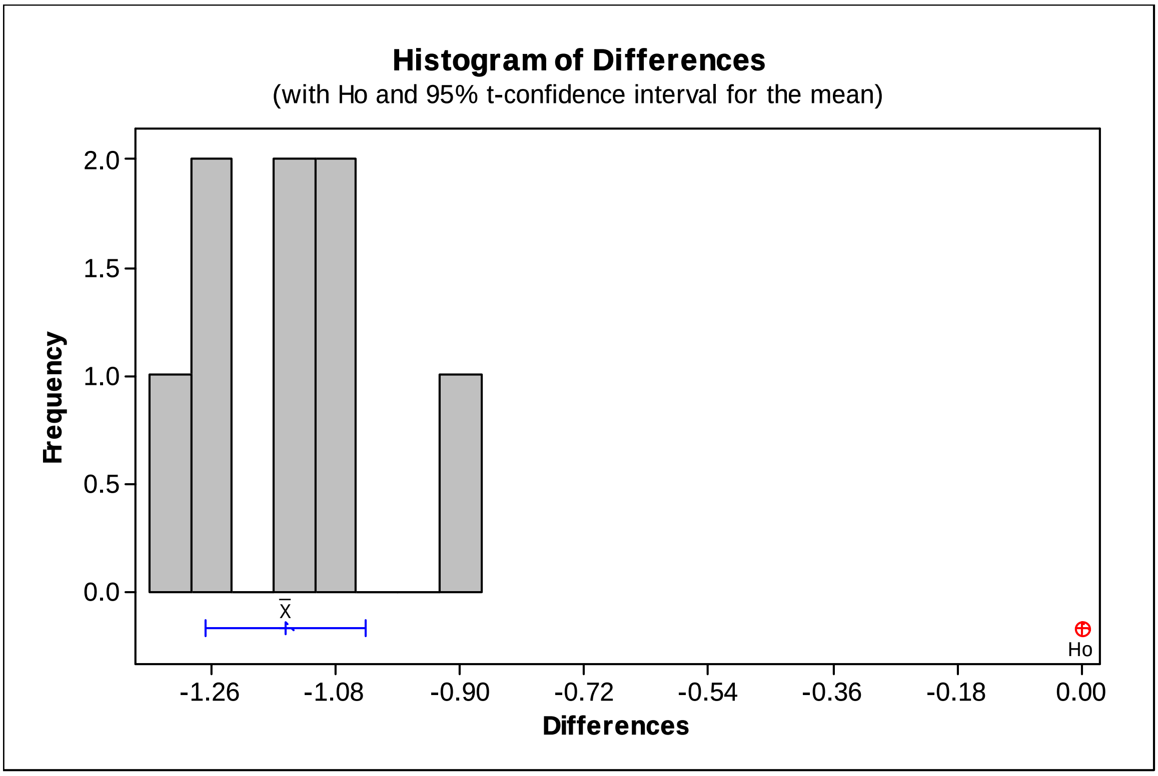

Figure 10-3 Histogram of the difference in plot means for soil carbon before and after ploughing, at the eight sampling plots. Bars are the mean of the five cores within each plot. The null hypothesis of no difference, H_o, lies outwith the 95 % confidence interval of the measurements.

Table 10-1 Analysis of Variance table for the effect of ploughing (represented as 'Year' – whether before (2000) or after ploughing (2003)) on soil carbon, using adjusted SS for tests. Plot was included as a random factor to account for spatial variation across the field.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Year	1	26.5617	26.5617	26.5617	312.25	0.000
Plot	7	3.8856	3.8856	0.5551	6.53	0.000
Error	71	6.0396	6.0396	0.0851		
Total	79	36.4868				

The results in Figure 10-3 and Table 10-1 show a highly significant decrease in soil carbon after ploughing ($p < 0.001$). The magnitude of this decrease is 1.15 kg C m^{-2} or 39 % of the initial value (or 0.80 kg C m^{-2} y^{-1} or 27 % y^{-1}, counting 528 days between the date of ploughing and the final soil sampling).

10.3.2. Comparison with eddy covariance measurements

Figure 10-4 shows a comparison of estimates of carbon emission from the ploughed field from the two methods. This shows that the direct measurement of soil carbon stock change gives a higher estimate than the eddy covariance flux measurements. Whether this difference (0.42 kg C m^{-2}) can be judged statistically significant is not simple, as rigorous confidence intervals can only be calculated for the soil carbon stock measurements.

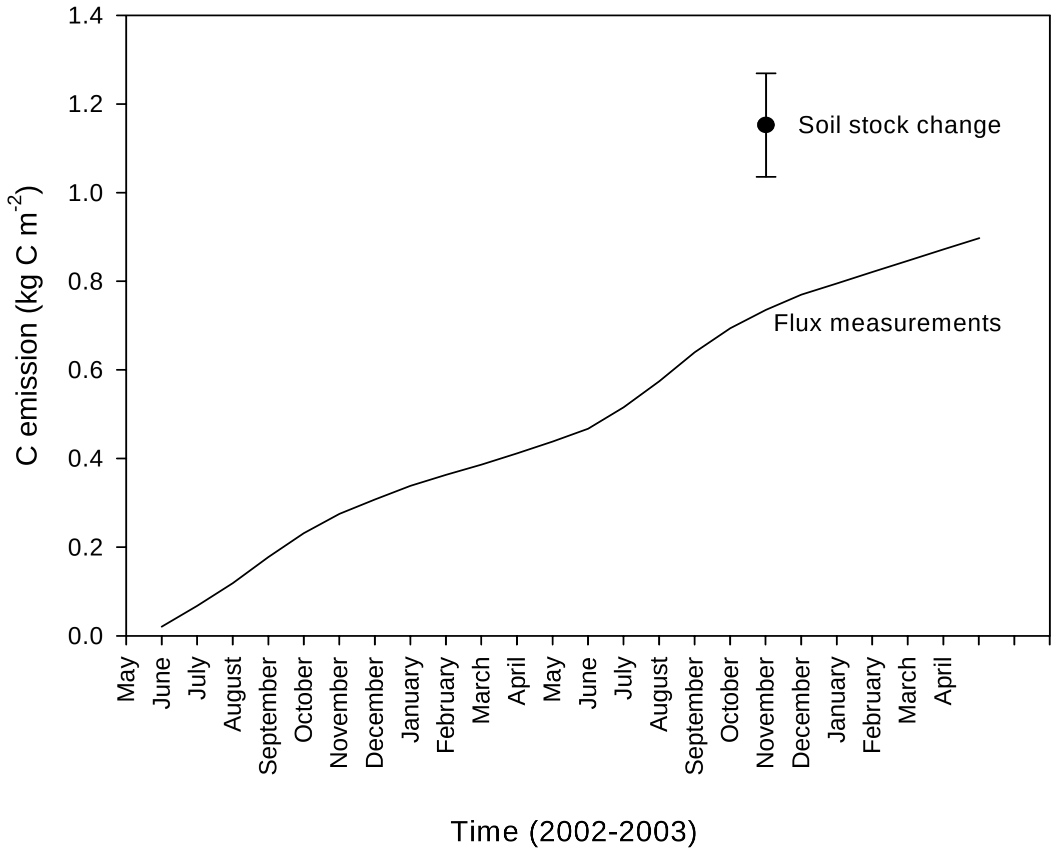

Figure 10-4 Comparison of estimates of carbon emission from the ploughed field from changes in soil stocks and by eddy covariance flux measurements. Error bars show the 95 % confidence interval in the change in soil carbon, based on the variability between plots.

10.4. Discussion

The discrepancy between the two methods raises the questions of which is more reliable, and should give the more accurate estimate of the true change. The soil stock change method has the advantage of being based on relatively simple chemical analyses and classical sampling methods, which permit the uncertainty to be estimated. The main disadvantage of this method is that natural spatial variability in soils usually overwhelms any signal of interest, such that either a very large sample size is needed to detect a statistically significant difference. Here, we largely overcome this problem by perturbing the system to such a large extent that the change is detectable with a reasonable sample size. The eddy covariance method has the advantage of directly measuring the flux of interest and integrating this over a large area. The problem of spatial variability is therefore avoided. The main disadvantages are that the random error in the estimate is not easily quantified (though it should be small), and there may be systematic errors related to failure to account for fluxes at very high and very low frequencies. This arises because (1) fluxes at frequencies higher than the slowest instrument response time (~0.5 s for the Li-Cor gas analyser) are not measured, and (2) fluxes at frequencies lower than the averaging time (15 mins) are not measured. Methods exist to correct for these 'flux losses' but this is still an area of ongoing research. Given that there are reasons to expect the eddy covariance measurements to underestimate the flux, whilst the stock change method is subject mainly to random error, we would suspect the latter to be the more accurate estimate in this instance. With a less dramatic experimental manipulation, the stock change method would be unlikely to detect a significant change without a very large sample size.

Table 10-2 shows an addition to the equivalent table in Levy *et al.*, 2004, using the soil stock change data, comparing the greenhouse warming potential (GWP) of the three gases measured. Using this higher flux estimate, CO_2 becomes an even more 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 10-2 Greenhouse warming potential (GWP) of the three gases measured at Poldean in the ploughed field. GWPs are calculated in terms of CO_2 equivalents, assuming standard IPCC values for the multiplicative factors for N_2O and CH_4.

	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	8.02			8.02
N_2O Exchange		0.0006		0.19
CH_4 Exchange			0.003	0.08
Total GWP				8.29

Figure 10-5 shows a comparison of measured carbon emissions with predictions from the existing inventory model, in which the litter input after ploughing is varied between 0.0 and 0.75 of that before ploughing. The inventory model is based on a single exponential decay function. The predictions where litter input are zero are very close to the measured values, suggesting that the model represents these conditions reasonably well. It would be expected that the measured values would lie somewhat below the litter input = 0 line, as some litter will have entered the soil, mainly after weed control treatments, so the model is underestimating the emissions to some extent.

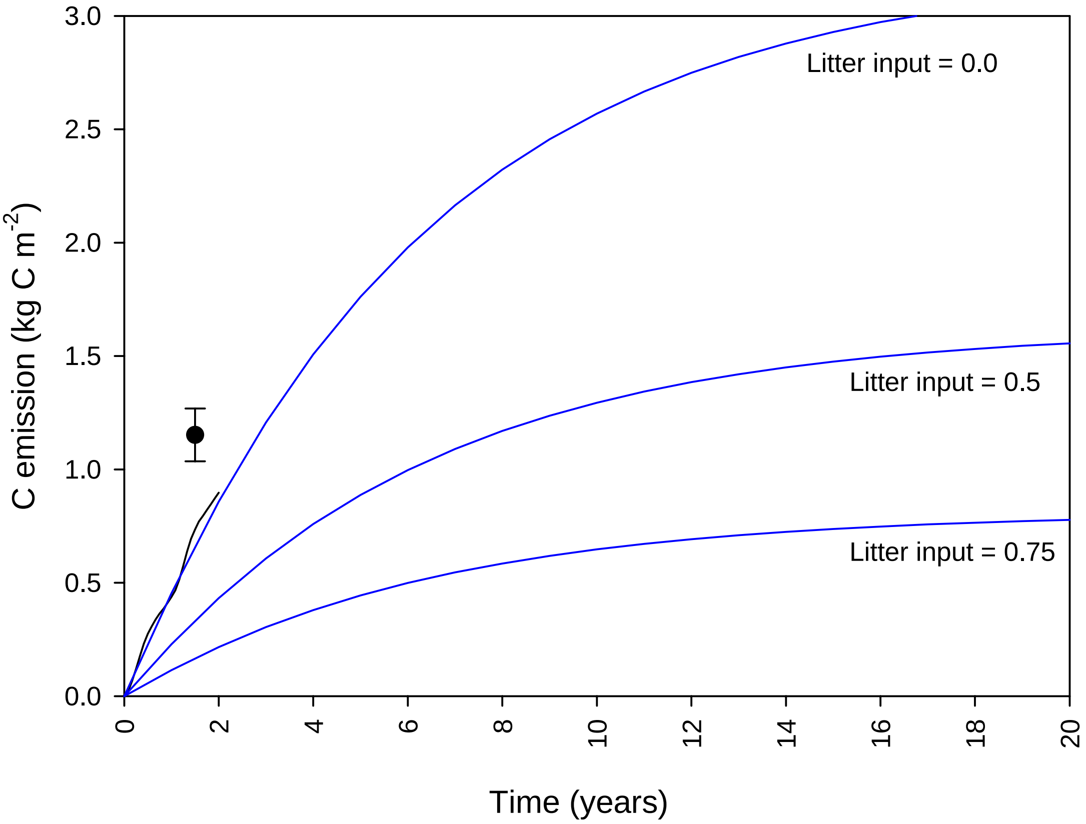

Figure 10-5 Comparison of measured carbon emissions (as in Figure 10-4) with existing inventory model predictions. Predictions are shown in which the litter input after ploughing is 0.0, 0.5 or 0.75 of that before ploughing.

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 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 representative 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. To explicitly separate these effects, we propose a plot-scale experiment to detect the effect of cultivation on soil organic carbon content.

Recent work (Smith & Conen, 2004, Li *pers. comm.*) suggests that the increase in N_2O emissions in “no-till” agriculture outweighs the effect of carbon sequestration, in terms of Global Warming Potential (GWP). It is therefore of interest to include measurements of N_2O emission in such studies. Results from the Poldean experiment showed no significant effect on N_2O emission, but were very variable and a higher sampling density would be needed to detect significant differences.

Here, we propose a plot-scale experiment with a Latin Square design, located close to CEH Bush, at a nearby SAC farm (House O’ Muir). Measurements will be made of:

- Initial and subsequent soil carbon stocks, by loss on ignition (LOI),

- Soil CO_2 fluxes using a Licor 6200 or EGM gas analyser,

- N_2O fluxes using both a static chamber method and possibly also using an automated sampling chamber, analysed on a GC.

Power analysis based on the variability in soil samples at Poldean suggests that 26 replicates per treatment would be needed to detect a change of 0.25 kg C m^{-2} (half the annual change observed at Poldean). With three treatments, this gives 78 experimental units. Figure 6 shows an outline of the proposed experimental design, with 81 units. The method proposed method is as follows:

<u>1. June 2005.</u>

An 11 x 11 m area of grassland will be harvested and sprayed with 'Roundup' herbicide. Herbicide applications will be repeated as necessary over the experiment to prevent vegetation regrowth.

	1	2	3	4	5	6	7	8	9	10
1	1	0	2	1	0	2	1	0	2	
2	0	2	1	0	2	1	0	2	1	
3	2	1	0	2	1	0	2	1	0	
4	1	0	2	1	0	2	1	0	2	
5	0	2	1	0	2	1	0	2	1	
6	2	1	0	2	1	0	2	1	0	
7	1	0	2	1	0	2	1	0	2	
8	0	2	1	0	2	1	0	2	1	
9	2	1	0	2	1	0	2	1	0	
10										

1 m

Legend
0 - not cultivated
1 - cultivated once
2 - cultivated n times
buffer

Figure 10-6. Replicated Latin Square experimental design, showing 9 x 9 m area with three treatments applied to 1 x 1 m plots in a 3 x 3 Latin Square, repeated 3 x 3 times.

<u>2. July 2005</u>

The outermost 1 m will be reserved as a buffer zone to reduce edge effects from surrounding vegetation. The inner 9 x 9 m will be divided into 1 m plots. Several soil cores will be taken from each plot, down to 15 cm depth and bulked. This will provide one sample from each of the 81 plots. These samples will be analysed by LOI to give initial soil carbon content. A sub-sample of material will be sent to CEH Lancaster for chemical analysis, to calibrate the LOI – C content relationship. Fluxes of CO_2 and N_2O will be made on all 81 plots using dynamic and static chambers, respectively.

3. July 2005.

The 81 plots will be allocated to three treatments:

0. control (uncultivated),

1. cultivated once, and

2. cultivated n times

and arranged in nine 3 x 3 Latin Squares (Figure 10-1). Treatment 1 will be cultivated once (only), in June 2005, to a depth of 15 cm using a rotovator. Treatment 2 will be cultivated at the same time and several times over the experiment to maximise the treatment effect, even though it is not realistic of normal practice.

4. July 2005 and bi-monthly until April 2006

Fluxes of CO2 and N2O will be made on all 81 plots at bi-monthly intervals. Treatment 2 will be re-cultivated ~quarterly.

5. April 2006

Soil cores will be taken from each of the 81 plots and soil carbon content measured by LOI (with a sub-sample going to CEH Lancaster for chemical analysis), as in May 2005.

Statistical analysis

The change in soil carbon content over the experiment will be compared in the three treatments using a one-way analysis of variance. Because the Latin Square design ensures that all treatments are distributed across the experimental area in a balanced way, this can be analysed as a simple ANOVA with no block effect, as a full Latin Square, or with intermediate degrees of blocking, depending on the spatial variation observed in the data. Dummy ANOVA tables using random data are given below for the cases of either (i) no blocking or (ii) accounting for row and column effects.

(i)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Cultivation	2	1.522	0.761	0.76	0.471
Residual	78	78.000	1.000		
Total	80	79.522			

(ii)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rows stratum	8	442.516	55.314	55.31	
Columns stratum	8	3.407	0.426	0.43	
Cultivation	8	8.984	1.123	1.12	0.362
Residual	56	56.000	1.000		
Total	80	510.907			

CO_2 and N_2O fluxes will be analysed in the same way, with the exception that a time series of data should be available at ~bi-monthly intervals. A repeated measures ANOVA technique may be applied to account for changes with time.

10.5. References

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10.6. Acknowledgements

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