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Influence of green manuring in wheat rotations under different cultivation systems

by

R.B. Overthrow[1] and P.C. Brookes[2]

[1]The Arable Group, Cirencester, Glos., GL7 7AH
[2]Agriculture and Environment Division, Rothamsted Research, Harpenden, Herts., AL5 2JQ

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Contents

Abstract

Winter wheat was grown in each of two rotations (i) continuous wheat, and (ii) rotational wheat in a sequence alternating with natural regeneration set-aside. For each rotation, three cultivation techniques were used to establish the wheat crop: (i) plough, (ii) minimum tillage (discing, one pass) and (iii) direct drill. Each treatment combination was then divided into two, one half being sown with white mustard as a green manure crop, prior to sowing the wheat crop. For the continuous wheat blocks, this involved sowing the mustard immediately after the harvest of the previous wheat crop, and for the rotational wheat, sowing mustard in spring in the set-aside stubble. In both cases the mustard was sprayed off prior to sowing the next wheat crop. The trial was run at Cirencester in Gloucestershire (medium soil over gravel) and Andover in Hampshire (light, shallow chalky soil). The four years of the project allowed four continuous wheat crops and two first wheats (after set-aside) to be examined, in terms of the influence of cultivation method on soil properties and microbiology, and crop yield, and the interaction of these with the growing of a green manure.

Soil analyses of microbial biomass (assessed as biomass carbon), and of microbial respiration (assessed as carbon dioxide release) indicated higher levels of these where non-inversion cultivations were employed (discing and direct drilling, compared to ploughing). Subsequently, higher levels of microbial biomass and respiration were also recorded where green manure had been incorporated, assumed to be a result of soil microbes feeding on the newly-introduced substrate. These changes in soil biochemistry were always greater in the deeper, heavier-textured soil at Cirencester than in the shallow chalk soil at Andover.

Yield increases in the wheat crops, as a result of green manuring, were not consistently evident until year 4, and then only in the rotational wheat with the relatively heavier soil. The soil assays which showed improvements in soil microbiology are known to be sensitive to early changes: it is to be expected therefore that translating these into increased yield would take time (increases in soil mineral N in early spring, following green manure incorporation, were noted, but only in the order of 20kg/ha or less).

Growing mustard as a catch crop between continuous wheats was not successful, due to the unpredictability of suitable rainfall in the short establishment window, and green manuring in general was not compatible with direct drilling, due to the lack of cultivation which would incorporate the mustard and thus benefit its breakdown and the wheat crop’s establishment.

Summary Report

Introduction

In order to obtain full benefit from a green manure (a growing crop incorporated into the soil to provide fertility) it must be efficiently decomposed and incorporated into soil organic matter, hence making nutrients available to subsequent crops. The success of this will depend on the population and activity of soil microbes responsible for this decomposition.

One factor which may influence microbial populations is the cultivation technique. Since much of the microbial activity takes place in the more aerobic upper soil layers, cultivations which keep it there, i.e. non-inversion, may help to maintain and improve the microbe population, whilst ploughing, which will continually bury these microbes to less favourable conditions at greater depth, might be expected to suppress any increase in microbial activity. This project studied the interaction between cultivation technique and green manure (white mustard) in terms of the latter's influence on crop yield and soil characteristics.

Methods

Winter wheat was grown as a) a continuous wheat, or b) a rotational crop in a sequence alternating with natural regeneration set-aside. Both crops were established using (i) plough (ii) minimum tillage (one pass with discs) or (iii) direct drilling, all sowing being carried out with a Vaderstad Rapid drill. Straw from previous wheat crops was chopped and spread.

The project was carried out between 2002 and 2006, using the blocks of land from an earlier cultivation project with continually ploughed, minimally-tilled and direct drilled areas respectively, cultivated thus since 1999. In the continuous wheat blocks, white mustard was sown after harvest using a Vaderstad 'Bio-drill' which combines disc cultivation with seed broadcasting, (mustard was broadcast pre-harvest, into the standing wheat crop, in the direct drill blocks) and allowed to grow before being destroyed prior to sowing the next wheat crop, i.e. a growing period of six to eight weeks. In the rotational wheat, mustard was sown with the Bio-drill for all cultivations, in the set-aside stubble in spring, and again destroyed prior to sowing the following wheat crop, i.e. with a growing season of three-four months.

Control blocks without mustard were included in all cases.

Soil analysis at the start of the project would give information on the effects of four years with the same cultivation technique up to that point, this project then giving further data on the influence of cultivation, and of the effects of and interaction with green manuring, on these soil characteristics. These included:

(i) soil pH

(ii) total carbon

(iii) total nitrogen

(iv) microbial biomass carbon

(v) soil respiration

(vi) water holding capacity

Other assessments included biomass of mustard produced, soil mineral nitrogen levels, and wheat yield.

Key results

1. Mustard biomass produced and nitrogen content

Continuous wheat: due to the short growing period for mustard between consecutive winter wheat crops, the amount of plant matter produced depended heavily on rainfall and soil moisture in this period. Total dry weight grown varied from 0 to 4928kg/ha, the higher weights being produced in the direct drill blocks where the mustard was sown (broadcast) earlier than in the other treatments. In the rotational wheat, dry matter weights produced were more consistent in the range 600-700kg/ha.

Nitrogen analysis of mustard prior to incorporation showed values in the range 5.0-6.0% at both sites, with little variation between cultivation treatments. This would give a potential nitrogen input into the soil of around 30-35kg/ha N in the rotational wheat, and between 5 and 250kg/ha N in the continuous wheat rotation, depending on the biomass of mustard achieved.

Analysis of soil mineral N showed that, in 2004 & 2006, incorporation of green manure led to an increase in the range 0-21kg/ha N, measured in early spring.

2. Soil analyses

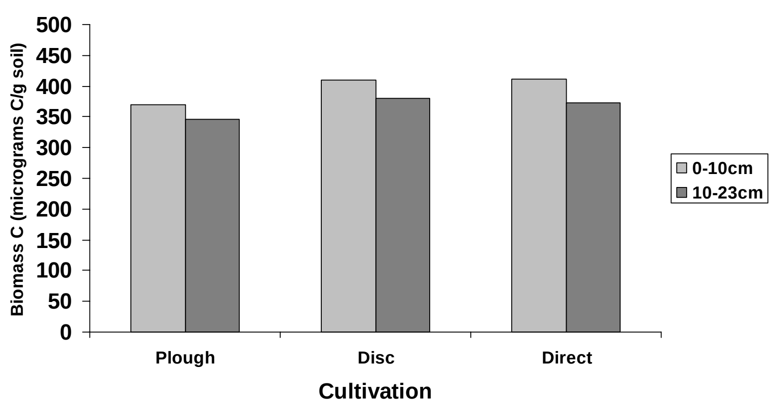
Detailed soil analyses were carried out at the start of the project (2002) and twice more in 2004 and 2006. The first set of analyses looked at the effects of four years' continuous cultivations from the previous project (as described in Methods) and the latter two examined the influence of green manure, and interaction of this with cultivation technique.

Soil pH, total carbon and total nitrogen, and water holding capacity showed small, mostly non-significant differences between cultivation and green manure treatments. Larger differences were seen in (i) microbial biomass and (ii) soil biomass respiration.

(i) **Microbial biomass** (assessed as biomass carbon), is an early indicator of changes in soil organic matter.

In the first assessment, which looked at the three cultivation treatments only, significant differences were seen in the levels of biomass-C, both between the cultivation treatments and between two soil depth profiles, at both trial sites (figs 1&2)

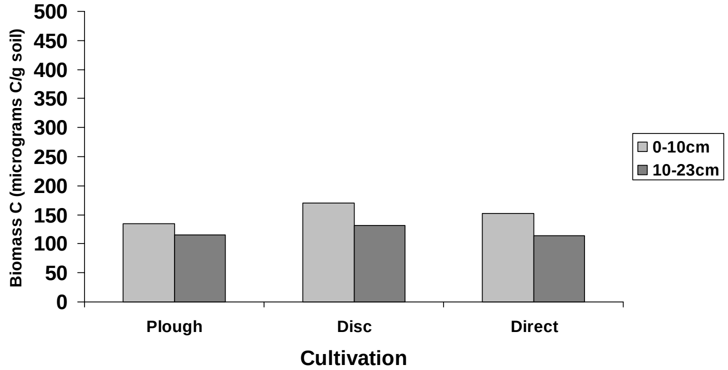
Figure 1. Biomass carbon in soil, Cirencester 2002



The non-inversion cultivation treatments show more biomass-C than the plough, and also more in the upper than in the lower soil layer. This indicates the ability of non-inversion to keep the microbes near the surface where they can multiply to a greater extent than when continually buried to greater depths as with the plough treatment.

Similar trends were seen at the Andover site:

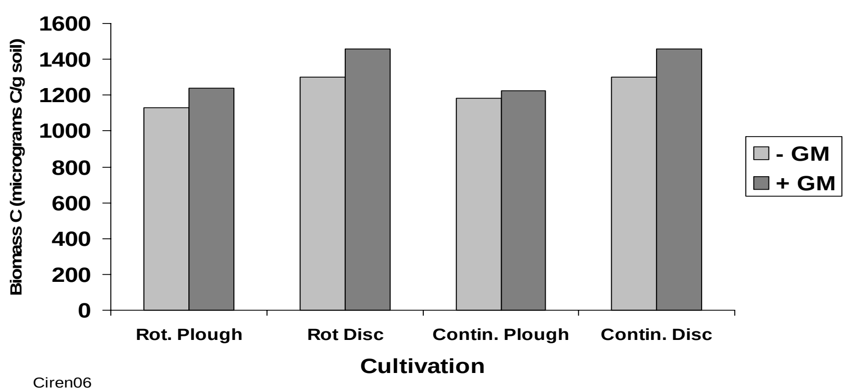
Figure 2. Biomass carbon in soil, Andover 2002.



Again, levels of biomass-C were higher in the non-inversion cultivations, in the upper soil profile, than in the plough treatment, where levels were lower and not significantly different between the two soil depths. However the most striking difference is in the comparative biomass-C levels between sites. The Cirencester soil (a reasonably deep, medium silty loam) had around three-four times the biomass-C than the Andover soil (light, thin chalky soil).

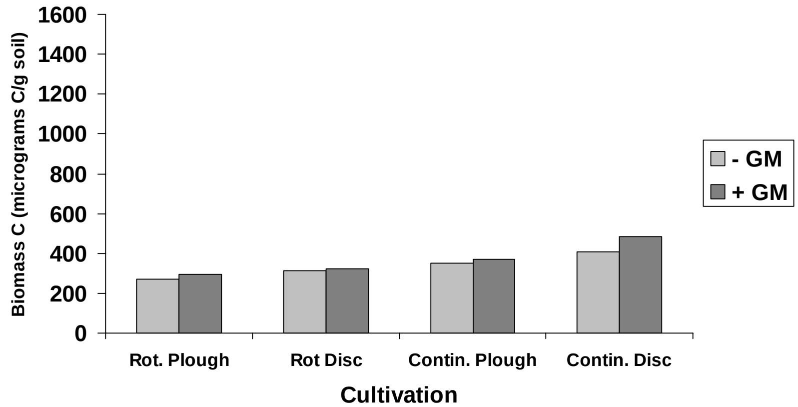
In the final assessment, the differences in biomass carbon at the two sites were still evident, whilst at both sites the influence of incorporated green manure was also identified (figs 3&4)

Figure 3. Biomass carbon in soil, Cirencester 2006
(Rotational and continuous wheat. Direct drill treatment not assessed).



Both the rotational and continuous wheat soils respectively show a higher biomass carbon level where green manure has been grown and incorporated. In addition, the difference between plough and disc, seen earlier, is still apparent, also there is an indication of a larger response to green manure with the non-inversion (disc) technique.

Figure 4. Biomass carbon in soil, Andover 2006.

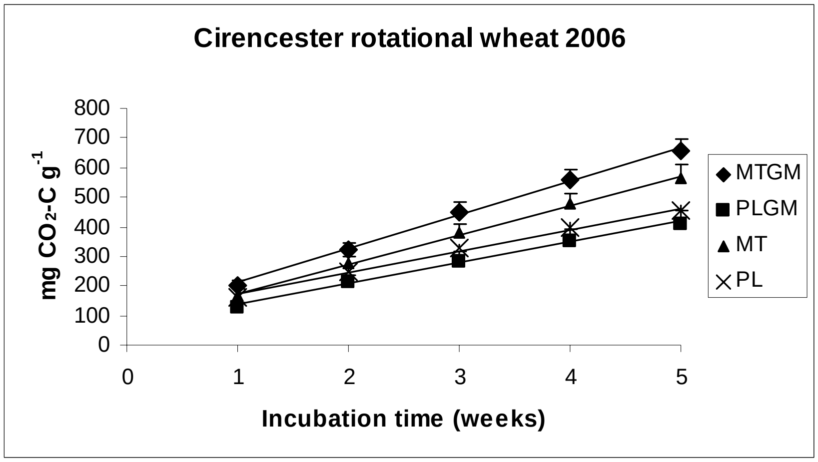


Here, the lower overall values in this ‘poorer’ soil are again apparent, but in addition any differences between treatments are also small (though still significantly different with the exception of the rotational wheat, disc treatment). Again the disc treatment shows more biomass-C than the plough, and in the case of the continuous wheat, shows a greater increase in biomass-C following the green manure. Despite these consistent trends, the soil at the Andover site regularly showed a much smaller microbe population, and appeared to have less ability to respond to factors which might improve this, and which had been seen to do so at Cirencester.

(ii) Soil respiration

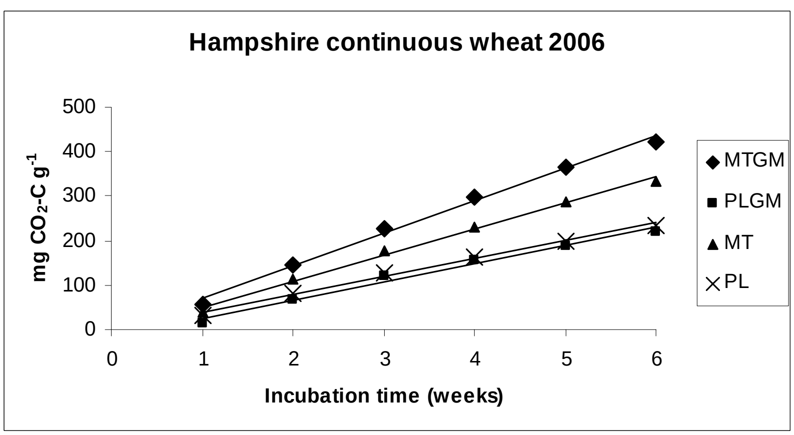
Soil respiration, i.e. CO_2 release, is another indicator of microbial population, also its activity in feeding on organic matter. Initial analyses showed higher levels of CO_2 release from the upper soil level, indicating greater microbial activity. Later analyses showed more released from the non-inverted soils than from ploughed soils, and a small positive effect of green manure. By the final analysis in 2006, however, there was consistently more CO_2 released in the disc treatment compared to the plough, and a greater release following green manure, again more marked in the disc treatment. As with other parameters, levels released were much lower from the Andover soil than the Cirencester soil, but the differences mentioned were still apparent.

Figure 5. Carbon dioxide release from incubated soil over six weeks. Cirencester 2006



The upper two lines on the graph represent the disced soil, indicating significantly more carbon dioxide release than the two lower lines representing the ploughed soil. The two upper lines show a significantly higher CO_2 emission where green manure had been added: within the two plough datasets there are no such significant differences.

Figure 6. Carbon dioxide release from incubated soil over six weeks. Andover 2006



There is less CO_2 released in the Andover soils, a likely reflection of the lower microbial biomass seen previously at this site. However the same differences are evident, with significantly more CO_2 released from the disced soil, and within this, more released where green manure had been incorporated. Again, there are no such differences within the two plough treatments.

3. Crop yields

Below is a summary table of the yield increases resulting from the incorporation of green manure, for all site/cultivation combinations.

Table 1. Increase in yield (t/ha) following growing and incorporation of green manure

	Cirencester		Andover	
	Continuous	Rotational	Continuous	Rotational
Plough 03	0.60	-	0.15	-
Plough 04	-	-0.97	0.29	-0.28
Plough 06	0.04	1.47s	0.34	-1.06
Disc 03	0.63	-	0.13	-
Disc 04	-	0.32	-0.16	-0.10
Disc 06	0.18	1.25s	-0.30	1.20
Direct Drill 03	-5.25	-	-0.07	-
Direct Drill 04	0.61s	-2.14s	-0.49	-0.93
Direct Drill 06	-0.51	0.80	0.60	-0.01

Yields from 2005 (continuous wheat only, both sites) were too variable to make valid conclusions.
In 2004 at Cirencester, dry weather prevented establishment of mustard in the continuous wheat (plough and disc).
s = statistically significant response
Yield responses were very variable throughout the project with only four significant responses to green manuring, one of which was negative. However there are some trends within the figures:

- More significant yield responses occurred in the rotational wheat, reflecting the difficulty in establishing a good mustard crop between continuous wheat crops.

- The responses were greater in the final year of the project, suggesting a time-lag before the observed improvements in soil microbiology translate into crop-available nutrients likely to raise yield.
- Most of the negative yield responses occurred in the direct drill/green manure combination. This is likely due to the lack of incorporation of the green manure after destruction with this cultivation method, coupled with the greater mustard biomass produced due to the earlier planting, leading to a heavy trash burden which affected crop establishment and compromised pre-emergence weed control.

4. Cost-benefit analysis

With few statistically significant yield responses it is not possible to give a detailed cost benefit assessment on the data. However a consideration of the costs of establishing the mustard will give an indication of the yield response required to offset these.

In this project the mustard was established with a Vaderstad Bio-drill, which combined a light discing with broadcasting the mustard into the working area of the discs. This method was used in the plough (as an additional pass) and the disc treatments (in the continuous wheat, as the discing operation itself, i.e. no further cultivation). Since this method would involve a stubble cultivation, the direct drill treatment (continuous wheat) used a different approach, the mustard being broadcast into the previous wheat crop 2-4 weeks before harvest. (In the rotational wheat, the blocks to be direct drilled were sown with mustard with the Bio-drill in April, as the other treatment blocks. The disc treatment received a further disc cultivation after destroying the green manure).

All blocks were sprayed with glyphosate prior to planting wheat.

The programme of cultivations for the green manure blocks is therefore as follows.

Plough, continuous wheat: seeder/cultivator August; spray off mustard, *plough and drill October*

Plough, rotational wheat: seeder/cultivator April; spray off July; *plough and drill October*

Disc, continuous wheat: seeder/*cultivator August*; spray off and *drill October*

Disc, rotational wheat: seeder/cultivator April; spray off July; *disc August; drill October*.

Direct drill, continuous wheat: mustard broadcast July; spray off and *drill October*.

Direct drill, rotational wheat; seeder/cultivator April; spray July; *drill October*.

The treatments in italics were carried out on the equivalent blocks without green manure.

Hence the following costs for each cultivation treatment have been assumed, solely attributable to growing the mustard (i.e. the extra operations over and above those used to establish the non-mustard control blocks).

1. Plough: 10kg/ha mustard seed (£15/ha) plus Biodrill establishment (estimated £15/ha), plus glyphosate to kill off (£11/ha including application costs)
= **£41/ha** (for both rotations)

2. Disc, continuous wheat: mustard seed only (£15/ha) plus glyphosate = **£26/ha,** or, rotational wheat: mustard seed + Biodrill, + glyphosate = **£41/ha**

3. Direct drill: Mustard seed (£15/ha) plus cost of broadcasting (estimated £12/ha in the continuous wheat, £15/ha in rotational wheat with Bio-drill) plus glyphosate = **£38-41/ha**.

Therefore, taking wheat grain prices as around £75-£80/tonne, a yield response of around 0.5 t/ha would be needed to finance the practice, perhaps as little as 0.33t/ha with the one-pass system used here in the continuous wheat discing treatment. It is difficult with the wide range of yield effects seen here to be conclusive, but such responses tended be seen in the later years of the project, although of the nine results for each cultivation treatment, there was only one significant cost-effective yield response in each case.

Also, if as suggested, the benefits from green manuring take time to build up and express as yield benefits, then the yield responses finally seen would need to finance the costs from earlier years.
It should also be remembered that growing a green manure or cover crop can have other benefits such as improved soil structure with the deeper-rooting crops, and removal of excess soil moisture in fallows following heavy winter rainfall, a problem on heavy soils with non-inversion cultivations. Such benefits are difficult to quantify within the protocol of this study.

Conclusions and Implications

The soil analyses, particularly those specifically measuring soil microbe activity, consistently indicated that a) non-inversion cultivation, and b) incorporation of mustard as a green manure, both led to increased microbe population and activity (compared to ploughing or no green manure respectively), particularly when the two were in combination. If it can be assumed that sufficient activity of this nature is necessary for effective decomposition of incorporated plant material, then non-inversion tillage would be expected to lay the foundation for extracting more benefit from green manuring than ploughing.

However, such benefits expressed as increased wheat yield were not apparent for most of the project. In the final year, after four continuous wheat crops and two first wheats respectively, increased yields were seen in the rotational (first) wheat at Cirencester. This was most likely because
a) the continuous wheat rotation, although it benefited from a mustard crop every year, did not show any consistent yield response to the incorporated mustard. The six week (approx) window for growing the mustard was insufficient and frequently very little biomass was produced. The exception was in the direct drill blocks where the mustard was broadcast into the previous wheat crop, giving a longer growing window and as a result better-established mustard producing more plant material to incorporate. However, this method was employed because of the inability to incorporate mustard seed when sowing it, since this would be an inappropriate cultivation for a direct drill regime. Subsequently, the lack of any cultivation to incorporate the mustard into the soil prior to sowing, coupled with the large amount of plant material involved, produced a large 'trash burden' which appeared to affect speed of establishment in the wheat crop (but not always final plant numbers) and also compromised pre-emergence herbicide performance. As a result the direct drilled wheat crops frequently had a poor start to the season. Hence green manuring, of the type employed here, is unlikely to be compatible with direct drilled continuous wheat (the direct drilled rotational wheat had few of the above problems, largely because the mustard was sown conventionally, and earlier, along with the other blocks, and could be destroyed well before the wheat crop was sown, allowing more natural breakdown of the mustard trash).

b) The Cirencester soil consistently showed higher soil microbe activity than the Andover soil, due to the texture and depth, and possibly history, of the former. In addition, any factors which improved the microbe activity were far less influential at Andover than at Cirencester. Hence it is to be expected that any yield benefits will be seen in deeper, heavier soils before they are seen in light stony or chalky soils as at Andover.

Therefore there is good evidence that green manuring will improve soil fertility, however it is likely to take time for such fertility to build up to a point where it will significantly increase crop yield. Up to that point, growers will need to bear the not-insignificant cost of growing the green manure. Any benefits are more likely to be seen where the green manure is allowed to establish and grow well, as in the rotational wheat in this project: the practice is less suitable for ‘catch cropping’ between consecutive winter wheat crops.

That said, there are other possible benefits of growing green cover in otherwise fallow land, as in the rotational wheat involved here. Removal of excess moisture on heavy soils, and improvement of soil structure generally, can also be useful benefits, though not possible to address here.

Technical Report

Introduction

Green manuring (incorporation of growing crops into the soil to provide fertility) is widely practiced in Europe, mainly to improve soil structure and/or substitute for artificial fertilisers. However their use in the UK has not been as extensive, and much of the research into green manures has shown little evidence of cost-effective benefits. The successful utilisation of a green manure crop will depend on its decomposition and incorporation into soil organic matter and hence to nutrients available to subsequent crops. This in turn will depend on the population and activity of soil microbes responsible for this decomposition.

It is believed that one factor which may influence microbial populations is the cultivation technique. Since much of the microbial activity takes place in the more aerobic upper soil layers, cultivations which keep it there, i.e. non-inversion, may help to maintain and improve the microbe population, whilst ploughing, which will continually bury these microbes to less favourable conditions at greater depth, might be expected to suppress any increase in microbial activity. Hence the success of a green manure in conferring benefits to a following crop may be influenced by cultivation technique, and it can be shown that much of the earlier work on green manures, discussed above, was carried out in plough-based growing systems. More recent research conducted by Levington Agriculture showed no effect of a range of green manures on the nitrogen response in a following spring barley crop, the green manures having been ploughed-in prior to sowing the spring barley (Richards, Wallace, Turner 1996).

Recent renewed interest in green manuring centres around several issues;

1. The cost of artificial fertilisers and the need to look for alternative sources of crop nutrients
2. Concerns over bare fallow, in terms of environmental profile and soil structure. A crop grown on fallow land will provide a better habitat for wildlife, as well as ‘trapping’ atmospheric carbon dioxide.

   In Northern Europe, green manures or catch crops are an integral part of programmes aimed at controlling nitrate leaching and pollution, being grown over winter to take up soil nitrogen residues.
3. In addition, the lack of a crop in a field for any length of time can, on heavier soils particularly, lead to retention of water in the soil creating adverse conditions for the establishment of a following crop. A crop grown in the fallow should remove the excess soil water accumulating

during the fallow period, and may also through root growth improve soil structure for both drainage and subsequent seedbed preparation.

There are therefore benefits to be gained in re-evaluating green manure crops and determining the circumstances under which the maximum benefits can be achieved.

This project has four main objectives:

- To evaluate the influence of green manure (mustard) grown as a catch crop and a set aside cover in a wheat only crop sequence, where the wheat crops were established following long term ploughing and non-inversion techniques respectively.
- To determine whether any benefits of a green manure cover in a set aside fallow are influenced by the cultivation regime, in particular;
- To determine whether long-term minimally tilled land has a higher level of biological activity compared to that in plough, and to determine whether if present such activity confers greater ability to incorporate green manure into the organic matter.
- To examine the economic case for green manure establishment (labour, time taken, method used) set against the value of any increased wheat production.

The project was carried out between 2002 and 2006, using the blocks of land from an earlier cultivation project with continually ploughed, minimally-tilled (disced) and direct drilled areas respectively, cultivated thus since 1999. Hence soil analysis at the start of the project would give information on the effects of four years with the same cultivation technique up to that point, this project then giving further data on the influence of cultivation, and of the effects of and interaction with green manuring.

Materials and methods

Field trials were conducted at two locations in the south of England; Andover in Hampshire and Cirencester in Gloucestershire. The Andover site was on a typical southern chalk soil type, (Carstens series) and the Cirencester site was a medium soil over gravel (Badsey series).

Crop details

Winter wheat was grown as a) a continuous wheat, or b) a rotational crop in a sequence alternating with natural regeneration set-aside.

In the continuous wheat blocks, white mustard was sown after harvest and allowed to grow before being destroyed prior to sowing the next wheat crop, i.e. a growing period of six to eight weeks. In the rotational wheat, mustard was sown in the set-aside stubble in spring, and again destroyed prior to sowing the following wheat crop, i.e. with a growing season of three-four months.

Control blocks without mustard were included in all cases.

The matrix of cropping treatments is therefore as follows:

2003		2004		2005		2006
WW	+/-GM	WW	+/-GM	WW	+/-GM	WW
Set-aside +/- GM		WW		Set-aside +/- GM		WW

Crop establishment

Both wheat crops (continuous and rotational) were sown, using a Vaderstad Rapid drill, following a) minimal tillage (discing), b) ploughing, or c) direct drilled (no seedbed cultivations). Straw from previous wheat crops was chopped and spread.

These cultivations were employed on the same areas of the trial throughout the project, and in addition the same cultivation regimes had been followed, again on the same respective trial areas, for four years prior to the start of this project, as part of an earlier HGCA-funded project (#1489)

White mustard was sown with a combination disc cultivator/seeder (the Vaderstad 'Biodrill') for all blocks apart from the direct drilled continuous wheat. Due to the need to avoid cultivations in these blocks prior to sowing, the mustard seed was broadcast into the previous wheat crop just prior to its harvest, in order to give the mustard as much opportunity as possible to establish in the absence of any seed incorporation.

In all cases the mustard was sprayed-off with glyphosate prior to the next crop being sown.

Assessments

Assessments were made of:

(i) wheat crop establishment

(ii) biomass of mustard produced prior to destruction

(iii) nitrogen content of mustard

(iv) wheat crop yield

In addition, soil analyses were carried out at regular intervals during the project to determine:

(i) soil pH

(ii) total carbon

(iii) total nitrogen

(iv) microbial biomass carbon

(v) soil respiration

(vi) water holding capacity

The analytical methods used for these tests are described in Appendix 1.

In this way the influence of cultivation technique and incorporation of a green manure on a) the physical and biological characteristics of the soil, and b) crop yield, could be assessed.

Results

1. Plant populations (wheat)

Plant establishment as a percentage of seeds sown was frequently around 50-60%, which may be considered low but reflects a continuous wheat situation where sowing is later than might be considered optimal, as a result of allowing time for a mustard crop to grow to a good size before destroying it, as was often the case in the continuous wheat.

The most consistent effect on establishment was that of cultivation technique, with ploughing giving the highest plant populations in many cases, at both sites. This was most commonly seen in the continuous wheat, the influence of ploughing in this respect being less consistent in the rotational (first) wheat crops. Direct drilling consistently produced the lowest established population in both rotations.

Green manure had little effect on establishment. Although it was seen to slow down establishment where not incorporated, i.e. in the direct drill blocks, the final plant population was not always affected and in many comparisons the establishment was slightly improved (not significant) where mustard had been grown.

Table 1. Plant population (plants/m^2)

	2003		2004		2005		2006	
		+GM		+GM		+GM		+GM
Andover								
Continuous								
Disc	212	202	221	231			172	168
Plough	223	206	217	217			133	147
Direct	135	171	236	214			114	138
Rotational								
Disc			213	207			91	115
Plough			199	196			106	114
Direct			187	194			98	121
Cirencester								
Continuous								
Disc	229	198	187	205	149	141	163	163
Plough	243	260	177	194	199	192	185	189
Direct	169	184	156	130	143	106	128	130
Rotational								
Disc			205	187			180	157
Plough			185	207			161	185
Direct			157	125			132	126

350 seeds/m^2 sown in each case.

2. Green manure biomass

Table 2. Dry matter of white mustard grown between consecutive winter wheat crops (kg DM/ha)

a) autumn sown (in continuous wheat sequence)

Andover

	2002 (autumn)	2003	2004	2005
Plough	746	327	164	112
Min till	584	377	93	95
Direct drill	2480	1114	383	897

Cirencester

	2002	2003	2004	2005
Plough	1028	0	211	9
Min till	1156	0	256	9
Direct drill	4928	3234	1110	0

b) spring sown (in set aside of rotational wheat sequence):

Cirencester

	2003	2005
(All cultivations)	681	750

As the mustard in set-aside was established by the same method in all blocks, no distinction was made between the cultivation treatments for this assessment.
(Data unavailable for Andover site).

Figures of mustard biomass are variable in the continuous wheat rotation. The short growing period in this case meant that the growth of the mustard was strongly dependent on sufficient moisture in the soil after harvest, and any prolonged dry weather at this time severely restricted growth. For example, at Cirencester in autumn 2003, no mustard grew in the minimum tillage and plough blocks, in common with many winter rape crops that season. The earlier planting in the direct drill blocks gave the mustard an advantage in this respect, and a good crop was achieved. At the Andover site, the earlier establishment of mustard in the direct drill blocks consistently gave higher biomass figures.

Although less data is available for the mustard grown in set aside in the rotational wheat, it was noted that, with a longer growing season, better, more consistent mustard crops were achieved in all cultivation blocks.

Nitrogen analysis of mustard prior to incorporation showed values in the range 5.0-6.0% at both sites, with little variation between cultivation treatments. This would give a potential nitrogen input into the soil of around 30-35kg/ha N in the rotational wheat, and between 5 and 250kg/ha N in the continuous wheat rotation, depending on the biomass of mustard achieved.

3. Soil analyses

(i) Soil pH

Analysis of soil pH was conducted on three occasions, 2002, 2004 and 2006, 0-10cm depth
In the latter two sample years the effects of green manure could be assessed.

Table 3. Effect of cultivation and green manure on soil pH (0-10cm) in continuous (Cont) and rotational (Rot) wheat

	Andover				Cirencester			
	2002	2004 Rot	2006 Rot	2006 Cont	2002	2004 Rot	2006 Rot	2006 Cont
Plough	7.4	7.1	7.0	7.1	7.7	7.7	7.6	7.3
Plough + GM	-	6.8	6.9	7.0	-	7.5	7.4	7.3
Min Till	7.2	6.6	6.5	6.1	7.8	7.5	7.5	7.3
Min Till + GM	-	6.5	6.4	6.7	-	7.6	7.6	7.4
Direct	7.3	6.4	-	-	7.7	7.6	-	-
Direct + GM	-	6.8	-	-	-	7.4	-	-

Note: at the time of the 2002 assessment, no green manure had been sown. Samples were bulked across both rotations. Continuous wheat blocks were only sampled in 2006. The 2006 assessments concentrated on differences between inversion (plough) and non-inversion (min. till) cultivations and the direct drill treatment was not included.

The Cirencester soil tended to be less acidic than the Andover soil. Effects of cultivation were small at Cirencester, though at Andover there was a tendency for non-inversion cultivation to produce lower pH. Effects of green manure on pH were small and inconsistent.

(ii) Total carbon (%)

Table 4. Effect of cultivation and green manure on total carbon content of soil (%)

	Andover				Cirencester			
	2002	2004 Rot	2006 Rot	2006 Cont	2002	2004 Rot	2006 Rot	2006 Cont
Plough	1.97	1.90	1.86	1.97	5.62	5.65	5.35	5.71
Plough + GM	-	1.88	1.93	2.07	-	5.91	5.60	5.58
Disc	2.30	2.23	2.31	2.33	5.86	5.87	5.70	6.13
Disc + GM	-	2.32	2.23	2.34	-	6.41	6.85	6.12
Direct	2.16	2.33	-	-	5.82	5.79	-	-
Direct + GM	-	2.22	-	-	-	6.05	-	-

In all three years both trials showed higher carbon levels with the two non-inversion treatments. In the rotational wheat at Cirencester (only) in 2006, green manure appeared to give slightly higher carbon levels.

(iii) Total nitrogen (%)

Table 5. Effect of cultivation and green manure on total nitrogen content of soil (%)

	Andover				Cirencester			
	2002	2004 Rot	2006 Rot	2006 Cont	2002	2004 Rot	2006 Rot	2006 Cont
Plough	0.19	0.19	0.18	0.19	0.59	0.60	0.57	0.61
Plough + GM	-	0.50	0.18	0.20	-	0.62	0.59	0.60
Disc	0.22	0.22	0.22	0.21	0.60	0.62	0.60	0.65
Disc + GM	-	0.23	0.21	0.21	-	0.65	0.63	0.64
Direct	0.21	0.22	-	-	0.61	0.61	-	-
Direct + GM	-	0.50	-	-	-	0.62	-	-

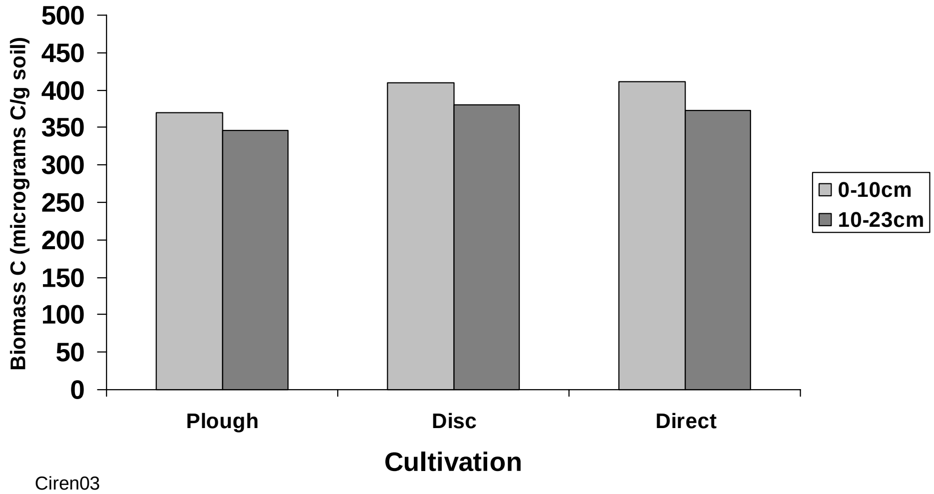
In 2002 differences between cultivation treatments were not significant. In 2004, both the plough and direct drill treatments showed significant increases in soil N levels where green manure was used, but this was not seen with the disc treatment. In 2006 N levels were again very similar with little or no differences between treatments, other than the consistently higher levels at Cirencester compared to Andover.

(iv) Microbial biomass

Microbial biomass was assessed as biomass carbon (i.e. carbon in living material). The soil microbial biomass is the collective mass of all the soil micro-organisms (e.g. fungi, bacteria, yeasts, actinomycetes, protozoa etc.), and can be considered as an ‘early warning’ of the direction of change in total soil organic matter, long before it can be detected by classical chemical analysis. (Powlson et. al. 1987, Anderson and Domsch 1989)

2002: In this first analysis, without the green manure comparisons, samples were taken from two soil depths.

Fig 1. Effect of cultivation on biomass carbon at different depths (mic.grams biomass C g^{-1} soil), Cirencester 2002

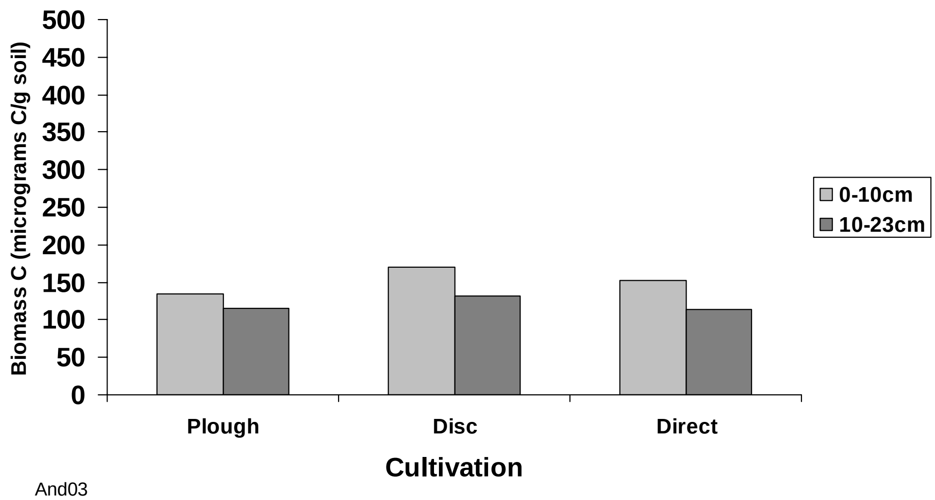


Soil depth:	0-10 cm	S.E.	10-23 cm	S.E.
Plough	370	40	346	22
Disc	410	55	380	26
Direct	411	43	373	33

There is significantly more biomass-C in the upper than in the lower soil layer with the disc and direct drill treatments. The difference between soil layers with the plough treatment is not significant. In addition, there is consistently more biomass-C in the upper layer for both the direct and disc treatments than in the plough treatment.

This indicates, even at this early stage, that microbial biomass is higher with non-inversion cultivations (these having been followed for four years at this point) and more concentrated in the upper soil layers where conditions are more conducive to their activity (i.e. more aerobic).

Fig 2. Effect of cultivation on biomass carbon at different depths (mic.grams biomass C g^{-1} soil), Andover 2002



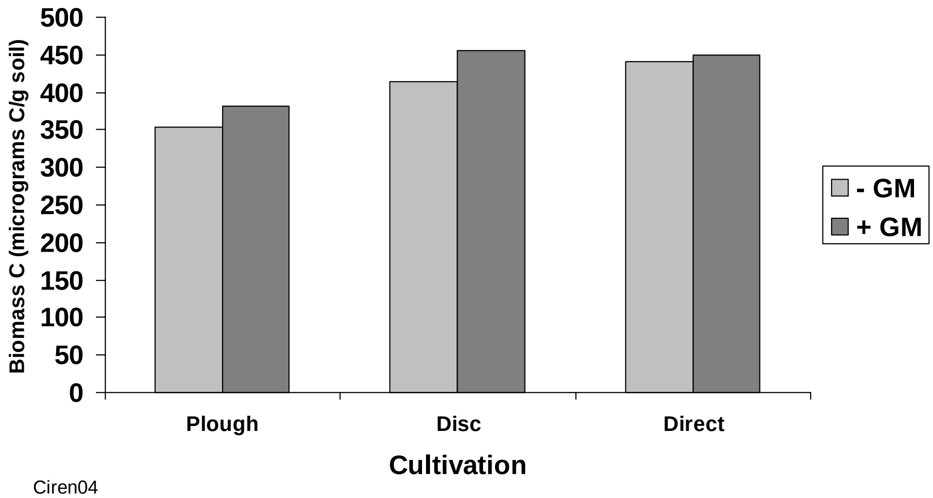
Soil depth:	0-10 cm	S.E.	10-23	S.E.
Plough	134	6	115	8
Disc	170	14	132	26
Direct	153	15	114	17

Similar trends to the Cirencester data are seen here, with larger differences in biomass-C between the two sample layers with the non-inversion treatments, and a smaller difference with the plough. Also, again the non-inversion treatments show higher levels than the plough in the upper layer, to a greater extent than in the lower sample layer. There is also considerably less biomass-C overall in this soil, compared to Cirencester. This may be a function of soil type and/or cropping history.

For the second set of analyses, comparisons were made between +/- green manure treatments, within each cultivation treatment, rather than between soil depths (figs 3 & 4). Only the continuous wheat blocks were sampled.

2004

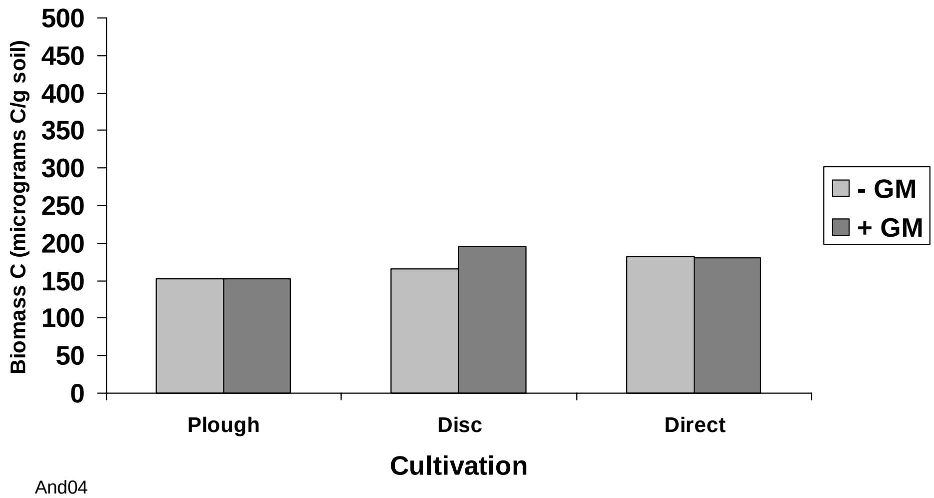
Fig 3. Effect of cultivation and green manure incorporation (+/- M) on biomass carbon (mic.grams biomass C g^{-1} dry soil), Cirencester 2004



	No GM	S.E.	+ GM	S.E.
Plough	353.39	5.38	382.24	18.59
Disc	414.50	6.06	455.43	6.45
Direct	440.79	11.34	448.64	10.95

The data show significantly more biomass-C where mustard had been grown, in the plough and disc blocks, but no significant such effect following direct drilling of the following wheat. There is also, as seen in 2002, significantly more biomass-C in the two non-inversion treatments than in the plough treatment, both with and without a preceding green manure crop.

Fig. 4 Effect of cultivation and green manure incorporation (+/- GM) on biomass carbon (mic.grams biomass C g^{-1} dry soil), Andover 2004

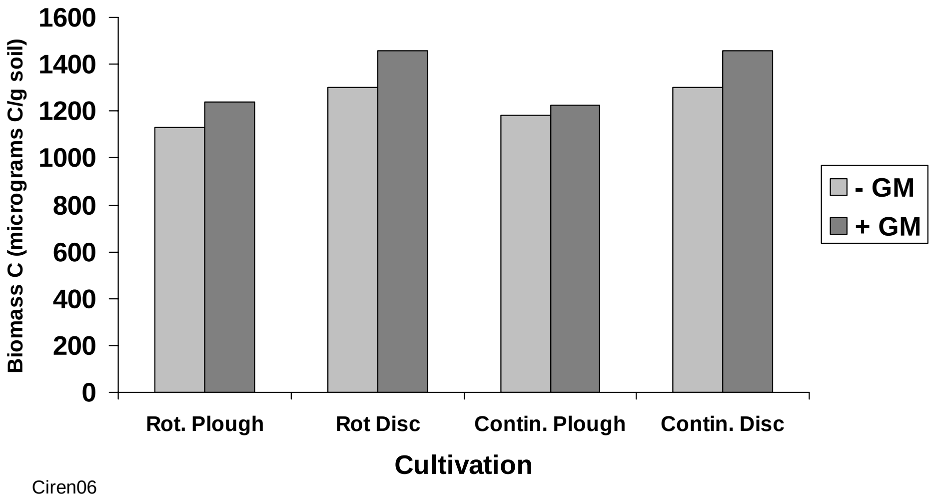


	No GM	S.E.	+ GM	S.E.
Plough	152.38	15.12	151.77	8.30
Disc	165.88	4.00	194.97	7.18
Direct	182.19	9.08	179.94	4.67

Results from this site again show considerably lower biomass-C values than those recorded at Cirencester, again presumed to be a reflection of soil type. Nevertheless there was a significant improvement from green manure in biomass-C in the disc treatment, but no significant differences with ploughing or direct drilling. The effects of cultivation on biomass-C are also smaller at this site, and not always significant.

2006

Fig 5. Effect of cultivation and green manure incorporation (+/- GM) on biomass carbon (mic.grams biomass C g^{-1} dry soil), Cirencester 2006



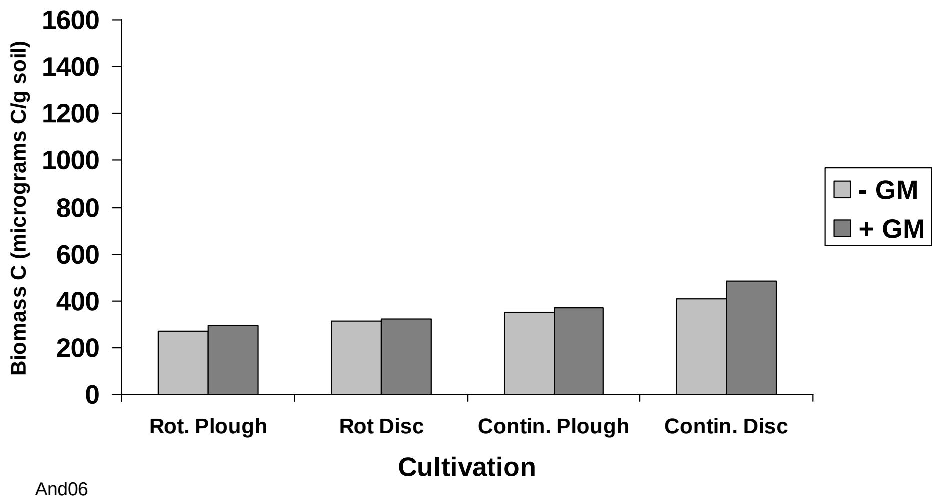
	No GM	S.E.	+ GM	S.E.
Rot. Plough	1125.30	39.52	1241.17	111.44
Rot. Disc	1300.13	36.32	1445.79	47.51
Contin. Plough	1164.42	119.82	1241.89	52.12
Contin. Disc	1464.39	44.84	1475.48	55.98

In this season a comparison was made between cultivations, rotation position and +/- green manure (mustard) for each of the sites. The cultivation comparisons were simplified as inversion v non-inversion (plough v disc respectively).

For all four rotation/cultivation comparisons, the previous incorporation of green manure led to an increase in the biomass-C. These changes were small but tended to be greater in the rotational wheat, where mustard had been grown in set-aside in the year previous to the wheat crop. As seen earlier, this approach produced more extensive growth in the mustard and hence more green manure biomass tended to be incorporated into the soil. In the continuous wheat the mustard was grown in a shorter ‘window’ between winter wheat crops and hence less mustard biomass was produced and incorporated. These differences are reflected in the figures here.

There is, however, once again an indication of higher biomass-C levels with non-inversion than with inversion or plough-based cultivation. This again is evident both with and without green manure.

Fig. 6. Effect of cultivation and green manure incorporation (+/- GM) on biomass carbon (mic.grams biomass C g^{-1} dry soil), Andover 2006



	No GM	S.E.	+ GM	S.E.
Rot. Plough	269.50	13.33	296.35	8.30
Rot. Disc	313.31	35.51	322.23	14.83
Contin. Plough	348.75	14.51	372.35	9.35
Contin. Disc	404.58	19.35	483.42	40.33

The levels of biomass-C were around a third those recorded at Cirencester in this season, a difference noted earlier. At this site, increases in biomass-C were recorded for all rotation/cultivation combinations as a result of green manure incorporation. Despite the lower overall levels, there is again more biomass-C in the disc treatments than in the plough treatments.

(v) Soil respiration

Microbial activity can also be assessed by measuring carbon dioxide production and release from the soil. This was measured on each of the three assay dates (2002, 2004, 2006).

Table 6. Cumulative evolution of CO_2 for three cultivation treatments at two soil depths.

(micrograms CO_2-carbon per gram dry soil)

Cirencester 2002

	µg of CO^2-C g^{-1}					
		weeks				
		1	2	4	6	8
	Disc 0-10 cm	216.5	369.2	635.2	830.6	1042.9 (90.0)
	Disc 10-23 cm	227.4	359.6	576.3	739.0	836.7 (143.9)
	Direct Drill 0-10 cm	185.2	326.5	547.2	719.3	911.2 (113.9)
	Direct Drill 10-23 cm	205.0	335.0	525.2	674.5	847.1 (135.8)
	Plough 0-10 cm	222.1	374.6	594.0	888.0	1086.8 (31.5)
	Plough 10-23 cm	175.0	303.6	510.9	643.9	837.4 (148.7)

Figures in brackets are standard errors (for final measurement only)

For all three treatments there was more CO_2 released in the upper sample depth than in the lower one, though these differences only started to become apparent after 4-6 weeks. The final differences between the two depths were greater for the disc and plough treatments than for direct drill.

Table 7. Cumulative evolution of CO_2 for three cultivation treatments at two soil depths.

(micrograms CO_2-carbon per gram dry soil)

Andover 2002

	µg of CO^2-C g^{-1}					
		weeks				
		1	2	4	6	8
	Disc 0-10 cm	55.5	131.0	265.1	390.8	499.1 (14.5)
	Disc 10-23 cm	73.9	116.1	190.2	244.5	312.3 (16.1)
	Direct Drill 0-10 cm	98.2	153.0	292.5	339.5	390.9 (65.7)
	Direct Drill 10-23 cm	74.6	143.0	258.3	369.5	485.3 (146.6)
	Plough 0-10 cm	64.3	105.0	212.8	285.3	374.8 (20.2)
	Plough 10-23 cm	44.2	69.9	157.1	217.0	292.7 (40.5)

Figures in brackets are standard errors (for final measurement only)

At this site the overall CO_2 amounts were considerably lower than at Cirencester. Differences between the cultivation treatments were also smaller, with no consistent differences between the two sample depths.

Table 8. Cumulative evolution of CO_2 for three cultivations treatment with and without green manure.

(micrograms CO_2-carbon per gram dry soil)

Cirencester 2004

µg of CO^2-C g^{-1}					
		weeks			
		1	2	4	6
	Disc - GM	176.4	307.8	506.6	663.7 (74.9)
	Disc +GM	212.6	338.3	528.6	680.9 (9.3)
	Direct Drill - GM	180.8	290.6	462.1	617.8 (22.7)
	Direct Drill +GM	178.3	290.8	449.8	597.7 (22.4)
	Plough -GM	172.5	266.0	393.9	493.7 (30.3)
	Plough +GM	163.1	268.1	397.5	494.6 (93.0)

Figures in brackets are standard errors (for final measurement only)

GM = green manure

In this assessment the influence of green manure incorporation was assessed for each of the three cultivation treatments. However, although, from the two-week assessment onwards, the ploughed soil showed less CO_2 evolution than the non-inversion treatments, there was no consistent influence of the green manure on this parameter for any of the cultivations. The disc treatment showed slightly more CO_2 evolution where green manure had been incorporated, at all four sampling dates, but the differences were not great.

Table 9. Cumulative evolution of CO_2 for three cultivation treatments with and without green manure.

(micrograms CO_2-carbon per gram dry soil)

Andover 2004

μg of CO^2-C g^{-1}					
		weeks			
		1	2	4	6
	Disc - GM	78.6	153.0	251.9	311.2 (19.9)
	Disc +GM	65.5	125.0	206.5	250.7 (31.7)
	Direct Drill - GM	86.5	156.9	287.6	348.9 (24.9)
	Direct Drill +GM	61.9	120.1	213.7	257.2 (32.6)
	Plough -GM	31.9	52.3	109.2	114.0 (18.4)
	Plough +GM	31.1	55.1	102.0	107.4 (8.8)

Figures in brackets are standard errors (for final measurement only)

Again the overall amounts of CO_2 evolved from soil samples at this site were considerably less than those from Cirencester. There is, however, a more marked effect of cultivation here, though again differences are small. The ploughed soil showed considerably lower CO_2 release than the disc or direct drill, though there is no evidence of higher CO_2 release where green manure was included.

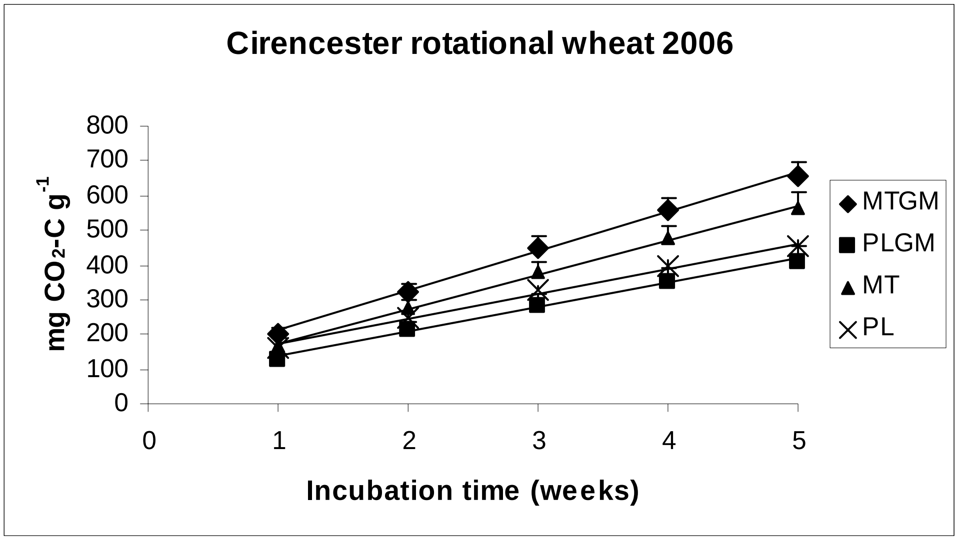
Table 10 & Fig. 7: Cumulative evolution of CO_2 for three cultivation treatments with and without green manure (micrograms CO_2-carbon per gram dry soil)

Cirencester 2006

μg of CO^2-C g^{-1}						
		weeks				
		1	2	3	4	5
	Continuous wheat:					
	Disc - GM	204.6	355.9	523.7	638.2	752.3 (44.9)
	Disc +GM	199.0	346.6	483.4	604.7	720.3 (33.3)
	Plough -GM	136.6	218.1	345.6	415.7	484.0 (51.6)
	Plough +GM	157.8	254.2	394.4	469.4	550.7 (25.5)
	Rotational wheat:					
	Disc - GM	168.6	273.4	377.0	477.1	563.7 (26.9)
	Disc +GM	203.6	323.4	450.0	556.3	654.9 (40.5)
	Plough -GM	161.6	250.1	327.2	394.8	451.9 (20.8)
	Plough +GM	128.0	210.6	284.7	353.8	411.0 (43.7)

Figures in brackets are standard errors (for final measurement only)

Fig. 7. Effect of cultivation technique and green manure on carbon dioxide release – Cirencester 2006



The graph shows the data for the rotational wheat blocks, indicating higher carbon dioxide release from the two disc (MT) treatments compared to the plough treatments. With the two disc treatments, there was significantly more released where green manure had been incorporated, indicating higher microbial activity as a result of non-inversion of the soil and the addition of a feed substrate. There was no significant effect of green manure with the two plough treatments.

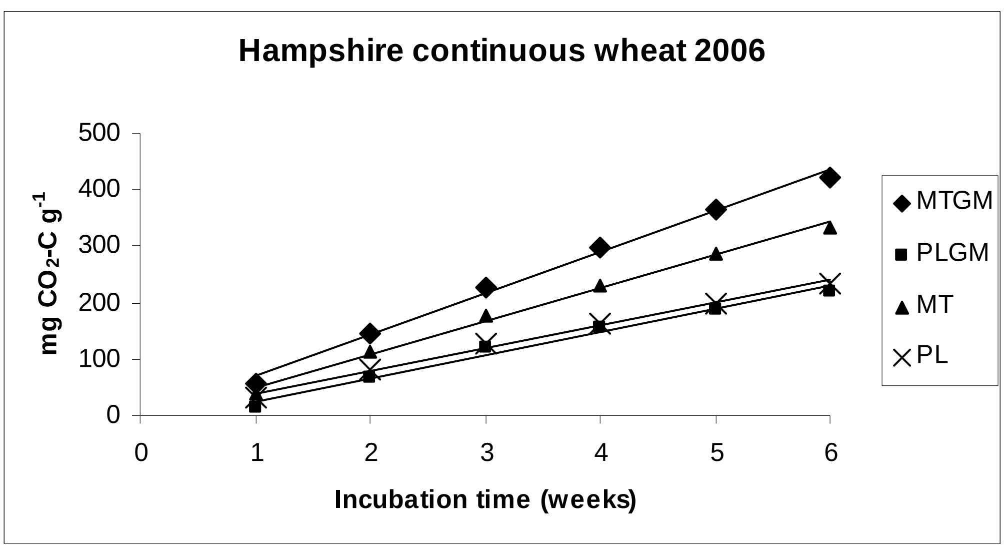
Table 11 & Fig. 8: Cumulative evolution of CO_2 for three cultivations treatments with and without green manure (micrograms CO_2-carbon per gram dry soil)

Andover 2006

µg of CO^2-C g^{-1}							
		weeks					
		1	2	3	4	5	6
	Continuous wheat:						
	Disc - GM	38.3	112.6	177.8	231.7	285.5	334.0 (96.0)
	Disc +GM	56.4	146.8	228.0	298.0	366.5	423.3 (48.3)
	Plough -GM	31.4	80.8	129.3	163.5	200.0	232.8 (17.2)
	Plough +GM	15.1	68.7	119.9	154.3	189.1	212.0 (15.9)
	Rotational wheat:						
	Disc - GM	79.1	150.8	217.4	283.9	343.0	391.2 (35.5)
	Disc +GM	78.4	152.5	225.5	305.4	371.4	424.4 (52.2)
	Plough -GM	11.3	55.5	95.3	128.0	158.1	184.9 (19.9)
	Plough +GM	14.5	59.6	102.2	140.1	171.3	198.4 (46.8)

Figures in brackets are standard errors (for final measurement only)

Fig. 8. Effect of cultivation technique and green manure on carbon dioxide release – Andover 2006



As at Cirencester the graph above (for continuous wheat) indicates the higher CO_2 release from the two disc (MT) compared to the two plough treatments (PL). The green manure led to higher levels released in the disced soil, but here the differences were not statistically significant. CO_2 release from the ploughed soil was not increased by the incorporation of green manure. (In the rotational wheat, the disc treatments also showed higher CO_2 release than the plough treatments, but the influence of green manure was not significant).

In all treatments, for both sites, higher cumulative rates of CO_2 were evolved from the disced treatments than the ploughed, and green manure increased soil respiration in the disc treatments only, but the differences were only significant at Cirencester in the rotational wheat.

(vi) Water-holding capacity

The ability of a soil to hold on to water will not only have benefits in dry seasons but is also an indicator of soil structure. Assessments of water holding capacity were carried out on the three assessment dates, the results shown below are for the final (2006) assessment, expressed as ml water retained per 100g dry soil.

Table 12. Effect of cultivation and green manure on water holding capacity of soil

	Cirencester	Andover
Continuous wheat:		
Disc - GM	113.1	66.8
Disc +GM	116.8	66.9
Plough -GM	108.6	61.8
Plough +GM	114.4	64.1
Rotational wheat:		
Disc - GM	107.5	69.1
Disc +GM	117.1	67.6
Plough -GM	116.9	63.3
Plough +GM	115.7	64.7

The Cirencester soil showed considerably higher water holding capacity than the Andover soil. At Andover the disc treatments showed higher values than the plough, but there was no consistent effect of green manure. The Cirencester figures indicate the reverse was at this site, the green manure increasing water holding capacity in the continuous wheat soil, and with the disc treatments in the rotational wheat soil, but there was no consistent effect of cultivation technique on this parameter.

Residual soil nitrogen

In a separate series of assays, soil from the treatment blocks at Cirencester were tested for mineral nitrogen in early spring of 2005 and 2006. Total available nitrogen (nitrate-N plus ammonium-N) was analysed as follows in table 12. Only the continuous wheat blocks were sampled.

Table 13. Available nitrogen (kg/ha) 0-40 cm profile: influence of cultivation and green manure, continuous wheat, Cirencester.

	2005		2006	
	- GM	+ GM	-GM	+GM
Disc	85	106	89	82
Plough	85	93	67	78
Direct drill	86	90	74	75

In 2005 there was a slightly higher soil N where green manure had been grown, for all three cultivation treatments. In 2006 there was a higher level with green manure for the plough treatment only. However, even where there was an increase, it was too small to be likely to influence the wheat crop's total fertiliser N requirement.

Summary of soil analyses

Several soil characteristics measured in the preceding sections were shown to be influenced by cultivation method and/or the incorporation of green manure prior to planting the wheat crop.
(i) Soil pH: this was little influenced by the factors mentioned, apart from at Andover (a chalky soil with generally higher pH than the Cirencester soil) where non-inversion cultivation tended to lower the pH slightly. No such effect was seen at Cirencester, and green manure did not influence pH at either site.

(ii) Total carbon: this tended to be slightly higher in the non-inversion cultivation treatments, but generally the differences were not significant. The greatest differences were seen when comparing the two trial sites, Cirencester showing three times the level of carbon in the Andover soil for all treatments.

(iii) Total nitrogen: Cirencester soil showed around three times the total N level of the Andover site, but differences between cultivation and /or green manure treatments were small and inconsistent.

(iv) Microbial biomass-carbon: this was significantly higher in the upper of the two soil profiles tested in 2002, at both sites and for both discing and direct drilling. There was no significant difference in microbial biomass between the two soil depths with the plough treatment. In 2004 and 2006, when only the top profile was sampled, there was consistently more biomass-C in the non-inversion treatments, and the incorporation of green manure further raised levels, though only in the non-inversion treatments in 2004. Where green manure increased biomass-C, the effects were greater in the rotational wheat where better mustard crops tended to be grown (larger biomass i.e.). These results suggest that non-inversion may allow a more extensive build-up of microbial biomass where the soil is not inverted, and that microbial biomass can be further increased by incorporating a green manure.

(v) Soil respiration: initial analyses showed higher levels of CO_2 release from the upper soil level, indicating greater microbial activity. Later analyses showed more released from the non-inverted soils than from ploughed soils, and a small positive effect of green manure. By the final analysis in 2006, however, there was consistently more CO_2 released in the disc treatment compared to the plough, and a greater release following green manure, again more marked in the disc treatment. As with other parameters, levels released were much lower from the Andover soil than the Cirencester soil, but the differences mentioned were still apparent.

(vi) Water-holding capacity (WHC): differences were not seen until the 2006 analysis, when the Cirencester soil showed higher WHC where green manure had been incorporated. This was not apparent at Andover, which once again showed considerably lower values than Cirencester, and at neither site did cultivation technique consistently increase WHC.

(vii) Soil mineral N: small differences in available nitrogen were noted in most treatments, in the form of higher levels where green manure had been grown. However these increases were small (maximum 21kg/ha extra) and allowing for the efficiency with which soil N is used (believed to be around 60%) then the contribution to the total N requirement of the crop is likely to be minimal.

Generally, therefore, both the use of non-inversion cultivations, and incorporation of green manure, appeared to improve microbial activity, this becoming more apparent over time and in the better soil at Cirencester. Other factors such as carbon and nitrogen content, pH , water holding capacity and soil mineral N in spring, were less obviously influenced.

4. Earthworm populations

As a further indication of organic matter buildup in relation to cultivation technique and green manure incorporation, assessments were made of earthworm numbers in each of the blocks. Due to dry weather in some years producing very few or no earthworms in the sample, and also variability in other results, reliable estimates of population were only achieved in two years. In 2005 both Cirencester and Andover were sampled, (continuous wheat) and in 2006 Cirencester only (rotational wheat).

Worms were collected from a 0.025m^3 soil sample, the population then estimated per m^3 of soil

Table 14. Total earthworm number/m^3

	Andover 2005	Cirencester 2005	Cirencester 2006
	Worms/m^3	Worms/m^3	Worms/m^3
Disc	552	1120	400
Disc +GM	440	883	441
Plough	240	480	200
Plough +GM	152	322	480
Direct drill	600	1200	1008
Direct drill +GM	640	1280	800

In the 2005 assessments, the green manure (GM) treatments appeared to reduce the worm population in the disc and plough treatments, whereas in the 2006 assessment at Cirencester, worm populations were higher where mustard had been grown and incorporated in the same treatments. The consistent effect across all assessments, however, was the influence of cultivation technique. Ploughing always resulted in the lowest population, these being in the order direct drill > disc > plough.

5. Crop yields

2003

Table 15. Continuous wheat yield (t/ha) and influence of green manure

In the first year only continuous wheats were grown, the rotational wheat being in the set-aside year of the rotation.

	Yield (t/ha)	
	Cirencester	Andover
Disc	6.35	7.11
Disc +GM	6.98	7.24
Plough	5.03	6.62
Plough +GM	5.63	6.77
Direct drill	7.86	6.66
Direct drill +GM	2.85	6.59
LSD (0.05)	*NS*	*0.58*

At Andover all treatments showed small yield effects where green manure (mustard) had been incorporated prior to sowing, but these differences were not statistically significant for any cultivation treatment. In the Cirencester trial high statistical errors make comparisons difficult, but neither the disc or plough treatments showed a yield benefit from green manure. One reason for the high errors in this trial is indicated by the direct drill treatments. Mustard planted after harvest of the previous wheat crop grew very well in the direct drill blocks (where the mustard had been broadcast pre-harvest) and the large amount of biomass produced (which was not subsequently incorporated into the soil due to the cultivation technique used) interfered with crop establishment and pre-emergence herbicide performance. Poor establishment and a high population of grass weeds subsequently reduced yield significantly, and suggests that this technique of catch cropping between two winter wheat crops did not suit a direct drilling regime where all of the green manure biomass is left on the soil surface.

Crop yield – 2004

Table 16. Yield of continuous and rotational (first) wheat and influence of green manure

	Yield (t/ha) – Continuous wheat		Yield (t/ha) – Rotational wheat	
	Cirencester	Andover	Cirencester	Andover
Disc	6.06	6.92	7.43	9.17
Disc +GM	-	6.76	7.11	9.07
Plough	6.29	6.80	8.07	9.49
Plough +GM	-	7.09	7.10	9.21
Direct drill	5.86	7.54	7.68	9.66
Direct drill +GM	6.47	7.05	5.54	8.73
LSD (0.05)	*1.34*	*0.96*	*1.34*	*0.96*

In the continuous wheat trials at both sites there were no significant differences between the three cultivation methods (without green manure). In the Cirencester continuous wheat trial a yield increase (non-significant) was seen in the direct drilled treatments (no mustard established in the other two treatments: see biomass assessments). No significant yield responses were seen in the rotational (first) wheats where mustard was grown in the previous set-aside.

In the Andover trial the ploughed continuous wheat showed a small (non-significant) yield response to green manure, whereas both the disced and direct drilled wheat showed yield penalties (not significant). As in the Cirencester trial, the rotational wheat showed no evidence of a yield response to the green manure, which in fact produced a large yield penalty in the direct drilled wheat (as in the Cirencester direct drilled wheat in 2003, qv).

2005: in the 2004/5 season, when only the continuous wheat was grown, delayed sowing due to a wet autumn, and high grass weed pressure at both sites led to very low yields with high variability in the data. As a result these yields are not presented.

Crop yield – 2006

Table 17. Yield of continuous and rotational (first) wheat and influence of green manure

	Yield (t/ha) – Continuous wheat		Yield (t/ha) – Rotational wheat	
	Cirencester	Andover	Cirencester	Andover
Disc	6.77	7.50	7.49	6.66
Disc +GM	6.95	7.20	8.74	7.86
Plough	7.43	5.44	8.43	7.84
Plough +GM	7.47	5.78	9.90	6.78
Direct drill	6.60	4.37	7.45	7.21
Direct drill +GM	6.09	4.97	8.25	7.20
LSD (0.05)	*1.00*	*1.30*	*1.25*	*(NS)*

Responses to green manure in the continuous wheat at both sites were small and not significant. In the rotational (first) wheat, all three cultivation treatments in the Cirencester trial showed large yield increase where green manure had been incorporated. These responses were statistically significant in the disc and plough treatments, making the plough + green manure combination the highest yielding. At Andover a large response was seen in the disc treatment, but in this trial none of the yield differences were significant.

Nevertheless the responses to green manure seen here represent the largest over the course of the project, and although in the rotational wheat only two mustard crops had been grown as green manure (in 2003 & 2005), this suggests that the benefits seen in the soil analyses (qv) may take time to show as improved crop yield. The yields seen here from the continuous wheats again suggest that the practice of catch cropping between successive wheat crops is unreliable as a means of improving crop yield, largely due to the restricted window available for establishing a mustard crop.

Summary of crop yield data

The trial design produced two years' yield data for the rotational wheat, each crop being a first wheat after natural regeneration set-aside, and four years' yield data for continuous wheat, though poor yields in 2005 meant only three of those years' data was presented.

In 2003 and 2004, there were generally no significant differences between the three cultivation techniques, except where direct drilling was highest yielding, at Cirencester in 2003 and Andover in 2004, both in continuous wheat (not significant). In the rotational wheat in 2004 at Cirencester, ploughing significantly out-yielded discing, but by 2006 the ploughing treatment was more consistently higher yielding, perhaps a reflection of the build-up of grass weeds at both sites, particularly in the continuous wheat.

Yield responses to the growing and cultivation/incorporation of green manure (mustard) were only seen occasionally until 2006, when such responses were more consistent across all cultivation treatments, though more so at Cirencester than at Andover. This perhaps relates to the lower levels of microbial activity seen at the Andover site, inhibiting the efficient utilization of the extra organic matter. The yield trends from the Cirencester site are more encouraging, but suggest that, although both the cultivation and green manure improved soil microbe activity (which was inherently higher at this site from the start), this did not translate into improved crop yield until several years after the start of the project.

It should also be noted that significant yield penalties were recorded on more than one occasion when mustard was grown prior to direct drilling the wheat. As discussed above, the lack of any incorporation into the soil left an often-considerable amount of plant material on the surface which was seen to interfere with crop establishment and weed control.

The table below summarises the yield responses to green manure for all cultivation treatments and sites.

Table 18. Yield increases/decreases resulting from green manure (t/ha)

	Cirencester		Andover	
	Continuous	Rotational	Continuous	Rotational
Plough 03	0.60	-	0.15	-
Plough 04	-	-0.97	0.29	-0.28
Plough 06	0.04	1.47s	0.34	-1.06
Disc 03	0.63	-	0.13	-
Disc 04	-	0.32	-0.16	-0.10
Disc 06	0.18	1.25s	-0.30	1.20
Direct Drill 03	-5.25	-	-0.07	-
Direct Drill 04	0.61s	-2.14s	-0.49	-0.93
Direct Drill 06	-0.51	0.80	0.60	-0.01

s = statistically significant.

The yield responses are generally inconsistent and only a few are statistically significant but there are trends in the data:

- There are no significant yield responses in the Andover trials. (The disc treatment showed a large yield response to green manure in 2006, but this was not significant. Otherwise the yield responses have been generally low). This site showed lower values than Cirencester for soil microbial activity and smaller influences on this from green manure and/or cultivations. It would also appear to have less potential to respond in crop yield terms.
- The responses in the Cirencester trials are generally higher than at Andover, with significant responses seen in the plough and disc treatments in 2006, and the direct drill in 2004.
- Responses also tended to be greater in the rotational wheat than in the continuous wheat. It should also be noted that in the disc treatment, there was a difference in the cultivation technique, in that for the continuous wheat, the discing that established the mustard immediately after the wheat harvest, also served as the final cultivation. In the rotational wheat, however, the mustard was established several months before the next crop was sown, and so a further cultivation was made in August after destroying the green manure. This meant that the mustard in the rotational wheat was cultivated in before planting the next wheat crop, whereas

in the continuous wheat sequence it was not, as was the case in the direct drill treatment. However the direct drill treatment suffered more from this (excessive surface trash etc) since the mustard was planted (broadcast) earlier and produced more biomass. This may further explain why positive responses tended to be greater in the rotational wheat than in the continuous wheat, for the disc treatment at least.

- In general, positive yield responses were more frequent towards the end of the project.
- There are negative responses to green manure, mostly in the direct drilling treatment for both continuous and rotational wheat. Despite the significant positive response in 2004 at Cirencester, the frequency of negative values in that section of the table suggests an incompatibility between the two practices.

Further to the issue of leaving the mustard on the soil surface, i.e. not mixing in with the soil prior to drilling: Coppens et al (2003), studying nitrogen dynamics of crop residues left on the surface as a mulch, or alternatively mixed into the soil, found that a much higher proportion of the nitrogen in the residue was released to the soil when that residue was mixed in, compared to being left on the surface. In addition, the additional moisture loss incurred in the surface mulch further slowed down its decomposition. This work underlines the importance of incorporating a destroyed cover crop into the soil, and further explains some of the findings in this project.

6. Cost-benefit analysis

With few statistically significant yield responses it is not possible to give a detailed cost benefit assessment on the data. However a consideration of the costs of establishing the mustard will give an indication of the yield response required to offset these.

In this project the mustard was established with a Vaderstad Bio-drill, which combined a light discing with broadcasting the mustard into the working area of the discs. This method was used in the plough (as an additional pass) and the disc treatments (in the continuous wheat, as the discing operation itself, i.e. no further cultivation). Since this method would involve a stubble cultivation, the direct drill treatment (continuous wheat) used a different approach, the mustard being broadcast into the previous wheat crop 2-4 weeks before harvest. (In the rotational wheat, the blocks to be direct drilled were sown with mustard with the Bio-drill in April, as the other treatment blocks. The disc treatment received a further disc cultivation after destroying the green manure).

All blocks were sprayed with glyphosate prior to planting wheat.

The programme of cultivations for the green manure blocks is therefore as follows.
Plough, continuous wheat: seeder/cultivator August; spray off mustard, *plough and drill October*
Plough, rotational wheat: seeder/cultivator April; spray off July; *plough and drill October*
Disc, continuous wheat: seeder/*cultivator August*; spray off and *drill October*
Disc, rotational wheat: seeder/cultivator April; spray off July; *disc August; drill October*.
Direct drill, continuous wheat: mustard broadcast July; spray off and *drill October*.
Direct drill, rotational wheat; seeder/cultivator April; spray July; *drill October*.
The treatments in italics were carried out on the same blocks without green manure.

Hence the following costs for each cultivation treatment have been assumed, solely for attributable to growing the mustard, i.e. over and above the cost of cultivations for the no-mustard control blocks.
1. Plough: 10kg/ha mustard seed (£15/ha) plus Biodrill establishment (estimated £15/ha), plus glyphosate to kill off (£11/ha including application costs)
= **£41/ha** (for both rotations)
2. Disc, continuous wheat: mustard seed only (£15/ha) plus glyphosate = **£26/ha,** or, rotational wheat: mustard seed + Biodrill, + glyphosate = **£41/ha**
3. Direct drill: Mustard seed (£15/ha) plus cost of broadcasting (estimated £12/ha in the continuous wheat, £15/ha in rotational wheat with Bio-drill) plus glyphosate = **£38-41/ha**.

Therefore, taking wheat grain prices as around £75-£80/tonne, a yield response of around 0.5 t/ha would be needed to finance the practice, perhaps as little as 0.33t/ha with the one-pass system used here in the continuous wheat discing treatment. It is difficult with the wide range of yield effects seen here to be conclusive, but such responses tended be seen in the later years of the project, although of the nine results for each cultivation treatment, there was only one significant cost-effective yield response in each case.

Also, if as suggested, the benefits from green manuring take time to build up and express as yield benefits, then the yield responses finally seen would need to finance the costs from earlier years.
It should also be remembered that growing a green manure or cover crop can have other benefits such as improved soil structure with the deeper-rooting crops, and removal of excess soil moisture in fallows

following heavy winter rainfall, a problem on heavy soils with non-inversion cultivations. Such benefits are more difficult to quantify within the protocol of this study.

Discussion

This project has looked at the benefits to a wheat crop that can be gained from a preceding green manure crop (white mustard) and whether any such benefits are influenced by the cultivation regime. The influence of the cultivations, mainly comparing inversion (ploughing) with non-inversion (discing or direct drilling), on the fate of the incorporated green manure was assessed by detailed monitoring of soil factors which would reflect the microbial activity in the different soils, this being influential in the efficient breakdown of green plant material into available crop nutrients.

The performance of the three cultivation techniques themselves varied over the course of the project. In the early years non-inversion cultivations gave equal or better yields than ploughing, particularly at the lighter soil site at Andover. However by the end of the four year rotations, ploughing was giving higher yields as grass weed populations built at both sites, particularly in the continuous wheat sequences. This underlines the generally accepted need for flexibility in cultivation policy.

Analysis of the soil under the different cultivation techniques demonstrated differences in the likely ability of the soil to break down the mustard. Previous studies had shown that non-inversion cultivations (minimum or zero tillage) allowed greater accumulation of biomass carbon in the upper soil layers (Hernanz et al 2002, Saffigna et al 1989). Without sufficient microbial activity of this sort, incorporated plant matter cannot be expected to be broken down into a usable form.

Early results from this project confirmed these differences, with significantly higher microbe numbers (measured as biomass carbon) in the non-inversion blocks compared to the plough blocks, and significantly more in the upper soil layer (0-10cm) than in the next layer down, in the non-inversion treatments. In the ploughed soils there were no significant differences between the soil layers in terms of biomass carbon, likely due to the plough dispersing this evenly through the plough layer, whilst the non-inversion cultivations maintained the biomass near to the surface. These differences were apparent at both sites, and since the cultivations were continued on similarly-cultivated areas from a previous four-year project, represent the result of four years of the respective cultivation regime.

Subsequent analyses continued to show significantly more biomass carbon in the non-inversion soils than in the ploughed soils. In addition, other assessments of microbial activity, such as carbon dioxide release, also showed more coming from the non-inverted soil

When mustard was grown and incorporated as a green manure, there were also consistent increases in biomass carbon and CO_2 release as a result, the latter also indicating microbial activity and breakdown of the new substrate. The next step was to assess whether this higher microbe activity results in better breakdown of an incorporated green manure crop which would consequently improve wheat yields.

Levels of biomass carbon also differed markedly between the two sites. The deeper soil at the Cirencester site (Badsey series) consistently showed three- to four-times the level of biomass-C recorded at the Andover site (Andover series chalk soil). In addition, any changes in biomass-C brought about by cultivation method or green manure were smaller in the Andover soil. There appeared to be less ability in the chalk soil to support soil microbes, and correspondingly less scope to improve the population.

Other soil characteristics such as pH, total carbon, total nitrogen and water holding capacity were less influenced by cultivation and green manure.

The assessments of microbial biomass and activity, chosen as giving earlier indication of changes in the soil microbiology compared to, for example, conventional organic matter assays (Powlson et al, 1987, Anderson et al, 1989) indicated effects of cultivation technique and green manuring fairly early in the project. These changes were consistent across sites and years, and showed that non-inversion tillage encouraged development of and activity in the soil microbe population necessary for the efficient conversion of incorporated green manure. The subsequent benefits to the wheat crop itself, in terms of yield increases, were not seen with any consistency until the end of the project (after four years of continuous wheat, or two of first wheat after set-aside) though it may be reasonable to assume these yield increases would have been seen with increasing regularity had the project continued for longer.

Other research into green manure has also shown small and/or inconsistent benefits. A review of long term farm trials in France by Arvalis, which included plough-based and direct drill systems, showed an average yield response to green manures (mustard, rye-grass, radish and others) of +1.0%, the maximum being achieved on one farm of +6%. In addition, there was no influence of green manure on the nitrogen fertiliser requirement of the following wheat crop in these studies. Any nitrogen taken up by the green manure, e.g. as intercepted leachable nitrate, was not always made available to the following wheat (Arvalis -Institut du vegetal (selected papers) no. 3 October 2006).

Environmental benefits of green manures are well documented. Although the green manures in this project were not used as over-winter ‘catch crops’, research in Belgium found that on average such crops intercepted around two thirds of the available leachable nitrate, though the range was 17 to >190kg/ha intercepted, depending on the catch crop used. (Bontemps et al, 2002). There is also much debate over the value of green manures in carbon sequestration. There is little doubt that a green cover crop will absorb more atmospheric carbon dioxide than bare soil or stubble, but this should be balanced against the carbon used to establish and destroy these crops. Various researchers have questioned the true carbon sequestration potential of farmland in this respect (Smith et al, 2005).

The majority of growers would be willing to plant a green manure or catch crop for the environmental benefits that may be achieved, however most would hope for some return on investment. Results here and elsewhere have indicated little if any short-term benefits in soil nitrate supply which may have reduced the amount of applied fertiliser required. Yield effects were inconsistent and often negative, and in general the practice of green manuring was rarely cost-effective, at least over the course of this project. This is to some extent not unexpected as any improvements in crop-available fertility from green manuring would be expected to take time to develop; the soil assays used here which detected changes in soil microbe activity in the early stages were perhaps over-optimistic in this respect.

Nevertheless if the trends seen in the final year are genuine then one would expect cost-effective yield responses to occur more regularly, though there were indications in these trials of where these are most likely to occur. The short growing window for the mustard green manure in the continuous wheat sequence did not allow for the accumulation of plant biomass in the same way as growing it in set-aside with a longer growing season. Hence it would be difficult to successfully build soil fertility in a continuous winter crop rotation. There is also the additional danger that slow growth in such a green manure crop would encourage delays in sowing to following wheat crop, thus allowing more growth from the green manure but incurring yield penalties in the wheat associated with late sowing.
Also, sowing wheat by direct drilling after a green manure crop is unlikely to be successful. Wheat yield results were not always against direct drilling, but they were unpredictable, and it can be said that there was potential for yield penalties if the green manure is not cultivated-in before sowing the wheat.

The experiences with the heavy trash burden produced, in terms of crop establishment and weed control, and other work showing the inefficiency of decomposition of residues left on the surface, suggest strongly that ‘true’ direct drilling, i.e. with no cultivation before sowing, is not likely to allow successful use of a green manure system (though other green manure crops, not tested here, may be more successful).

Therefore in terms of the original objectives of the project, (see page 13)

- *To evaluate the influence of green manure (mustard) grown as a catch crop and a set aside cover in a wheat only crop sequence, where the wheat crops were established following long term ploughing and non-inversion techniques respectively*

Mustard grown as a green manure improved the yield of wheat grown on the heavier of the two soils, in a wheat-set aside rotation, though these benefits were not recorded until the fourth year of that rotation. As a catch crop in a continuous wheat sequence, or in either sequence on the lighter of the two soils, the mustard had less or no effect on wheat yield. In all situations, however, changes in soil microbiology and biochemistry indicated that the right conditions were developing for yield benefits, possibly in the longer term.

- *To determine whether any benefits of a green manure cover in a set aside fallow are influenced by the cultivation regime, in particular;*

Where significant yield increases in the wheat crops following green manure were noted, there was no clear relationship with the cultivation regime

- *To determine whether long-term minimally tilled land has a higher level of biological activity compared to that in plough, and to determine whether if present such activity confers greater ability to incorporate green manure into the organic matter.*

Biological activity, in terms of total microbial biomass and microbial respiration, was higher in soils following minimally tilled (non-inversion) cultivation. This was seen in both soil types and in both rotations, though to a lesser extent in continuous wheat. However, subsequent changes in soil mineral nitrogen, total nitrogen and soil organic carbon, though consistent, were small and not significant, suggesting more time is needed for the observed benefits to translate into increased soil fertility likely to increase crop yield.

- *To examine the economic case for green manure establishment (labour, time taken, method used) set against the value of any increased wheat production.*

The total cost of establishing a green manure in this way was calculated as needing a wheat yield increase of between 0.3 and 0.5 t/ha (at autumn 2006 grain prices) depending on the establishment method used. Such cost-effective yield increases were observed, but again only on the heavier soil in the latter stages of the project.

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Appendix A

Soil analysis methods

1. pH measurements

Distilled water (10 ml) was added to a beaker of moist soil (10g). Each sample was stirred by hand for one minute. Then, the mixture was left to stand for 30 minutes. After this time, each sample was stirred again for one minute and left to stand for another 30 minutes. The pH of the supernatant was measured using a standard pH-meter.

2. Total Carbon and Nitrogen measurements

Soil samples were air- dried at 25 deg. C. Each sample was milled using a TIMA Mill machine. Then, 500 mg samples were accurately weighed and analysed on the LECO CNS analyser.

3. Microbial biomass

Soil microbial biomass was determined by the method of Vance et al., (1987). Briefly, samples to be fumigated were weighed into glass bottles and non-fumigated samples (the controls) into plastic bottles. For the Gloucester samples, 40g portions of moist soil were used and for Hampshire 35 g moist soil portions. All the bottles were then put into air-tight 50 l drums with water and soda-lime for seven days at 25°C to allow the soil to equilibrate.

Fumigation of soil samples was done by placing the glass jars of soil in a large vaccum desiccator lined with moist paper. A beaker containing 30ml of alcohol-free $CHCl_3$ and anti-bumping granules was then placed in the desiccator. The desicator was then evacuated until the $CHCl_3$ boiled vigorously, the tap on the desiccator closed and the desiccator placed in the dark at 25°C for 24 hours. Then, the beaker of $CHCl_3$ and the moist paper lining were removed from the desiccator and all residual $CHCl_3$ vapour removed from the soil samples by repeated evacuation. The control soils, and blanks, were extracted with 0.5 M K_2SO_4 (1 : 4 soil : solution ratio) for 30 minutes at the time fumigation commenced. The fumigated samples were then filtered (Whatman No. 42) and analysed immediately or stored frozen at -18 ^{o}C prior to analysis. Organic C in the soil extracts was measured by automated uv-persulphate oxidation (Wu et al., 1990)

Biomass C (B_c) was calculated from: $B_c = 2.22\ E_c$

where E_c = [(organic C extracted from fumigated soil) minus (organic C extracted from control soil)].

The factor 2.22 is a proportionality constant, to account for the fact that about 45 % of the microbial C is made extractable to 0.5 M K_2SO_4 following $CHCl_3$ fumigation.

4. Soil respiration

Glass vials containing moist soil (20g) were placed into 1 l brown glass bottles, sealed with rubber bungs and incubated at 25°C. The brown glass bottles also contained 20 ml 1 M NaOH, to absorb CO_2 and 10 ml water to prevent the samples from drying. The NaOH was replaced at weeks 1, 2, 4 and 6. At each change of NaOH the previous aliquots were temporarily stored, prior to analysis, in an air-tight 2.5 l glass jar with a vial of soda lime. The vials can be stored like this for many weeks, if necessary. The CO_2 evolved and trapped during incubation was determined by titration with an automated Radiometer TIM 85 Titration system. The amount of CO_2-C evolved was calculated from the volume of standardised 0.5 M HCl neutralised between pH 8.3 and 3.7

5. Water holding capacity

Water holding capacity (WHC) represents the maximum quantity of water the soil can hold. For standard conditions, the WHC of studied soil must be between 40% and 50% (Vance et al., 1987). Soils that are not within this range, should be dried or wetted accordingly. To measure WHC the volumetric method was used.

A short length of rubber tubing was attached to the stem of each 100 ml glass funnel and a clip placed on each piece of tubing to close it completely. Glass wool weighed to 0.29 g was rolled into a cylinder and placed in the top of the funnel stem. 50 g of moist soil was put into the funnel and 50 ml of water added and left for 30 minutes to saturate the soil. After this time, the clips were opened for 30 minutes and water allowed to drain into a measuring cylinder held beneath the funnel. Blanks were set up in the same way but did not contain the 50 g of soil. These were used to measure the volume of water retained by the glass wool. The volume of water held by the soil was determined by the difference in volume of water collected and that retained in the glass wool, from 50 ml.