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Improvement of soil structure and crop yield by adding organic matter to soil

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1. Abstract

Soil quality is intimately linked with soil biology. Recent research at Rothamsted Research (RRes) has shown that addition of Farm Yard Manure (FYM) can improve barley grain and straw yield within two years by more than 1t ha^{-1} each. Penetrometer measurements attribute this increase to an improvement in ease of root exploration in the soil, which, in turn, may be attributed to an increase in earthworm biomass and activity. These results suggest benefits from adding the right kind of organic matter can be achieved relatively rapidly in soils by feeding the soil organisms, which then bring about desirable changes in soil condition. We hypothesised crop yields will increase quickly (within four years) as a result of improved soil physical condition that results from feeding soil organisms, especially earthworms, with relatively small amounts of suitable organic matter additions.

To test these ideas, we set up field experiments at Rothamsted Research farm (flinty clay loam soil) in Harpenden between 2012 to 2017. The four harvest years of the project allowed three field experiments to run. These covered two tillage regimes, four arable crop rotation combinations, five nitrogen treatments and fourteen organic matter recipes at a range of concentrations. Additionally, two outdoor pot experiments, growing winter wheat under a range of earthworm amendments, seven organic matter recipes and four soil types, were studied. The influence on soil physical properties, crop yields and earthworm populations were examined on selected plots and pots. Different methods were used on selected plots to examine soil physical properties. Methods included bulk density, infiltration, penetrometer, aggregate stability, resistance to ploughing or CT scans of the pores in soil. Earthworm populations were determined on selected plots by handsorting one 20 x 20 x 20cm cube taken from a plot. Microbial biomass, fungal biomass and microbial community composition were also measured.

Five commercial growers' trials were held at Haines Barn, Woodbridge, Butterwick, Terrington and Spalding (England). Data from three independent trials at AFBI (Northern Ireland), three at NIAB (England) and one at JHI (Scotland) were also included. These data included some yield data on cereal or horticulture cultivations, soil physical measurements and an earthworm survey.

Crop yields were determined on every plot, with a beneficial yield effect detected on both the Rothamsted trials after two years of amendments. Amended soils in a pot experiment testing the effect of soil type had more tillers and greater grain masses than unamended soils but there was no significant difference between soil types. Yield improvement in a European study did increase with texture in the order clay<silty clay loam<sand.

Differences in soil physical properties were not evident after two years. This was linked to the high proportion of flint in these soils (20 % stones by volume) affecting some of the methods.

Adding organic amendments to soil in two field experiments was found to change the yield response of four crops (spring barley, winter wheat, oilseed rape, winter oats) to N. Amendments increased yields but by a greater amount in a tilled system than a system with reduced tillage. An increasing amount of amendment increased yield but there is evidence of a maximum in this response to amendment, beyond which the yield response declines. The amendments contained nutrients which helps to explain why crops yield well at low rates of mineral N application but not why they yield more overall. The full benefits from amending soil does not appear immediately and two or three years of application may be needed. Spring crops appear to benefit more than winter crops but in years when yields are good the benefits of amending soil are less clear, both in absolute and relative terms. Quality was either unaffected by amendment (N) or improved (TGW) and to the extent that might attract a premium (oil). A straightforward economic analysis suggests that acquiring and spreading amendments should cost no more than £50 t^{-1} C spread if amending is to be economic.
Several additional pieces of work were undertaken to try to understand why yields respond to organic amendments. Our initial hypothesis was that organisms rearrange the structure of soil to their own benefit while dwelling there and that this in turn improved the environment for crops. Amendments increased microbial biomass, earthworm biomass (g m^{-2}) and numbers (m^{-2}) on certain occasions but there was no overall statistical difference between amendments and no statistically consistent benefit to mass or numbers of organisms. Means to increase earthworm numbers, such as grinding up part of the amendment to make it more easily ingested by earthworms, staging the application four times per year or eliminating fungicide from the earthworm's diet, all increased earthworm numbers and biomass but did not increase yields in the field.

All wheat crops grown with non-crop residue amendments were first wheats in these experiments. However, FYM was found to have altered N response curve of wheat in historic experiments where take-all was additionally present, such that up to 1t extra grain ha^{-1} was obtained.

Infiltration of water through soil was increased by amending soil, but not significantly. The plough draught forces (in kPa) were significantly reduced by amending soil and in proportion to the amount and energy content of the amendments. No significant difference, however, was found in measurements of soil mechanical impedance to a hand-operated penetrometer, nor in bulk density. However, there was no significant relationship between draught forces in autumn with the yield the following summer except, between autumn 2014 and summer 2015.

Despite the lack of conclusive evidence, it is surmised that amendments increase yield and that the most plausible mechanism is that the soil organisms have improved the structure or the ease with which the plant can rearrange the soil structure to its own benefit.

2. Introduction

The addition of organic matter such as Farm Yard Manure (FYM) to soil usually increases crop yields (Johnston et al., 2009) and improves fertility (Cooke, 1967) and soil quality generally (Weinhold et al., 2004). However, these benefits have been largely attributed to the nutrients contained in and added along with the organic amendments. Some work has suggested additional benefits of organic amendments, perhaps due to improvements in soil structure and the water release curve that allow roots to access water and nutrients more readily and which lead to increased porosity in soil (Johnston et al., 2009). Such findings are by no means universal and are often greater for spring-sown rather than winter-sown crops (Hijbeek et al., 2016), possibly because of the need for a spring-sown crop to establish a root system as quickly as possible.

Part of the difficulty in establishing the benefits of added organic matter (OM) is in distinguishing the nutrient from the non-nutrient effect. In order to do this, we examine data where the yields have been measured at different rates of application of mineral N both with and without OM. In this way, it becomes possible to plot response curves to applied mineral N and calculate the amount of N (Nopt) needed to achieve optimum yield (Yopt) with and without OM. These response curves vary with season, but it is possible to assess in general whether the yield obtained with OM plus mineral N is greater than without no matter how much mineral N is applied. In much of the previous work that has found evidence of a benefit of OM (or otherwise), it is possible that insufficient mineral N to reach maximum yield was applied along with the OM. In other words, the full response curve is not described and because of this it is not possible to compare the maximum or optimum yields attainable in both cases. Indeed, the conclusion has usually been that the nutrients applied with the organic amendment lead to the same yield as with mineral N. This is eminently reasonable, but misses the potential additional response to more N still. Our key resource is a series of experimental trials where sufficient N has been given to allow us to infer the full response of crops to N and any changes that result from adding OM to soils. In these trials, we look for evidence of the mechanisms that lead to changes in the response curve.

Earthworms have been observed to relieve soil compaction (Capowiez et al., 2012) and increase the infiltration of water by creating a greater quantity of air and water holding macropores (Capowiez et al., 2009). Anecic earthworms (e.g. *Lumbricus terrestris*) create permanent vertical burrows that increase the infiltration of water and create ‘paths of least resistance’ through which plant roots can penetrate. Endogeic earthworms (e.g. *Allolobophora chlorotica*) create a network of horizontal macropores that increase the soil water holding capacity (Capowiez and Belzunces, 2001). Earthworms of different ecological groups interact to improve soil structure because different species move through soil in different but nonetheless beneficial ways. *A. chlorotica* are known to avoid and not interact with the larger vertical burrows made by anecic earthworms (Capowiez and Belzunces, 2001). We hypothesise that the burrowing activity of earthworms combined with organic amendments may create a network of pores that increase water holding capacity, increase infiltration, and decrease resistance to the penetration of plant roots.

Our overarching hypothesis is that adding organic matter to soil feeds the soil organisms which change the fertility (in the total sense of the word) possibly by re-arranging the structure of the soils to their own benefit but also to the benefit of crops exploiting the same soils.

We further hypothesised that crop yields will increase quickly (within four years) as a result of improved soil physical condition which results from addition of relatively small amounts of suitable organic matter additions. To explore these ideas, we set up a series of field and pot experiments, amended soil with organic matter and measured the yield response and changes in organisms and structure using a wide range of techniques.

Because not all farmers have access to amendments at economic prices, we investigated other means of increasing fresh OM in soil such as reduced tillage and pre-treatment of crop residues to increase the amount retained in soil.

3. Materials and methods

To test the hypotheses a mixture of existing and new experiments was used (Table 3.1). The existing experiments have associated historical data which was used to support the analyses carried out in this research, but the treatment structure was not altered in any way. The new trials were set up with treatments specifically chosen to test our experimental hypotheses. Field and pot experiments were set up and the pot experiments embraced trials under both ambient and controlled environmental conditions.

Table 3.1. Summary showing the details of different experiments used in this study

Trial name	**Location**	**Purpose**	**Treatments**
		Existing trials	
Broadbalk LTE (1852- present)	RRes, Harpenden	To study the effect of FYM and inorganic fertilizers on wheat yield	FYM: 0- 3 t C ha^{-1} Fertilizer N: 0-288 kg N
Hoos Barley LTE (1852- present)	RRes, Harpenden	To study the effect of FYM and inorganic fertilizers on spring barley yield	FYM: 0- 3 t C ha^{-1} Fertilizer N: 0-144 kg N
Woburn LTE (1964- present)	RRes, Woburn	To study the benefits of applying organic amendments to soil and crop yield	Organic matter (compost, peat, straw, leys and FYM): 0-3.5 t C ha^{-1}
		New trials managed by Rothamsted Research	

Fosters (2013-present)	RRes, Harpenden	To study the effect and residual effect of organic amendments along with inorganic N fertilizer on soil and crop yield	Organic matter (Compost, Anaerobic digest, straw, FYM and straw in combination with other organic amendments): 0 - 3.5 t C ha^{-1} Fertilizer N:0-260 kg N ha^{-1} (depending on the crop)
New Zealand (2013- present)	RRes, Harpenden	To study the effect and residual effect of organic amendments along with inorganic N fertilizer on soil and crop yield	Organic matter (Compost, and FYM): 0 - 3.5 t C ha^{-1} Fertilizer N:0-260 kg N ha^{-1} (depending on the crop)
Great Knott III (2013-2015)	RRes, Harpenden	To study the effect straw application on soil and crop yield	Straw: 1.8-7.3 t C ha^{-1}
Trials managed by partner organisations			
Sustainability trial for arable rotations (STAR) (2005- present)	Otley, Suffolk	Cultivations and rotations for sustainable farming	Four rotations: Winter cropping, Spring cropping, Continuous wheat and Alternate fallow. Four cultivation methods: Annual plough, Managed approach, Shallow tillage and Deep tillage.
New Farming Systems (2007-present)	Morley, Norfolk	Rotations to improve sustainability, resilience and outputs	Three rotations: Winter break, Spring break and Mixed cropping Four management systems: Current, legume, Current plus brassica cover crop, and current plus legume cover crop Three N managements: Untreated, Half dose, and full dose.
Mid Pilmore (2003-present)	Perthshire, Scotland	To study the effects of different tillage methods on production	Five soil tillage practices with cultivation to a range of depths: 0 cm (no-till) to 40 cm (deep plough). Two fertiliser levels: 90 and 180 kg N ha^{-1}
Saxmundham	NIAB, Cambridge	To test the effects of rotations and additions of organic matter on yields	FYM and mineral fertilizers

Agri-Food BioSciences Institute of Northern Ireland (AFBI)	Northern Ireland	To test the effects of slurry and manure on cropping under conventional and ploughed systems.	Various organic amendments versus mineral nutrition
Pot experiments			
Soil type pot experiment	RRes, Harpenden	To study the benefits of applying organic amendments to soil and crop yield	Organic matter (Straw, anaerobic digest, compost, FYM, and straw in combination with other OM amendments): 0-3.5 t C ha^{-1}
Saxmundham pot experiment	NIAB, Cambridge	To study the effect of FYM on wheat yield	Recent FYM, LT FYM and added earthworms

Existing experiments on the addition of FYM to winter wheat on Broadbalk field and spring barley on Hoos field at Rothamsted Research (RRes) have been described elsewhere (e.g. Johnston et al., 2009), on the use of FYM at Saxmundham (Cooke and Williams, 1971), on the addition of different organic amendments on a sandy loam soil at Woburn (Mattingley,1974), on tillage at Mid-Pilmore (Newton et al., 2012), and at Morley and Otley (Stobart et al., 2016, Stobart et al., 2014, Morris et al., 2014, Hallett et al., 2014). A range of trials under different climates from a European project (Hibeek et al., 2016) has also been included in the synthesis of the results in order to assess the wider applicability of the results beyond the climate of SE England where the majority of the field experimentation took place.

There were two pot experiments under ambient conditions, both growing winter wheat. One experiment tested the 4 different OM amendments applied to Fosters but on three contrasting soil types in order to evaluate the effect of texture more widely than at Rothamsted but more economically than by setting up other field trials elsewhere. The other pot experiment tested the specific effect of adding earthworms or FYM on yields from heavy soils where earthworms were less abundant than might be expected. A range of smaller pot experiments were also carried out to test specific ideas relative to the growth of earthworms under laboratory conditions with a view to suggesting measures that might improve earthworm numbers in practice.

3.1. Field trials

The main field trials were conducted at the Rothamsted Farm, Harpenden, Hertfordshire. There were three new field trials employed during the project (2013-2016): New Zealand, Fosters and Great Knott III. All trials were arranged as a randomised block design. The cultivations were performed on the same area (GPS located) over the 4-years of the project and covered a range of tillage, arable rotations, organic matter recipes and amounts, and nitrogen levels.

The soil in all three experiments as well as on the long-term Broadbalk and Hoos field trials is a well-drained Batcombe series flinty silty clay loam (average 25% clay, but somewhat variable) over clay with flints, latitude 51.8°N longitude 0.4°W in the East of England at an altitude of 130m with mean annual temperature of 10°C and mean annual rainfall of 700mm.

In addition, trials were established on commercial fields (Section 4.11) on a range of soil types in the East of England.

Data from other fields managed by Rothamsted Research, by NIAB and the James Hutton Institute were also used in this study.

3.1.1. **Existing field trials managed by Rothamsted Research**

3.1.1.1 Broadbalk wheat (RRes)

The Broadbalk field experiment has tested the effect of different rates of nutrients (chiefly N) in combination with different management practices (rotation and pest control) on yield of (mainly) winter wheat, among other treatments, since 1843. FYM has been applied at the annual rate of 35 t ha^{-1} (fresh material) along with two different rates of mineral N throughout (*i*, N0 and *ii* until 2005, N2, thereafter N3). Between 1985 and 2000 an additional N rate (N4) applied to wheat grown in rotation also received FYM. These plots were used to test the hypothesis that application of FYM ameliorates the effect of Take All (*Gaeumannomyces graminis*) on yield. Plot size is 24.38 x 5.3 m for the mineral N plots, 24.38 x 2.85 m for the FYM plots. Harvested area is 0.00512 ha in both cases.

3.1.1.2 Hoos barley (RRes)

Hoos field has grown spring barley since 1852 comparing yields on plots that receive both mineral N and dressings of either 0 or 35 FYM t ha^{-1} in the autumn. Additional plots were set up in the year 2000 that replicate the FYM treatments. However, they differ in that levels of native soil organic matter are much less than in the existing long-term FYM plots. It was the observation that yields on these plots, established in 2000, increased rapidly as a result of amendment that led to the current research proposal on which we now report.

3.1.1.3 Woburn organic manuring experiment (RRes)

The Woburn organic manuring (WOM, Mattingley, 1974; Mattingley et al., 1974) experiment has run on Stackyard field at the Woburn experimental farm (52 01°N, 00 36°W, ca 100m AOD) from 1966 until the present but with some modifications. It tests the effects of different organic amendments to soil in four replicated blocks in conjunction with different rates of application of N. The experiment is run on a contrasting soil to Rothamsted – a loamy sand – and as such crops are much more subject to drought than they would be in the deep silty clay loam at Rothamsted. The experiment makes use of different amendments (compost, peat, straw, leys) and FYM applied at two different rates. However, periodic changes in experimental setup and treatments mean that not all amendments (e.g. compost) have been applied throughout the 50-year duration of the experiment. The blocking has changed too, as has the complexity of the experiment. The value for the current research is that there is thus a scale of both carbon in the amount of amendment applied and N fertiliser applied giving the potential to investigate the response of crops to different rates of added organic matter as well as to N. This scale of amendment in not present in the other long term experiments at Rothamsted, although it has been imposed on the new AHDB-funded Rotations Partnership experiments. The WOM experiment is run as a rotation and there are confounding effects of year and crop that must be acknowledged in understanding the experimental results. In an attempt to account for these confounding effects we also ran a computer simulation model (Dailey *in preparation*, Coleman et al *submitted*) of the most important processes in the soil-crop system, to try to understand and generalise the benefits of applying organic amendments to soil.

3.1.2. **New field trials managed by Rothamsted Research**

3.1.2.1. Fosters field experiment *(2 crops x 2 blocks x (5 N rates x 4 OM types + 5 OM rates x (4 OM types +3 mixtures)) =220 experimental plots)*

On Fosters field, located at Rothamsted Research farm, 220 ploughed plots tested 5 rates of addition of 4 kinds of organic matter (OM) amendment and 3 mixtures with straw, and with the background N-response measured at 5 rates of N. Two arable rotation series were compared in two replicate blocks, with half the field sown with each crop in 220 plots (Table 3.1.1). The soil has a total organic C of 1.6 % and pH of 6.99.

Crop details

Table 3.1.1. Cropping details on Fosters field.

Block	**2013**	**2014**	**2015**	**2016**	**2017[1]**
W Rotation 1	Winter Wheat, ww	Spring Barley, sb	Winter Oats, woats	Winter Wheat, ww	Winter Wheat, ww
E Rotation 2	Spring Barley, sb	Winter Oilseed Rape, osr	Winter Wheat, ww	Spring Barley, sb	Winter Wheat, ww

[1]Experiment continues with funding from SARIC to look at effect of withholding OM. Reporting here is up until 2016 only.

Table 3.1.2.Treatments on Fosters field

Organic matter	Carbon rate (tonnes C ha^{-1})	Nitrogen rate (kg N ha^{-1}) N0-N4, rates vary with crop but are reckoned in relation to RB209 guidance, such that N3 is the recommended rate
Straw		N0-N4,
Anaerobic digestate		N0-N4
Anaerobic digestate + Straw		N3
Compost		N0-N4
Compost + Straw		N3
Farmyard manure		N0-N4
Farmyard manure + straw		N3

Trial details

The trial is managed using a conventional regime (fertiliser, pesticides) and is tilled by ploughing. Both the organic amendments and nitrogen treatments (Table 3.1.2) were applied by hand each year in the autumn (farmyard manure was chopped first with a muck spreader).

3.1.2.2 New Zealand field experiment *(3 replicates x (3 rates of 2 types of OM x 5 rates of N including shared OM and N controls) = 75 experimental plots)*

On New Zealand field, two amendments at 3 rates of application were tested under reduced tillage with a similar assessment of the response to added N fertiliser.

Crop details

The crop rotation for the New Zealand experiment was spring barley (2013), winter oilseed rape (2014), winter wheat (2015), spring barley (2016: with no organic amendments) (Table 3.1.3). The organic amendments were applied to the same plots year on year, however the mineral N rotated hence different plots were sampled between years (Table 3.1.4).

Table 3.1.3. Cropping details on New Zealand field.

2013	2014	2015	2016[1]	2017[1]
Spring Barley	Oilseed Rape	Winter Wheat	Spring Barley	Spring Barley

[1]Funded for 3 years under Defra SP1312. Continues with funding from SARIC to look at effect of residual years. Reporting here is up to 2015 only

Table 3.1.4. Treatments on New Zealand field.

Organic carbon:	Nil	Compost	Farmyard Manure
Amount (kg C ha^{-1})	0	2.5, 3.5	2.5, 3.5
Nitrogen (kg N ha^{-1})	Five rates, 0 up to 260 (depending on crop type)		

Trial details

The trial was managed using a conventional regime (fertiliser, pesticides) under minimum tillage between 2013 and 2016. For tillage, a Lemken Karat stubble cultivator consisting of tines, discs and a crumbler roll was used at a depth of ca. 10 cm. Both the organic amendments and nitrogen treatments were applied by hand (farmyard manure was chopped first with a muck spreader).

3.1.2.3 Great Knott III field experiment *(4 blocks x (2 rates of straw x 3 pre-treatments + 1 control) =28 plots)*

On Great Knott III, the growth of winter wheat established under conventional tillage was examined in relation to a number of novel ways of pre-treating crop residues before incorporation.

Crop details

The crop rotation for Great Knott III field was winter wheat for all the three years during 2013-2015 (Table 3.1.5). Wheat straw was applied at different rates as part of the treatments (Table 3.1.6).

Trial details

The trial was managed using a conventional regime (fertiliser, pesticides) and tilled by ploughing. Nitrogen was supplied as two splits at the recommended RB209 levels.

Table 3.1.5. Cropping details on Great Knott III field.

2013	2014	2015
Winter Wheat	Winter Wheat	Winter Wheat

Table 3.1.6. Treatments on Great Knott III field.

Amount (t straw ha^{-1})	2013	2014	2015
0	Nil	Nil	Nil
4.5	No chop	Normal - chop 90%, grind 10% (application: initial 25% total followed by 3 staged applications of remainder winter/spring)	Normal - chop 90%, grind 10% (application: initial 25% total followed by 3 staged applications of remainder winter/spring)
4.5	Normal[a] - chop 90%, grind 10%	Normal - chop 90%, grind 10%	Normal - chop 90%, grind 10%
4.5	Normal, conditioned[b]	Normal - chop 100 %	Normal - chop 100 %
19	No chop	4x Normal - chop 90%, grind 10% (application: initial 25% total followed by 3 staged applications of remainder winter/spring)	4x Normal - chop 90%, grind 10% (application: initial 25% total followed by 3 staged applications of remainder winter/spring)
19	4x Normal - chop 90%, grind 10%	4x Normal - chop 90%, grind 10%	4x Normal - chop 90%, grind 10%
19	4x Normal, conditioned	4x Normal - chop 100 %	4x Normal - chop 100 %

[a] as obtained from the field

[b] Rolled in order to split open the straw and permit easier colonisation by fungi

3.1.3. Trials managed by partner organisations

3.1.3.1. STAR, NFS (NIAB)

The 'Soil Platforms' project (AHDB Project 3786 - Platforms to test and demonstrate sustainable soil management: integration of major UK field experiments) works with some of the longest running contemporary UK soil tillage experiments. The four sites within the 'Soil Platforms' project are at Mid Pilmore (Perthshire, Scotland, established 2003), the Centre for Sustainable Cropping (CSC) (Perthshire, Scotland, established in 2011), Sustainability Trial for Arable Rotations (STAR) Suffolk, established 2005) and New Farm Systems (NFS) (Norfolk, established 2007). Each site features contemporary tillage, with some also exploring crop rotation. Soil physical conditions and other production characteristics, along with yields and farm gate economics, are being assessed within the contrasting farming system based approaches. The primary focus of this work is around the interaction of crop yield and tillage.

The STAR and NFS sites are fully replicated randomised designs using large plots and farm scale equipment. While soil types differ (STAR - heavy soil, clay loam; and NFS - medium soil, sandy loam) tillage approaches are common to both studies; systems used are plough (inversion to *c*. 20 cm), deep non-inversion (to *c*. 20 cm) and shallow non-inversion (to *c*. 10 cm). Both studies use a common cropping approach of winter wheat every other year with combinable break crops in intervening seasons. The crop rotation (choice of combinable break crop) varies within and between studies. Further detail of treatment, system and findings for STAR and NFS can be found in Stobart *et al*. (2014) and Morris *et al*. (2014).

3.1.3.2. Mid-Pilmore (JHI)

Reduced tillage for arable cropping is increasingly common in the UK and is the focus of our investigations at this site. The effect of tillage intensity on earthworm populations is not well known so we used this experiment at Mid Pilmore (Perthshire, Scotland) to look at the effects of tillage on yields.

3.1.3.3. Saxmundham

The Saxmundham experiment is a resource now run by NIAB which tested the effects of rotations and additions of OM but has been under grass for the last two years for lack of the resource to manage it. The soil is of Beccles series similar to the STAR trial and close in distance. This particular soil is problematic to manage because it readily forms large clods that do not weather down because of the unfavourable (i.e. not sufficiently heterogeneous) distribution of pores. Rothamsted observations of this soil were that structure improved marginally with OM addition but these improvements did not result in yield increases (Cooke and Williams, 1971). Earthworms and other macrofauna were largely absent. It is not clear if the structure was poor because of the absence of worms or if the poor structure precluded colonization by soil macro-organisms.

Historical crop yields at this site have been greater on plots receiving FYM than on soils receiving mineral N only, but not by as much as seen elsewhere such as at Rothamsted. Measurements of the water release curve suggested less additional water could be held in the FYM Saxmundham soils relative to controls compared with Rothamsted or elsewhere. These observations led us to question whether the issues – water, earthworms and yield - might be connected. In particular, we hypothesised that the absence of earthworms might be the reason why the added FYM might not be incorporated into SOM sufficiently to improve the water holding characteristics of the soil and that this in turn might be the reason why the crops do not out-yield the control plots as much as elsewhere. Whether it is the relative absence of worms that leads to the relative absence of SOM it is not possible to say.

3.3.3.4 AFBI

Trials at the Agri-Food BioSciences Institute of Northern Ireland test the effects of slurry and manure on cropping under conventional and ploughed systems and in particular the availability of N to the crop receiving amendments and to subsequent crops. The trial compared crops that continued to receive amendment with crops that received amendment in the initial or initial two years only. The cropping and the amendments differed by site: at Hillsborough winter wheat in 2013 was amended with broiler litter, hen manure or pig slurry, subsequent crops in 2014 (winter barley) and 2015 (spring wheat) received compost across all plots. At Downpatrick spring wheat in 2013 was grown with and without broiler litter and additional fertiliser applications and was followed by winter barley (2014) again with and without broiler litter and additional fertiliser applications; maize was grown in 2014 and not harvested. At Crossnacreevy spring barley in 2014 was amended with either pig or cattle slurry or AD and followed in 2015 by winter barley + spring barley (because of poor establishment) with plots to which the amendments are applied and others from which amendments were withheld. The later sowing of spring barley in 2015 resulted in it not being harvested.

3.2. **Pot experiments**

Two outdoor pot experiments were conducted in outdoor protected sand beds under ambient temperature conditions at Rothamsted Research. Plant yields were compiled per pot. The components of yield were recorded: the number of plants, number of ears, grains per ear, and total grain weight.

3.2.1. **Soil type pot experiment (216 pots)**

Winter wheat was established with 30 kg of a loamy sand soil (source Butt Close field Woburn), silty clay loam soil (source Fosters field) and sandy clay loam soil (source Warren field, Woburn) under a range of organic matter recipes at 5 rates in duplicate. A mixture (endogeic: anecic) of 10 earthworms after harvest of Fosters field were collected and added to the pots at the start of the experiment in the ratio of 5:1. Drainage holes in the pots were taped up with plastic gauze to allow water to leave or seep into the soil but prevent earthworms from escaping. Up to 10 wheat plants per pot were established during two years and the pots were weeded by hand. The pots were watered daily by an automated system during Spring and Summer. The pots were harvested by hand, amendments were applied in the autumn and forked into the soil surface (Table 3.2.1).

Table 3.2.1. Treatments for soil type pot experiment.

Organic matter amendments	Carbon rate (tonnes C ha^{-1})	Nitrogen rate (kg N ha^{-1})
Straw		
Anaerobic digestate		
Anaerobic digestate + Straw		
Compost		
Compost + Straw		
Farmyard manure		
Farmyard manure + straw		

3.2.2. **Saxmundham pot experiment (32 pots)**

We obtained soil from the plots in Rotation I of the Saxmundham field experiment, inferred from Trist and Boyd (1966) and Salter and Williams (1969) in the Saxmundham experiment (Beccles series, Trist and Boyd, 1966) that had received either 13.5 t FYM ha^{-1} (6 tons $acre^{-1}$) or none and combined these background treatments with new interventions of either earthworms or none and freshly added manure or none and set up a pot experiment with four-fold replication. One winter wheat plant was established per pot and the soils were amended with either farmyard manure (25 t ha^{-1}) or 5 endogeic earthworms (30 g m^{-2}) or both farmyard manure and earthworms, and a control (no amendments). All pots received 160 kg N ha^{-1}. The pots were watered, weeded and harvested by hand.

3.3. **Quality of organic amendments**

Quality of organic amendments used in the experiments were analysed for C, N (Table 3.3.1) and energy contents (Table 3.3.2) for different years of the experiment.

Energy content of organic amendments were measured by bomb calorimetry by Sciantec Analytical Services Ltd. such as is used in food analysis (Table 3.3.2). Cellulose was estimated from literature values of FYM and AD (Bhogal, et al, 2010) and compost (Tambone et al., 2009).

Table 3.3.1. Carbon and nitrogen content (%) of different organic amendments applied in Fosters and New Zealand during 2013-2016.

	2013			2014			2015			2016			average		
	N	C	C:N ratio	N	C	C:N ratio	N	C	C:N ratio	N	C	C:N ratio	N	C	C:N ratio
AD	2.43	41.67	17.14	1.03	43.00	20.52	1.95	43.05	22.10	1.50	43.35	28.90	1.73	42.77	24.75
compost	1.39	29.33	21.07	2.10	25.31	24.52	1.62	19.83	12.23	1.48	19.51	13.17	1.65	23.50	14.26
FYM	2.71	30.80	11.38	2.13	21.88	10.27	2.01	42.13	20.96	2.77	37.14	13.39	2.41	32.99	13.72
straw	0.50	45.91	92.20	0.70	44.64	63.40				0.80	43.96	55.16	0.53	44.57	84.40
OSR residues							0.72	45.03	62.96						
Wheat straw							0.53	44.57	84.40						
barley straw							0.69	46.83	67.77						

Table 3.3.2. Energy content of amendments measured by using bomb calorimetry.

Sample	Cellulose g/100g dry matter	Gross Energy (MJ/kg)
Barley straw	35.8[1]	17.03
Farmyard manure	15.9	12.51
Anaerobic digestate	7.9	11.46
Compost	4.38	7.964
Wheat straw	35.8[1]	16.38

[1] Cellulose values derived from literature values (Bhogal et al., 2010; Liu and Sun, 2010). Hence the same value is attributed to wheat and barley

3.4. Crop measurements

3.4.1. Crop yields

All plots in all years were harvested using a Sampo 2010 plot combine over an area of 9 m x 2 m from the centre of each plot (undisturbed by soil sampling) but note additional harvest in 2014, below. Moisture content was assessed, and yields were expressed at 85% dry matter for cereals and 90% dry matter for oilseeds (Appendix I and Appendix II). To check the nutrient composition of the cereals, grains and straw were oven dried at 80 °C for 48 h after collection and ground to <0.5 mm using a stainless steel centrifugal mill (Retsch 400). To assess the total N content, subsamples of spring barley were analysed by LECO (TruMac Combustion Analyser). An analytical replicate was performed for every ten samples for quality control of the procedure, with an acceptable 3.4 ± 0.9 % difference, well within the tolerance limit of <5 %. In 2014, there was a problem with the Sampo and yields were collected from the discard with a Haldrup over a 1 x 9 m strip. Although these data were less variable than the data collected with the Sampo there was no difference in the statistical analysis.

3.4.2. Thousand grain weight

The thousand grain weight (TGW) is the weight in grams of 1000 cereal kernels, determined using an automatic grain counter (Numigral 1, Chopin Technologies, France). After counting, the grain is dried overnight at 105 degrees C. The TGW for all these crops for different years were given in Appendix III.

3.4.3. Oil content

Water and oil content was determined from paired 6 g (8 ml) OSR seed samples taken from the harvested sample of each plot using a Minispec mq-20, pulsed time-domain NMR analyser (Bruker-BioSpin, Rheinstetten, Germany). Due to the different relaxation decays of the neutrons in the various sample components, moisture and oil can be detected and clearly distinguished. Initial calibration was obtained using OSR seed samples of different water and oil contents that were previously analysed by a wet-chemical method. Oil contents were corrected based on a standardised seed water content of 90 g/kg (Appendix IV).

3.4.4. Nitrogen content of grain

Nitrogen contents (from which to infer protein) were measured in 2013 and 2016 by the LECO on all grain and straw samples taken from the Fosters trial. In this way, a direct comparison can be made between the spring barley and winter wheat crops grown on the same plots, but following 4 years of amendment with OM.

3.5. Soil measurements

3.5.1. Earthworm and soil microbiology

3.5.1.1. Earthworms

There was some variation between the methods used to sample for earthworms. The general methodology is described below and deviations from it described with the relevant field, pot or laboratory experiment.

Earthworms were sampled based on the BS EN ISO 23611-1:201 Soil was sampled as a cube of 20 cm x 20 cm x 20 cm (w x b x d) and immediately sorted by hand to enumerate both the total and species level population density (abundance) and biomass. Earthworm species were identified using the OPAL Open Air Laboratories system. Prior to biomass estimates, earthworms were washed in deionised water to remove surplus soil and then blotted on tissue paper to remove surplus water prior. The earthworms were then weighed on an analytical balance (4DP). Mustard extractions were attempted at earlier stages of the experiment, however, this was discontinued as the mustard solution did not percolate into the soils effectively and the time of infiltration was very variable.

For the Fosters experiment, only plots involving the N fertiliser application rate at RB209 (Defra Fertilizer Guidance) but including the plots amended with straw mixtures were assayed for earthworms. Factorial nested ANOVA was applied to the entire datasets using time, crop, presence/absence of OM amendment of any form (‘Amend’), OM rate, and straw: other organic material mixtures (‘Mixture’) as treatment terms.

For the New Zealand study, worms were assayed twice per annum in 2014 and 2015. Frequency and biomass data were analysed by factorial nested ANOVA using time, presence of organic amendment ('Amend'), OM rate, OM type and N fertilisation rate as factors.

For the Mid-Pilmore trial (JHI), we measured earthworm populations in the final year of a long-running (14 years) spring cropping field trial managed using different tillage intensities (zero tillage, shallow non-inversion tillage (<7 cm), conventional ploughing (20 cm), conventional ploughing followed by compaction, and deep ploughing (ca. 35 cm) to investigate the effects of spring tillage and tillage intensity on earthworm populations. We used two methods to estimate earthworm populations (hand sorting and mustard extractions).

3.5.1.2. Soil microbiology

Plots within both the New Zealand and Fosters experiments were assessed prior to the establishment of the experiment to ensure that there was no high underlying variability (baseline assessment). Once the experiment was established, soils from each of the designated experimental plots were re-sampled to determine treatment effects at various times throughout the trial (Table 3.5.1)

Five soil samples (10 cm diameter to 10 cm depth) were randomly taken within each designated plot using a trowel, but avoiding a central plot strip (1 m wide) to avoid damage to the crop and so affecting yield estimates. Resultant soil samples were homogenised from within each plot, passed through a 2 mm sieve and stored at 5°C until analysis. This mode of sampling was repeated for each plot.

Table 3.5.1. Plot sampling dates for microbiology

	New Zealand		Fosters		
Time period	Sampling date	Crop	Sampling date	R1 Crop	R2 Crop
Baseline survey	9th/10th April 2013	Spring Barley	9th/10th April 2013	Winter Wheat: drilled 08/11/12, harvested 18/08/13	Spring Barley drilled 21/02/13 harvested 19/08/13
Autumn 2013	28th October	Winter OSR	11th November[1]	waiting for Spring Barley	Winter OSR drilled 13/08/13
Spring 2014	1st May	Winter OSR	1st May[1]	Spring Barley: drilled 12/03/14 harvested 06/09/14	Winter OSR: harvested 14/07/14
Autumn 2014	15th October	Winter Wheat	18th November[1]	Winter Oats: drilled 22/10/14	Winter Wheat: drilled 25/09/14
Spring 2015	5th May	Winter Wheat	17th April[1]	Winter Oats: harvested 04/08/15	Winter Wheat: harvested 17/08/15
Autumn 2015	28th November	Spring Barley	20th November: Rotation 1 only[2]	Winter Wheat: drilled 15/10/15	waiting for Spring Barley
Spring 2016	Not sampled	Spring Barley	6th April	Winter Wheat, harvested 11/06/16	Spring Barley: drilled 17/03/16 harvested 23/08/16

[1] anaerobic digestate plots not sampled, [2] rotation 2 not sampled.

Soils were sampled within both crop rotations of the "Fosters" experiment from plots (Appendix V) that had mineral nitrogen applied at RB209 rates, and the following organic amendment treatments (two replicates):

- Organic amendment type (seven types): i) straw, ii) compost, iii) compost + straw, iv) farmyard manure (FYM), v) FYM + straw, iv) anaerobic digestate (AD), vii) AD+ straw
- Organic amendment rate (four rates): 1, 1.75, 2.5, 3.5 t C/ha
- Control with no organic matter but mineral N applied at RB209
- Control with no organic matter or mineral N applied

Soils were sampled from plots on the experiment on New Zealand field (Table 3.5.2) from the following treatments (three replicates):

- Organic amendment type: Compost and FYM
- Organic amendment rates: zero, 2.5 and 3.5 t C/ha

Table 3.5.2. Subset of New Zealand plots sampled for microbiology analysis. Note that plots receiving different N rates rotate over the years of the experiment in the sequence N3-> N2-> N1-> N0-> N4, so that previous year's fertilizer rate does not have a residual influence on results. OM treatments do not rotate

OM Type	**OM rate (C t/ha)**	**N rate (kg N/ha)**	**Autumn 2013 (no crop)**	**Spring 2014 (SB)**	**Autumn 2014 (OSR)**	**Spring 2015 (OSR)**	**Autumn 2015 (WW)**
	0	0	24, 27, 56	24, 27, 56	24, 27, 56	11, 39, 51	11, 39, 51
	0	180	21, 48, 55	21, 48, 55	21, 48, 55	6, 31, 64	6, 31, 64
	2.5	0	9, 40, 60	9, 40, 60	9, 40, 60	5, 35, 68	5, 35, 68
	2.5	180	14, 42, 69	14, 42, 69	14, 42, 69	20, 29, 59	20, 29, 59
	3.5	0	2, 34, 73	2, 34, 73	2, 34, 73	8, 43, 57	8, 43, 57
	3.5	180	3, 30, 66	3, 30, 66	3, 30, 66	18, 33, 63	18, 33, 63
	2.5	0	1, 32, 75	1, 32, 75	1, 32, 75	4, 26, 72	4, 26, 72
	2.5	180	10, 37, 74	10, 37, 74	10, 37, 74	7, 36, 65	7, 36, 65
	3.5	0	19, 45, 71	19, 45, 71	19, 45, 71	15, 28, 61	15, 28, 61
	3.5	180	17, 46, 67	17, 46, 67	17, 46, 67	12, 50, 70	12, 50, 70

SB: Spring barley, OSR: Oilseed rape, WW: Winter wheat

3.5.1.3. Microbial methods

Microbial biomass-C was determined using the fumigation-extraction procedure (Jenkinson & Powlson 1976) using the K_{EC} of 0.45 (Vance et al. 1987). Carbon was extracted with 40 ml of 0.5 M potassium sulphate, and analysed using a Burkard Scientific SFA-2000 Segmented Flow Analyser.

Phospholipid fatty acid analysis (PLFAs) provides a community structure profile (fingerprint) by identifying fatty acid biomarkers (extracted from phospholipid membranes) unique to the membranes of microorganisms. The relative abundance of these fatty acid biomarkers is used as a profile of the microbial community, because specific fatty acids can be used as indicators for the presence of groups of organisms within the soil microbial community. In this study, PLFA profiles were determined using an adaptation of the Frostegård *et al*. (1993) method as described in Pawlett *et al*. (2012). Lipids were extracted from approximately 7 g freeze-dried soil using the Bligh and Dyer solvent ratio of chloroform, methanol and citrate buffer (ratio 1:2:0.8 v/v/v), fractionated by solid phase extraction, and the phospholipids derivatised by mild alkaline methanolysis. The resultant fatty-acid methyl esters (FAMEs) were separated by gas chromatography (Agilents, USA) using a HP-5 (Agilent Technologies) capillary column (30 m length, 0.32 mm ID, 0.25 µm film). The temperature program started at 50°C (1 min), to 160°C at 25°C/min, followed by 2°C/min to 240°C and 25°C/min to 310°C (10 min). The injector temperature was set at 310°C, Flame Ionization Detector set at 320°C, and He flow set at 1 ml/min. The resultant FAMEs were calculated as relative abundance (mol %). Fatty acids were identified by comparison of sample retention time to a standard qualitative bacterial acid methyl ester mix (Supelco) and by using gas chromatography coupled with mass spectroscopy (Agilent, USA). Indicator fatty acids included: the sum of *i*15:0, *ai*15:0, 15:0, 16:1, *i*16:0, 16:1ω9, 16:1ω7 t, *i*17:0, *ai*17:0, *cyc*-17:0, 17:0 and *cyc*-19:0- total bacteria (Frostegård and Bååth 1996), the sum of the *iso* and *anteiso* branched fatty acids *i*15:0, *ai*15:0, *i*16:0, *ai*16:0, *i*17:0, *ai*17:0- Gram-positive bacteria (Zelles 1999), and the sum of 16:1, 16:1ω9, 16:1ω7c, 16:1ω7t, 16:1ω5, 21:1- Gram-negative bacteria (Zelles 1999).

In addition to using the PLFA bioindicator fatty acid (18:2ω6, 9), fungal biomass was also estimated using the ergosterol method described by Ruzicka et al (1995). This method uses non-alkaline extraction in combination with ultrasonication to enhance the release of ergosterol from fungal membranes. Hexane: propanol-2-ol (98:2 v/v) was added to 5 g of freeze-dried soil, and a duplicate spiked with 100 µg ergosterol. After fifteen minutes, methanol: ethanol (4:1 v/v) was added, the sample stored at 4°C for two hours, and then 20ml Hexane: propanol-2-ol (98:2 v/v) added prior to sonication (150W for 200 seconds). The top layer was removed and centrifuged at 7000 x g for 10 mins prior to being analysed by High Performance Liquid Chromatography (HPLC) which comprises of the Kontron pump, 565 auto sampler, 535 UV detector, Knauer degaser an Ezchrom Elite software (SCI Tek instruments, Olney, UK) and 150×4.6mm Lichrosorb Si 60 (10µm particle size) (phenomenex, Macclesfield, UK). Ergosterol was calculated as "Recovery percentage" = $[(Erg_{spike} - Erg_{soil})/Erg_{added}] \times 100$.

3.5.1.4. Statistics (for microbiology)

Total microbial biomass and fungal biomass data were analysed by analysis of variance (ANOVA) via General Linear Models (GLM) followed by post-hoc Fisher LSD. PLFA data was analysed using principal component analysis (PCA) followed by ANOVA of the resultant PC factor scores to determine whether there were any significant effects of the experimental design on the PC factor scores. The time effect was explored using repeated measures ANOVA (RM_ANOVA) through GLM. Data was nested to include the control (unamended by organic fertilisers) plots. Statistics were performed using Statsoft, Inc. (2012) STATISTICA version 11 (data analysis software system**),** with an alpha value of 0.05.

3.5.2. **Soil borne diseases**

The original experimental protocol did not include a test of the effect of amendments on soil-borne diseases and the rotations were chosen to avoid the complication of a second (or third) wheat in the series. However, the long-term experiment on Broadbalk field provides the opportunity to test the effect of FYM at 35 t ha^{-1} $year^{-1}$ on yields in rotation and after 2 or 3 years. There are several differences with this set of data compared with the systematically designed experiments on Fosters and New Zealand fields, however. There are currently two series of plots that receive FYM (at 0 and 96 kg applied mineral N ha^{-1} in addition to the FYM) where wheat was grown in rotation but between 1985 and 2000 there was a third series (at 192 kg N ha^{-1}). Three data are not sufficient to fit four parameters in the linear plus exponential (lexp) model for the N response curves (Eq [1], section 3.7.1). Data from the plots receiving mineral N only (7 rates N between 1985 and 2000) were pooled with the data from the plots receiving FYM giving 10 data in all. Separate values of A, B, and C were fitted to each dataset but a common value of *r* (Eq. [1]), giving 7 parameters, 10 data and so 3 degrees of freedom. A take-all rating score was derived (TAR) as described by Dyke and Slope (1978). Roots were examined after washing and plants with take-all graded: slight (less than 25% of roots infected), moderate (25-75%), severe (more than 75 %); the proportion of roots infected was estimated, roots were not counted. From these gradings a weighted 'take-all rating' (TAR) was calculated: TAR = % plants with slight infection + 2 (% moderate) +3 (% severe); thus maximum TAR = 300.

3.5.3. **Draught forces**

Soil strength as measured by specific draught has been shown to be related to soil clay and soil organic carbon (SOC) content (Watts et al., 2006; Peltre et al., 2015). Large applications of organic matter, inducing large SOC contents in soil, may substantially reduce draught force, but applications of mineral fertilizers at farm-relevant rates have also been shown to moderate draught force requirements (Watts et al., 2006; Liang et al., 2013; Peltre et al., 2015). Inputs of above- and below-ground crop residues and organic amendments affect soil bulk density, tensile strength, clay dispersibility and soil cohesion (Schjønning et al., 1994, 2012; Munkholm et al., 2002) and thereby also tillage draught. Soil water content is known to play a key role in soil friability and draught force requirements (Watts & Dexter, 1994; Perfect et al., 1997; Arvidsson et al., 2004; Munkholm, 2011). More recently Peltre *et al* (2017) found:

- Draught force was significantly smaller in the spring than in the autumn. In the autumn when soils were drier, and specific draught was correlated with several soil characteristics, whereas water content was the dominating parameter in the spring when soils were wetter.
- In the autumn and spring, SOC normalized by clay content explained 38 and 5% of the variation in specific draught, respectively.
- Specific draught did not differ significantly among individual fertilization treatments.
- SOC was closely correlated with clay and water contents and bulk density, and with yield of the preceding wheat.

In previous work, we found that the forces required to pull a plough through the soil could detect differences in the amounts of organic matter in the long-term Broadbalk experiment at Rothamsted (Watts et al 2006). In this work a coupling was used between the plough and power take-off made from a block of solid steel and equipped with sensors to detect the forces transmitted through the plough because of its interaction with the soil (Scholz, 1966). The forces recorded depend on the forward motion of the tractor and on soil factors such as texture, water content and organic matter. The solid steel block is expensive and heavy for farmers to deploy and we sought a simpler, if still experimental design, based on a lightweight frame

3.5.3.1 Equipment

The Rothamsted plough draught measuring unit consists of an instrumented frame, a depth measuring wheel assembly and a GPS speed transducer (Figure 3.1). The bespoke frame is designed to attach to any CAT II linkage tractor, the implement (plough) then attaches to the frame. Implement draught is measured using 3 horizontally orientated 25 kN load pins (Model KMD R917000175, Bosch Rexroth AG, Schwieberdingen, Germany). Two of these pins are situated at the point where the tractor lower links attach to the load frame. The third pin is fitted at a swivelling joint within the frame situated between the tractor/frame top link attachment pin and the frame/implement attachment pin. The depth sensing wheel attaches to the implement (plough) frame. The pivot geometry of the wheel assembly provides motion to a potentiometer which outputs a voltage proportional to the implement depth. The GPS speed measuring device (Dicky-John, iSpeed II, Colombes, France) is magnetically attached to the load frame. It produces a frequency that is proportional to the plough-implement speed. This frequency is converted to a voltage within a data logger enclosure that is fitted inside the tractor cab.

All the load, depth and speed sensing transducers are connected to a data logger (OM-LGR-5325, OMEGA Eng., Manchester, UK) via a removable umbilical. The data logger is mounted in an enclosure box which also contains a stabilised power supply unit, a frequency converter, a fuse block and multi connectors. Power for the box is supplied via a cable which plugs into the in-cab tractor accessory socket. Data from the sensors is collected at 10 Hz.

Figure 3.1 Images of the draught sensing frame in place between the tractor and the plough

3.5.3.2 Field operation

The same 3 furrow reversible plough (Ransomes 300 Series) was used for all measurements although different tractors were used each season (75-100 kW range). Furrow width was 0.36 m and the nominal depth was set to 0.22 m. The same tractor engine speed and gears were used in each season to give a forward speed of 1.2 to 1.5 m/s.

The Fosters experiment was ploughed up and back in the normal way for a reversible plough. Each run crossed a strip 10 plots and the tramlines between them and two data sets were collected (only in one direction) for each strip of 10 plots. This procedure was repeated until the whole experiment had been ploughed and 44 data sets had been collected with all 220 plots ploughed. An extra channel on the data logger was used to mark the start and finish point when the tractor crossed a start and finish datum lines. Data was transferred from the logger to a laptop for processing.

3.5.3.3 Pre-processing data sets

Pre-processing involved converting speed measurements on each data set into distances and calculating the boundaries of each plot, then confirming the start and finish points with the correct distance apart. Once the plot boundaries had been determined, we selected a datum some 3 m from this boundary (allowing the plough to be fully inside the plot) to a point where the front furrow of the plough was about to leave the plot. This was typically 50 data points. Two sets of mean values of the each of the 5 sensors were determined for each plot. It is noteworthy that the original data sets showed a sharp increase in draught as the plough crossed the tramlines or a reduction in draught if the tramlines had been sub-soiled.

Draught force D, (kN) were determined by summing the horizontal force derived from each pin, depth d, (m) from the depth sensor calibration. Here we are interested in specific draught S, (kPa) as measure of soil strength. S for each plot is calculated by dividing mean draught, $\overline{D}$ by the product of width of ploughing, w (3 x 0.36 = 1.09 m) and the mean depth $\bar{d}$.

3.5.4. **Tension infiltrometery**

Infiltration was measured on duplicate plots receiving N fertiliser at RB209 rates plus either no amendment or applications of AD, FYM, compost or straw at 3.5 t C ha^{-1} on Fosters in the summer of 2013 using a Guelph permeameter (e.g. Moya-Esparcia, 2014). Infiltration was also measured on plots receiving 0, 2.5 or 3.5 t ha^{-1} of either compost or FYM on New Zealand field in 2014 using the paint can method developed within this project for farmer's use (Moya-Esparcia, 2014). Briefly, a tin 11.5 cm in diameter and 11.5 cm in height with a hole at 5 cm from the base (and covered with insulation tape) was used. Sand was added until it was level with the hole. A 10 cm high soil core was affixed with narrow tape (19 mm) on the inside and was used to take a 5 cm soil depth core, the soil core dug out (so not to disturb the core) and was placed in the tin. Water was then added to the tin (not the core) saturating the soil from below. Once filled, the outside insulation tape on the tin was removed and the timer started to record the amount of time for water to decline from the top to the bottom of the tape in the soil corer. The infiltration rate (mm hr^{-1}) was calculated by dividing the increment (mm) by the time (hr). This was performed in triplicate on selected plots (n = 15).

3.6. Computer assisted Tomographic Scanning (CT) for soil structure

3.6.1. Soil sampling for CT scan

Fosters trial is a 220 plot complete randomised block design, and 12 plots were chosen for analysis. These were the controls (no organic amendment) at nil (n = 2 plots) and at the recommended fertiliser rate 190 kg N ha^{-1} (n = 2 plots), and the organic amended plots at the recommended fertiliser rate (as above): anaerobic digestate (n = 2), compost (n = 2), farmyard manure (n = 2) or oat straw (n = 2) applied at 2.5 t C ha^{-1}. These organic matter treatments had been applied each Autumn and ploughed in for the previous four years prior to soil sampling for this analysis. The high number of flints in this soil preclude soil core collection, thus soil clods were analysed. One large (20 cm x 20 cm) soil block per plot was collected at pre-harvest using a 14 cm wide gardening fork the day before analysis. The vertical orientation was maintained and the block was broken by hand (along natural aggregates) to make a ca. 10 cm x 10 x 8 cm clod. This was placed in a small plastic box (11 cm x 11 cm x 10 cm) for transportation, and for analysis (i.e. clods were analysed in the box).

3.6.2. X-ray computed tomography (CT Scanning)

CT scanning was performed using a Phoenix v/tome/xm scanner (GE sensing and Inspection Technologies, Wunstorf, Germany), set at 190 Kv and 200 µA, with a 0.5 mm Cu filter. Each scan took 33 minutes to complete. The total number of images for each clod was 2400 per scan at a detector size of 2014 x 2024 pixels creating 31 GB file sizes. Data are given in mm. Aggregate (clod) size was 10x10x8 cm as above, giving a potential pixel side of about 80 µm. In other words, we sampled pores down to a minimum of silt-size.

3.6.3. Image processing

Image processing analysis was performed on the raw grey-scale images using ImageJ 1.44 (http://rsbweb.nih.gov/ij/). Each clod image was cropped to a 44.8 x 44.8 mm x 19.2 mm (700 x 700 x 301 pixels) area to exclude the outside edge and edge effects, giving a final pixel dimension of 64 µm. A median filter (radius 2 pixels) was used to remove noise but maintain borders. To separate pores from the matrix, different threshold settings were compared and the Otsu (1979) global automatic threshold algorithm was selected for the optimum analysis of all 12 samples. After application, the resulting black and white images were inverted so that the pores were recoloured to black prior to analysis. These binary images (301 images per sample) were analysed using the instrument Analyse Particles tool which calculates each individual pore size and shape (ca. 100, 000 pores per image stack).

3.6.4. Statistical analysis

Genstat (18th addition, VSN International Ltd., UK) was used to perform the statistical analyses. General ANOVA (Analysis of Variance) was used with the following parameters: Block = Block/Plot/Slice, Treatments = split/Nrate/omtypes, where split and N-rate were two factor categories comparing the presence/absence of organic amendment or N-rate respectively. The OM types included each organic amendment (anaerobic digestate, compost, farmyard manure or oat straw). The residual graphs were checked to meet the normality assumption, and for four parameters (average size, perimeter, feret and area) required log transformation to meet the normality assumption. Differences obtained at levels $p \leq 0.05$ were reported as significant. Feret is the longest dimension of a pore in these 2D section, the perimeter is the distance in pixels around each pore and the area the number of pixels contained within.

3.7. Determination of response curves and yield optima

Linear plus exponential response curves (lexp. George, 1984) were fitted to each data set from each year. However, where only four data were available (Hoos barley) or where data were pooled (Broadbalk), it was necessary to fix the exponent, *r*, to 0.99 as indicated in Eq [1] leaving at least one degree of freedom for the model:

$$Y = A + B * r^N + C * N \quad [1]$$

$$Y = A + B * r^N \quad [1a]$$

where *Y* is yield in t ha^{-1}, *A* *B* and *C* are constants with *B* and *C* < 0. If *ß* is the break-even ratio (BER, the point at which an increment of additional yield only just pays for the additional increment of N fertiliser needed), *Nopt* is the total application of N. *Yopt* is the yield at this application of N found by substituting *Nopt* into [1]. If the price of N is £0.5 kg^{-1} and the value of wheat is £140 (current prices, January 2017) then the BER is 0.00357 (0.5 per kg/0.14 per kg). Historically the value of BER has been close to 0.003 and this value is used for *ß* throughout.

$$Nopt = \frac{\ln((-ß - C)/(B * \ln(r)))}{\ln(r)} \quad [2]$$

$$Nopt = \frac{\ln((-ß)/(B * \ln(r)))}{\ln(r)} \quad [2a]$$

Response curves and the derived summary parameter, Yopt and Nopt were determined for Broadbalk (disease), Hoos field (initial observations), Fosters, New Zealand and Great Knott fields (main experimental trials), WOM (contrasting sandy soil, rotational crops) and the European database (rotational crops and contrasting climates). Not all curves reach a maximum yield within the range of N applications tested. In such cases, the parameter *C* cannot be estimated and Eqs [1a] and [2a] must be applied instead.

3.8. Modelling

Modifications to these formulae [1] and [2] were made to account for the combined effects of N and OM on yield. Two modifications were tested to scale the organic matter (O) addition (1b) and to allow a separate exponent (2b).

$$Y = A + B * r^{N+\alpha*O} + C1 * N + C2 * O \qquad [1b]$$

$$Y = A + B1 * r1^{N} + B2 * r2^{(1+O)} + C * N * (1 + O) \qquad [2b]$$

Parameters of these curves were derived by fitting eq [1b] or [2b] as appropriate using a genetic algorithm (GA, Charbonneau and Knapp, 1995) to determine the region that contains the global minimum and finding the actual minimum with a simplex search whose apices are initiated with the suite of parameters from the GA search.

3.9. Earthworm pot experiments

Experimental microcosms were constructed using polyethene bags and 1 pint (0.57 Litre) plastic drinking cups. Soil was wetted up to 70% of the water holding capacity and a treatment applied, as described below, before 500 g (dry wt.) of soil was added to each polythene bag. A pin was used to perforate the top of each plastic bag to allow the circulation of air. The bag was placed in the plastic drinking cup to ensure at least 10 cm depth of soil for the earthworms to burrow (Lowe and Butt, 2005). The mass of a single earthworm was determined before it was added to each microcosm at the start of the experiment. This stocking density is below the 3–5 adult worms l^{-1} rate recommended by Lowe and Butt (2005) so it is unlikely that the earthworms were stressed due to a lack of space. Experimental microcosms were arranged in a complete randomised block design in a controlled environment chamber, in constant darkness at 15^{o} C. Earthworms were removed from the microcosms by destructive sampling and thorough mixing of the soil every 2 weeks for the duration of the experiment to ensure that the removal of each earthworm had an equal impact on the soil structure and the position of the food in each microcosm. Earthworms were washed by submerging them in deionised water, blotted dry, their mass determined, and then returned to the same microcosm.

Before earthworms were added to the experimental microcosms, soil was thoroughly mixed with five rates of <1 mm milled farmyard manure, compost, or anaerobic digestate, each relating to 0, 2, 4, 6 and 8 g C kg^{-1} soil (13 treatments). Each of these 13 treatments was further amended and thoroughly mixed with <1 mm milled straw at five rates, also relating to 0, 2, 4, 6 and 8 g C kg^{-1} soil. Each of the resulting 65 treatments was replicated four times comprising 260 experimental microcosms in total. No further applications of organic amendments were made to the pots after this initial addition. Every two weeks of the 12 week duration of the experiment the earthworms were removed from the microcosms, their mass determined, and returned. The soil was homogenised each time the earthworm was removed.

We obtained a source of straw from trials carried out at AFBI where the object is to compare the responses of different varieties of cereal to a number of factors, including fungal attack – the recommended list trials at Hillsborough and Crossnacreevy. Samples of straw are retained from these experiments. Four replicate pots were set up, receiving one of five rates of straw (0, 0.4, 0.8 1.2, 1.6 or 2 g pot^{-1} per fortnight) to pots containing 400 g soil (from Fosters field at Rothamsted). At the end of the experiment the results were analysed by repeated measures REML for the difference in earthworm growth between pots receiving straw without/with fungicide after 2, 4, 6, 8 and 10 weeks.

4. Results

4.1. Fosters field experiment at Rothamsted

4.1.1. Crop yields at Fosters

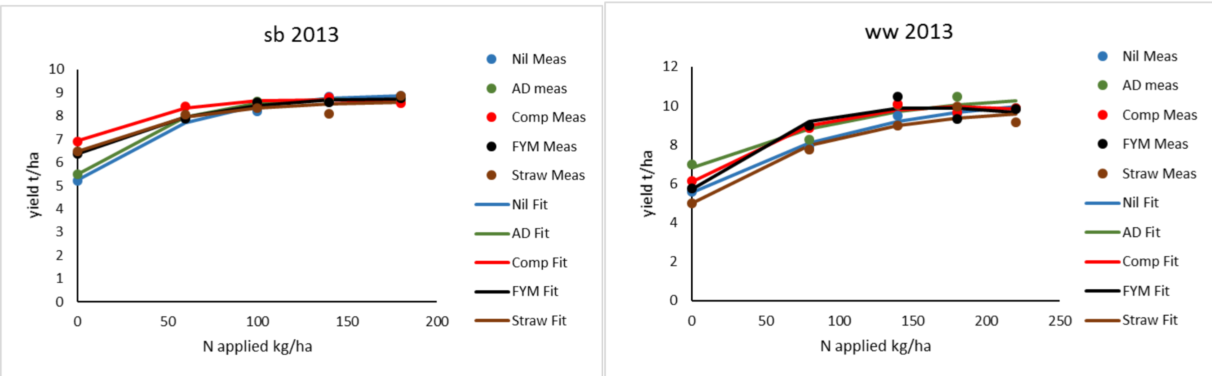

Figure 4.1.1. Yield response of spring barley and winter wheat to N with and without amendment in 2013 in Fosters.

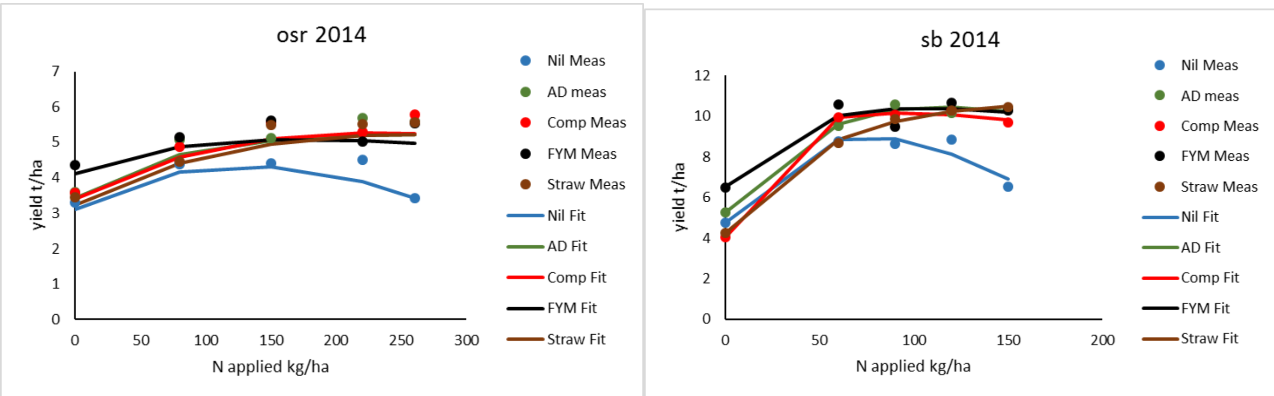

Figure 4.1.2. Yield response of oilseed rape and spring barley to N with and without amendment in 2014 in Fosters.

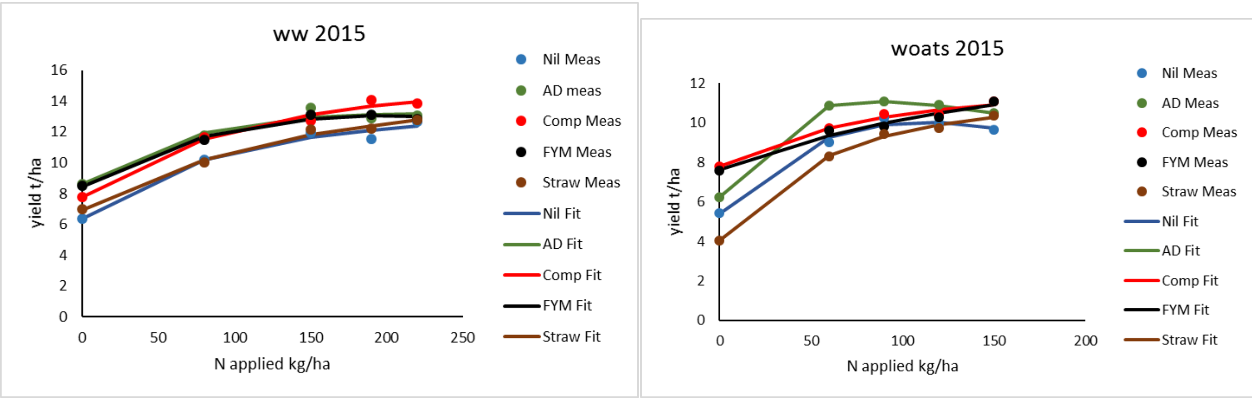

Figure 4.1.3. Yield response of winter wheat and winter oats to N with and without amendment in 2015 in Fosters.

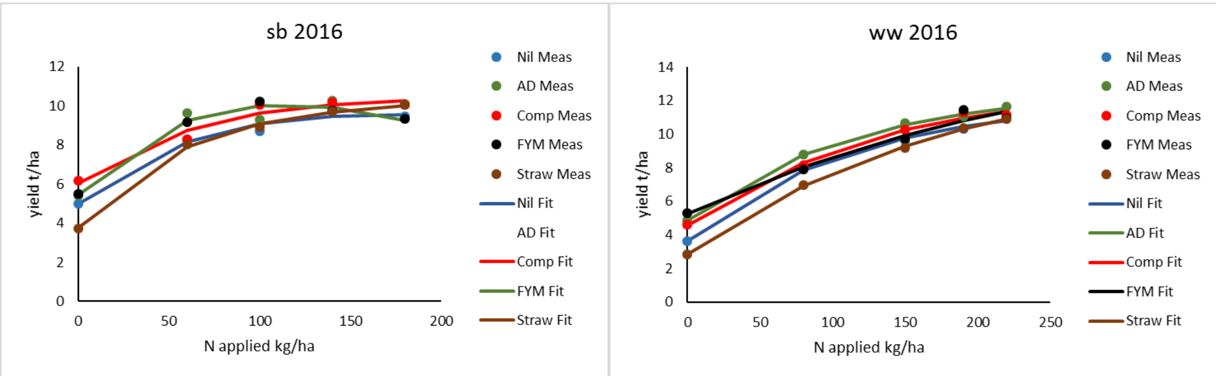

Figure 4.1.4. Yield response of spring barley and winter wheat to N with and without amendment in 2016 in Fosters

As expected from prior work (Hoosfield), there were no significant differences between yields receiving amendments and the controls in the first year of the experiment (harvest 2013).

The values of Nopt and Yopt are given in Table 4.1.1 and as percentage difference from the control (Yopt_amend – Yopt_nil) in Table 4.1.2. It was slightly surprising that the amended treatments on the West block (R1) yielded less in 2013 than the control, although this effect is less apparent in the East block (R2). Subsequently, amended treatments yielded consistently more (10%) with there being little difference between the cropping blocks (9.2, 10.2%; Table 4.1.1). Not all amendments yield more than the nil (control) but this is partly because of large field variation especially in the control (e.g. Yopt SE 0.823, ww 2015). As borne out by the analysis of variance (Table 4.1.1), the response to amendments is highly significant in all years apart from 2013. In contrast to recent data from comparable European studies (Hijbeek et al., 2016), there was no significant difference between spring (10.6%) and winter (9.3%) sown crops although as found by Hijbeek et al the spring crops do benefit slightly more.

Where Nopt exceeds the maximum level of N applied, this maximum has been substituted from Nopt and Yopt calculated on the basis of the maximum application. This was the case for all data from Fosters East (R2, ww) in 2016. Standard errors, where available, are derived from the calculated Nopt, however.

Table 4.1.1. Optimum yield and optimum nitrogen fertilizer requirement under different crops for different years in Fosters. These Nopts are unconstrained in order to calculate the SEs. Yopts in this and subsequent tables are at Nopts constrained to the maximum N level applied

		West				East			
		Yopt	SE	Nopt	SE	Yopt	SE	Nopt	SE
	Spring barley					Winter wheat			
2013	nil	8.82	0.139	150	23.4	10.12	0.164	277	**7.1**
	ad	8.73	0.039	126	3.8	10.33	**0.349**	**253**	**20.2**
	compost	8.7	0.076	108	7.3	9.87	0.168	162	26.1
	FYM	8.69	0.071	142	16.9	9.92	0.361	143	27.7
	straw	8.58	0.238	152	81	9.55	0.46	220	120
	Oil seed rape					Spring barley			
2014	nil	4.29	0.271	93	12.3	9.0	0.377	75.5	4.74
	ad	**5.1**	0.124	161	30.8	**10.5**	0.165	110	9.11
	compost	**5.14**	0.129	169	37.7	**10.46**	0.203	98.1	5.428
	FYM	**4.99**	0.226	108	22.8	**10.49**	0.48	103	27
	straw	**5.11**	0.122	200	70	**10.44**	0.05	139	4.3
	Winter wheat					Winter Oats			
2015	nil	12.62	0.823	276	203	10.05	0.164	104	8.2
	ad	13.12	0.245	169	38.5	**11.23**	0.142	93	3.86
	compost	**14.97**	1.687	414	1135	**11.24**	0.544	203	125
	FYM	13.0	0.176	186	37.5	**11.44**	**0.213**	**263**	**10.0**
	straw	**13.01**	**0.216**	**306**	**7.0**	10.28	0.211	158	19.8
	Spring barley					Winter wheat			
2016	nil	9.53	0.212	149	26.9	11.31	0.132	327	3.4
	ad	**10.19**	0.357	128	28.5	**11.98**	0.094	320	2.6
	compost	**10.2**	0.323	163	54.4	**11.72**	0.238	322	6.6
	FYM	**10.07**	0.112	108	3.695	11.33	0.453	309	14.3
	straw	**9.95**	0.162	169	18.1	11.18	0.298	338	6.9

*Letters in bold letter indicate yield is statistically significant from the respective nil treatment for each year and crop.

The benefits of amending soil were expressed for each crop in each year in a number of ways (i) as the difference (diff) between Yopt with amendment and Yopt without (Yopt_with – Yopt_nil); (ii) as the ratio of Yopt with amendment to Yopt without (Yopt_with/Yopt_nil). The expectation is that this number will be greater than unity; and (iii) the difference between this number and one represents the fractional increase (Yopt_with /Yopt_nil – 1). The values of Yopt used here are calculated from values of Nopt constrained to be no greater than the maximum amount of N applied. Some values of Nopt (Table 4.1.1) are infeasibly large and not permissible under NVZ rules. The values in Table 4.1.2 are representative of practice, therefore the benefits in years 2013 to 2016 averaged across both crops in each year are -0.1, 1, 0.8 and 0.5 t ha^{-1} respectively.

Table 4.1.2. Benefits of treatments relative to the control for west and east blocks of Fosters.

	2013	**2014**	**2015**	**2016**
West				
	Spring barley	Oil seed rape	Winter wheat	Spring barley
diff	-0.167	0.786	0.853	0.532
ad	0.988	1.176	1.063	1.042
compost	0.985	1.202	1.128	1.076
FYM	0.987	1.161	1.053	1.056
straw	0.965	1.192	1.032	1.050
mean	0.981	1.183	1.069	1.056
East				
	Winter wheat	Spring barley	Winter oats	Winter wheat
diff	-0.028	1.407	0.778	0.477
ad	1.031	1.166	1.106	1.068
compost	0.997	1.133	1.090	1.051
FYM	0.996	1.158	1.090	1.049
straw	0.964	1.170	1.025	1.009
mean	0.997	1.157	1.078	1.044

Table 4.1.3. Statistical significance of the effect of organic amendments and nitrogen on crop yield.

	OM	OM rate	OM rate within each type of OM	OM and nitrogen	OM and nitrogen rates	Nitrogen rates
2013						
Wheat and barley						
Grain	0.13	0.743	0.690	0.013	0.694	**<0.001**
SED	0.279	0.211	0.557	0.249	0.557	0.249
Straw	0.308	0.241	0.807	0.075	0.987	<**0.001**
SED	0.228	0.172	0.455	0.204	0.455	0.204
1000 Grain weight	0.018	**<.001**	**0.009**	0.235	0.414	**<0.001**
SED	0.695	0.525	11.39	0.622	1.39	0.622
2014						
Winter oilseed rape						
Seed	0.337	0.664	0.718	**0.001**	0.170	<**0.001**
SED	0.250	0.189	0.500	0.224	0.500	0.224
Straw	0.307	0.132	0.345	0.002	0.767	<**0.001**
SED	0.326	0.246	0.652	0.292	0.652	0.292
1000 Grain weight (g)	0.451	0.967	0.426	0.572	0.391	0.033
SED	0.089	0.067	0.178	0.079	0.178	0.079
Oil content (%)	0.447	0.052	0.666	**<0.001**	0.048	**<0.001**
SED	0.344	0.067	0.178	0.079	0.178	0.079
Oil yield (t ha^{-1})	0.383	0.780	0.786	**<.001**	0.430	<**0.001**
SED	0.116	0.088	0.232	0.104	0.232	0.104
Oil yield, 91% (t ha^{-1})	0.447	0.052	0.666	<**0.001**	0.048	**<.001**
SED	0.313	0.236	0.625	0.280	0.625	0.280
Spring barley						
Grain	0.253	0.051	0.532	<**0.001**	0.007	<**0.001**
SED	0.312	0.236	0.624	0.279	0.624	0.279
Straw	0.765	0.638	0.916	0.026	0.448	**<0.001**
SED	0.371	0.281	0.742	0.332	0.742	0.332

1000 Grain weight (g)	0.299	0.727	0.872	0.497	0.049	**<0.001**
SED	0.550	0.416	1.101	0.492	1.101	0.492
2015						
Winter wheat						
Grain	0.075	0.097	0.385	**<0.001**	0.159	**<0.001**
SED	0.265	0.200	0.530	0.237	0.530	0.237
Straw	0.013	0.074	0.276	**<0.001**	0.276	**<.0.001**
SED	0.272	0.205	0.544	0.243	0.544	0.243
1000 Grain weight (g)	0.634	0.339	0.458	0.017	0.513	0.095
SED	0.457	0.346	0.915	0.409	0.915	0.409
Winter oats						
Grain	0.077	0.403	0.704	**<0.001**	0.313	**<0.001**
SED	0.449	0.339	0.898	0.402	0.898	0.402
Straw	**0.009**	0.564	**0.007**	**<0.001**	0.238	**<0.001**
SED	0.326	0.247	0.652	0.292	0.652	0.292
2016						
Winter wheat						
Grain	**0.002**	**0.008**	0.068	**<0.001**	0.072	**<0.001**
SED	0.201	0.152	0.401	0.179	0.401	0.179
Straw	**0.004**	0.225	0.174	0.022	0.060	**<0.001**
SED	0.249	0.188	0.498	0.223	0.498	0.223
1000 Grain weight (g)	0.664	0.474	0.054	0.003	0.691	<**.001**
SED	0.373	0.282	0.746	0.334	0.746	0.334
Spring barley						
Grain	0.363	0.685	0.684	**<.001**	**<0.001**	**<0.001**
SED	0.205	0.155	0.409	0.183	0.409	0.183
Straw	0.777	0.727	0.111	0.020	0.548	**<0.001**
SED	0.198	0.150	0.397	0.178	0.397	0.178
1000 Grain weight (g)	0.141	0.545	0.461	0.022	0.639	0.150
SED	0.407	0.307	0.814	0.364	0.814	0.364

SED: Standard error of difference of means

* *Letters in bold letter indicate statistical significance at P< 0.01

Yields of barley on the Hoosfield experiment at Rothamsted (section 3.1.1.2) were maintained in amended plots, varying much less from year to year than the unamended plots. This is illustrated in Figure 4.1.5 where the effect of amendment is much greater in years when the unamended crop yields poorly. In this experiment, it appears that the amendments are conferring a degree of stability to the yields making the cropping system more resilient to the differences in years.

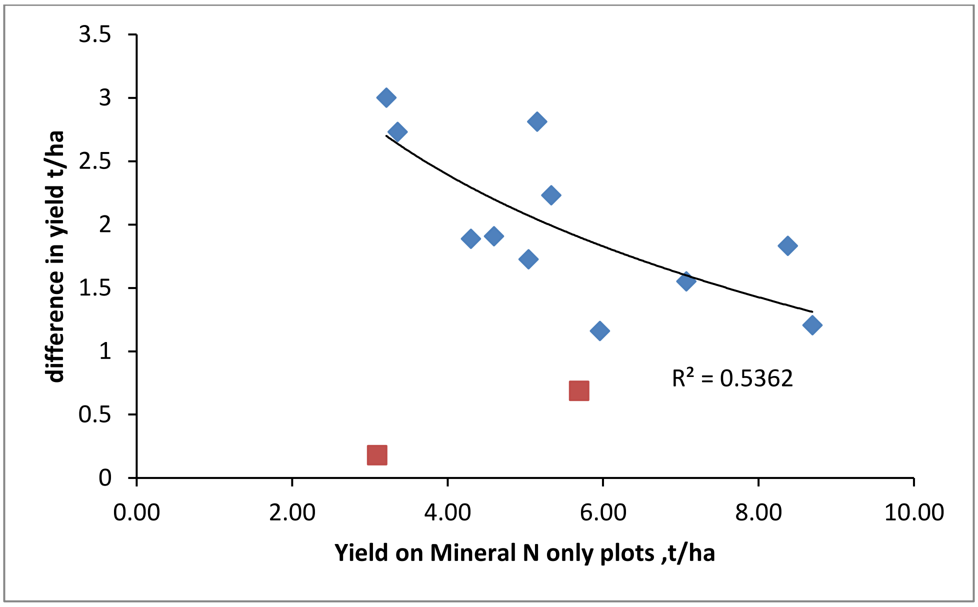

Figure 4.1.5. Difference in optimum yield between amended and unamended crops (Yopt_with – Yopt_nil) plotted against Yopt_nil in data from the Hoosfield long-term spring barley experiment at Rothamsted 2000-2013, where amended on the Yopt_with plots began in 2000. Red squares are differences in the first two years of the experiment; blue diamonds are harvest data during 2003-2013; Pearson correlation coefficient for a logarithmic relationship 0.732 with 9 degrees of freedom $p<0.05$).

4.1.2. **Crop quality**

4.1.2.1 Crop N content

Amending soils with OM was either neutral or beneficial (in the sense that more N is likely to lead to better protein) with respect to the N content of grain in the first year of application (2013) (Table 4.1.4 – Table 4.1.7). However, none of the increases were sufficient to attract a premium. It was not our intention in the project to pursue the milling premium, however. Barley %N were approximately the same with as without amendment at the lowest and highest rates of N application and so would not attract a penalty in the sense that malting barley requires low rather than high Ns. Wheat %Ns were slightly greater with amendment than without although not sufficiently so to attract a premium or bread-making quality. There was no consistent effect of the rate of application of any of the amendments on %N in 2013.

Table 4.1.4. N in Barley Grain 2013 in relation to amendment at different rates of N.

N-rate	none	SE	AD	SE	compost	SE	FYM	SE	straw	SE
0	1.19	0.09	1.18	0.02	1.22	0.02	1.23	0.01	1.24	0.05
80	1.29	0.07	1.41	0.06	1.41	0.15	1.31	0.05	1.40	0.04
150	1.45	0.01	1.67	0.07	1.51	0.07	1.55	0.08	1.47	0.14
220	1.56	0.04	1.72	0.13	1.64	0.13	1.62	0.00	1.53	0.06
260	1.90	0.03	1.85	0.04	1.71	0.09	1.66	0.18	1.69	0.13

Table 4.1.5. N in Wheat Grain 2013 in relation to amendment at different rates of N

N-rate	none	SE	AD	SE	compost	SE	FYM	SE	straw	SE
0	1.18	0.06	1.23	0.04	1.21	0.02	1.17	0.00	1.24	0.02
80	1.25	0.01	1.31	0.02	1.28	0.01	1.32	0.01	1.21	0.05
150	1.56	0.11	1.51	0.05	1.60	0.08	1.49	0.08	1.44	0.05
220	1.65	0.05	1.78	0.03	1.55	0.03	1.62	0.07	1.71	0.11
260	1.62	0.04	1.85	0.10	1.69	0.03	1.63	0.06	1.61	0.04

Table 4.1.6. Nitrogen in Barley grain 2013 in relation to different rates of amendment

Rate (t C ha^{-1})	AD†	SE	AD + Straw	SE	Compost	SE	Compost + Straw	SE	FYM‡	SE	FYM + Straw	SE	Barley Straw	SE
0	1.63	0.01	1.63	0.01	1.63	0.01	1.63	0.01	1.63	0.01	1.63	0.01	1.63	0.01
0.3	1.64	0.01	1.54	0.05	1.64	0.24	1.60	0.10	1.56	0.08	1.58	0.12	1.56	0.03
0.7	1.67	0.06	1.71	0.05	1.65	0.12	1.51	0.21	1.65	0.07	1.54	0.09	1.56	0.03
1.5	1.75	0.14	1.68	0.06	1.63	0.11	1.52	0.00	1.52	0.01	1.65	0.12	1.51	0.06
3.5	1.66	0.06	1.66	0.04	1.68	0.05	1.74	0.20	1.76	0.08	1.61	0.10	1.67	0.08

Table 4.1.7. Nitrogen in Wheat grain 2013 in relation to different rates of amendment

Rate (t C ha^{-1}	AD†	SE	AD + Straw	SE	Compost	SE	Compost + Straw	SE	FYM‡	SE	FYM + Straw	SE	Barley Straw	SE
0	1.68	0.09	1.68	0.09	1.68	0.09	1.68	0.09	1.68	0.09	1.68	0.09	1.68	0.09
0.3	1.55	0.03	1.56	0.03	1.61	0.01	1.62	0.04	1.65	0.03	1.68	0.04	1.72	0.04
0.7	1.74	0.00	1.71	0.09	1.65	0.05	1.62	0.10	1.57	0.03	1.68	0.08	1.72	0.04
1.5	1.70	0.05	1.71	0.06	1.65	0.02	1.60	0.07	1.62	0.14	1.57	0.08	1.33	0.03
3.5	1.67	0.12	1.57	0.09	1.65	0.00	1.66	0.04	1.79	0.08	1.58	0.10	1.69	0.08

†Anaerobic digestate; ‡Farm yard manure; SE: Standard error

In 2016, grain N was analysed for selected treatments focussing only OM amended treatments (**Error! Not a valid bookmark self-reference.**Table 4.1.8 – Table 4.1.10). There was no significant difference between amending or not and with rate of application. Unamended treatment (RB209-no-amendment) had an %N of 1.754% while the amended treatment was 1.735 %.

Table 4.1.8**.** Nitrogen in barley grain 2016 in relation to different rates of amendment

Rate	Anaerobic digestate	SE	Compost	SE	FYM	SE	Straw	SE
0	1.72	0.02	1.72	0.02	1.72	0.02	1.72	0.02
0.3	1.58	0.04	1.71	0.04	1.59	0.02	1.70	0.02
0.7	1.68	0.05	1.60	0.04	1.64	0.01	1.63	0.02
1.5	1.70	0.04	1.74	0.02	1.67	0.09	1.58	0.08
3.5	1.64	0.04	1.75	0.04	1.69	0.06	1.63	0.08

Table 4.1.9**.** Nitrogen in wheat grain 2016 in relation to different rates of amendment

Rate	Anaerobic digestate	SE	Compost	SE	FYM	SE	Straw	SE
0	1.79	0.02	1.79	0.02	1.79	0.02	1.79	0.02
0.3	1.81	0.04	1.81	0.04	1.73	0.01	1.80	0.11
0.7	1.91	0.01	1.80	0.29	1.77	0.02	1.74	0.10
1.5	1.80	0.07	1.94	0.01	1.90	0.09	1.79	0.01
3.5	1.81	0.04	1.83	0.11	1.86	0.04	1.72	0.03

Table 4.1.10. ANOVA terms for grain N (%) for Fosters in 2016.

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
blocks stratum	1	0.00493	0.00493	0.31	
blocks. Units. stratum split	1	0.27014	0.27014	17	<.001
split.OM	3	0.04352	0.01451	0.91	0.441
split.omrate	3	0.02351	0.00784	0.49	0.689
split.nrate	1	0.36722	0.36722	23.11	<.001
split.OM.omrate	9	0.09081	0.01009	0.63	0.762
Residual	53	0.84235	0.01589		
Total	71	1.64248			

Split is a factor category comparing the presence/absence of organic amendment

4.1.2.2. Thousand grain weight (TGW)

Amending soils with OM leads to a small but significant increase in grain size (Thousand grain weight Table 4.1.3). Despite the advantages of larger TGW such as milling quality and better germination, larger grains do not attract a premium and so any increases as a result of amendment do not have an economic benefit.

4.1.2.3. Oil content

Oil content of OSR in 2014 was increased significantly by the level for all the amendments except straw (Figure 4.1.6). Since oil attracts a premium above 40% these increases have a small economic benefit but are likely to vary in practice between varieties.

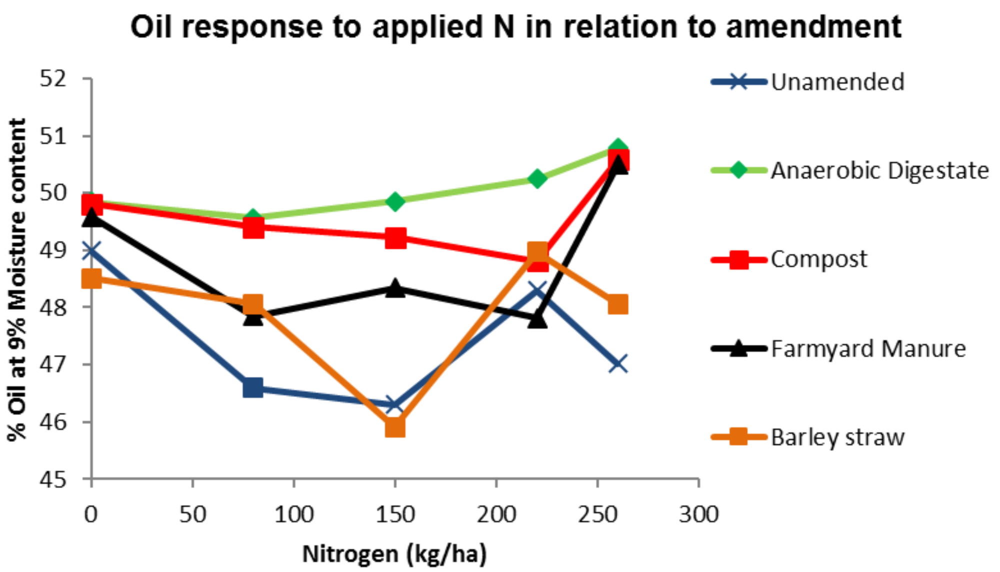

Figure 4.1.6. Oil response to applied N in relation to various amendments.

4.1.3. **Soil physical measurements**

4.1.3.1. Infiltration rate

Tension infiltration measurements were made on duplicate plots from the winter wheat block for 5 treatments (N3 - Main amendments only i.e. no mixtures, at the C4 - 3.5 t C ha^{-1} addition rate plus unamended control) in 2013. This showed that there was a non-significant (p=0.096) trend of improved infiltration on plots amended with farmyard manure, straw and anaerobic digestate (Figure 4.1.7). Differences between amendments were still less significant (p=0.336). Later work testing simple methods of measuring infiltration that farmers could use (Moya-Esparcia, 2014) also failed to find any significant difference in infiltration between amendments and the control.

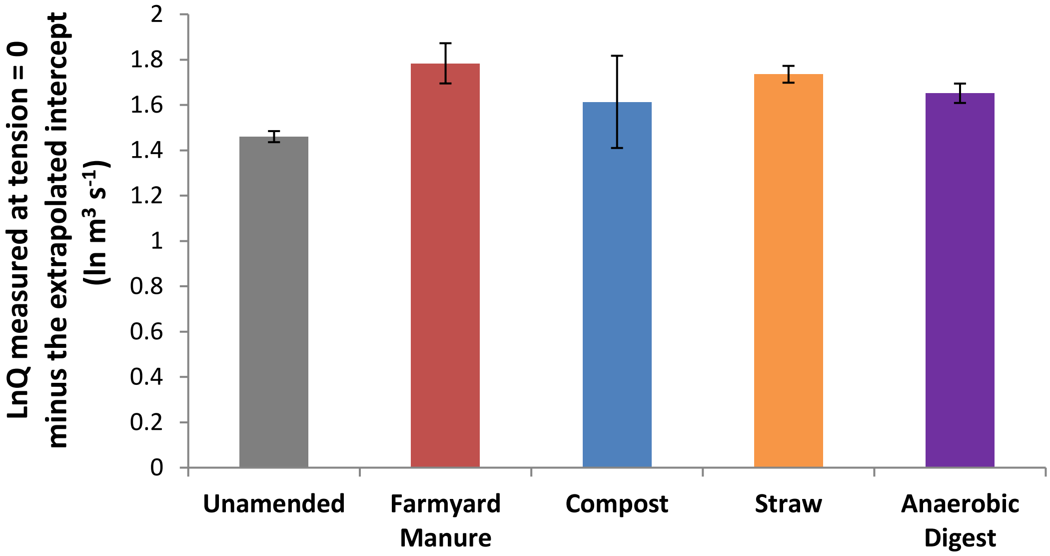

Figure 4.1.7**.** Tension infiltration measurements in 2013. LnQ – logarithm of the inferred water infiltration rate at zero tension

Penetrometer measurements were made on 58 plots for all 7 treatments and the control in 2014. However, there was no significant effect on soil strength detected (Figure 4.1.8).

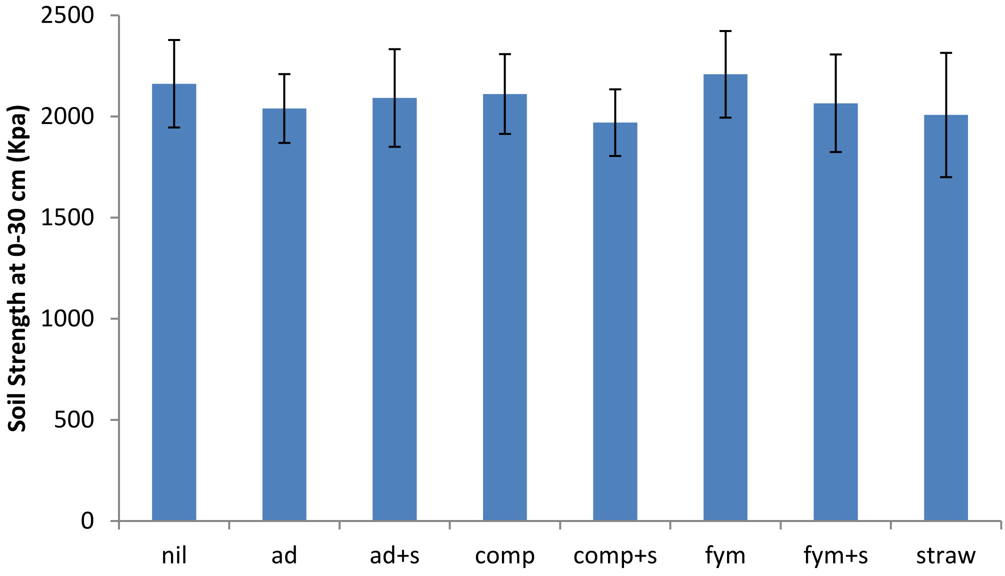

Figure 4.1.8**.** Penetrometer measurements in 2014

4.1.3.2. Bulk density determinations

Bulk density measurements were made on the samples taken for CT scans in spring 2016, receiving 3.5 t ha^{-1} FYM, AD, compost, straw or no amendment. However, there were no significant differences in bulk density between the amended and non-amended soils.

4.1.3.3. Earthworm populations

Mustard extraction procedures were deemed unreliable due to extremely slow infiltration rates of the expellant solution through the pit bottoms. This was pervasive across all plots and times, with some instances of more rapid infiltration which was not associated with any particular circumstance. Due to this degree of inconsistency, data arising was not considered sufficiently comparable to warrant further analysis since the results would not be reliable.

Earthworm abundances and biomass were in general highly variable between plots, ranging from 0-1450 individuals m^2 with associated biomass of 0-311 g m^{-2} across all treatments and times, and numbers showing a highly skewed distribution. One occurrence of an extremely large biomass value of 311 g m^{-2} was recorded, which was due to the otherwise unique presence of a large individual of *Lumbricus terrestris*, and which was treated as an outlier and removed for ANOVA. Statistical analysis of log-transformed data revealed that there was no simple or overarching effect of any of the main treatments upon earthworm numbers. For example, the overall mean log number of worms for unamended and amended soil (across all OM types) was 2.37 and 2.30 (SED 0.08) respectively. Overall, neither OM type nor rate nor mixture form had a consistent and consistently significant effect upon worm numbers. There was a single instance of a significant interaction term, *viz*. a fourth-order interaction between Crop x Amend x OMrate x Mixture (Table 4.1.11). The basis of this was related to idiosyncratic effects of these factors upon worm numbers, with the most obvious being related to a lower frequency of worms in Winter-oat plots in specific circumstances (Appendix VI). The overall geometric mean frequency of earthworms across the study, was 232, with 95% confidence intervals of 210-256. It is possible that it is some unmeasured factor such as movement and activity of earthworms might respond more consistently to the amount or nature of the amendment.

Table 4.1.11**.** ANOVA terms for earthworm frequency (numbers m^{-2}, log10 transformed data) recorded from Fosters experiment.

Source of variation	df	Mv	ss	ms	VR	F pr
Time stratum						
Crop	5		8.63	1.73		
Residual	-3		0.00			
Time.blocks stratum	3		0.07	0.02	0.18	
Time.blocks.wplots stratum						
Crop	5		2.90	0.58	4.32	0.349
Residual	1		0.13	0.13	2.05	
Time. blocks. wplots. subplots stratum						
Amend[1]	1		0.05	0.05	0.75	0.388
Crop.Amend	5		0.10	0.02	0.31	0.903
Amend.OMrate	1		0.01	0.01	0.19	0.666
Crop.Amend.OMrate	5		0.42	0.08	1.30	0.275
Amend.OMrate.Mixture	1		0.20	0.20	3.08	0.083
Crop.Amend.OMrate.Mixture	5		0.86	0.17	2.63	**0.030**
Amend.OMrate.Mixture.OMtype	6		0.19	0.03	0.48	0.824
Crop.Amend.OMrate.Mixture.OMtype	30		1.38	0.05	0.70	0.857
Residual	73	-5	4.77	0.07		
Total	138	-5	18.83			

[1] Amend is a factor with two levels indicating the addition or not of organic matter

These results were also manifest for the total worm biomass, i.e. no remotely significant effects of organic amendments in terms of presence or absence, rate or form (Table 4.1.12). The overall biomass across all treatments was 46.1 g m^{-2} (s.e. 2.59). The significance of the fourth-order interaction manifest for numbers was diminished to <10%.

Table 4.1.12. ANOVA terms for earthworm biomass (g m^{-2}) recorded from Fosters experiment.

Source of variation	df	mv	ss	ms	VR	F pr
Time stratum						
Crop	5		2.77	0.55		
Residual	-3		0.00			
Time.blocks stratum	3		0.02	0.01	0.02	
Time.blocks.wplots stratum						
Crop	5		5.30	1.06	2.52	0.444
Residual	1		0.42	0.42	3.97	
Time.blocks.wplots.subplots stratum						
Amend	1		0.03	0.03	0.26	0.613
Crop.Amend	5		0.34	0.07	0.63	0.674
Amend.OMrate	1		0.10	0.10	0.97	0.329
Crop.Amend.OMrate	5		0.13	0.03	0.25	0.939
Amend.OMrate.Mixture	1		0.08	0.08	0.74	0.393
Crop.Amend.OMrate.Mixture	5		1.13	0.23	2.13	0.071
Amend.OMrate.Mixture.OMtype	6		0.27	0.05	0.43	0.860
Crop.Amend.OMrate.Mixture.OMtype	30		1.90	0.06	0.60	0.940
Residual	73	-5	7.74	0.11		
Total	138	-5	19.07			

[1] Amend is a factor with two levels indicating the addition or not of organic matter

Seven species of earthworm were represented, with *Aporrectodea* species, principally *A. longa* and *caliginosa* forms, being by far the most abundant (Figure 4.1.9). With two species only being abundant in adult forms, the very low frequency of other species confounded the appropriateness of the application of diversity indices, and these data were likewise considered unreliable in terms of allowing any incisive detection of treatment effects and associated interpretation. As such, there was no consistent evidence for any significant effects of organic matter amendment upon the diversity or species composition of earthworm communities. Earthworm biomass in 2013 is shown in Figure 4.1.10.

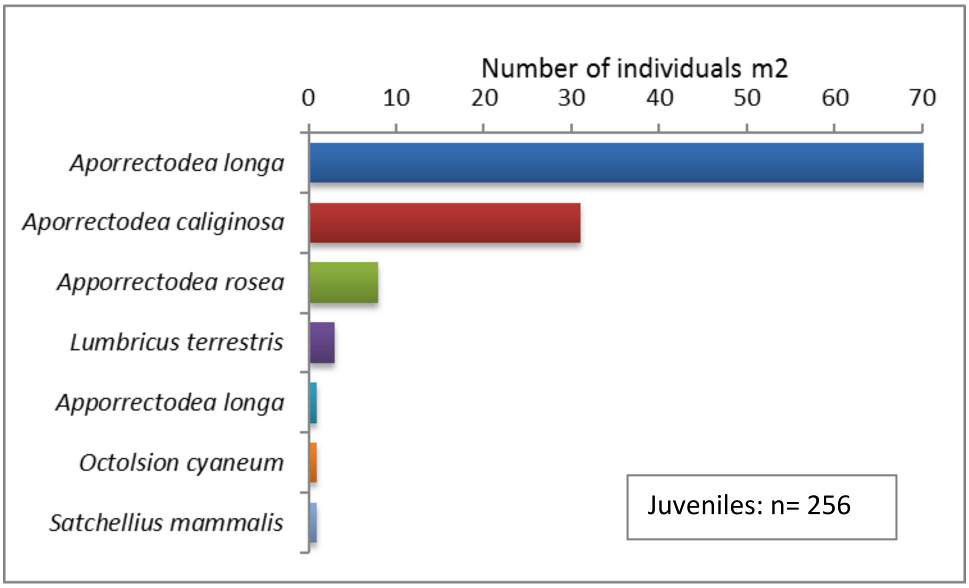

Figure 4.1.9. Example of earthworm species and associated frequency of occurrence across all treatments and replicates for Fosters, Spring 2015.

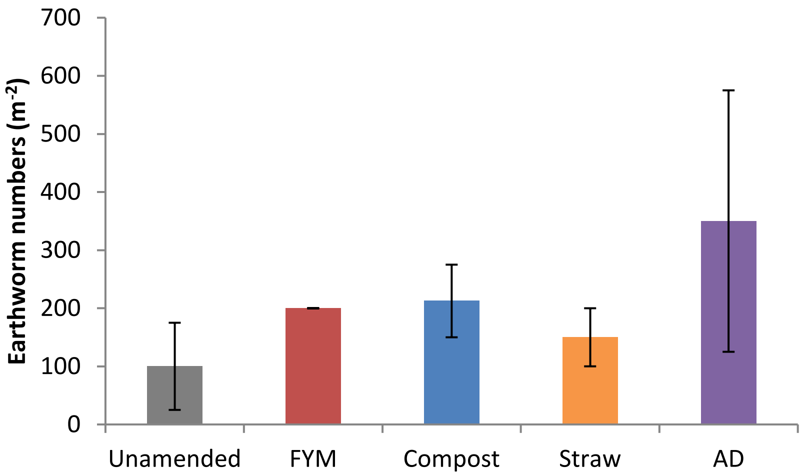

Figure 4.1.10. Earthworm numbers under different organic amendments in 2013.

Earthworm populations were determined on 48 plots (all organic recipes) in spring 2014.

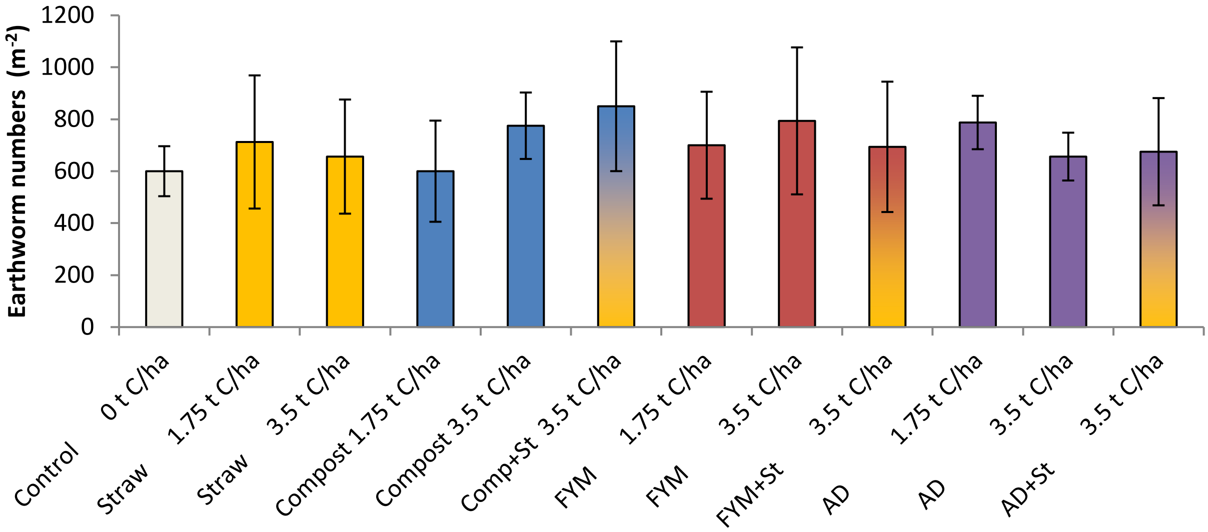

Figure 4.1.11. Earthworm numbers under different organic amendments in 2014.

Earthworm populations were also determined on 48 plots (all organic recipes) in spring 2015. There was no significant trend in earthworm populations under different organic matter recipe amendments (Figure 4.1.12).

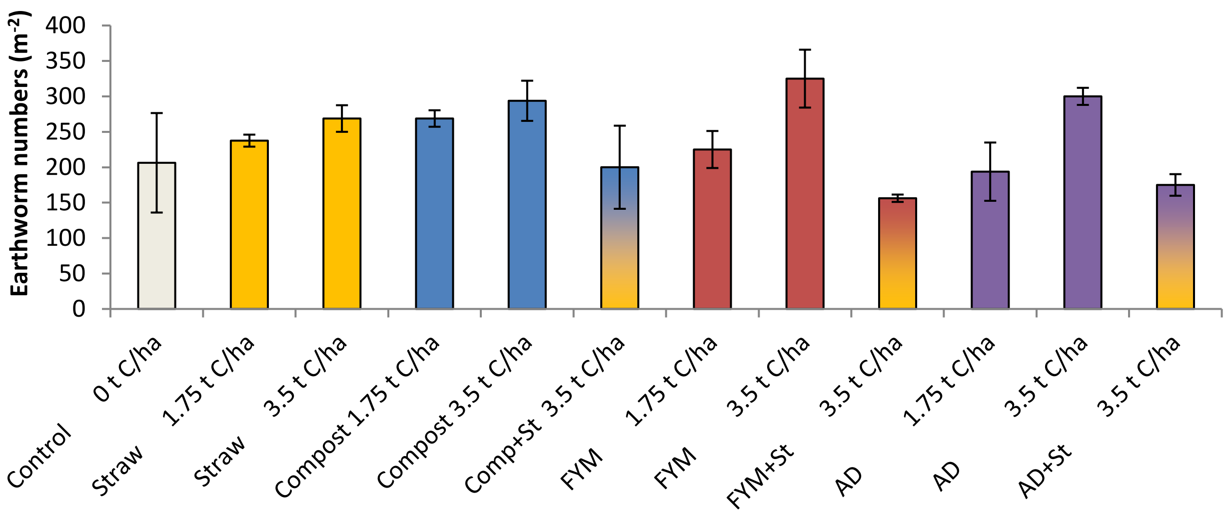

Figure 4.1.12**.** Earthworm numbers under different organic amendments in 2015.

4.1.4. **Microbiology**

4.1.4.1. Microbial biomass

There was a significant difference (Table 4.1.13) in soil microbial biomass between rotations, with additional organic matter interactions (irrespective of either type or application rate) in soil sampled during autumn 2013 (Figure 4.1.13), autumn 2014 (Figure 4.1.14) and spring 2015 (Figure 4.1.15).

Table 4.1.13. Microbial biomass ANOVA p values for each sampling period.

Treatment Effect	Autumn 2013	Spring 2014	Autumn 2014	Spring 2015	Autumn 2015	Spring 2016
(1) Organic Matter (“OM”)	0.316	0.498	0.460	0.368	0.845	0.107
(2) Rotation	<**0.001**	0.056	<**0.001**	**0.021**	-	0.882
(3) Rotation x “OM”	<**0.000**	0.245	<**0.001**	**0.030**	-	0.691
(4) Organic Type (“OT”)	0.209	0.875	0.907	0.697	0.160	0.250
(5) “C Rate”	0.332	0.961	0.462	0.443	0.599	0.425
(6) Rotation x “OT”	0.387	0.547	0.824	0.913	-	0.644
(7) Rotation x “C Rate”	0.101	0.557	0.251	0.650	-	0.522
(8) “OT” x “C Rate”	0.151	0.604	0.846	0.724	0.906	0.364
(9) Rotation x “OT” x “C Rate”	0.511	0.698	0.995	0.885	-	0.974

Bold p values signify significant ($p<0.05$) effects; OM Organic Matter (irrespective of type), OT Organic Type. Dashes indicate no data available.

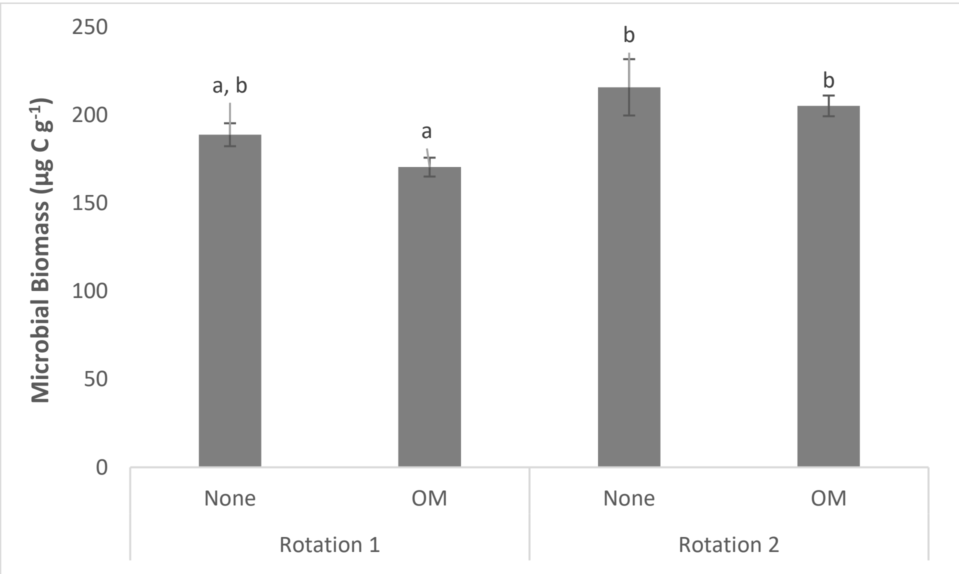

Figure 4.1.13. Microbial biomass means (error bars signify SE; n=4 where no OM was applied and 48 where applied) from the autumn 2013 sampling period showing the “Rotation x OM” interaction effect. Letters above the bars signify homogenous ($p>0.05$) means. OM organic amendment (irrespective of type).

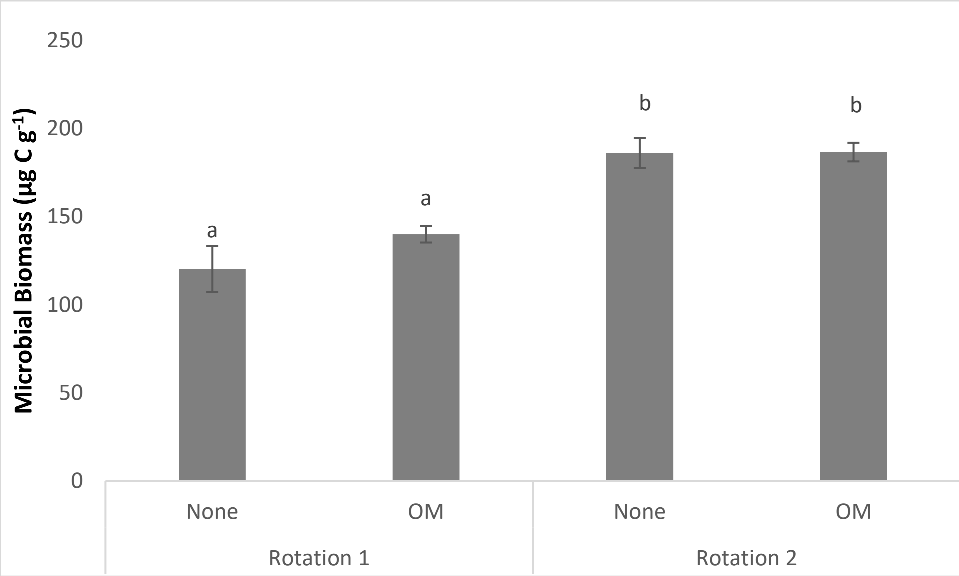

Figure 4.1.14. Microbial biomass means (error bars signify SE; n=4 where no OM was applied and 48 where applied) from the autumn 2014 sampling period showing the “Rotation x OM” interaction effect. Letters above the bars signify homogenous (p>0.05) means. OM organic amendment (irrespective of type).

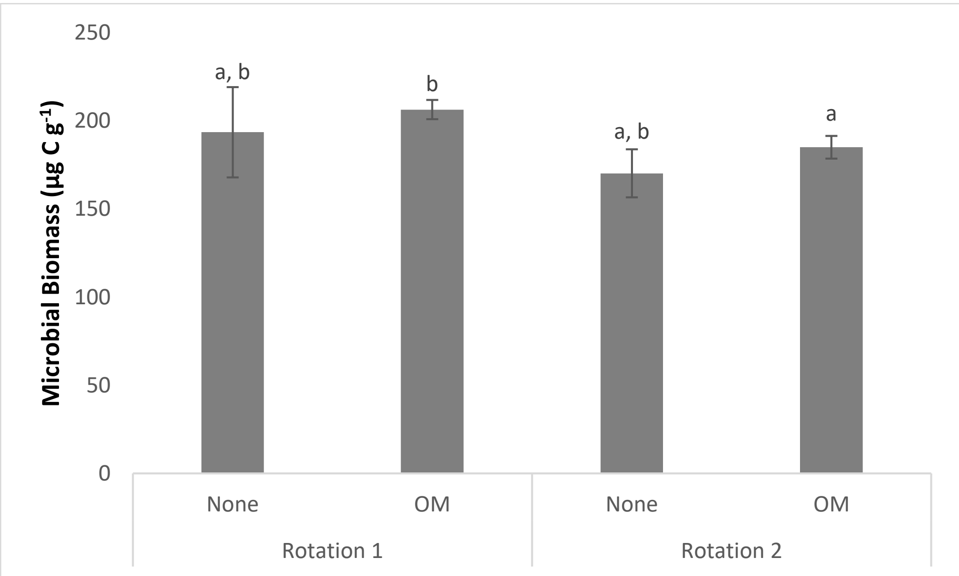

Figure 4.1.15. Microbial biomass means (error bars signify SE; n=4 where no OM was applied and 48 where applied) from the spring 2015 sampling period showing the “Rotation x OM” interaction effect. Letters above the bars signify homogenous (p>0.05) means. OM organic amendment (irrespective of type).

Where the data was further analysed by RM-ANOVA (Repeated Measures; Table 4.1.14: Figure 4.1.16), a significant "Rotation x OM" effect was observed in spring 2014. However, there were no treatment effects or differences between rotations for the soil sampled during autumn 2015 or spring 2016. Means (± SE) for all treatments are reported in Appendix VII A and VII B.

Table 4.1.14. Microbial biomass Repeated Measures-ANOVA p values,

Effect	p value
(1) Rotation	0.462
(2) Organic Matter ("OM")	0.853
(3) Rotation x "OM"	0.569
(4) Organic Type ("OT")	0.768
(5) "C Rate"	0.958
(6) Rotation x "OT"	0.472
(7) Rotation x "C Rate"	0.720
(8) "OT" x "C Rate"	0.377
(9) Rotation x "OT" x "C Rate"	0.920
TIME	<**0.001**
TIME x (1)	<**0.001**
TIME x (2)	0.292
TIME x (3)	<**0.001**
TIME x (4)	0.950
TIME x (5)	0.935
TIME x (6)	0.872
TIME x (7)	0.445
TIME x (8)	0.934
TIME x (9)	0.873

Bold p values signify significant ($p<0.05$) effects; OM Organic Matter (irrespective of type), OT Organic Type. Dashes indicate no data available. Note: The RM-ANOVA does not include anaerobic digestate plots or plots from Rotation 2 during autumn 2015. Numerals applied to main effects relate to those then mapped to Time effects in lower portion of table

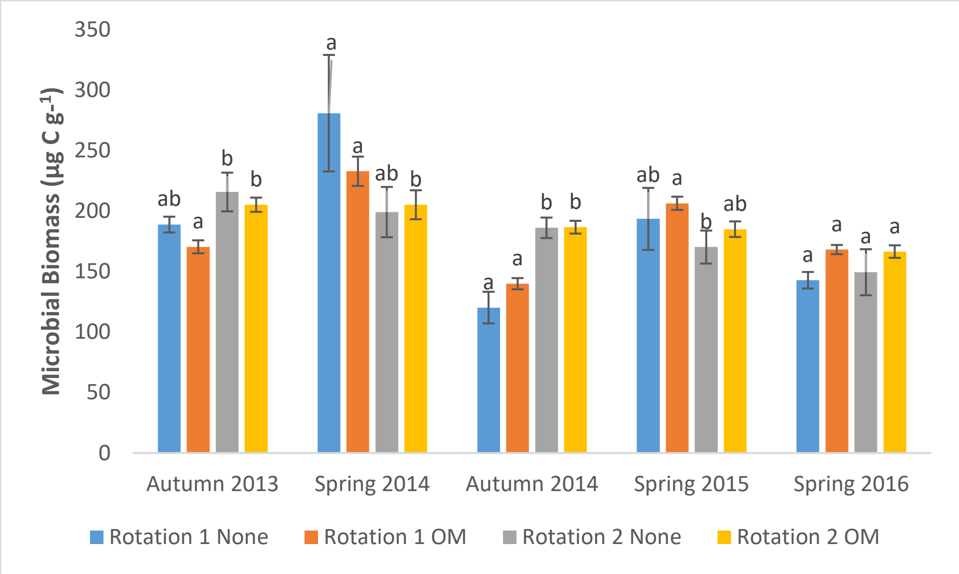

Figure 4.1.16. Microbial biomass means (error bars signify SE; n=4 where no OM was applied and 48 where applied) for each time period showing the significant "Time x Rotation x OM" interaction from Repeated Measures ANOVA. Letters above the bars signify homogenous ($p>0.05$) means within each sampling time. OM organic amendment (irrespective of type).

The significant "Rotation x OM" interactions occurred due to differences between rotations rather than between treatments, as there was no significant difference in microbial biomass between the control plots (with no organic matter additions) and those where organic matter had been applied at any of the sampling times (Figure 4.1.13 – Figure 4.1.15).

In autumn 2013 (Figure 4.1.13), the significant effect was due to greater microbial biomass for Rotation 2 (East) compared to Rotation 1 (West) where organic matter (irrespective of type) had been applied, Rotation 2 having the greater biomass. Rotation 1 was just coming out of a winter wheat crop and waiting for spring barley (no cover crop). By comparison, Rotation 2 had a young OSR crop (following spring barley). However, there was no significant difference between rotations for the control plots, or within each rotation comparing the control to the amended plots.

In spring 2014 (Figure 4.1.16), microbial biomass was less in the plots where organic matter had been applied in Rotation 2 compared to their equivalent organic amendment plots in Rotation 1. Similarly (to autumn 2013), this difference may reflect the stage in the crop growth rather than the crop. Rotation 1 had just seen the harvest of a winter wheat crop and drilled to spring barley only a few weeks before sampling, whereas Rotation 2 was in the mid-stage of OSR. Therefore it is likely that resources from crop inputs were limited during the fallow period following the WW crop compared to mid-season for OSR. Again, there was no significant difference either between rotations for the control plots or within rotations comparing the control to the plots that had received

organic amendments. In autumn 2014 (Figure 4.1.14) Rotation 2 had significantly greater microbial biomass overall compared to Rotation 1. Here, both rotations were at an early stage of crop growth (Rotation 1 with winter oats after spring barley and Rotation 2 was just starting with winter wheat (after OSR). This may suggest that winter oats are exerting a greater demand for available resources (and so resulting in reduced microbial biomass) compared to winter wheat.
Similarly to the previous sampling times, there was no significant difference between the control plots and those that had organic matter applied within each rotation. In spring 2015 (Figure 4.1.15), the significant effect was due to greater microbial biomass for Rotation 1 (winter oats) compared to Rotation 2 (winter wheat) where organic matter (irrespective of type) had been applied. However, similarly to the earlier sampling times, there was no significant difference between rotations for the control plots, and no significant difference between the plots that had received organic amendments compared to the control.

4.1.4.2. Fungal biomass

There was a significant “Rotation x OM” interaction effect for soil fungal biomass (Table 4.1.15 and Table 4.1.16). This interaction effect occurred in soil sampled during spring 2014 (Figure 4.1.17) and autumn 2014 (Figure 4.1.18) and denotes a significant difference between rotations, with additional organic matter interactions (irrespective of organic matter type or rate) (Figure 4.1.19 for repeated measures ANOVA interaction). In autumn 2013, there was also a significant “Rotation x Organic Type x C Rate” interaction effect (Table 4.1.15 and Table 4.1.16: Figure 4.1.20 and Figure 4.1.21). There were no treatment effects, or differences between rotations, on fungal biomass for the soil sampled during spring 2015, autumn 2015 or spring 2016. Means for all treatments are reported in Appendix VII.

Similarly to microbial biomass, where “Rotation x OM” interactions occurred, the interaction was due to differences between rotations rather than between treatments as there was no significant difference in fungal biomass between the control plots (with no organic matter additions) and those where organic matter had been applied at any of the sampling times (Figure 4.1.17 and Figure 4.1.18). In spring 2014, Rotation 1 (spring barley) had greater fungal biomass compared to Rotation 2 (WOSR), but there was no significant difference within either rotation where the control plots are compared to those with organic matter manipulations. However, in autumn 2014 this was reversed as Rotation 2 - winter wheat had greater fungal biomass compared to Rotation 1 (winter oats), but similarly to spring 2014 there were no treatment effects within each rotation. For the “Rotation x Organic Type x C Rate” effect which was observed in soil during autumn 2013 (Figure 4.1.20 and Figure 4.1.21), there were no obvious trends with either organic matter type or application rate.

Table 4.1.15. Fungal biomass ANOVA p values for each sampling period.

Treatment effect	**Autumn 2013**	**Spring 2014**	**Autumn 2014**	**Spring 2015**	**Autumn 2015**	**Spring 2016**
(1) Organic Matter ("OM")	0.740	0.981	0.396	0.193	0.095	0.050
(2) Rotation	0.159	<**0.001**	<**0.001**	0.585	-	0.422
(3) Rotation x "OM"	0.179	<**0.001**	<**0.001**	0.521	-	0.386
(4) Organic Type ("OT")	0.274	0.317	0.446	0.458	0.688	0.086
(5) "C Rate"	0.783	0.564	0.278	0.833	0.672	0.478
(6) Rotation x "OT"	0.708	0.155	0.076	0.376	-	0.987
(7) Rotation x "C Rate"	**0.043**	0.477	0.662	0.859	-	0.353
(8) "OT" x "C Rate"	0.302	0.876	0.594	0.873	0.993	0.321
(9) Rotation x "OT" x "C Rate"	**0.029**	0.248	0.196	0.955	-	0.575

Bold p values signify significant (p<0.05) effects; OM Organic Matter (irrespective of type), OT Organic Type. Dashes indicate no data available.

Table 4.1.16. Fungal biomass Repeated Measures-ANOVA p values.

Effect	p values
(1) Rotation	0.195
(2) Organic Matter ("OM")	0.481
(3) Rotation x "OM"	0.224
(4) Organic Amendment Type ("OT")	0.751
(5) "C Rate"	0.413
(6) Rotation x "OT"	0.856
(7) Rotation x "C Rate"	0.441
(8) "OT" x "C Rate"	0.655
(9) Rotation x "OT" x "C Rate"	0.258
TIME	<**0.001**
TIME x 1	<**0.001**
TIME x 2	0.977
TIME x 3	<**0.001**
TIME x 4	**0.027**
TIME x 5	0.352
TIME x 6	0.131
TIME x 7	**0.012**
TIME x 8	0.717
TIME x 9	**<0.001**

Bold p values signify significant (p<0.05) effects. Numerals applied to main effects relate to those then mapped to Time effects in lower portion of table.

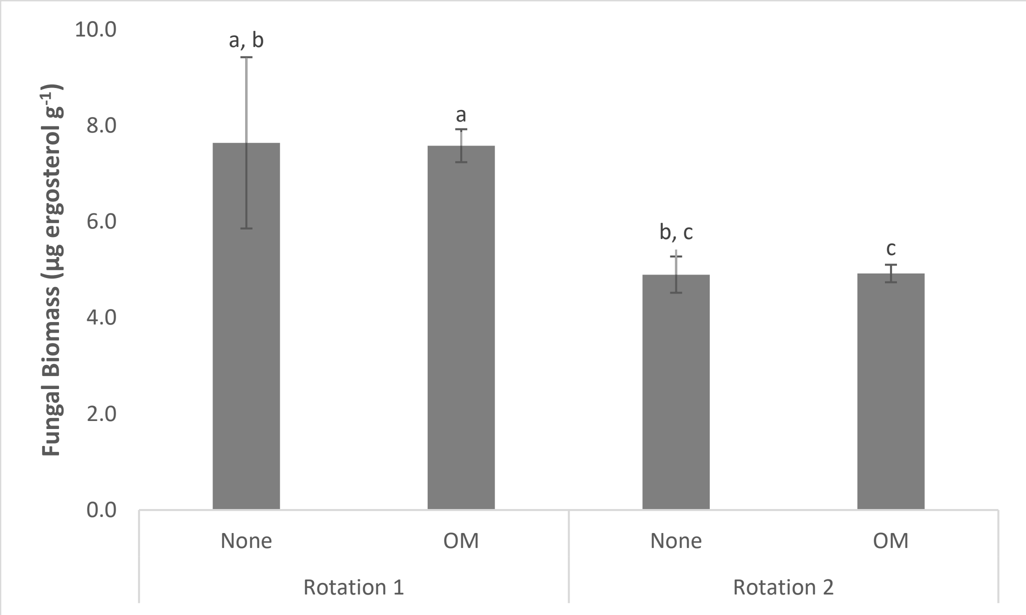

Figure 4.1.17. Fungal biomass means (error bars signify SE; n=4 where no OM was applied and 48 where applied) from the spring 2014 sampling period showing the "Rotation x OM" interaction effect. Letters above the bars signify homogenous ($p>0.05$) means. OM organic amendment (irrespective of type).

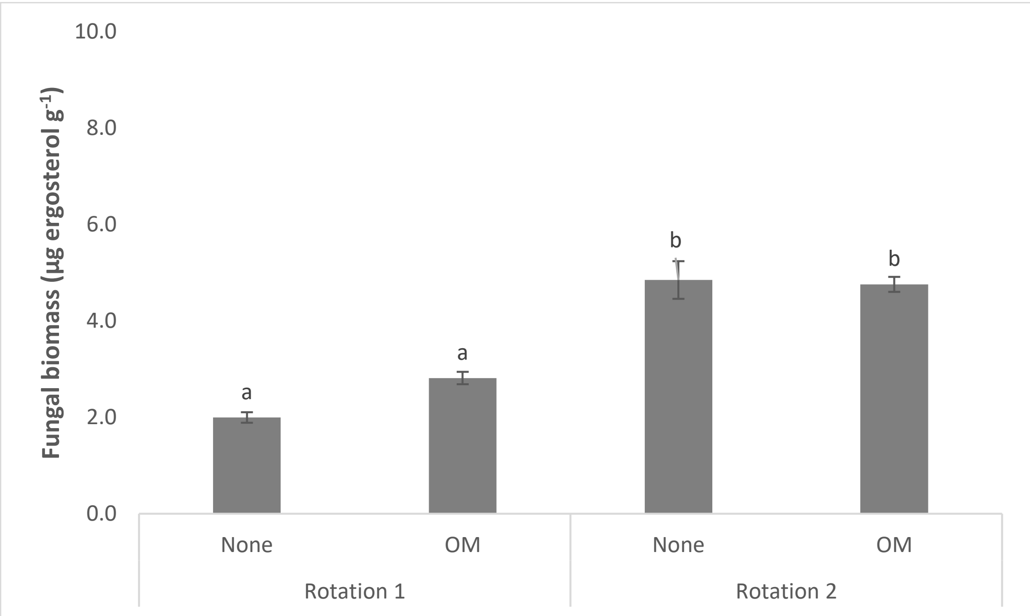

Figure 4.1.18. Fungal biomass means (error bars signify SE; n=4 where no OM was applied and 48 where applied) from the autumn 2014 sampling period showing the "Rotation x OM" interaction effect. Letters above the bars signify homogenous ($p>0.05$) means. OM organic amendment (irrespective of type).

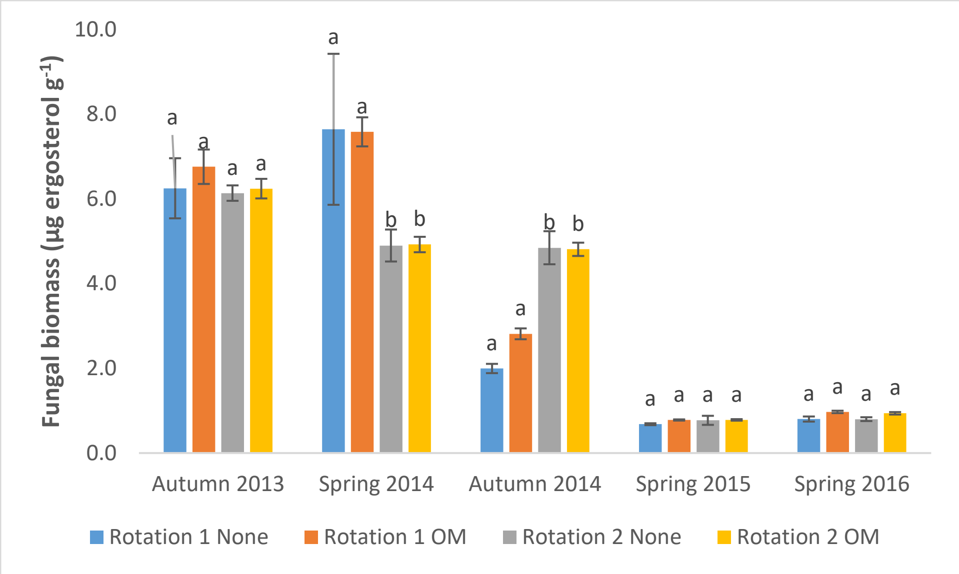

Figure 4.1.19. Fungal biomass means (error bars signify SE; n=4 where no OM was applied and 48 where applied) for each time period showing the significant "Time x Rotation x OM" interaction from RM-ANOVA. Letters above the bars signify homogenous (p>0.05) means within each sampling time. OM organic amendment (irrespective of type).

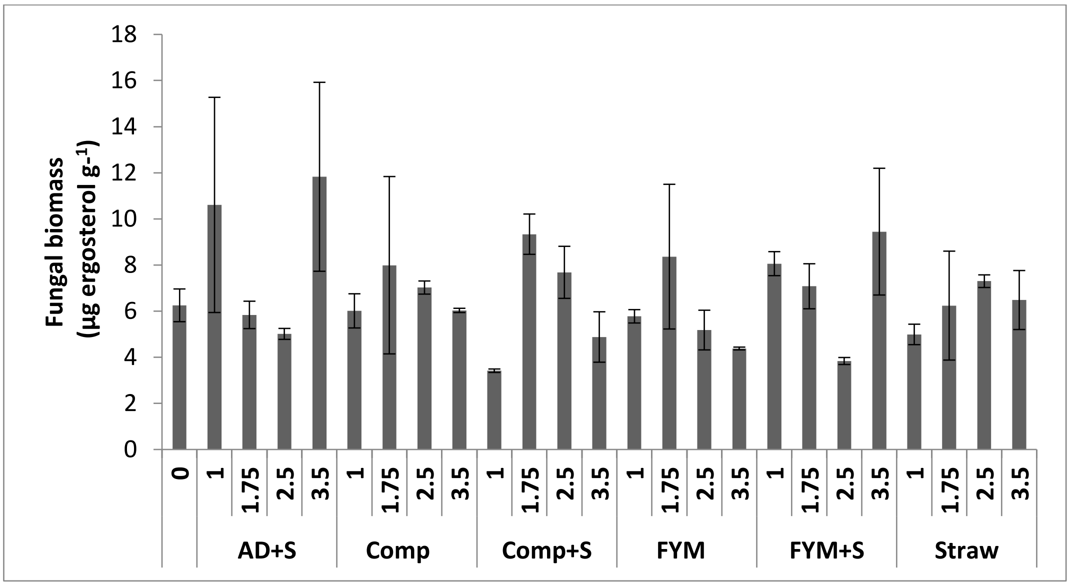

Figure 4.1.20. Fungal biomass means (error bars signify SE; n=2) from the autumn 2013 sampling period Rotation 1 showing the "Rotation x Organic Amendment Type x Carbon Rate" interaction effect. Numbers below the x axis represent organic matter application rates (C-t/ha). Letters above the bars signify homogenous (p>0.05) means.

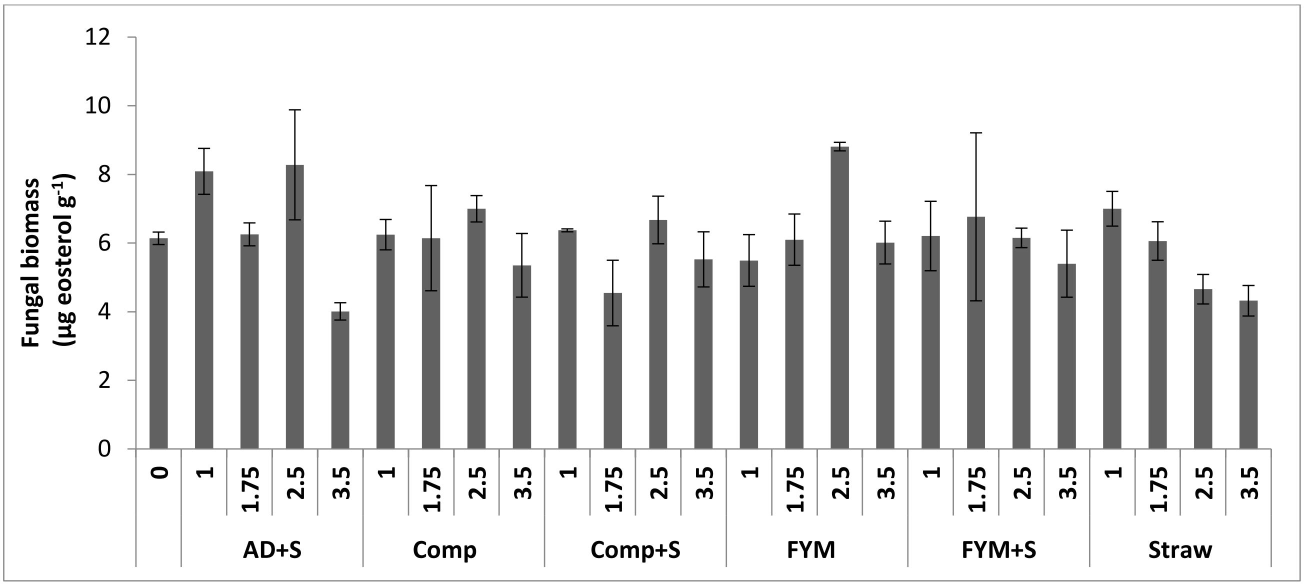

Figure 4.1.21. Fungal biomass means (error bars signify SE; n=2) from the autumn 2013 sampling period Rotation 2 showing the "Rotation x Organic Amendment Type x Carbon Rate" interaction effect. Numbers below the x-axis represent organic matter application rates (C-t/ha).

4.1.4.3. Microbial community phenotypic composition

ANOVA of principal component analysis (PCA) factor scores generated from the phospholipid fatty acid (PLFA) profiles identified a significant "Rotation x OM" interaction on the first Principal Component (PC1) at all sampling times following the Principal Component Analysis (PCA), and in addition there was a significant "Rotation x OM" interaction effect on PC2 in autumn 2014, spring 2015 and spring 2016. There was also a significant effect on PC2 (control Vs. OM) in the soils sampled during autumn 2015 soils. These effects of organic matter were irrespective of either the type or the application rate. In addition, there was a significant effect of the application rate of organic matter (irrespective of organic matter type) on PC1 of the PLFA profile of soils sampled in spring 2016 (Table 4.1.17a-b, Table 4.1.18).

Table 4.1.17.a. ANOVA P values of PCA factor scores

	2013		2014			
	Autumn		Spring		Autumn	
Effect	**PC1**	**PC2**	**PC1**	**PC2**	**PC1**	**PC2**
(1) OM	0.96	0.754	0.401	0.382	0.342	0.957
(2) Rotation	<**0.001**	0.094	<**0.001**	0.919	<**0.001**	**0.001**
(3) Rotation x OM	<**0.001**	0.38	<**0.001**	0.71	<**0.001**	**0.005**
(4) OT	0.445	0.892	0.538	0.682	0.098	0.085
(5) C Rate	0.346	0.202	0.821	0.197	0.211	0.386
(6) Rotation x OT	0.518	0.448	0.792	0.976	0.154	0.469
(7) Rotation x Rate	0.197	0.459	0.38	0.526	0.385	0.396
(8) OT x Rate	0.978	0.629	0.865	0.448	0.888	0.899
(9Rotation x OT x Rate	0.185	0.722	0.361	0.192	0.569	0.603

Bold p values signify significant (p<0.05) effects; OM Organic Matter, OT Organic Type.

Table 4.1.17.b**.** ANOVA P values of PCA factor scores

	2015				2016	
	Spring		Autumn		Spring	
Effect	**PC1**	**PC2**	**PC1**	**PC2**	**PC1**	**PC2**
(1) OM	0.993	0.378	0.556	**0.025**	0.099	0.309
(2) Rotation	**0.001**	0.984	-	-	<**0.001**	<**0.001**
(3) Rotation x OM	**0.001**	**0.048**	-	-	<**0.001**	<**0.001**
(4) OT	0.886	0.833	0.536	0.244	0.339	0.199
(5) C Rate	0.646	0.625	0.374	0.882	<**0.001**	0.962
(6) Rotation x OT	0.772	0.911	-	-	0.267	0.198
(7) Rotation x Rate	0.5	0.92	-	-	0.829	0.33
(8) OT x Rate	0.954	0.968	0.806	0.825	0.17	0.322
(9) Rotation x OT x Rate	0.48	0.819	-	-	0.734	0.293

Bold p values signify significant (p<0.05) effects; OM Organic Matter, OT Organic Type.

Dashes indicate no data available.

Table 4.1.18. RM-ANOVA p values of PC factor scores generated from PLFA profiles

Effect	PC1	PC2
(1) Rotation	<**0.001**	0.352
(2) Organic Matter ("OM")	0.076	0.115
(3) Rotation x "OM"	<**0.001**	0.468
(4) Organic Amendment Type ("OT")	0.317	0.947
(5) "C Rate"	**0.014**	0.153
(6) Rotation x "OT"	0.171	0.459
(7) Rotation x "C Rate"	0.313	0.901
(8) "OT" x "C Rate"	0.516	0.980
(9) Rotation x "OT" x "C Rate"	0.522	0.678
TIME	<**0.001**	<**0.001**
TIME x 1	<**0.001**	<**0.001**
TIME x 2	0.538	0.168
TIME x 3	<**0.001**	<**0.001**
TIME x 4	0.981	0.422
TIME x 5	**0.020**	0.779
TIME x 6	0.957	0.490
TIME x 7	0.320	0.428
TIME x 8	0.771	0.929
TIME x 9	0.440	0.912

Bold p values signify significant ($p<0.05$) effects. Numerals applied to main effects relate to those then mapped to Time effects in lower portion of table.

The significant “Rotation x OM” interaction effects within each sampling time are visualised in Figure 4.1.22–Figure 4.1.25, and the significant effect of organic matter (Rotation 1 only) in autumn 2015 is apparent in Figure 4.1.26. The primary effect on microbial community composition was that of the rotation, which was significantly different on PC1 at all times (where both rotations were compared). There were no significant differences within each rotation (comparing the control to the organic treated plots) for the autumn 2013, spring 2014, and autumn 2014. However, significant differences within rotations were observed for spring 2015 (Figure 4.1.25) and autumn 2015 (Figure 4.1.26) on PC2 within Rotation 1 (only). Additionally, effects of organic matter application rate (irrespective of organic matter type) were identified in spring 2016 (Table 4.1.17b: Figure 4.1.27). This effect was significant on PC1 within both rotations, and is evident by a gradual shift in microbial community composition with increasing organic matter application rate. Figure 4.1.28 reveals the shift in microbial community composition with organic matter application rate in the spring 2016 soils compared to the microbial community composition of the previous sampling times.

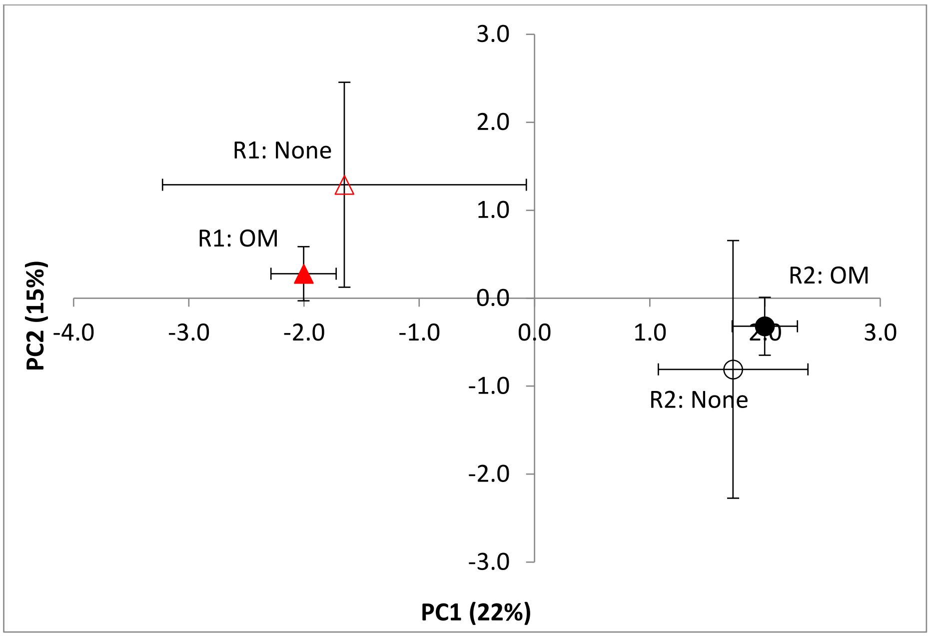

Figure 4.1.22. Microbial community profiles showing the "OM x Rotation" interaction (autumn 2013). Points show means of PCs (error bars signify SE; n=4 where no OM was applied and n=48 where applied; values in parentheses denote percent variation accounted for by respective PCs). Red triangles represent Rotation 1, black circles represent Rotation 2. Empty shapes represent controls with no organic matter additions; filled shapes represent organic matter applications (irrespective of type).

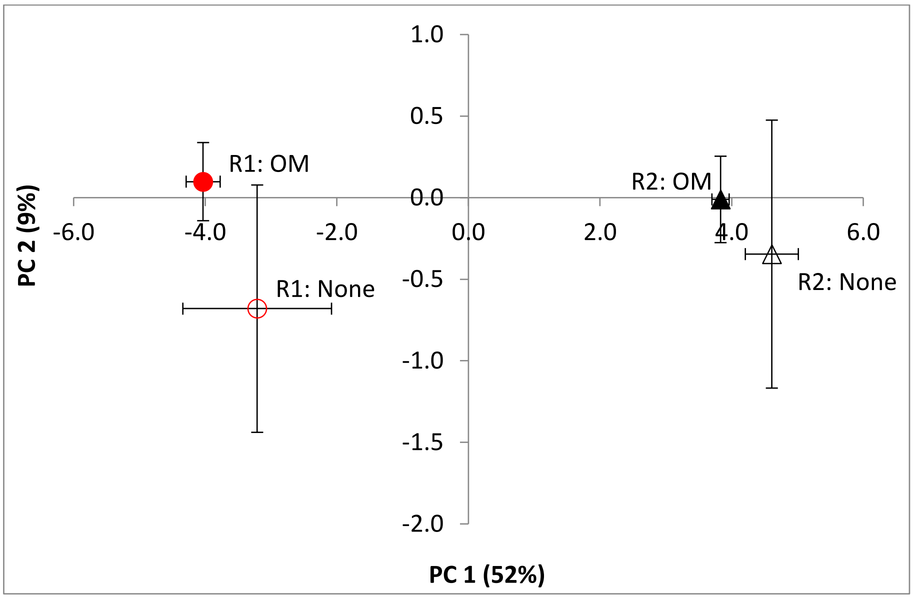

Figure 4.1.23. Microbial community profiles showing the "OM x Rotation" interaction (spring 2014). Points show means of PCs (error bars signify SE; n=4 where no OM was applied and n=48 where applied; values in parentheses denote percent variation accounted for by respective PCs). Red circles represent Rotation 1, black triangles represent Rotation 2. Empty shapes represent controls with no organic matter additions; filled shapes represent organic matter applications (irrespective of type).

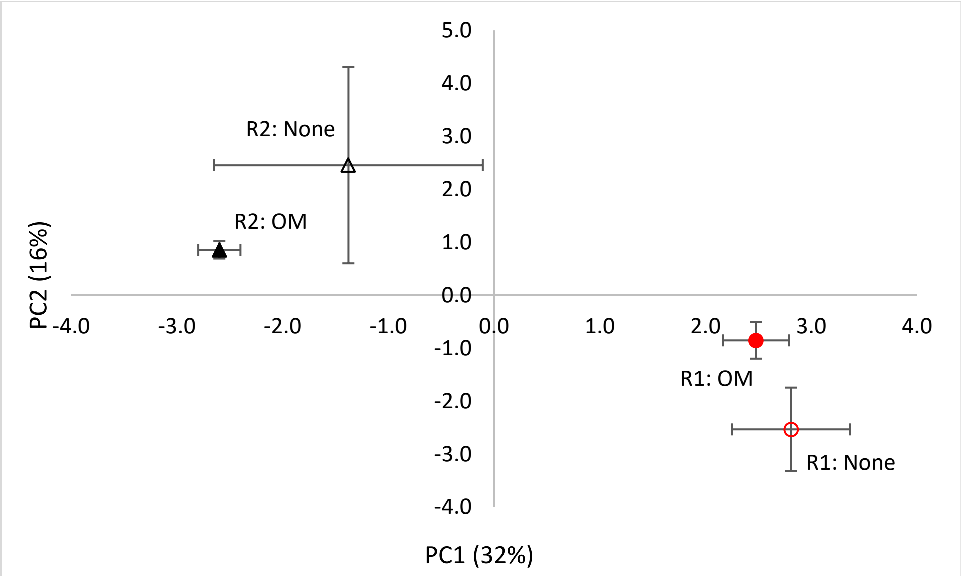

Figure 4.1.24. Microbial community profiles showing the “OM x Rotation” interaction (autumn 2014). Points show means of PCs (error bars signify SE; n=4 where no OM was applied and n=48 where applied; values in parentheses denote percent variation accounted for by respective PCs). Red circles represent Rotation 1, black triangles represent Rotation 2. Empty shapes represent controls with no organic matter additions, filled shapes represent organic matter applications (irrespective of type).

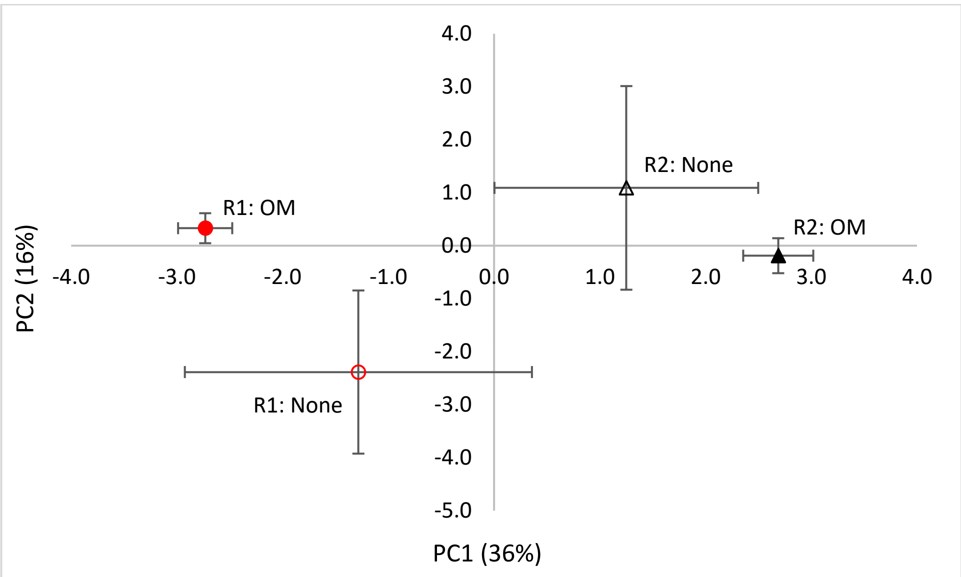

Figure 4.1.25. Microbial community profiles showing the “OM x Rotation” interaction (spring 2015). Points show means of PCs (error bars signify SE; n=4 where no OM was applied and n=48 where applied; values in parentheses denote percent variation accounted for by respective PCs). Red circles represent Rotation 1, black triangles represent Rotation 2. Empty shapes represent controls with no organic matter additions; filled shapes represent organic matter applications (irrespective of type).

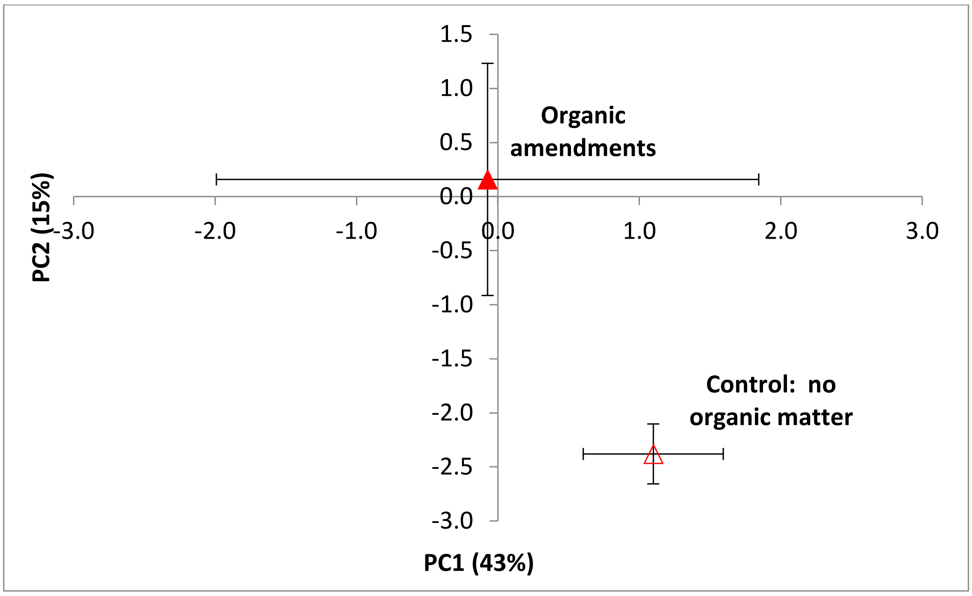

Figure 4.1.26.Microbial community profiles showing the effect of organic matter applications (irrespective of type or rate) soils sampled in Rotation 1 (autumn 2015). Points show means of PCs (error bars signify SE; n=4 where no OM was applied and n=48 where applied; values in parentheses denote percent variation accounted for by respective PCs). Empty triangles represent controls with no organic matter additions; filled triangles represent organic matter applications (irrespective of type).

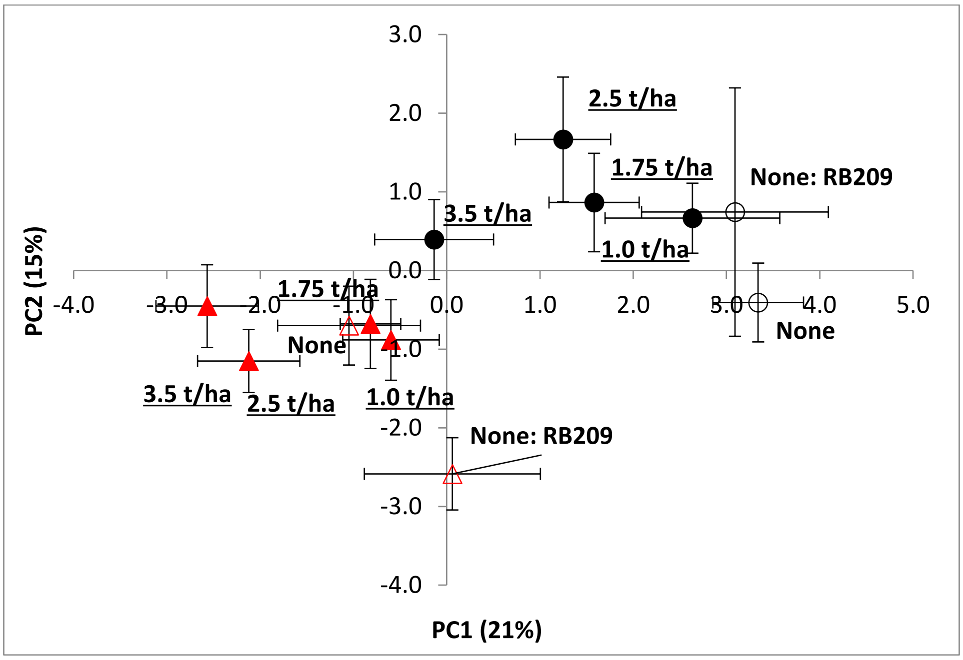

Figure 4.1.27. Effect the carbon application rate (irrespective of organic matter type) on microbial community profiles (spring 2016). Points show means of PCs (error bars signify SE; n=4 where no OM was applied and n=48 where applied; values in parentheses denote percent variation accounted for by respective PCs). Red triangles represent Rotation 1, black circles represent Rotation 2. Empty shapes represent controls with no organic matter additions; filled shapes represent organic matter applications (irrespective of type).

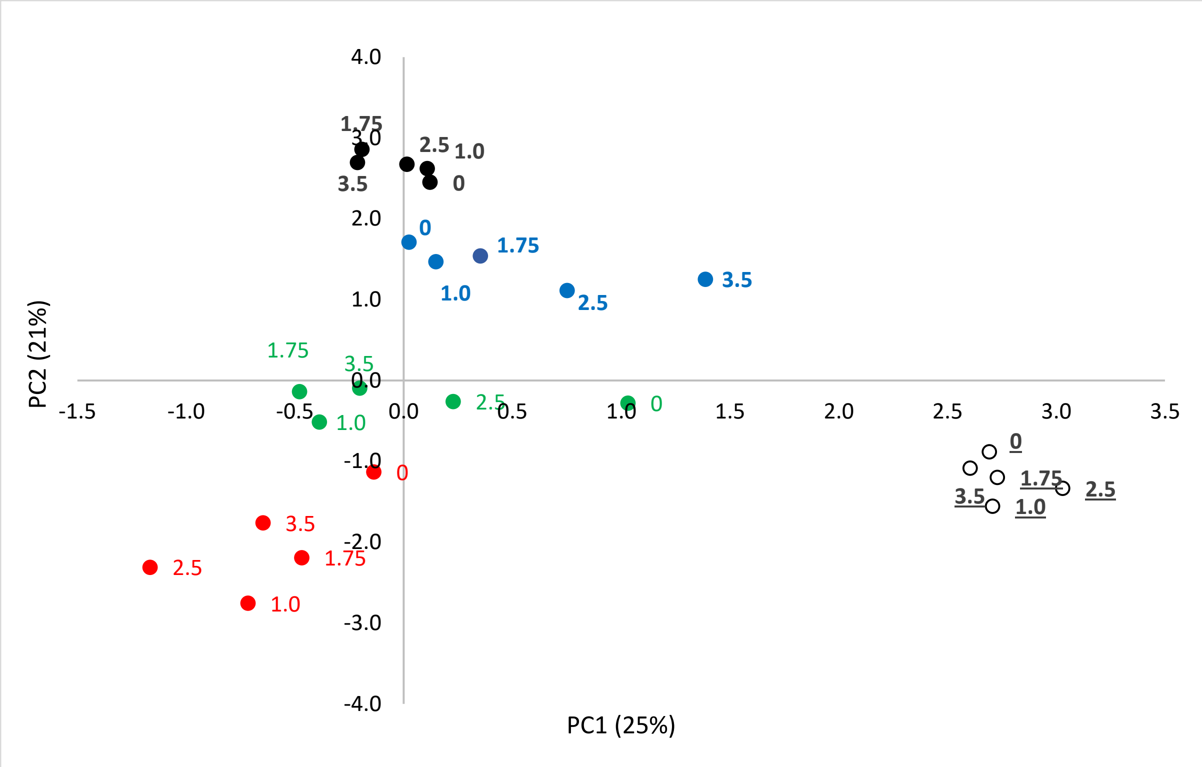

Figure 4.1.28. Time x Rate interaction (irrespective of organic matter type or rotation) on microbial community profiles during spring 2016 (blue circles) compared to autumn 2013 (black circles), spring 2014 (open circles), autumn 2014 (red circles), and spring 2015 (green circles). Points show means of PCs (error bars signify SE; n=4 where no OM was applied and n=48 where applied; values in parentheses denote percent variation accounted for by respective PCs). Numbers represent the rate (t/ha) of organic matter addition (irrespective of type).

4.1.4.4. Fatty acid bioindicators

All fatty acid bioindicators assessed showed a significant "Time x Rotation x OM" interaction effect (Table 4.1.19). As such, the effect of organic matter application was irrespective of either the type or application rate. Effects on arbuscular mycorrhizal fungi (Figure 4.1.29), total bacterial fatty acids (Figure 4.1.30), Gram positive fatty acids (Figure 4.1.31) and Gram negative fatty acids (Figure 4.1.32) were all primarily due to differences between rotations as there were no significant differences between the control plots and those that had received organic matter manipulations within either rotation.

Table 4.1.19. Repeated Measures-ANOVA p values of PLFA bioindicator FAs

Effect	MUFA: G- FAs	iso anteiso: G+ FAs	AM	Bacterial FAs
(1) Rotation	**0.002**	0.183	<**0.001**	**0.002**
(2) Organic Matter ("OM")	0.625	0.798	0.375	0.266
(3) Rotation X "OM"	<**0.001**	0.246	<**0.001**	**0.001**
(4) Organic Type ("OT")	0.930	0.470	0.840	0.593
(5) "C Rate"	0.600	0.283	0.028	0.580
(6) Rotation x "OT"	0.572	0.750	0.116	0.613
(7) Rotation x "C Rate"	0.828	0.893	0.277	0.925
(8) "OT" x "C Rate"	0.991	0.841	0.249	0.995
(9) Rotation x "OT" x "C Rate"	0.876	0.634	0.297	0.595
TIME	<**0.001**	<**0.001**	<**0.001**	<**0.001**
TIME X 1	<**0.001**	<**0.001**	<**0.001**	<**0.001**
TIME x 2	0.200	0.964	0.510	0.793
TIME x 3	<**0.001**	<**0.001**	<**0.001**	<**0.001**
TIME x 4	0.814	0.065	0.372	0.079
TIME x 5	0.999	0.945	0.905	0.904
TIME x 6	0.999	0.291	0.713	0.760
TIME x 7	0.347	0.628	0.734	0.079
TIME x 8	0.126	0.473	0.644	0.243
TIME x 9	0.999	0.567	0.669	0.946

Bold p values signify significant ($p<0.05$) effects, FA fatty acids, MUFA monounsaturated FAs, G- Gram negative bacteria, G+ Gram positive bacteria, AM arbuscular mycorrhizal fungi. Numerals applied to main effects relate to those then mapped to Time effects in lower portion of table.

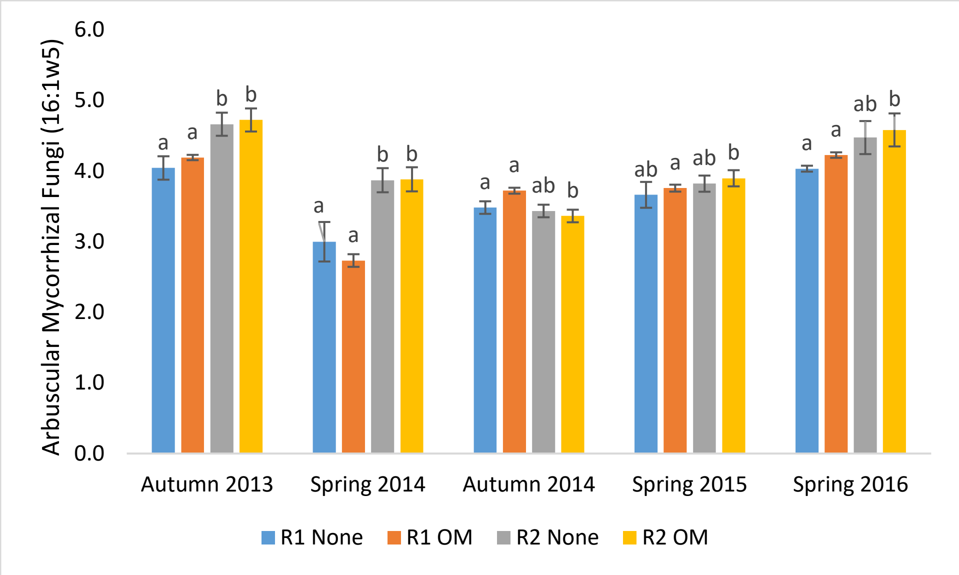

Figure 4.1.29. Arbuscular mycorrhizal fungi FA indicator (16:1w5) means (error bars signify SE; n=4 where no OM was applied and 48 where applied) showing the “Time x Rotation x OM interaction”. Letters above the bars signify homogenous (p>0.05) means within each sampling time. OM organic amendment (irrespective of type).

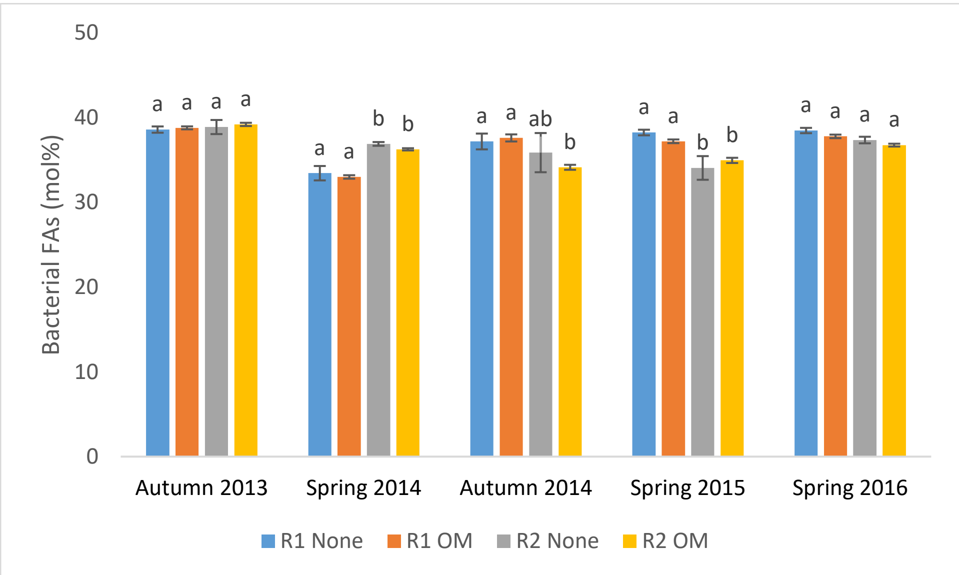

Figure 4.1.30. Bacterial fatty acid means (error bars signify SE; n=4 where no OM was applied and 48 where applied) showing the “Time x Rotation x OM interaction”. Letters above the bars signify homogenous (p>0.05) means within each sampling time. OM organic amendment (irrespective of type).

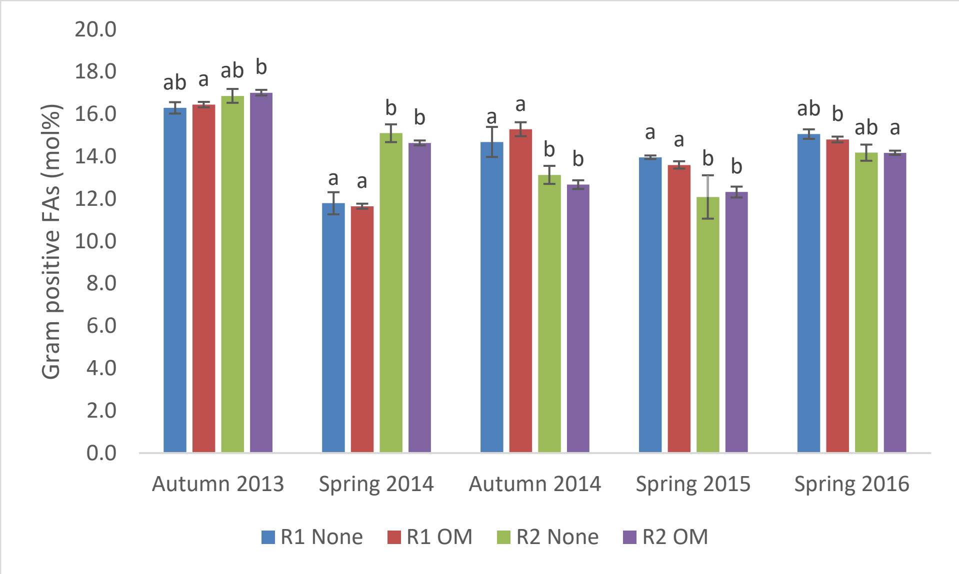

Figure 4.1.31. Gram positive fatty acid means (error bars signify SE; n=4 where no OM was applied and 48 where applied) showing the “Time x Rotation x OM interaction”. Letters above the bars signify homogenous (p>0.05) means within each sampling time. OM organic amendment (irrespective of type).

Figure 4.1.32.Gram negative fatty acid means (error bars signify SE; n=4 where no OM was applied and 48 where applied) showing the “Time x Rotation x OM interaction”. Letters above the bars signify homogenous (p>0.05) means within each sampling time. OM organic amendment (irrespective of type).

4.1.5. Image processing

Amendment increased the total number of pores (p=0.013) in the samples by 50% compared with non-amended soils (353 versus 202). None of the other measures of porosity were significant in relation to the treatments as factors. However, the treatments introduce different levels of energy into the soil (they receive the same amount of carbon) and from this perspective should not be treated as factors but as independent variables. Re-analysing in this fashion established clear trends with increasing levels of energy or cellulose in the substrates (Table 3.3.2). Since all amended treatments sampled had received the same amount of carbon with amendment, it is only in quality that they differ. The results are consistent with the idea that increased amendment leads to a greater number, but not volume (area was measured) of pores and therefore to the view that the pores have been reduced in size. Whether this is desirable or not depends on the sizes of the pores that have disappeared and the size of the pores that have been created. There were no statistical differences and no obvious trends in independent measurements of bulk density in the October and March on the plots before which measurements on the samples taken for CT scans. But there were very large background differences between the blocks which means we have to be cautious about further analysis. It is possible that there is an optimum size of pore, or optimum change in volume that the energy-deficient compost brings about more readily than the energy-rich FYM, but it is not possible to be conclusive with such a small number of data. There was no significant relationship with the specific yields on the particular plots in the harvest year (2016) from which the soil samples were taken for CT scanning, and also there was no a significant relationship with plough draught measurements made in the autumn of 2015.

In view of the success of cellulose (Table 4.10.1) in explaining differences in the growth of earthworms, we explored the use of the cellulose content in the amendments instead of energy to explain the variation in structural parameters, but without improvement. Calorific energy input thus seems the best indicator of short-term changes in structural properties of soil detected with CT scans.

Table 4.1.20. Statistical significance of addition of OM amendments to soil structural parameters determined from CT scans in relation to the energy content of the amendments

Measure	**r**	**Significance**
Count	0.907	*
Area	-0.653	NS
Ferret	-0.821	*
average_size	-0.745	NS
LogPerim	-0.872	*
circularity	0.797	NS
feret angle	0.00723	NS
porosity	-0.654	NS

- Significant at $p<0.05$

All treatments, apart from the controls had the same amount of soil carbon added (2.5 t ha^{-1}). The C contents vary somewhat, so other material must be present in the amendments made to soil. The nitrogen contents of the amendments vary but N cannot explain the variations in structural parameters in Table 4.1.20 because the contribution of straw is in relation to its high energy content. It contains very little N. This other material, whatever it is, must include components that determine the energy content profiles of the amendments. Of the two nil treatments, the one receiving fertiliser fits the relationships implied above least well in all cases. This would be consistent with the idea that crops that grow well invest a larger amount (not necessarily proportion) of photosynthate below-ground. If so, the nil plot receiving fertiliser in these subset of the experimental data ought to be assigned a carbon input value greater than the nil-nil amendment fertiliser treatment, which would improve the relationships in all cases still further. If these putative inputs contain carbohydrates, they are likely to be high in energy and so move the fertiliser N treatment further along the x axis than might be expected from the carbon content alone. This reasoning suggests the importance of the energy contained in amendments for bringing about the change in structure on the small scales detected within these CT scans.

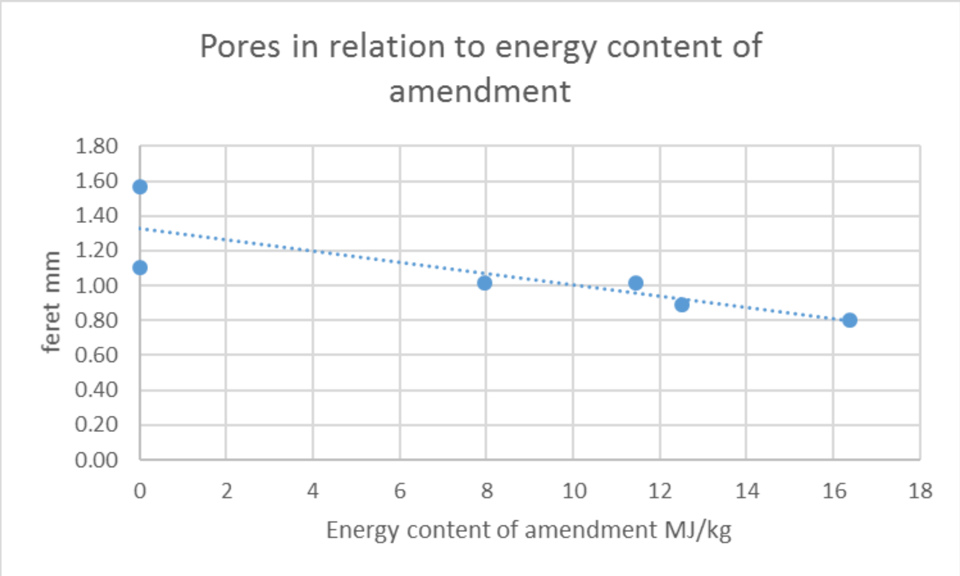

Figure 4.1.33. Feret in relation to energy content of amendment.

4.2. New Zealand field experiment at Rothamsted

4.2.1. Crop yields at New Zealand

Previous studies at Rothamsted on spring barley established after conventional tillage (Hoos barley) have found that a yield effect occurs from Year 3, following the addition of organic matter. This data is in agreement with the observed lack of significant differences in yields from organic matter treatments on Hoosfield. Yields were not significantly different in year 1 (Spring Barley, Figure 4.2.1) or year 2 (Oilseed Rape, Figure 4.2.2) but amended treatments were significantly different from controls in year 3 ($p<0.05$, winter wheat, Figure 4.2.3).

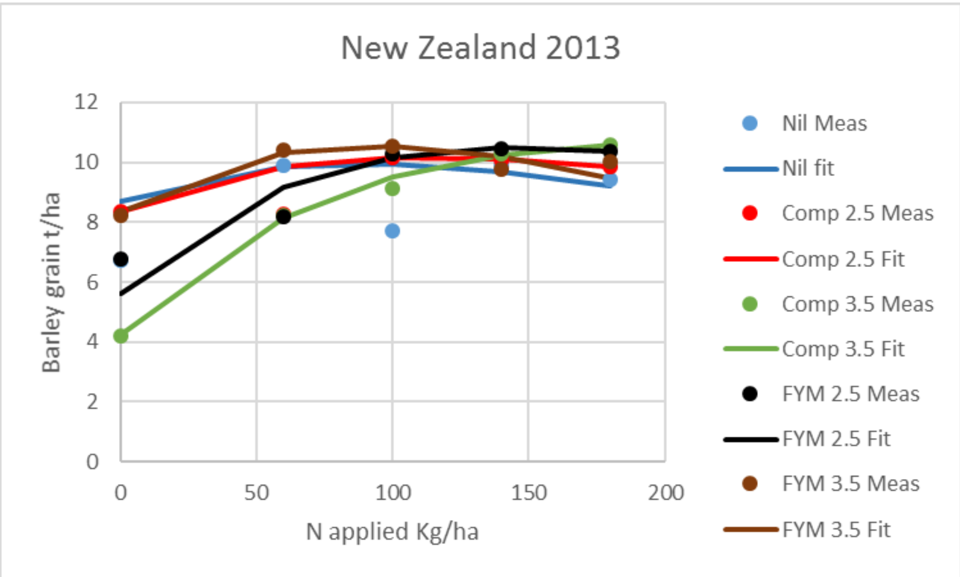

Figure 4.2.1. Year 1 - Barley grain yields under different compost or farmyard manure amendments (0, 2.5 or 3.5 t C ha^{-1}) and Nitrogen rates. Fitted lexp curves

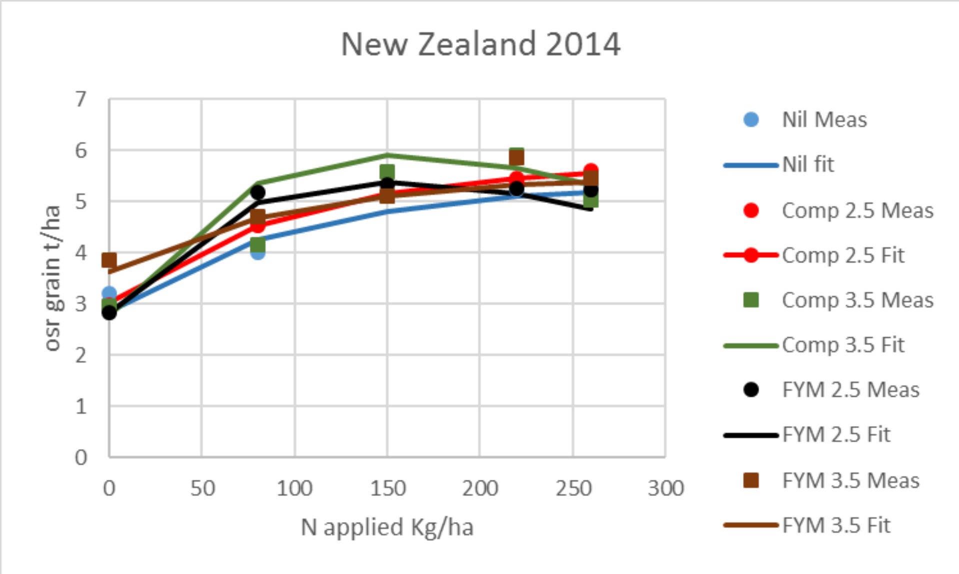

Figure 4.2.2. Year 2 - Oilseed rape yields under different compost or farmyard manure amendments (0, 2.5 or 3.5 t C ha^{-1}) and Nitrogen rates. Fitted lexp curves

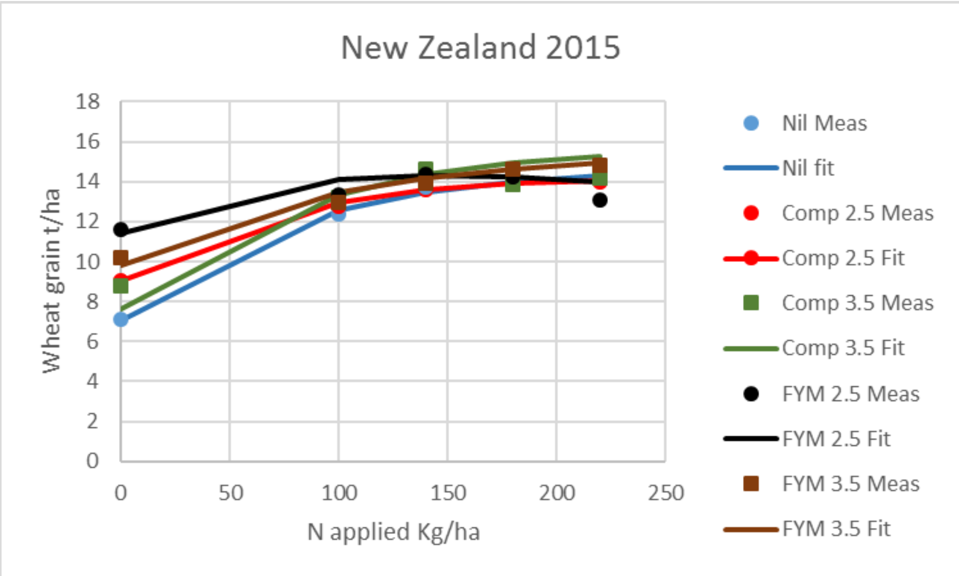

Figure 4.2.3. Year 3 - Wheat yields under different compost of farmyard manure amendments (0, 2.5 or 3.5 t C ha^{-1}) and Nitrogen rates. Fitted lexp curves.

The amount of nitrogen needed for optimum yield decreases with added OM to the reduced tillage trials on New Zealand field, even if the first year. The interaction between kind of OM (including none) and rate (amount applied) was significant in the first year (Table 4.2.1) in 2013. However, the effect of addition of OM on yields was not significant in 2014 (Table 4.2.1 – Table 4.2.2).

Table 4.2.1. ANOVA terms for grain yield of spring barley in 2013.

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Blocks stratum	2	2.181	1.09	0.93	
Blocks.Plots stratum					
Split	1	2.743	2.743	2.33	0.134
Nitrogen	4	107.334	26.834	22.78	<**0.001**
Split.OM	1	5.451	5.451	4.63	**0.037**
Split.OMrate	1	0.259	0.259	0.22	0.641
Split.Nitrogen	4	14.94	3.735	3.17	**0.022**
Split.OM.OMrate	1	7.891	7.891	6.7	**0.013**
Split.OM.Nitrogen	4	4.386	1.097	0.93	0.454
Split.OMrate.Nitrogen	4	9.345	2.336	1.98	0.112
Split.OM.OMrate.Nitrogen	4	22.348	5.587	4.74	**0.003**
Residual	48	56.553	1.178		
Total	74	233.433			

Split is a factor category comparing the presence/absence of organic amendment

Table 4.2.2. ANOVA terms for grain yield of oilseed rape in 2014.

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	0.5135	0.2568	1.18	
Block.*Units* stratum					
N_rate	4	55.1191	13.7798	63.34	<**0.001**
OM	1	0.6464	0.6464	2.97	0.091
N_rate.OM	4	0.7208	0.1802	0.83	0.514
OM.OM_type	1	0.2955	0.2955	1.36	0.25
OM.OM_rate	1	0.1673	0.1673	0.77	0.385
N_rate.OM.OM_type	4	1.1703	0.2926	1.34	0.267
N_rate.OM.OM_rate	4	2.3287	0.5822	2.68	**0.043**
OM.OM_type.OM_rate	1	0.2475	0.2475	1.14	0.291
N_rate.OM.OM_type.OM_rate	4	1.3802	0.3451	1.59	0.193
Residual	48	10.4417	0.2175		
Total	74	73.0309			

Although the effect of amendment is significant in 2015 (Table 4.2.3), by and large there are no significant differences in the yield optima in the reduced tillage experiment on New Zealand field (Table 4.2.4– Table 4.2.5). This suggests that at least some of the benefits that arise in tilled soils from adding amendments are already present or have already been conferred by reducing the intensity of tillage. The New Zealand field (2.6% OM, 1.5% OC) has a different history of land-use from Fosters field but a similar content of organic carbon (1.4% OC).

Table 4.2.3. ANOVA terms for grain yield of winter wheat in 2015.

Source of variation	d.f.	s.s.	m.s.	v.r.		F pr.
Block stratum	2	0.8394	0.4197	0.6		
Block.Plot_1 stratum						
N_rate	4	259.2906	64.8227	92.6		<**0.001**
OM	1	7.2614	7.2614	10.37		**0.002**
N_rate.OM	4	13.5615	3.3904	4.84		**0.002**
OM.OM_type	1	3.2055	3.2055	4.58		**0.037**
OM.OM_rate	1	0.0436	0.0436	0.06		0.804
N_rate.OM.OM_type	4	9.6688	2.4172	3.45		**0.015**
N_rate.OM.OM_rate	4	4.721	1.1803	1.69		0.169
OM.OM_type.OM_rate	1	0.0825	0.0825	0.12		0.733
N_rate.OM.OM_type.OM_rate	4	4.0508	1.0127	1.45		0.233
Residual	48	33.6011	0.7			
Total	74	336.3262				

Table 4.2.4. Optimum yield and optimum nitrogen fertilizer requirement under different crops for different years in New Zealand.

	Yopt	SE	Nopt	SE
2013				
nil	9.38	0.789	127	117
Comp_2.5	10.12	ND	90	ND
Comp_3.5	10.7*	0.325	206	41
FYM_2.5	10.85	1.247	233	311
FYM_3.5	10.0	0.307	91	11.1
2014				
nil	5.36	0.329	260	107
Comp_2.5	5.43	0.048	206	22.6
Comp_3.5	5.37	0.348	179	83
FYM_2.5	5.45	0.141	137	8.8
FYM_3.5	5.95	0.51	346	ND
2015				
nil	14.39	0.228	236	37
Comp_2.5	14.08	0.239	196	49
Comp_3.5	14.19	0.283	164	33
FYM_2.5	13.29	0.429	116	23
FYM_3.5	14.96*	ND	220	ND

*Where Nopt exceeds the top rate of fertiliser applied, this top rate has been used to calculate Yopt. The standard error is estimated (where possible) at the calculated, original optimum N rate.

ND not determined

Table 4.2.5. Change in Yopt or Nopt as a result of amending soil with the materials at the level indicated

	mean 2.5	mean 3.5	mean compost	mean FYM	Mean
Yopt t ha^{-1}	0.17	0.38	0.15	0.67	0.34
Nopt kg ha^{-1}	-44	-25	-46	11	-26

Barley grains in 2013 were significantly larger with OM than without. This appears to be largely due to larger grains in the compost treatment although the difference between compost and FYM was not significant (Table 4.2.6). There was no significant effect of the amendments on oil content in the osr in 2014 (Table 4.2.7). Nitrogen reduced oil content, possibly as a result of larger grains.

Table 4.2.6. ANOVA terms for 1000 grain weight of spring barley in 2013.

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	1.351	0.676	0.26	
Block.Plot stratum					
N_rate	4	71.13	17.782	6.94	<**0.001**
Split	1	5.576	5.576	2.18	0.147
N_rate.Split	4	5.409	1.352	0.53	0.716
Split.OM	1	16.12	16.12	6.29	**0.016**
Split.OM_rate	1	0.433	0.433	0.17	0.683
N_rate.Split.OM	4	7.197	1.799	0.7	0.594
N_rate.Split.OM_rate	4	3.894	0.974	0.38	0.822
Split.OM.OM_rate	1	1.261	1.261	0.49	0.486
N_rate.Split.OM.OM_rate	4	22.093	5.523	2.16	0.088
Residual	48	122.989	2.562		
Total	74	257.454			

Split is a factor category comparing the presence/absence of organic amendment

Table 4.2.7. ANOVA terms for oil content (%) of oilseed rape in 2014.

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	0.1261	0.063	0.18	
Block.Plot1 stratum					
N_rate	4	96.1377	24.0344	67.98	<**0.001**
OM	1	0.232	0.232	0.66	0.422
N_rate.OM	4	0.8022	0.2005	0.57	0.688
OM.OM_type	1	0.4917	0.4917	1.39	0.244
OM.OM_rate	1	0.0003	0.0003	0	0.976
N_rate.OM.OM_type	4	1.674	0.4185	1.18	0.33
N_rate.OM.OM_rate	4	1.9564	0.4891	1.38	0.254
OM.OM_type.OM_rate	1	0.0043	0.0043	0.01	0.913
N_rate.OM.OM_type.OM_rate	4	1.0608	0.2652	0.75	0.563
Residual	48	16.9713	0.3536		
Total	74	119.4568			

4.2.2. **Crop N content**

There was little difference in %N of barley grown with or without amendment in 2013 (Table 4.2.8). Thus, amendments are unlikely to affect the malting quality of barley.

Table 4.2.8. Spring barley grain nitrogen (%) on New Zealand Field in 2013 in relation to the amendments and in relation to the N applied.

		Nil (0 t C/ha)		**Compost 2_5[1] (2.5 t C/ha)**		**Compost 3_5 (3.5t C/ha)**		**FYM 2_5 (2.5 t C/ha)**		**FYM 3_5 (3.5t C/ha)**	
		Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
		%	%	%	%	%	%	%	%	%	%
Nil	0	1.4	0.0	1.5	0.2	1.5	0.0	1.4	0.0	1.4	0.0
N1	60	1.5	0.0	1.4	0.0	1.4	0.0	1.4	0.0	1.6	0.1
N2	100	1.6	0.0	1.6	0.1	1.5	0.1	1.7	0.1	1.7	0.1
N3 (RB209)	140	1.7	0.0	1.6	0.0	1.7	0.1	1.8	0.1	1.7	0.1
N4	180	1.9	0.0	1.6	0.2	1.9	0.1	1.9	0.0	1.9	0.1

[1]Treatments were either 2.5 t C or 3.5 t C ha^{-1}, 2_5 and 3_5 respectively

4.2.3. **Soil physical measurements**

4.2.3.1. Bulk density

The bulk density was determined on three plots per treatment in 2013, and no significant difference was determined (Figure 4.2.4).

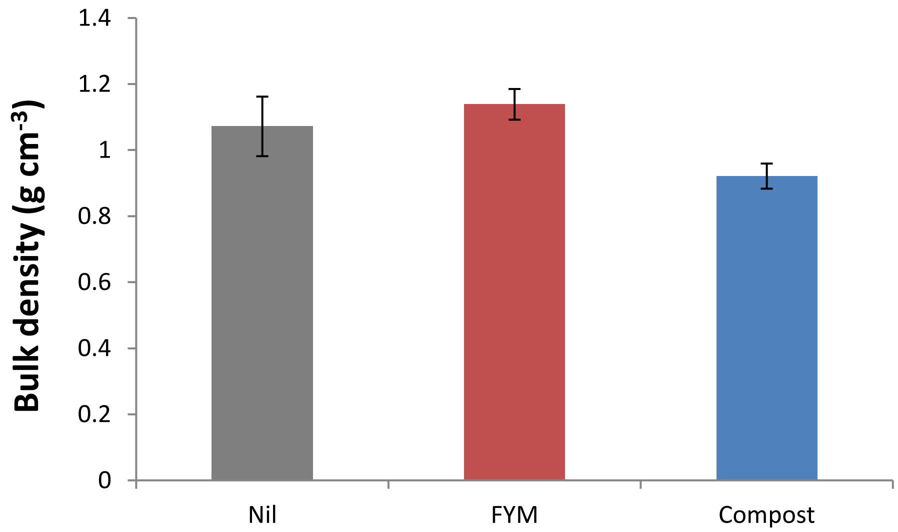

Figure 4.2.4. Bulk density on New Zealand field experiment in 2013

4.2.3.2. Infiltration

The infiltration rate was determined using the paint can (Moya-Esparcia, 2014) method on three plots per treatment in 2014. This showed that infiltration rates were higher when the soils were treated with compost or farmyard manure at either 2.5 or 3.5 t C/ha than the control (no organic amendment) but not significantly. The large number of flints in the soil made it difficult to get a uniform and representative sample for the infiltrometer, which is a common problem with portable instruments to measure infiltration. There was a trend (p = 0.07) in increased infiltration rates as a result of the organic amendments, with rates generally two-fold faster on organic treated plots in comparison to the control plots (Figure 4.2.5). Taken separately from the manure treatment, the compost treatment is statistically different from the control, but as the experiment was not designed to make this specific test it is technically not valid to make the comparison.

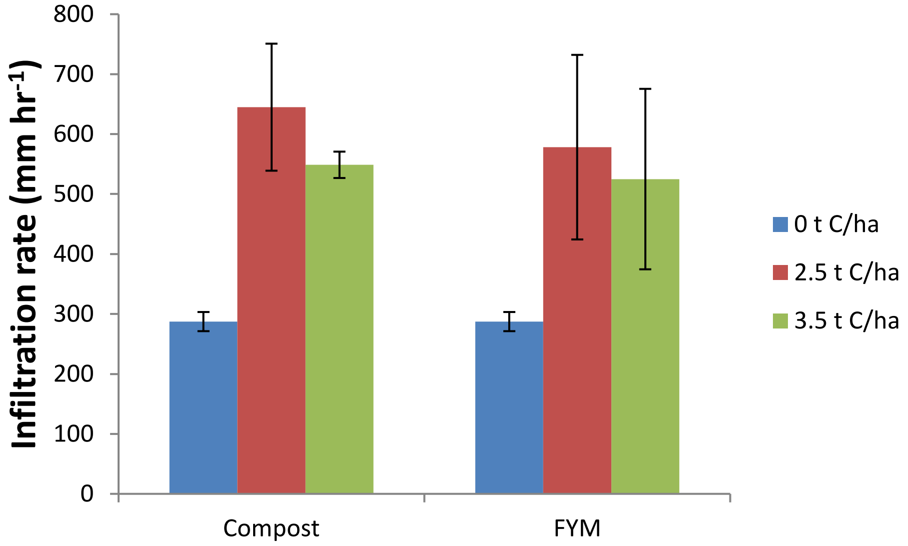

Figure 4.2.5. Infiltration rates under different organic matter amendments in 2014.

4.2.4. **Earthworm populations**

Mustard extraction procedures were deemed unreliable due to extremely slow infiltration rates of the expellant solution through the pit bottoms. This was pervasive across all plots and times, with some instances of more rapid infiltration which was not associated with any particular circumstance. Due to this degree of inconsistency, data arising was not considered sufficiently comparable to warrant further analysis since the results would not be reliable.

Earthworm abundances and biomass were in general highly variable between plots, ranging from 0-1275 individuals m^{-2} with an associated total biomass of 0-208 g m^{-2} across all treatments and times. Data distributions were such that they did not require transformation for ANOVA. There was no significant effect of any of the organic amendment or N fertilisation rate treatments upon earthworm frequency. The overall mean frequency of earthworms across all treatments was 321 (SE 32.5).

Table 4.2.9. ANOVA terms for earthworm frequency (numbers m^{-2}) recorded from New Zealand experiment.

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Time stratum	1	1380167	1380167	17.4	
Time.Block stratum	4	317042	79260	1.25	
Time.Block.Plot stratum					
N_rate	1	6000	6000	0.09	0.760
Amend[1]	1	12760	12760	0.20	0.656
N_rate.Amend	1	94	94	0.00	0.970
Amend.OM_rate	1	27552	27552	0.43	0.514
Amend.OM_type	1	13333	13333	0.21	0.649
N_rate.Amend.OM_rate	1	11719	11719	0.18	0.670
N_rate.Amend.OM_type	1	175208	175208	2.76	0.104
Amend.OM_rate.OM_type	1	110208	110208	1.74	0.194
N_rate.Amend.OM_rate.OM_type	1	110208	110208	1.74	0.194
Residual	45	2858417	63520		
Total	59	5022708			

[1] 'Amend' is a factor with two levels indicating the addition or not of organic matter

The overall biomass of worms across all treatments and times was 54.2 g m^{-2} (s.e. 5.8). However, there was a significant third-order interaction between the presence of OM, its type and N fertilisation rate, with respect to total worm biomass (Table 4.2.10).

The basis of this was that in the presence of organic amendment, worm biomass was significantly greater where N fertilisation was applied in combination with compost. but was significantly reduced by N fertilisation in combination with FYM (Table 4.2.11). In the absence of organic amendment, there was no effect of N fertilisation, and biomass under such treatments was comparable to the greatest biomass values in soils amended with organic materials (Table 4.2.11; Figure 4.2.6 – Figure 4.2.8).

Table 4.2.10. ANOVA terms for earthworm biomass (g m^{-2}) recorded from New Zealand experiment.

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Time stratum	1	34532	34532	22.09	
Time.Block stratum	4	6253	1563	0.78	
Time.Block.Plot stratum					
N_rate	1	1046	1046	0.52	0.475
Amend[1]	1	344	344	0.17	0.681
N_rate.Amend	1	5	5	0.00	0.959
Amend.OM_rate	1	444	444	0.22	0.641
Amend.OM_type	1	133	133	0.07	0.798
N_rate.Amend.OM_rate	1	868	868	0.43	0.515
N_rate.Amend.OM_type	**1**	**8306**	**8306**	**4.13**	**0.048**
Amend.OM_rate.OM_type	1	3468	3468	1.72	0.196
N_rate.Amend.OM_rate.OM_type	1	3711	3711	1.84	0.181
Residual	45	90548	2012		
Total	59	149659			

[1] 'Amend' is a factor with two levels indicating the addition or not of organic matter

Table 4.2.11. Mean total earthworm biomass (g m^{-2}) with respect to presence/absence of organic amendment, its type, and N fertilisation rate.

		OM type		
OM	N rate	Compost	FYM	Nil
No (n=6)	N0			54.2
	N3			63.7
Yes (n=12)	N0	34.1	63.8	
	N3	68.5	45.5	

s.e.d. for min-rep = 25.9; max-min = 22.4; max.rep=18.3

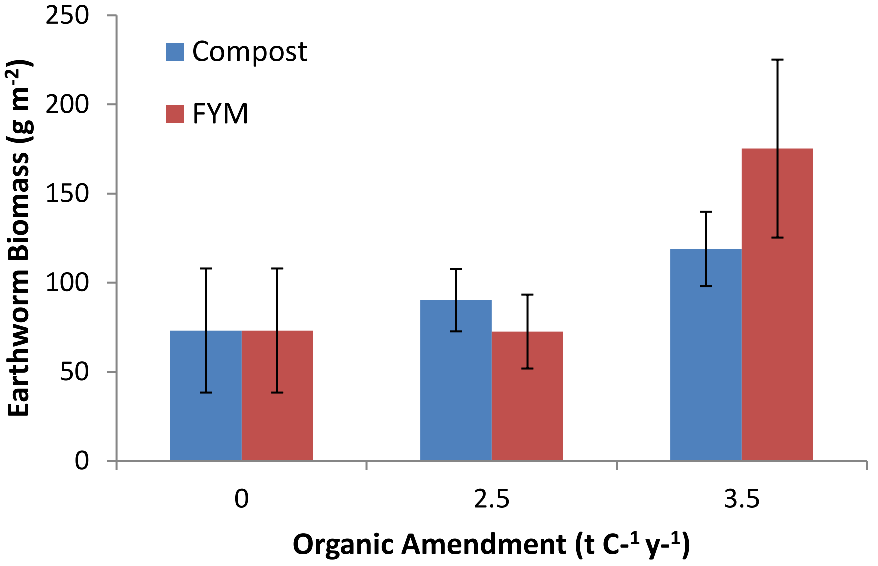

Figure 4.2.6. Earthworm biomass under different organic amendments in 2013.

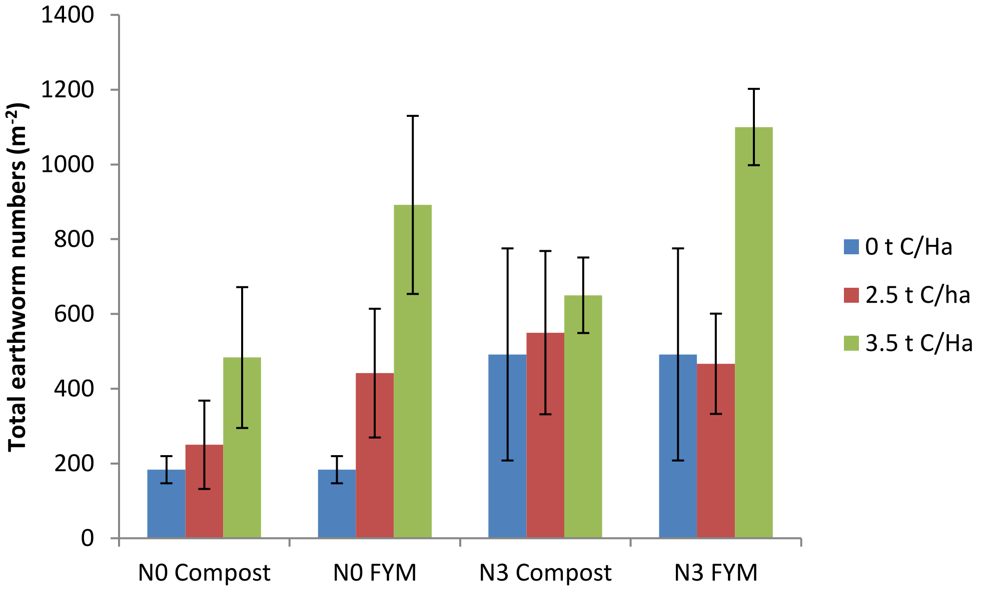

Figure 4.2.7. Earthworm numbers under different organic and inorganic amendments in 2014

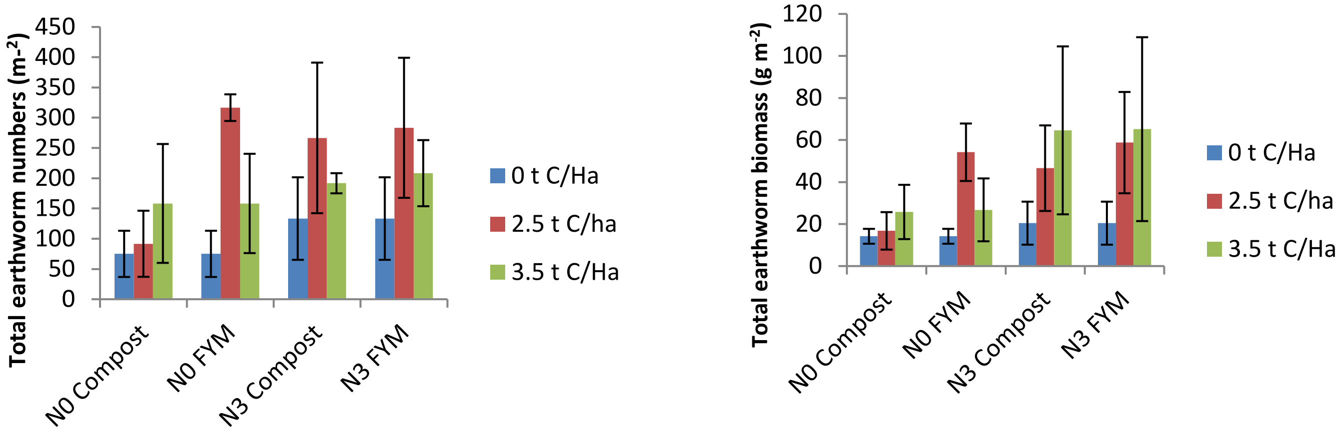

Figure 4.2.8. Earthworm biomass and numbers under different organic and inorganic amendments in 2015.

4.2.5. **Microbiology**

4.2.5.1. Microbial biomass

There was a significant (Table 4.2.12) increase of microbial biomass with organic matter application; this was manifest as an RM-ANOVA main effect with no interactions, and so was irrespective of the sampling time, the type or application rate of organic matter applied, or mineral nitrogen application (Figure 4.2.9). The proportion of increase (compared to the control) was variable throughout the duration of the experiment, the greatest being a 37% increase in autumn 2015 and the least being a 12% increase in autumn 2014.There was also a significant difference in microbial biomass between sampling times, with additional interactions with the nitrogen application rate ("Time x Organic Amendment x N Rate") (Table 4.2.12; Figure 4.2.10). During spring 2014, microbial biomass was greater in the plots that had received both organic matter and mineral nitrogen applications compared to plots that had received only organic matter or only mineral N applications. Similarly, in autumn 2014 where organic matter was applied microbial biomass was greater in the plots that also had mineral nitrogen compared to those that had no mineral N. In autumn 2015, the plots that had organic matter applications but no mineral nitrogen had greater microbial biomass compared to the control plots with no organic matter or mineral N applications. There were no significant treatment effects on microbial biomass in the soils samples during autumn 2013 or spring 2015. Microbial biomass means for all treatments and sampling times are presented in Appendix IX.

Table 4.2.12. RM-ANOVA p-values of microbial biomass, fungal biomass, and PLFA PC scores. Numerals applied to main effects relate to those then mapped to Time effects in lower portion of table.

			PLFA	
	Microbial Biomass	**Fungal Biomass**	**PC1**	**PC2**
1. OM	**0.024**	0.192	0.148	0.148
2. N Rate	0.490	0.776	0.952	0.660
3. OM x N Rate	0.768	0.879	0.481	0.818
4. Organic Type	0.245	0.836	0.115	**0.044**
5. Organic Type x N Rate	0.468	0.763	0.398	0.681
6. Organic Rate	0.220	0.105	0.371	0.954
7. Organic Rate x N Rate	0.713	0.623	0.991	0.902
8. Organic Rate x Organic Type	0.571	0.750	0.484	0.718
9. Organic Type x Organic Rate x N Rate	0.354	0.819	0.688	0.910
Time	<**0.001**	<**0.001**	**<0.001**	**<0.001**
Time x 1	0.811	0.078	0.897	0.849
Time x 2	0.787	0.931	0.495	0.053
Time x 3	**0.035**	0.932	0.934	**0.041**
Time x 4	0.547	0.082	0.920	0.133
Time x 5	0.955	0.409	0.932	0.996
Time x 6	0.599	0.068	0.421	0.597
Time x 7	0.372	0.462	0.239	0.964
Time x 8	0.272	0.995	0.802	0.980
Time x 9	0.286	0.959	**0.022**	0.550

Bold *p* values signify significant ($p<0.05$) effects, OM organic matter (all types).

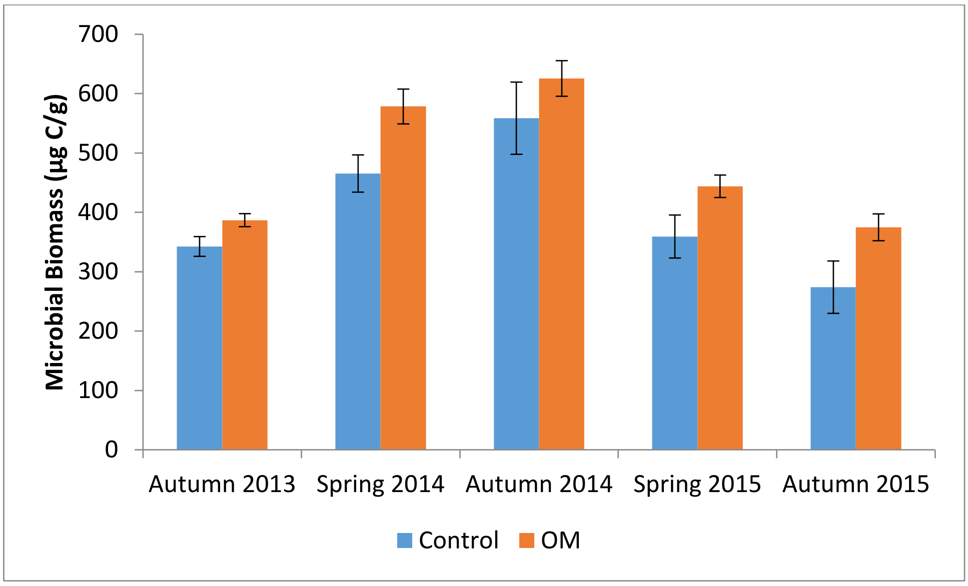

Figure 4.2.9. Microbial biomass increase following organic matter applications (irrespective of organic matter type or application rate). Data are means (±SE: n=6 for the control and 24 where organic matter was applied) at each sampling time. OM organic matter (irrespective of type).

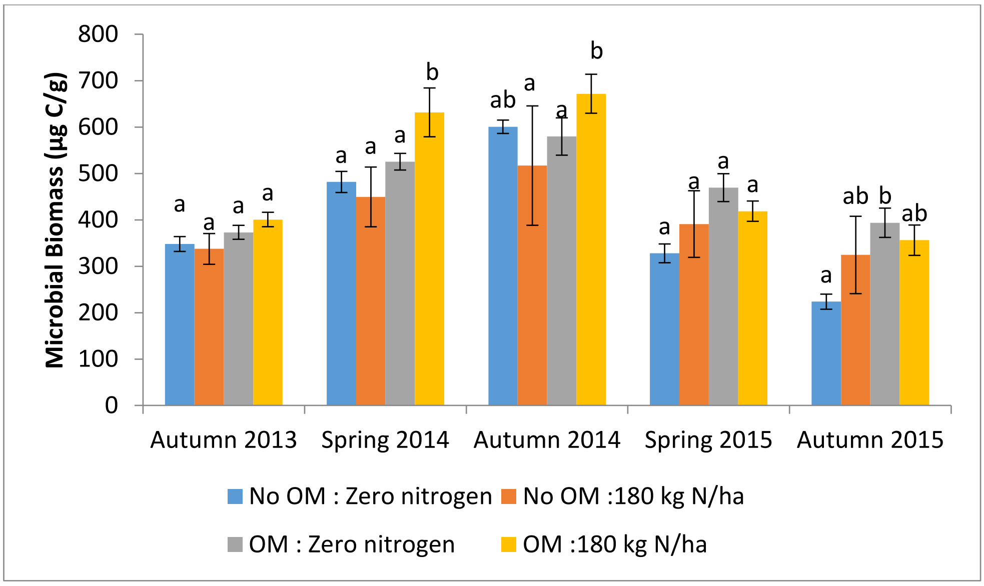

Figure 4.2.10. "Time x OM x N Rate" interaction effect (data are means ±SE: n=3 where no organic matter was applied and 12 where it was applied). Letters above the histogram bars denote significant difference within each sampling time.

4.2.5.2. Fungal biomass

The only significant effect on fungal biomass was a change in time (Table 4.2.12; Figure 4.2.11) (but this was irrespective of experimental manipulations imposed. Fungal biomass was greatest during 2014 (both spring and autumn) compared to all the other sampling times. Fungal biomass means for all treatments and sampling times are presented in Appendix X.

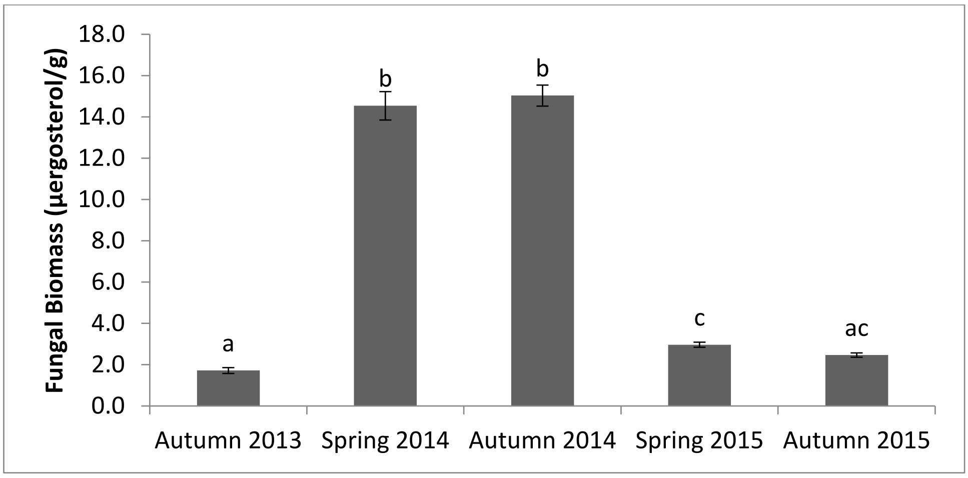

Figure 4.2.11. Fungal biomass throughout the duration of the experiment (New Zealand field). Data are means (±SE: n=30). Letter above the histogram bars denote significant difference.

4.2.5.3. Microbial community phenotypic composition

RM-ANOVA of PCA factor scores identified the type of organic amendment applied as a significant main treatment effect on PC2 (Table 4.2.12; Figure 4.2.12). Factor scores associated with the compost plots were significantly different to those of the plots that had received either farmyard manure or no organic matter applications (control plots), of which there was no significant difference.

There was also a significant shift in the microbial community's PLFA profile on either PC1 or PC2 between all sampling times (Table 4.2.12; Figure 4.2.123)**,** with additional time interactions on PC1 (Time x Organic Type x Organic Rate x N Rate: Figure 4.2.14) and PC2 (Time x OM x N Rate: Figure 4.2.15)**.** There were no treatment effects in autumn 2013 (PC1 and PC2), spring 2014 (PC1), spring 2015 (PC2), or autumn 2015 (PC1 and PC2).

The "Time x Organic Type x Organic Rate x N Rate" effect on PC1 was due to significant treatment effects in autumn 2014 and spring 2015. In autumn 2014, the microbial community in the plots that had received the high compost application rate (3.5 t/ha) and with mineral N applications was significantly different to the plots that had received the medium application rate of FYM (no mineral N applied) and the control (no mineral N applied). In spring 2015, the microbial community composition of the plots that had received the farmyard manure at the medium application rate (no mineral N) was different to that of the other plots. For PC2, the "Time x OM x N Rate" interaction was due to treatment effects during 2014 (spring and autumn). In spring 2014 the plots with no organic matter but with mineral nitrogen applied were significantly different to all other plots, of which there was no significant difference. In autumn 2014, the control plots (i.e. no organic or mineral N applications) were significantly different to all other treatments.

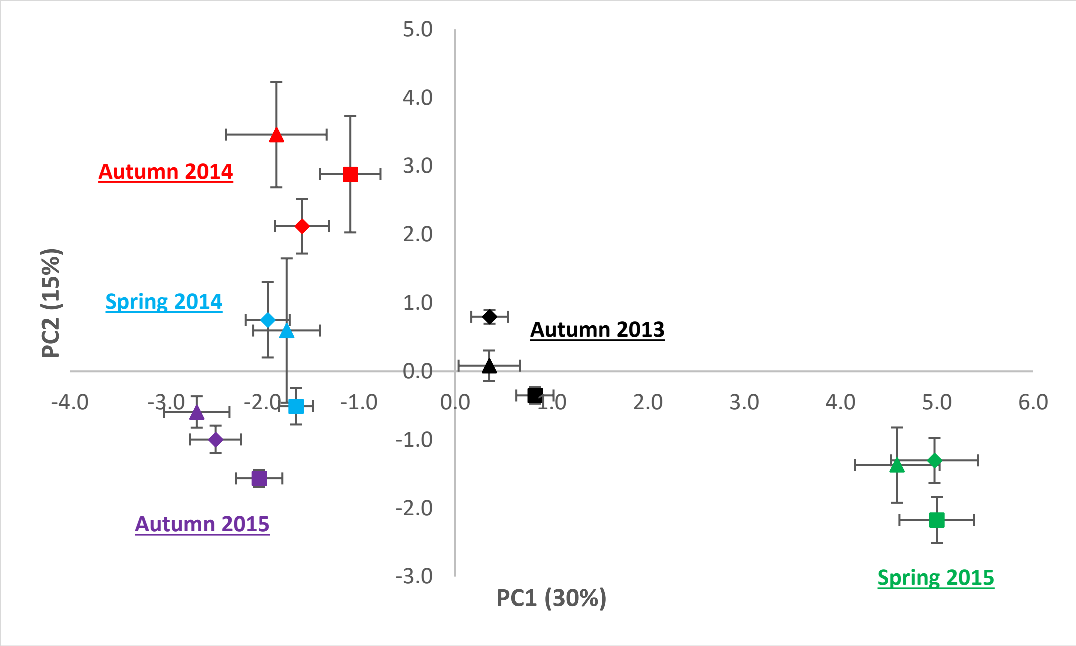

Figure 4.2.12. Microbial community (PLFA) factor scores showing the community shift (on PC2) following organic matter applications. Points show means of PCs (error bars signify SE; n=6 for the control plots and 12 where compost and farm yard manure were applied; values in parentheses denote percent variation accounted for by respective PCs). Triangles denote no organic matter applications, diamonds farm yard manure, squares compost.

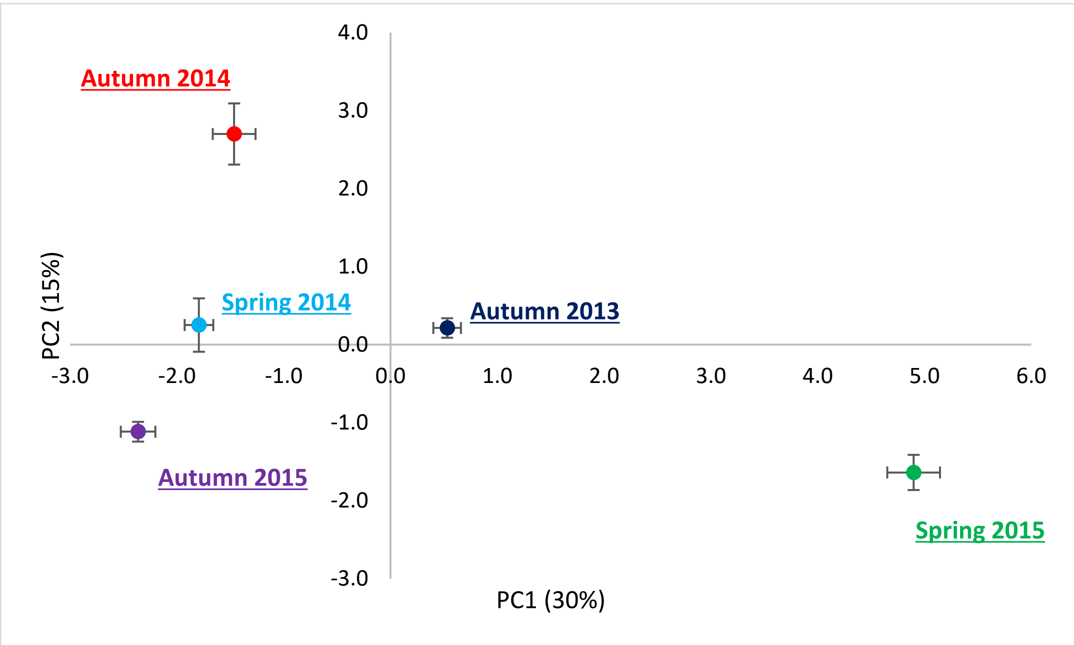

Figure 4.2.13. Microbial community profile (PLFA) shift between sampling times. Data are PCA factor score means (±SE: n=30).

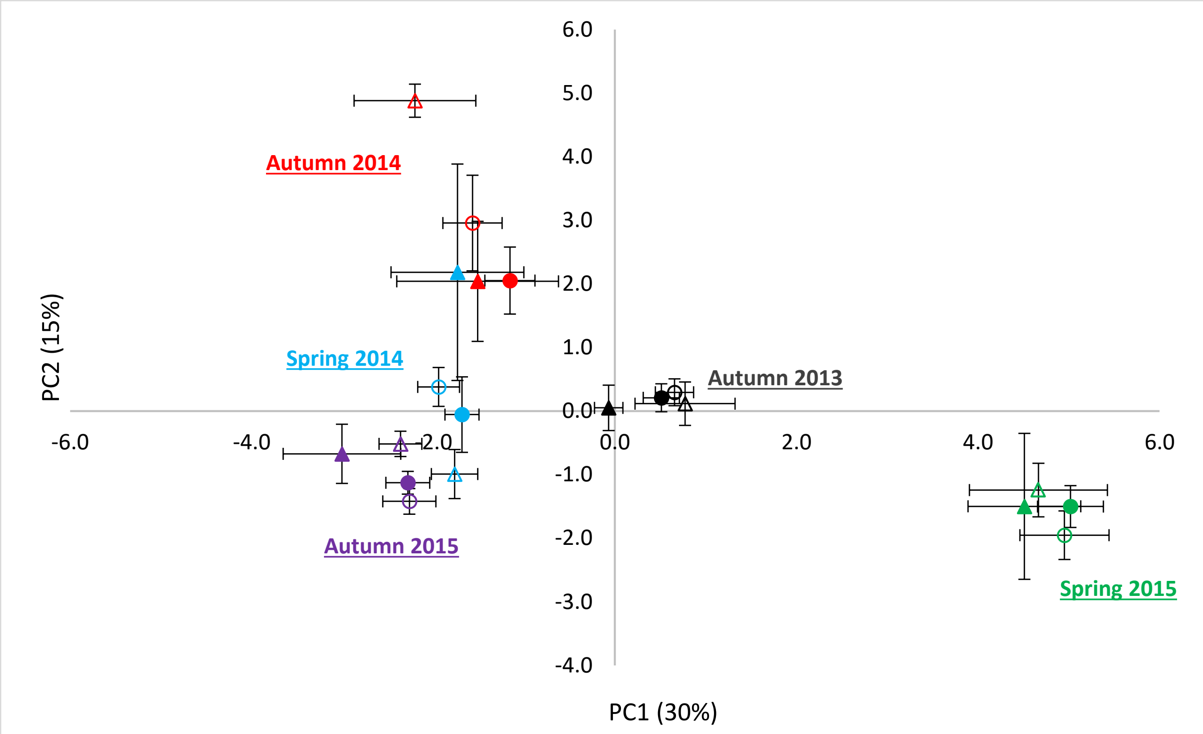

Figure 4.2.14. Showing the "Time x organic amendment x N Rate" effect on microbial community profiles. Points show means of PCs (error bars signify SE; n=3 for the control plots and 12 where organic amendments and mineral nitrogen have been applied values in parentheses denote percent variation accounted for by respective PCs). Triangles have no organic matter applications. Circles have organic matter applied. Open shape has no mineral nitrogen applied. Closed shape has mineral nitrogen applied.

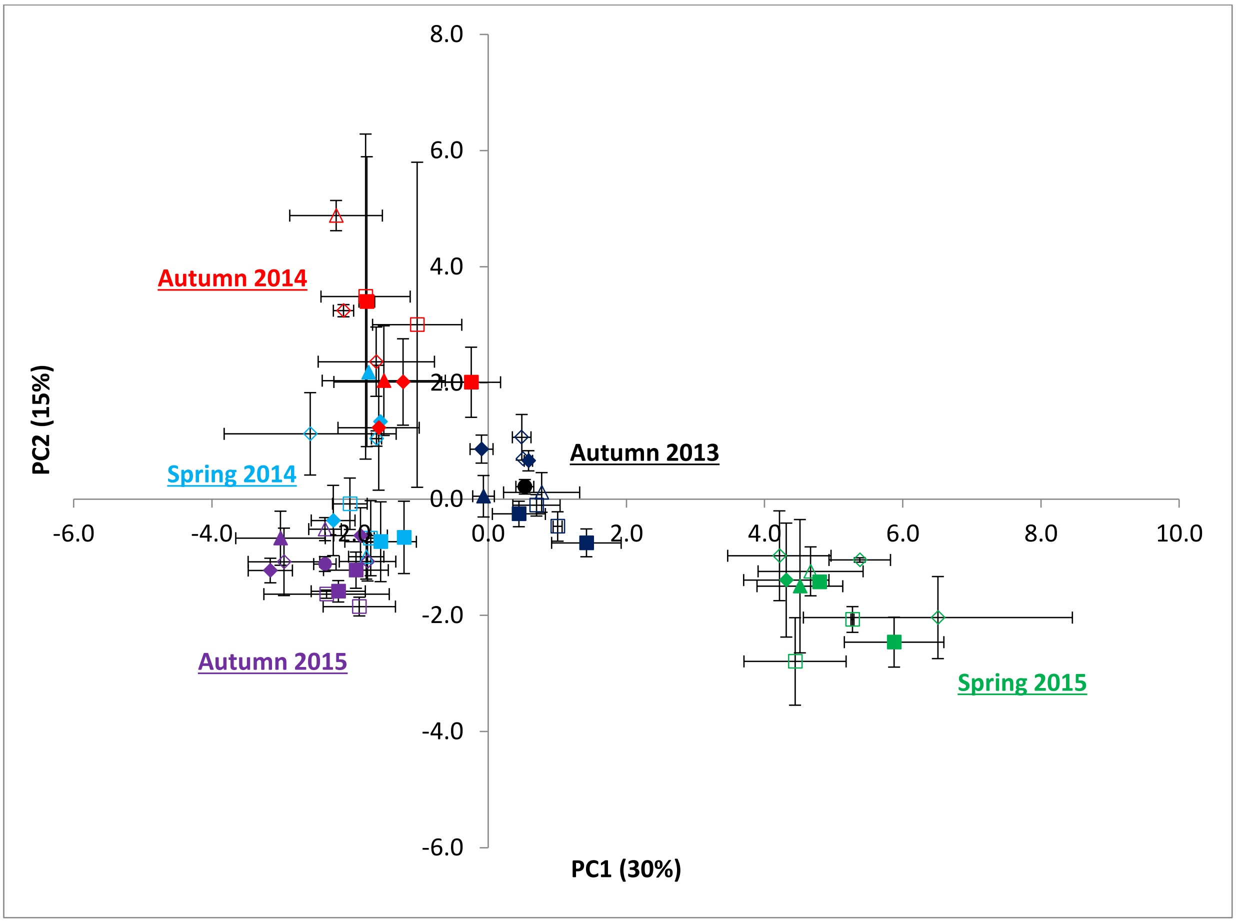

Figure 4.2.15. Microbial community (PLFA) shift between sampling times and organic matter treatments (“Time x organic amendment type x organic amendment rate x N Rate” interaction effect). Points show means of PCs (error bars signify SE; n=3; values in parentheses denote percent variation accounted for by respective PCs). Different sampling times are coded by colour: autumn 2013 black, spring 2014 sky blue, autumn 2014 red, spring 2015 green, autumn 2015 purple. Organic amendments are coded with shape (triangle: no organic matter applied, square: compost, diamond: farmyard manure; open symbols: no mineral nitrogen, filled symbols: mineral nitrogen applied). The duplicate shape (organic matter amendment type) represents the two application rates of 2.5 t/ha and 3.5 t/ha (no significant effect of rate).

4.2.5.4. Fatty acid bioindicators

All PLFA fatty acid bio-indicators varied significantly between sampling times (Table 4.2.13; Figure 4.2.16–Figure 4.2.19). There was also a significant “Time x Organic Type” interaction effect on the fatty acid bioindicator for arbuscular mycorrhizal fungi, and a “Time x OM x N Rate” interactions for the total bacterial fatty acids and Gram negative fatty acids. The plots that had compost applied had a greater proportion of arbuscular mycorrhizal fungi compared to the control and those that had farm yard manure applied (Figure 4.2.17). The only sampling time that this did not occur was in autumn 2014 after OSR.

Table 4.2.13. RM ANOVA terms for PLFA bioindicators, New Zealand experiment. Numerals applied to main effects relate to those then mapped to Time effects in lower portion of table.

	MUFA	iso anteiso	AM	Bacterial
Effect	G- FAs	G+ FAs		FAs
1. OM	0.536	0.611	<**0.001**	0.231
2. N Rate	0.051	0.221	0.667	0.921
3. OM x N Rate	0.925	0.930	0.948	0.846
4. Organic Type	0.770	0.406	<**0.001**	0.566
5. Organic Type x N Rate	0.985	0.965	0.740	0.913
6. Organic Rate	0.559	0.860	0.464	0.796
7. Organic Rate x N Rate	0.527	0.187	0.136	0.227
8. Organic Rate x Organic Type	0.717	0.771	0.607	0.748
9. Organic Type x Organic Rate x N Rate	0.530	0.830	0.456	0.502
Time	**0.003**	<**0.001**	<**0.001**	**0.019**
Time x 1	0.106	0.921	0.728	0.540
Time x 2	**0.010**	0.586	0.276	0.125
Time x 3	<**0.001**	0.059	0.528	**0.001**
Time x 4	0.471	0.386	<**0.001**	0.727
Time x 5	0.948	0.999	0.221	0.994
Time x 6	0.929	0.598	0.892	0.464
Time x 7	0.542	0.658	0.253	0.645
Time x 8	0.829	0.948	0.933	0.920
Time x 9	0.702	0.821	0.190	0.977

FA fatty acids, MUFA monounsaturated FAs, AM arbuscular mycorrhizal FA, G- Gram negative bacteria, G+ Gram positive bacteria, OM organic matter (irrespective of type).

In spring 2014 and autumn 2015, Gram negative bacterial fatty acids were proportionately greater where mineral nitrogen had been applied but only where no organic matter was applied. Conversely, in autumn 2014 the proportion of Gram negative bacteria was greater where no mineral N had been applied. Where organic matter had been applied (all sampling times) there was no significant difference between the plots that had received mineral N compared to those that had not. There was no significant effect of organic matter application on Gram negative fatty acids in either the autumn 2013 or spring 2015 sampling times.

There were proportionately more Gram positive bacteria where mineral nitrogen had been applied but only where no organic matter was applied. In autumn 2014 the opposite occurred in that the proportion of Gram positive bacteria was greater where no mineral N had been applied. Where organic matter had been applied (all sampling times) there was no significant difference between the plots that had received mineral N compared to those that had not. There was no significant effect of organic matter application on Gram negative fatty acids in either the autumn 2013 or spring 2015 sampling times.

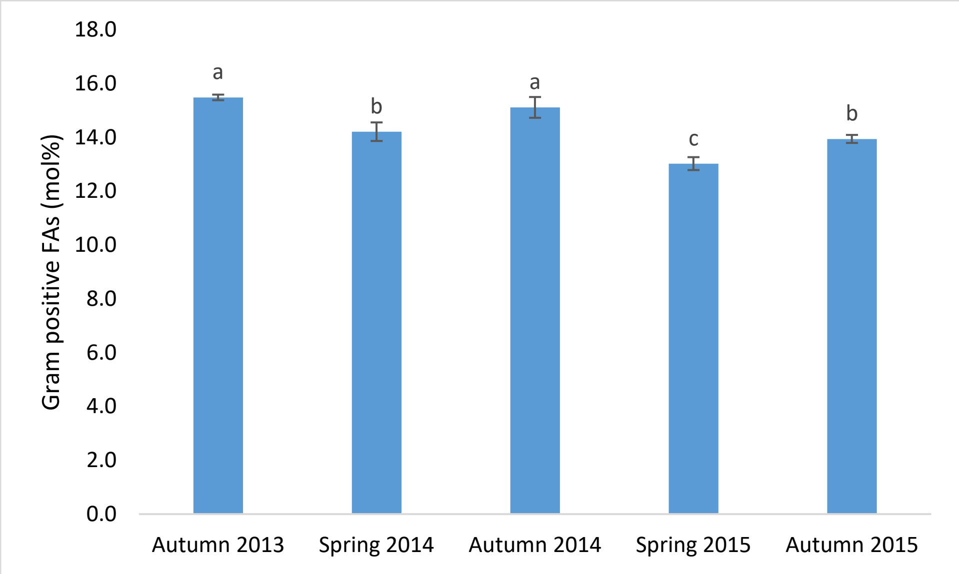

Figure 4.2.16. Change of Gram positive bacterial fatty acids throughout the New Zealand field trial. Data are means (±SE: n=30 for each sampling time).

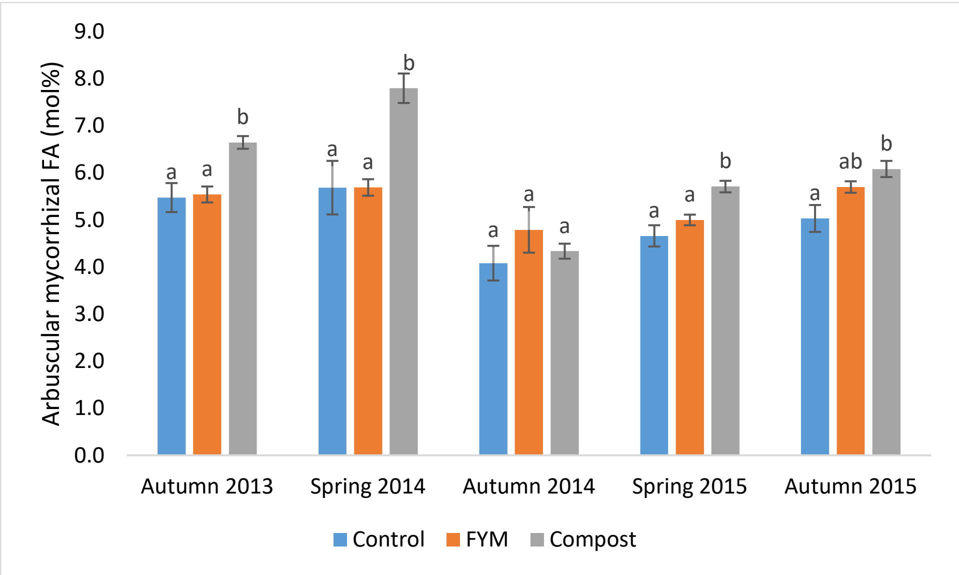

Figure 4.2.17. Change in arbuscular mycorrhizal fungi (as indicated by the fatty acid 16:1w5) with time and different organic matter applications (irrespective of application rate). Data are means (±SE: n=6 where no organic matter was applied and 12 where it was applied). Letters above the histogram bars denote significant difference within each sampling time.

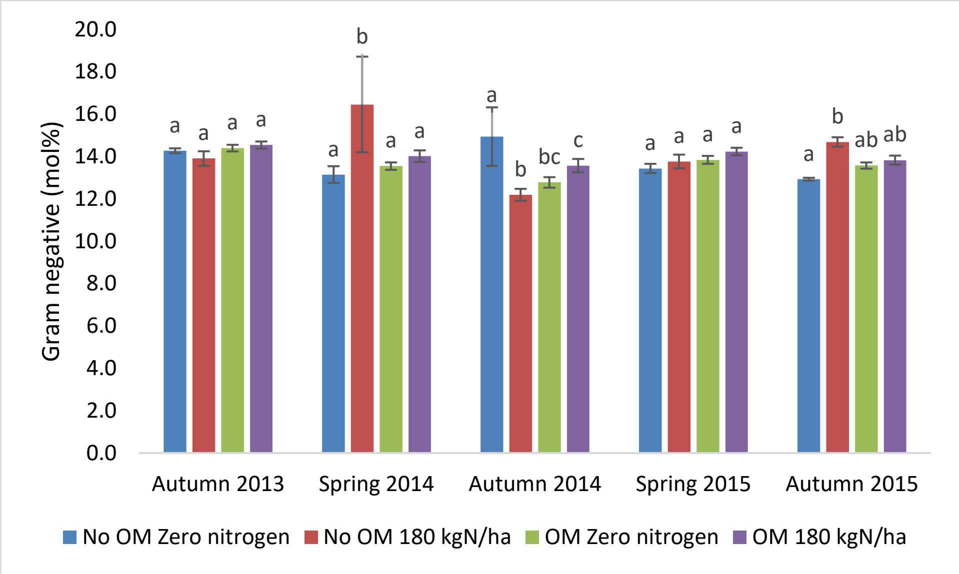

Figure 4.2.18. Change in Gram negative bacterial fatty acids with time, organic matter applications (irrespective of type or rate) and mineral N applications. Data are means (±SE: n=3 where no organic matter was applied and 12 where it was applied). Letters above the histogram bars denote significant difference within each sampling time.

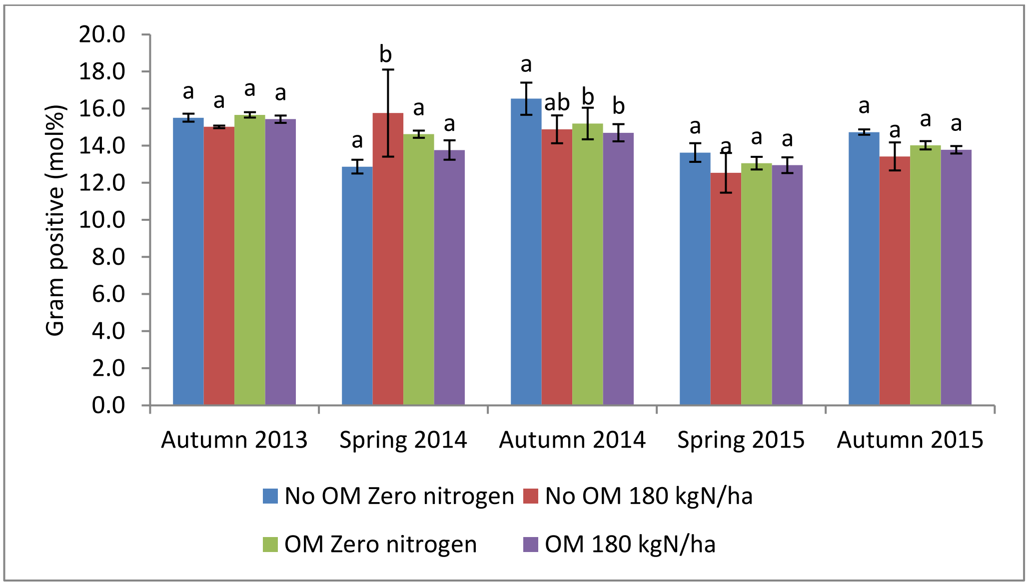

Figure 4.2.19. Change in Gram positive bacterial fatty acids with time, organic matter applications (irrespective of type or rate) and mineral N applications. Data are means (±SE: n=3 where no organic matter was applied and 12 where it was applied). Letters above the histogram bars denote significant difference within each sampling time.

4.3. Pot experiments to evaluate the benefits of amending soils of differing textures

The large experiments on Fosters and New Zealand fields at Rothamsted explore the effect of amendments in practice. They suffer from the limitation of being on a single soil type. Three additional means of extending the research to other soil types were attempted within this project. They are (i) a series of pot experiments with different soils (ii) a series of trials in practice that also uncover difficulties of using amendments in practice (Section 4.11) and (iii) a network of European trials where N response curves have been measured with and without organic amendments (Section 4.12). Here we report on the pot trials.

Two contrasting soils from Woburn experimental farm were used alongside a Rothamsted soil for comparison with the main field trials. These were a loamy sand from Butt Close field (0.58% C, 7.2% clay) and a sandy clay loam from Warren Field (1.9% C, 26% clay).

Grain yields per pot did not differ significantly among treatments in 2014 and 2015 and in particular between soils. This may perhaps have partly been because the results on the loamy sand soil were much more variable than on the other soils. However, there were differences in the components of yield in the different soils.

The unamended soils had significantly fewer tillers at harvest than the amended treatments ($p=0.035$) and as a result had fewer grains per plant ($p=0.054$), yield per plant ($p=0.029$) and grains per plot ($p=0.01$). A complicated 4-way interaction was present among the grains per ear but on inspection this appeared to be due to one anomalously high datum. The measurement has been included in the analysis but the interaction discounted. Removing it altogether made no difference to the above based on 3-way and fewer interactions.

4.4. Saxmundham experiment to test whether the absence of worms leads to poor structure or whether poor structure depletes soil organisms

We carried out an earthworm survey on two plots in the Saxmundham experiment to establish a baseline with which to compare our intended experiment, but also to compare with other surveys at Rothamsted and elsewhere (Figure 4.4.1). The earthworm biomass was significantly greater in the long term FYM plots than in the controls but overall rather less than would be expected in fields at Rothamsted such as Fosters (section 4.1.3.3, >50 g m^{-2}) which we have already established is itself somewhat depleted in earthworm numbers and biomass.

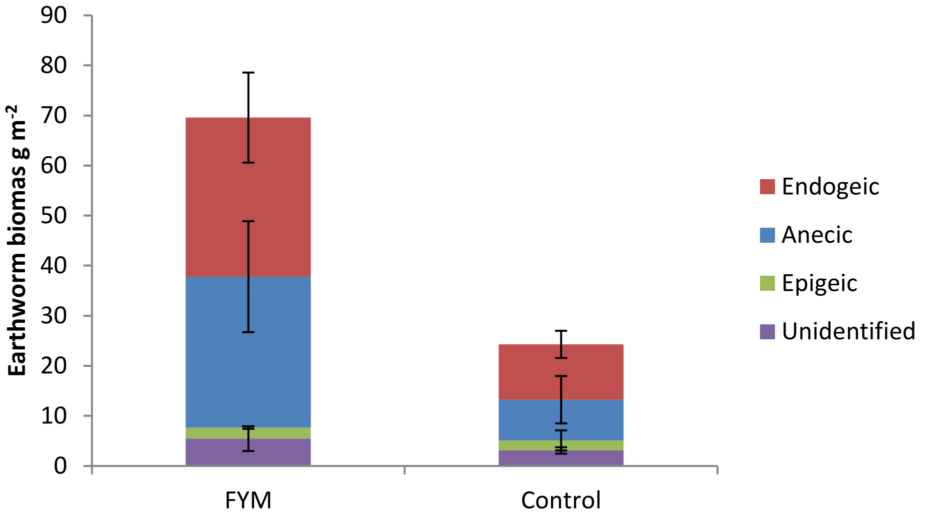

Figure 4.4.1. Earthworm biomass in Saxmundham experiment.

Since this was a pot experiment, it was possible to make comparisons between treatments only. Extrapolation to plants ha^{-1} or t ha^{-1} can be made, but the former is afflicted by edge effects and the latter by plant density in the extrapolations. In the analysis, 'FYM' is the long term field treatment and 'manure' refers to our experimental amendment in pots.

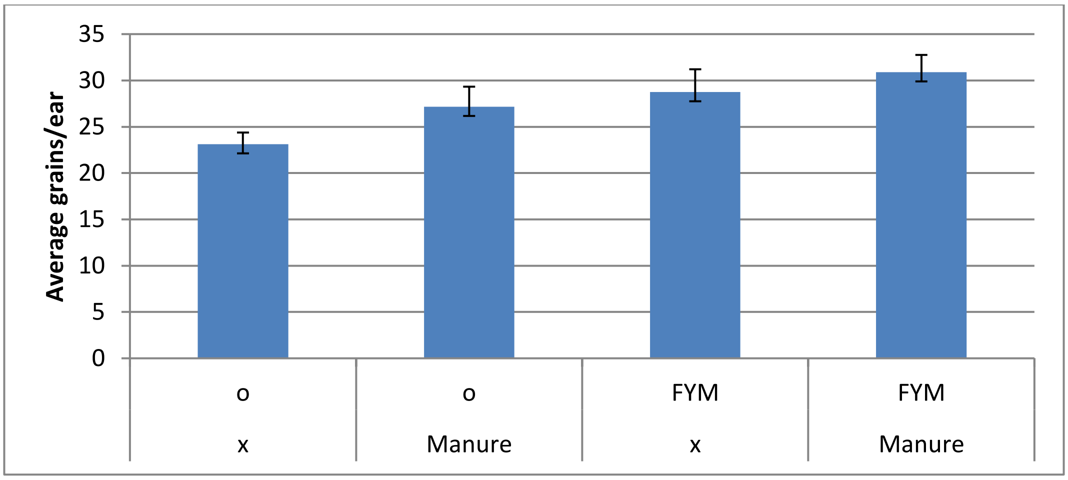

Figure 4.4.2. Average grains per ear in relation to long term (FYM) or recent (Manure) amendments in the pot trial using soil from the Saxmundham experiment. 'o' means no FYM, x means no manure

In contrast to the results from the soil texture experiment where the number of ears per pot was the best determinant of yield, the Figures (Figure 4.4.2) suggest that in the Saxmundham soils it is the numbers of grains per ear that increase as a result of amendment.

The sandy clay Beccles series soil from Saxmundham exhibited all of the difficulties for which this soil is well known. As the soil dries it remains retentive of a large volume of water to the extent that the soil is physically weak until a point at which its strength increases rapidly with a small change in water content. Such hard-setting soils are difficult to work, especially from a timeliness point of view, but also from the point of view of the organisms that live in the soil such as earthworms. At the end of our trial, few worms had survived a prolonged wet period that the pots had suffered. Evidence, in the form of tunnels, was present that the worms had worked the soil. There was no suggestion that this evidence of the presence of worms or the stability of the soil had any effect on any of the yield parameters measured.

4.5. Woburn organic manuring experiment

Equation [2b] (Section 3.8) was used to estimate the combined response of yields to N and amendment from this experiment for a variety of crops. The average value of Copt was 2.1 t C ha^{-1} $year^{-1}$ (SE 0.42). There is some variation in this value of Copt for different crops, but it would be unwise to try to extract a more precise value than that of the average for all crops given the large SEs associated with these data (0.3 - 0.5). Values of Copt were larger towards the end of the experiment (2004 on), perhaps pointing the benefits of amendments to modern crop varieties rather than older ones.

A computer simulation model (Dailey et al., in prep; Coleman et al., submitted) was modified and used to assess the benefits of organic matter to yields in the Woburn Organic Manuring experiment. Briefly the modified model allows changes in bulk density to be modelled in relation to organic amendments. As a result of this change, stresses to crop growth are generally reduced: the soil volume is increased thus retaining and supplying more water, the soil water release curve is changed so allowing more water to be stored in the available range and better drainage of water under wet conditions. Figure 4.5.1 compares the difference in yields with and without amendment.

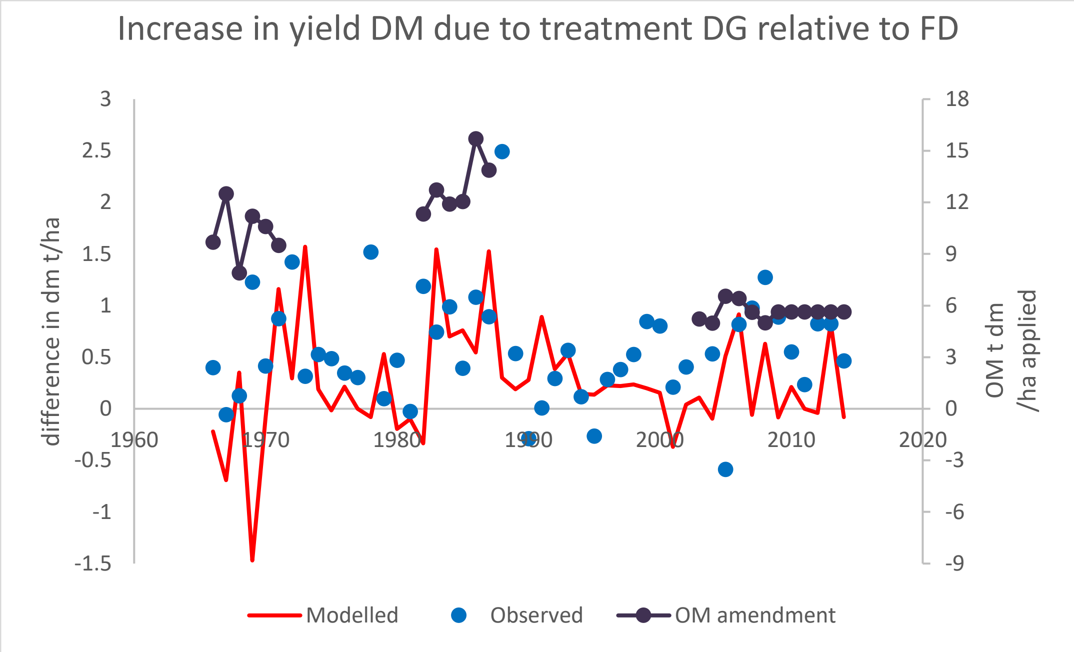

Figure 4.5.1. Modelled and measured differences in standardised yields on plots receiving either FYM (DG) or fertiliser P & K equivalent to that contained in the FYM (FD). Measurements and simulations are at the average rate of 4 applications of N which differed from year to year and crop to crop. FYM was not applied in all years. The years in which FYM is applied and the amount is indicated on the figure as 'OM amendment'.

In general, it takes at least two years before an effect of amendment on yield is seen which is borne out by experimental results on Hoos field and on Fosters. Of interest is that the effect takes at least 5 years to be lost completely. Further work on this is continuing and will be reported on within the SARIC project (BYOSOLID, NE/M016714/1).

4.6. Great Knott III experiment with straw

Under laboratory conditions earthworms have been observed to grow and mature faster if fed finely ground straw (Lowe and Butt, 2003). We first confirmed these results for the earthworms and some of the amendments used in these trials (section 4.10), then tested field strategies for increasing earthworm numbers hypothesising that these would lead to increases in yield. A field experiment was set up with four-fold block replication testing the addition of 3 rates of addition of straw (0, field residues and 4 x field residues) and the intention of testing 3 ways of pre-treating the straw physically (none, splitting and comminution). Reports in the popular press suggest that splitting straw lengthways makes it easier for microbes to gain ingress to start decomposition and perhaps for worms to drag into burrows. However, it proved impossible to find suitable machinery to split straw on a large scale. Accordingly, in year one the straw was rolled mechanically in order to break it open in as many places as possible – both lengthways and crossways. This is labelled 'conditioned'. In the second year of the trial this treatment was replaced with a series of staged applications. Here the hypothesis is that earthworms and other soil fauna would benefit from a year-round supply of organic matter, such as is present under perennial crops. Because anecic earthworms have the habit of drawing relatively large pieces of intact straw into their burrows, we ground 10-15% of the mass of straw applied to this experiment only (see Table 3.1.6).

4.6.1. **Crop yields**

Straw rate and treatment significantly reduced wheat grain yield in 2014 (Figure 4.6.1). However, this can be partly attributed to the poor pre-existing condition of two of the experimental blocks in the field (see Section 4.13.2)

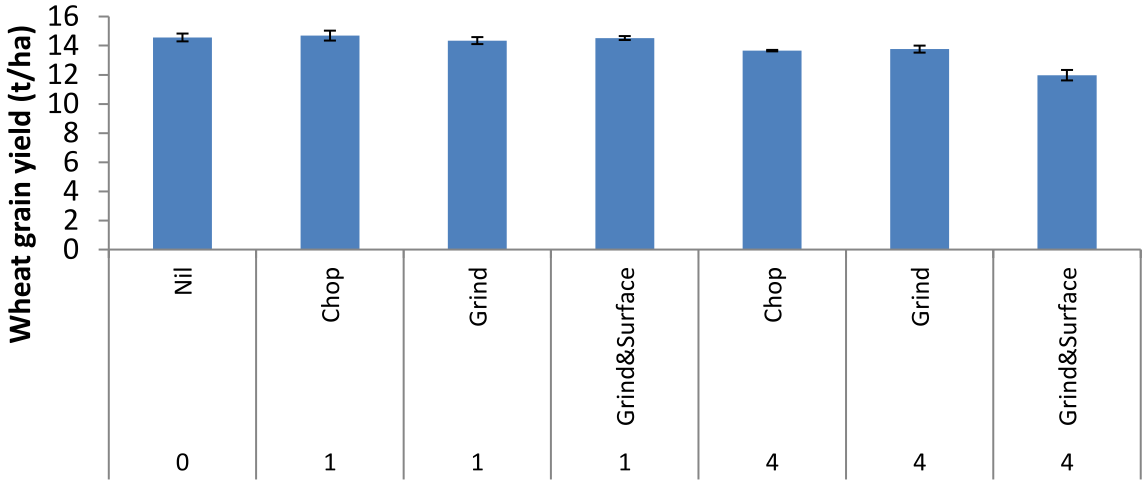

Figure 4.6.1. Wheat grain yield in 2014. Data on x-axis refer to relative quantities of straw applied with 1 being 1x the yield of straw per plot for that year, 4 being 4 x that rate and 0 no addition. Straw was either chopped (chop) or chopped and 10% ground (Grind) both residues were ploughed into the soil. Treatment Grind and Surface was applied four times during the growing season to the surface of the soil.

4.6.2. **Soil physical measurements**

Penetrometer measurements were made across the experiment in September 2013 after the first harvest and 6 months after the initial set of treatments. No trends were evident (Figure 4.6.2).

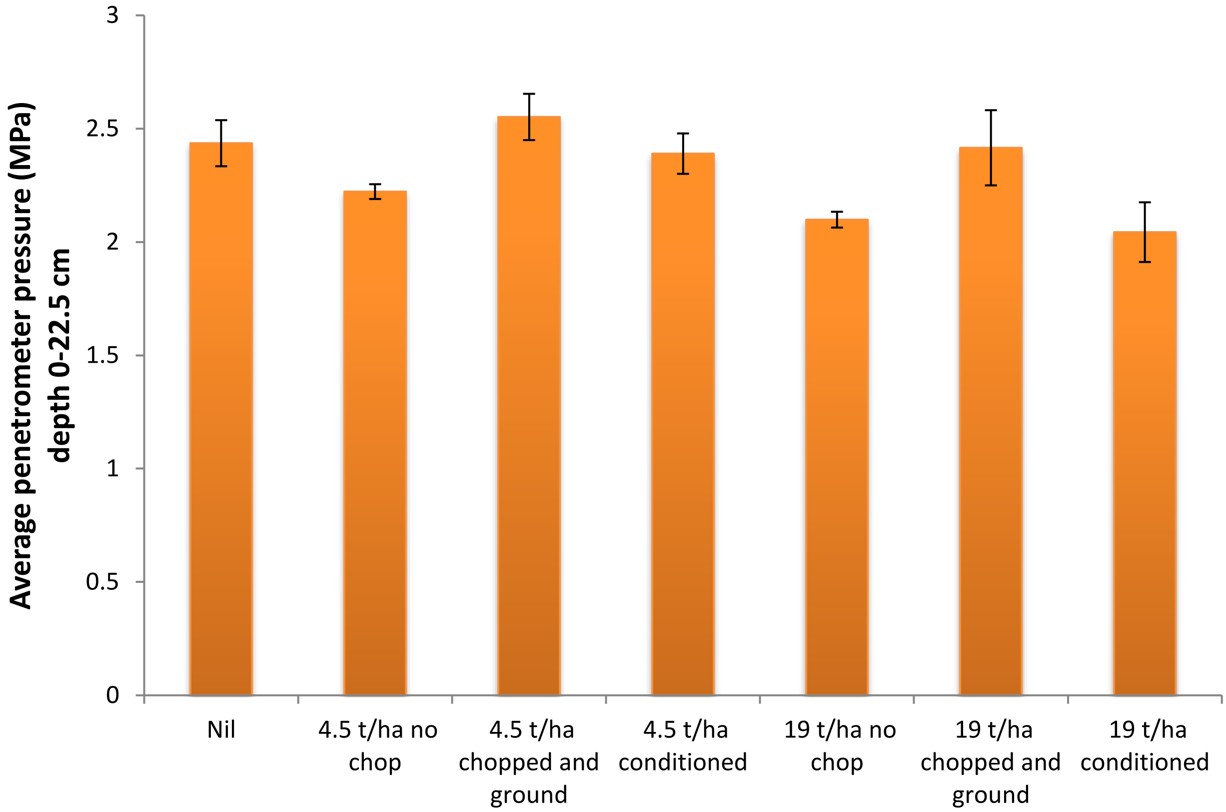

Figure 4.6.2. Penetrometer measurements in 2013. Treatments were 4.5 or 19 tonnes straw added per hectare, untreated, chopped and ground or conditioned which in 2013 was rolling the straw to try to split as much of it open with the intention of allowing more rapid colonisation by fungi

Penetrometer measurements were also made across the experiment in May 2014 after two rounds of treatments, and on this occasion the greatest straw rate (4x) significantly decreased soil strength (p=0.031) in the top 30cm (Figure 4.6.3). However, there was a significant interaction between grinding and surface applying (p=0.009) which appears to be the result of the inconsistent and strong increase in penetrometer resistance in the grind and surface applied treatment with the normal (1x) rate of straw application, which contrasts with the reverse trend in the chopped straw only treatments. There are complications with pre-existing compaction in some plots in this field as discussed in Section 4.13.2.

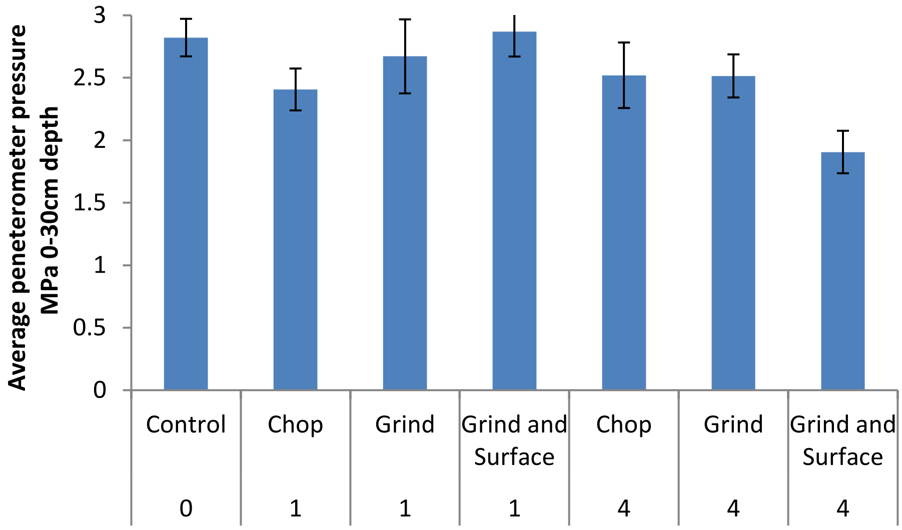

Figure 4.6.3. Penetrometer measurements in 2014. Treatments were altered for the second and 3rd applications. Straw was either chopped (chop) or chopped and 10% ground (Grind) both residues were ploughed into the soil. Treatment Grind and Surface was applied four times during the growing season to the surface of the soil. Rate 0,1x and 4x refer to proportions of straw applied in relation to the quantity of residue left on the experimental plot area. Thus, 4x received 4 times the quantity of residue its area had produced. These rates of application are similar to those in 2013.

Thus, over the time-course of this experiment and at very large rates of application of OM, a reduction in penetrometer resistance was detectable in these soils which would be expected to translate into a reduction in resistance to root exploration of the soil. It is worth noting that the large reduction in penetrometer resistance came about partly in the plots that were originally in poor condition.

4.6.3. **Earthworm populations**

All plots were surveyed in 2014 and 2015 to determine earthworm populations, and the results showed that both straw rate and pre-treatment significantly affected earthworm biomass (Figure 4.6.4 – Figure 4.6.5).

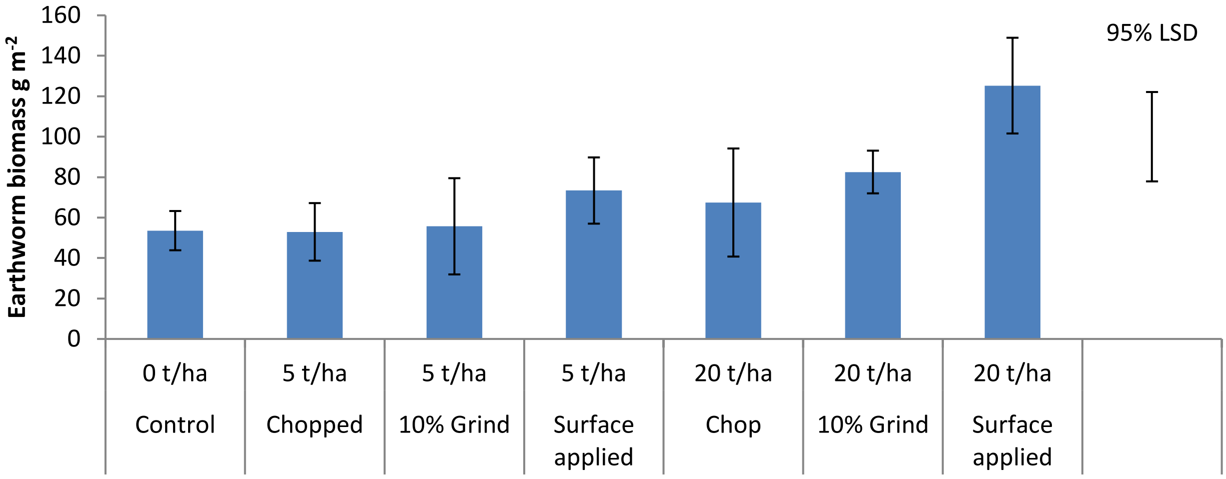

Figure 4.6.4. Earthworm biomass under different straw amendments in 2014.

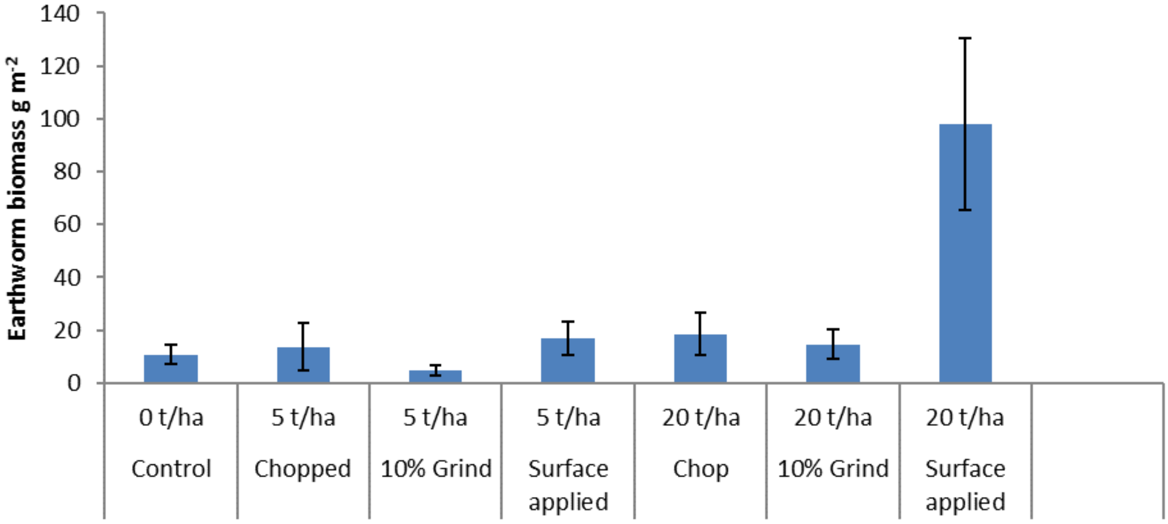

Figure 4.6.5**.** Earthworm biomass under different straw amendments in 2015.

Large amendments of straw (20 t ha^{-1}) significantly increased earthworm numbers and biomass as hypothesised but depressed yields. Staging applications (4 times throughout the year) tended to have the effect of raising earthworm numbers but the results were not significant. However, there was a significant pre-existing trend in the field that has impacted on these results. See section below on draught forces. Over the time course of this experiment, large additions of OM (straw) have led to an increase in the earthworm number which may have been responsible for reducing the resistance to penetrometer pressure and presumably root extension.

4.6.4. **Soil borne diseases**

Take-all (*Gaeumannomyces graminis*) infection reduces yield by impacting root growth and survival. However, it can be ameliorated partially by suppling additional N. We reasoned that a sensitive indicator of the effect of take-all in relation to a series of N response curves would be GperN = Yopt/Nopt: that is the amount of grain delivered per unit of N applied at the optimum rate.

Values of the rate of take-all infection rate (Dyke and Slope 1978; Gutteridge et al, 2003; ERA, 2016) were compared with GperN (Figure 4.6.) and correlations calculated between TAR and GperN to assess the existence of an association. In the mineral N wheats with 20 df these were 1st wheat: 0.496 ($p<0.05$); 2nd wheat: 0.306 (NS); 3rd wheat: 0.449 ($p<0.05$). No significant relationships were observed between TAR and the wheats grown in rotation but receiving FYM.

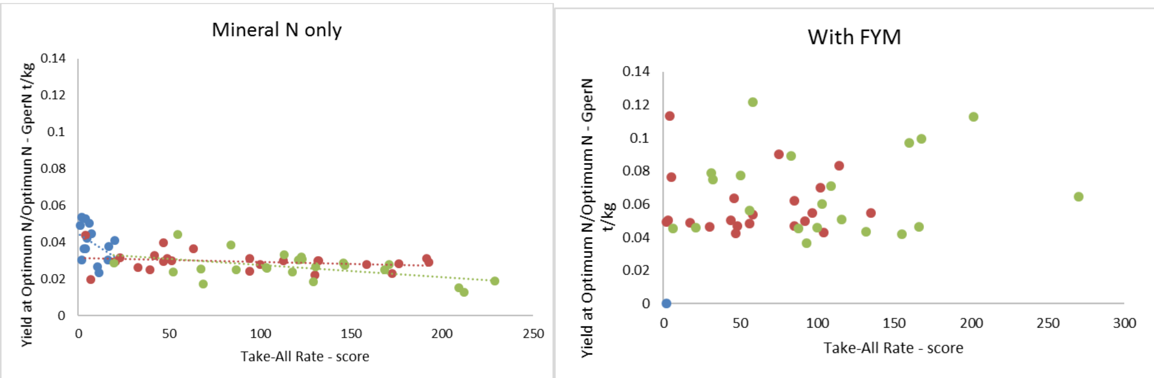

Figure 4.6.6. GperN: Grain yield (Yopt) at the optimum rate of N applied (Nopt) divided by Nopt, i.e. Yopt/Nopt in relation to the Take-All Rate (TAR) measured on selected plots of the Broadbalk continuous wheat experiment between 1985 and 2000. Nmin, plots receiving mineral fertiliser only; FYM plots receiving FYM as well as mineral N (see section 3.1.1.1), Blue 1st, red 2nd and green 3rd Wheats

GperN on the FYM treatments was roughly double the value on the Nmin plots (mean value 0.06 versus 0.03 tonnes grain kg^{-1} N). TAR scores on both mineral N and FYM plots were similar (Figure 4.6., X-axes), so FYM has not eliminated or reduced take-all, i.e. it probably does not affect the fungus. In addition, no relationship between GperN and TAR is apparent in the FYM plots, But GperN is significantly reduced in the Nmin plots by take-all, indicating the Take-All has affected yields on the mineral N only plots but not the FYM plots. It seems likely that the presence of FYM enables the wheat crop to partly overcome the effects of the disease by supplying more N or reducing the impedance to additional root growth or both.

4.7. Mid-Pilmore trial (JHI)

4.7.1. Crop yields

The experiment compared deep (40cm depth) and conventional (20cm depth) ploughing, minimum and zero tillage and a soil compaction treatment. Grain yield varied by 13% between tillage treatments in the years 2004 to 2008, with conventional and deep plough conditions generally the highest yielding and zero tillage the lowest (Newton et al., 2011).

4.7.2. Earthworms

In terms of anecic earthworms, tillage intensity was a highly significant factor ($p < 0.001$) with zero tillage associated with 8 – 17 *Aporrectodea longa* per m^2 in comparison to their being uncommon (<1 per m^2) in the tillage treatments. No *Lumbricus terrestris* earthworms were found. In terms of epigeic and endogeic earthworms, tillage had a highly significant effect ($p < 0.001$) with zero tillage associated with 1.6 – 3.2 times more endogeic earthworm biomass than any of the tilled treatments. Furthermore, tillage intensity had a significant impact ($p < 0.05$) on endogeic earthworm numbers, with the smallest populations associated with compacted soils. These results suggest that long term spring tillage and cropping are detrimental to earthworm populations, particularly anecic earthworms which were largely absent from this field.

4.8. NIAB trials at Morley (NFS) and Otley (STAR)

We have tested the effect of reducing tillage on soil organic matter, structure and yield in experiments at Rothamsted and elsewhere and for longer periods of time NIAB have examined the effects of tillage on yield and on profitability (Morris et al., 2014 ; Stobart et al., 2017). For STAR, significant differences were apparent in some seasons, but across seasons wheat yield did not differ significantly with tillage practice. For NFS, significant yield differences with respect to tillage were apparent across seasons, with the lowest yields being associated with shallow non-inversion tillage. Hallett *et al*. (2014) have identified, at all sites, pans under shallow non-inversion tillage that will limit root growth, potentially impacting on crop performance. Margins (£ ha^{-1} based on STAR and NFS prices and practices from Morris *et al*. (2014)) indicate that the highest STAR and NFS margins have been associated with the deep non-inversion systems.

Findings suggest only small percentage yield reductions with shallow tillage (*cf*. plough systems). Over seasons, these reductions were not significant at STAR (heavy soil), but were significant at NFS (medium soil). On both sites, deep non-inversion tillage tended to give higher margins and would result in faster working speeds (*cf*. plough systems). Full details of these trials are available in the final report of AHDB project RD-2012-3876 (AHDB Project report PR574).

4.9. AFBI

4.9.1. Crop yield

Yields in 2013, the only year of application of the various materials at Hillsborough, from amended and unamended plots did not differ significantly (10.5 to 11.2 t/ha at 15% moisture content here and in all references to yields below), provided the crop also received mineral N. N applied either as organic manure or as urea or inorganic fertiliser was the over-riding determinant of yield, the lack of P or K in the urea or inorganic N treatments did not affect yields. Yields in subsequent years when amendments were withheld on some plots ,also did not differ significantly except where fertiliser N was also withheld.

Yield at Downpatrick in 2013, was largely, but not wholly, related to the provision of N either as broiler litter and/or as inorganic fertiliser (yield increasing by 15 kg per kg available N, irrespective of material; R^2 = 85%). Adding in yields and the available N provided in 2014, strengthened the response to available N so that yield increased by 18 kg per kg available N (R^2 = 91%). The trial was in maize in 2015 and so yields were not determined.

Yield at Crossnacreevy in 2014, the first year of the experiment, was less strongly related to the N provided, varying between 4.4 and 5.2 t/ha where N available varied between 166 kg/ha from the pig slurry, 87-88 kg/ha from the cattle slurry and digestate and 50 kg/ha as inorganic. An additional 90 kg/ha inorganic N applied as a top-dressing had no effect. The control yielded 2.6 t/ha without and 2.9 t/ha with the topdressing. Yields were not determined in 2015 because the barley sown in the spring failed to establish and wet winter weather prevented whole-crop harvesting of the barley sown in the summer.

4.9.2. Soil analysis

Soil analyses were usually conducted annually and the pattern of responses varied amongst the three trials/experiment. At Hillsborough, most nutrients and related characters (OM, total soil N, total Soil C) showed decreases or little or no change following application of the organic manures over the period 2014 to 2016, whilst the urea, inorganic N and control tended to show increases, the main exception being Mg which increased following all treatments at both 0-15 and 15-30 cm depths.

At Downpatrick, only pH and P increased over the period 2013 to 2016, K, Mg and S decreasing by over 40% relative to their values in 2013. Soil OM, total C and total N decreased by up to 20% relative to their initial values in 2013 in almost all treatments. The most notable exception was where broiler litter treatment which received no additional fertiliser in any year showed the biggest increase in P in both soil depths over the period. Otherwise, P increased more and other parameters showed smaller deceases where broiler litter was applied either with or without additional fertiliser than where inorganic fertiliser or no fertiliser was applied.

At Crossnacreevy, soil OM, total C and total N showed little change between 2014 and 2016, despite no crop material being removed during 2015 to 2016. P, K and S increased at 0-15 cm and K decreased at 15-30 cm. The organic materials, cattle and pig slurries and digestate, displayed quite different patterns of change for P, K and S over the period.

4.9.3. **Earthworms**

Earthworm numbers increased in response to nutrient input but also varied with nutrient source, season and method of cultivation which makes an overall comparison difficult. Biomass of earthworms recovered at Hillsborough was approximately 5x that at Crossnacreevy, most likely due to minimum tillage at Hillsborough cf. ploughing at Crossnacreevy. A predominance of endogeic species at Crossnacreevy but anecic *L. terrestris* at Hillsborough supports this.

Generally, the organic materials tended to increase earthworm numbers and biomass more than the inorganic fertilisers. The effect of fertiliser input was greatest within season. At Crossnacreevy, the fertiliser application from the previous year did not benefit earthworm biomass the following year; whilst at Hillsborough, differences between treatments lessened with each successive year, although earthworm numbers increased overall, perhaps caused by a residual effect.

At Crossnacreevy in 2014, earthworm biomass increased most following pig slurry (p-0.027), but in 2015 the dairy and digestate treatments had a greater effect than the pig slurry, inorganic fertiliser or control treatments, largely agreeing with what was found in the long-term grassland slurry experiment, where earthworm biomass increased substantially in cattle slurry treated plots (Murchie et al. 2015).

At Hillsborough, hen manure had the greatest impact on earthworm numbers, with evidence of a residual treatment effect in year 3. Earthworm numbers were initially reduced by pig slurry application, dead earthworms having been seen on the soil surface shortly after application, but by the autumn earthworm populations had recovered. Application of organic manures to cereals increased earthworm populations but the benefits are likely to be subsumed by the effects of cultivation. Hillsborough soil had a substantially greater maximum earthworm biomass (93±21 g m^{-2}) than Crossnacreevy soil (16±1.9 g m^{-2}), probably because it was min-tilled. What is most striking about the Hillsborough experiment was the substantial increase in *L. terrestris*. Anecic species, in particular *L. terrestris*, which have vertical burrows, are highly vulnerable to predation by the New Zealand flatworm, *Arthurdendyus triangulatus*. In a field-based study in Northern Ireland, flatworms reduced *L. terrestris* biomass in plots by 75% (Murchie and Gordon, 2013). Large-scale control of *A. triangulatus* is not feasible. However, agronomic techniques that enhance *L. terrestris* populations could be a good way of mitigating against the damage caused by this invasive pest.

4.9.4. Nutrient supply

Availability of nutrients to the following crop (legacy effect) was generally low, as anticipated by RB209 and in Teagasc guidance about organic manures. However, in a few cases, recovery by the following crop was poorer where materials had been applied in the previous year when compared with the control (nil OM + nil fertiliser N) treatment. This suggests that nutrients supplied in the amendments were being locked up in the soil becoming unavailable to the crops. These effects were not observed where either organic or inorganic nutrients were provided but it is not known if this simply because they were masked or because they were counteracted in some way.

Where additional inorganic fertiliser was a treatment, crop yield and recovery of nutrients was enhanced. This suggests that losses and/or lock-up of nutrients provided by organic materials needs to be, and can be, counteracted by use of inorganic N in particular, to encourage growth of and scavenging by roots to ensure adequate access to nutrients where organic materials have been applied. The treatments included in these farm trials and experiment were not designed to determine how inorganic N can be used to catalyse utilisation of organic material nutrients. Therefore, it has not been possible to develop guidelines for best practice using these results.

Guidance provided on use of organic manures states that their nutrient content must be taken into account when making decisions on how much inorganic fertiliser to apply. Whilst this is ideal and encourages responsible use of both sources of nutrients, results in this project show that the approximations used in the currently complex guidance are still not sufficiently comprehensive to cover all the dynamics of nutrients in the materials applied and in the soil over time as crops grow.

4.10. Earthworm pot experiments

Earthworms benefit agriculture by providing several ecosystem services. Therefore, strategies to increase earthworm abundance and activity in agricultural soils should be identified, and encouraged. *Lumbricus terrestris* earthworms primarily feed on organic inputs to soils but it is not known which organic amendments are the most effective for increasing earthworm populations. We conducted earthworm surveys in the field and carried out experiments in single-earthworm microcosms to determine the optimum food source for increasing earthworm biomass using a range of crop residues and organic wastes available to agriculture. We found that although farmyard manure increased earthworm populations more than cereal straw in the field, straw increased earthworm biomass more than manures when milled and applied to microcosms. Earthworm growth rates were positively correlated with the calorific value of the amendment and straw had a much higher calorific value than farmyard manure, greenwaste compost, or anaerobic digestate. Reducing the particle size of straw by milling to < 3 mm made the energy in the straw more accessible to earthworms

A comparison was made with the amounts of carbon, energy and cellulose contained within amendments and the growth of *Lumbricus terrestris* earthworms at 15^{o}C in 1 L microcosms for 12 weeks. Residual degrees of freedom is 63 in all cases.

Table 4.10.1. Earthworm growth in relation to ther total C, cellulose or energy content of added organic amendments

Amendment	Carbon added	Cellulose Added	Energy added
Variance Ratio with Earthworm growth	122.55 P<0.001	368.89 P<0.001	215.83 P<0.001

All three measures of the value of amendments, total C, cellulose or energy thus explain the variation in earthworm growth well (Table 4.10.1). The fact that cellulose content of the amendments appears to be better than the other metrics at explaining the increase in earthworm biomass may help to explain partially and slightly puzzling results (Bhogal et al., 2010) and anecdotal reports in practice that paper crumble is good agent for improving soil quality. Earthworms which are thought to be an excellent indicator of soil health appear to respond better to the addition of cellulose, in which paper crumble is rich, rather than other components tested here. Thus, if already abundant, earthworms may improve soil structure as a result of increased activity derived from the cellulose in paper crumble. If earthworms are not already abundant, improvements in structure would not be expected because the worms will take one or two years to multiply and will require nutrients as well as the energy present in the paper crumble to grow in numbers.

4.10.1. **Fungicides and earthworm growth**

Certain fungicides and other agro-chemicals are thought to reduce the growth of earthworms. It therefore seems possible that soil organisms, including earthworms, are better able to make use of straw and other crop residues when fungicides are absent. Accordingly, we hypothesised that earthworms growing from straw supplied as a substrate would grow better on fungicide-free straw.

Earthworm biomass and growth over time on the plots receiving straw without fungicides were significantly greater than the corresponding biomass in pots receiving fungicide-treated straw (Table 4.10.2). Rate in the above table refers to rate of addition of OM (0 – 2 g per pot per fortnight).

Table 4.10.2. Wald tests for fixed effects comparing the growth of earthworms fed either straw from crops treated or not treated with fungicides.

Sequentially adding terms to fixed model:

Fixed term	Wald statistic	d.f.	Wald/d.f.	chi pr
Straw	123.90	1	123.90	<**0.001**
rate	42.44	4	10.61	<**0.001**
Straw.Fungicide	12.56	1	12.56	<**0.001**
Straw.rate	0.00	0	*	*
Straw.Fungicide.rate	3.51	4	0.88	0.477

4.11. Growers' network

The growers' network was conceived as a way of evaluating the ideas behind our research in practice and take in a range of soil types. With funding from the Waitrose Agronomy group, a number of growers and other suppliers led and managed by ProduceWorld (PW) were identified who agreed to take amendments and evaluate yields in a simple fashion on a variety of soil types. A protocol was devised to support the experiments and the project team met with the suppliers several times in the early years of the project. The experimental work within the growers' network was run by in-kind contributions. Thus, the growers carried out their work without financial support from AHDB and PW helped to obtain and supply amendments including compost from Organic Recycling Ltd. and anaerobic digestate from Staples Vegetables Ltd. These materials were used in both grower trials and the small plot trials held at Rothamsted Research. Unfortunately, commercial decisions on prioritisation of activities resulted in much of this work being discontinued and thus there are few results to report. The engagement with industry provided insight into the feasibility and appropriateness of small plot trial activities as well as a platform for wider industry KE.

Results in 2016 are available from Gedgrave, near Woodridge in Suffolk. AD was applied at 3 and 15 t ha^{-1}, compost, duck and pig manure were applied at 5 and 30 t ha^{-1} and straw was applied at rates of 1 and 5 t ha^{-1}. There were two replicate plots of each treatment/rate combination and four control plots with no addition. Yields of rye were significantly increased (4.9%) in 2016 by two years of these amendments applied in 2014 and 2015 as opposed to the control, but there were no individually significant effects due to rate or kind of amendment (Figure 4.11.1). Similar yield increases (7%) were found in previous HGCA funded trials (Wallace and Carter, 2007). There were no differences in worm biomass, worm numbers, soil organic carbon and no differences in bulk density in any of the treatments at this site.

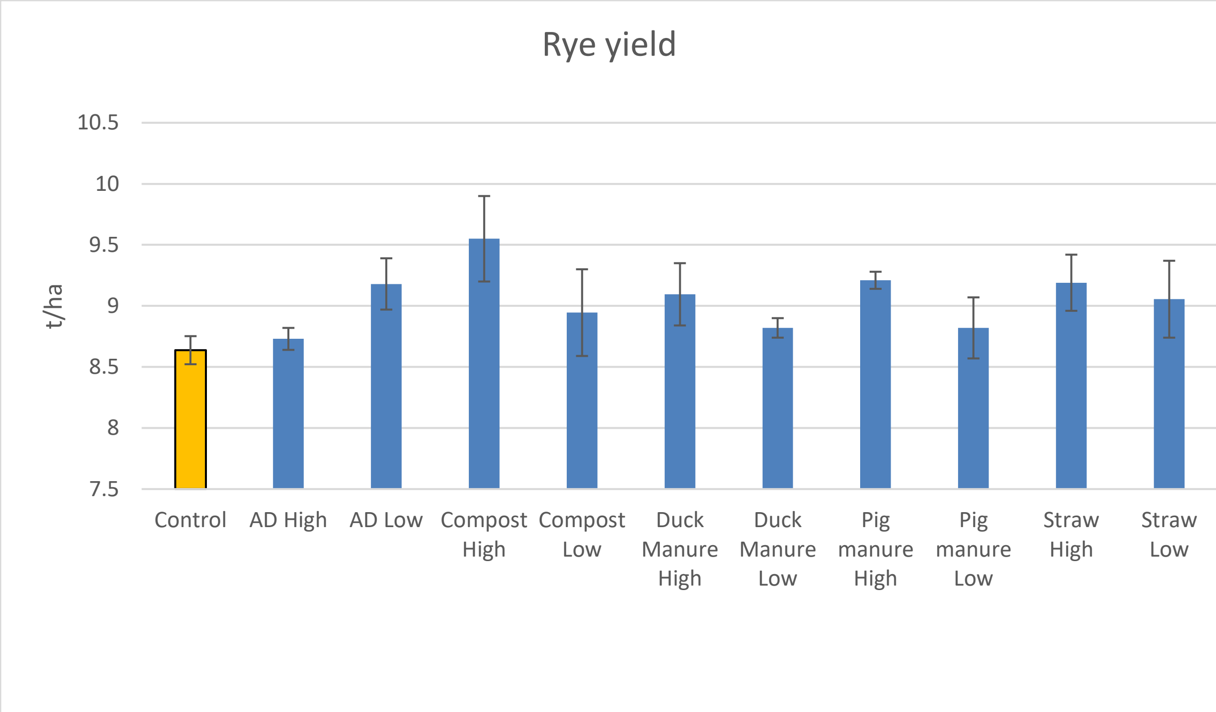

Figure 4.11.1. Yields of Rye in 2016 at the Woodbridge site. High and low refer to the rates of application.

4.12. **European survey**

The following is a brief abstract from an article published in the journal Plant and Soil (Hijbeek et al., 2016) for which response to N with and without organic amendments were calculated on data from 20 long-term experiments in Europe supplying 107 year-site-crop-amendment combinations. More information and data is available online (Hijbeek et al., 2016. doi:10.1007/s11104-016-3031-x)

“A meta-analysis was performed using data from 20 long-term experiments in Europe. Maxima of yield response curves to nitrogen were compared, with and without organic inputs, under abundant P and K supply.

We were surprised to find that, across all experiments, the mean additional yield effect of organic inputs was not significant - 1.4 % ± 1.6 (95 % confidence interval)). In specific cases however, especially for root and tuber crops, spring sown cereals, or for very sandy soils or wet climates, organic inputs did increase attainable yields. A significant correlation was found between increase in attainable yields and increase in soil organic matter content”.

4.13. **Draught forces**

4.13.1. **Fosters**

With our plough draught implement, we were able to plough Fosters field three times in the autumns of 2013, 2014 and 2015 after the 1st 2nd and 3rd crops in the rotations. Unfortunately, the sensor pins were found to be damaged in 2016 and could not be replaced in time before the crop was drilled for the follow-on SARIC-funded project on the residual effects of organic matter (BYOSOLID), the establishment of which was judged to take priority over the plough-draught work. Measurements were made of the soil water content from each plot at the same time as ploughing and measurements were made of the texture on half of the plots in 2015. We assumed that texture will not change but that water content will and is important to know as water content will affect the mass of soil that must be turned by the plough. However, water content was not found to have any influence as a covariate on the statistical analysis, but texture was.

Plough draught did not differ across blocks once the spatial covariate was taken into account but did differ significantly across rotation in all 3 years ($p<0001$)). Although this might not be surprising given the different crops, it appears likely that the background soil condition in the field is variable, because the draught forces were very different in one of the cropped blocks from the other three. Texture was measured on soil taken from a sub-set of plots in the experiment in 2015 and although differences in texture were small they were significantly related to draught forces in conjunction with rotation (interaction rotation.Clay with draught in 2014 $p>0.02$). In the analysis of variance, however, silt content consistently increased the significance of other effects when it was included as a co-variate and so has been preferred in what follows.

In 2013, the two rotation halves were ploughed at different times and we were also unable to measure depth of ploughing; together these features make the data from this first year less reliable than the subsequent years' ploughing. These limitations were avoided or corrected in 2014 and so the data from 2014 and 2015 are more reliable.

Taking 2015 as an example (Table 4.13.1), differences between OM at different rates are significant ($p<0.001$). As observed above this also differs across rotation ($p=0.025$). Draught forces declined with amendment in the order Compost+Straw > none > FYM > AD+Straw > FYM+Straw > AD> FYM+Straw > Straw. Linear regression was performed on a restriction of the data to the plots receiving organic matter only in order to ascertain the benefit of amendment. The energy content of the amendments in this regression reduce the specific plough draught by 0.10 kPa per hectare per MJ per kg OM applied ($p=0.01$) or by 5.0 kPa per tonne C applied ha^{-1} (NS, $p=0.077$).

Table 4.13.1. ANOVA terms for plough draught 2015 (Covariate: Silt).

Source of variation	d.f.	(m.v.)	s.s.	m.s.	v.r.	cov.ef.	F pr.
Block stratum							
Covariate	1		261	261			
Block.*Units* stratum							
Rotation	1		21313	21313	129.78	0.96	<**.001**
split	2		4590.9	2295.4	13.98	0.99	<**.001**
Rotation.split	2		3696.8	1848.4	11.25	0.86	<**.001**
split.OM	6		4152.2	692	4.21	0.93	**0.003**
split.omrate	4		1298.3	324.6	1.98	0.88	0.122
split.nom	4		841.1	210.3	1.28	0.94	0.298
split.nrate	5		5019.2	1003.8	6.11	0.97	**<.001**
Rotation.split.OM	6		2785.7	464.3	2.83	0.93	**0.025**
Rotation.split.omrate	4		1024.1	256	1.56	0.75	0.209
split.OM.omrate	17	-1	10865.1	639.1	3.89	0.94	**<.001**
Rotation.split.nom	4		1882.7	470.7	2.87	0.94	**0.039**
Rotation.split.nrate	4	-1	10638.1	2659.5	16.19	0.91	**<.001**
split.nom.nrate	15	-1	3840.5	256	1.56	0.86	0.143
Rotation.split.OM.omrate	4	-14	1320.4	330.1	2.01	0.94	0.117
Rotation.split.nom.nrate	7	-9	2972.1	424.6	2.59	0.97	**0.031**
Covariate	1		331.5	331.5	2.02		0.165
Residual	32	-74	5255.4	164.2		1.03	
Total	119	-100	40942.4				

Split is a factor category comparing the presence/absence of organic amendment

Although there are differences between crops, texture too has an effect. Lower plough draught in 2015 significantly increased yields in 2016 by 11.4 kg per kPa reduction (p=0.022) on average and lower draught in 2014 increased yields by 36.6 kg per kPa reduction (P<0.001) in 2015. Plots not receiving amendment were excluded from these calculations since those also receiving little N yielded poorly for obvious reasons. These reductions in draught are clearly variable but are in the range of 10-20%. This is likely to translate into a fuel saving of the order of 2-3 l ha^{-1} or £1-2 ha^{-1}. If the benefits persist for longer than the year of amendment these savings might be doubled or tripled but are clearly not large.

The implement developed here is able to detect changes in draught forces but these are sensitive to other factor such as texture too. The implement is somewhat fragile and not suitable for widespread deployment. Robust instruments (Scholz,1966) are probably too cumbersome for routine use. Research on the ways in which fuel consumption changes with tillage might overcome both issues.

4.13.2. Great Knott III

Plough draught was also assessed on the Great Knot III experiment that tested the effect of pre-treating straw on earthworm growth and yield. We hypothesised that it would be possible to detect changes in soil condition that were associated with changes in yield. Quite severe pre-existing soil compaction was detected instead. The experimental plots were arranged in two parallel rows in the field (X coordinates 1-2, Y coordinates 1-14). Plough draught was very significantly related to Y but not X ($P<0.001$). The issues are present in the last two plots in each of the two rows (plots 13,14 and 27, 28). These affect the treatment structure such that it is difficult to be confident of the experimental results. Neither Y nor S as a covariate was found to be helpful in re-analysing the experiment to test the hypothesis that pre-treatment of straw could increase yields by increasing the activity of the soil organisms. However, the draught implement proved itself highly successful at detecting compaction in the field that the Rothamsted farm staff were unaware of. Otherwise they would not have allocated us the site.

The deployment of the draught implement may be considered a success in terms of its ability to detect prior compaction and to pick up small differences in texture. These are the major properties of soil to which it responds. The detection of compaction might be extremely helpful to growers and the draught forces seem to be surprisingly sensitive to texture. Given that texture does not change, all other things being equal, it becomes possible to see the changes in draught that can be attributed to amending soil with organic matter. As a means to determine absolute values of soil organic matter the implement may have limited use. As a means to detect unexpected compaction or variations in texture or changes with SOM with time, it may have more promise. Because this implement is fragile and because previous implements are unwieldy, the path to exploitation may be to use our implement to calibrate outputs from the tractor control system and data acquisition on fuel consumption as well as power take-off.

4.14. **Modelling the response to organic amendment**

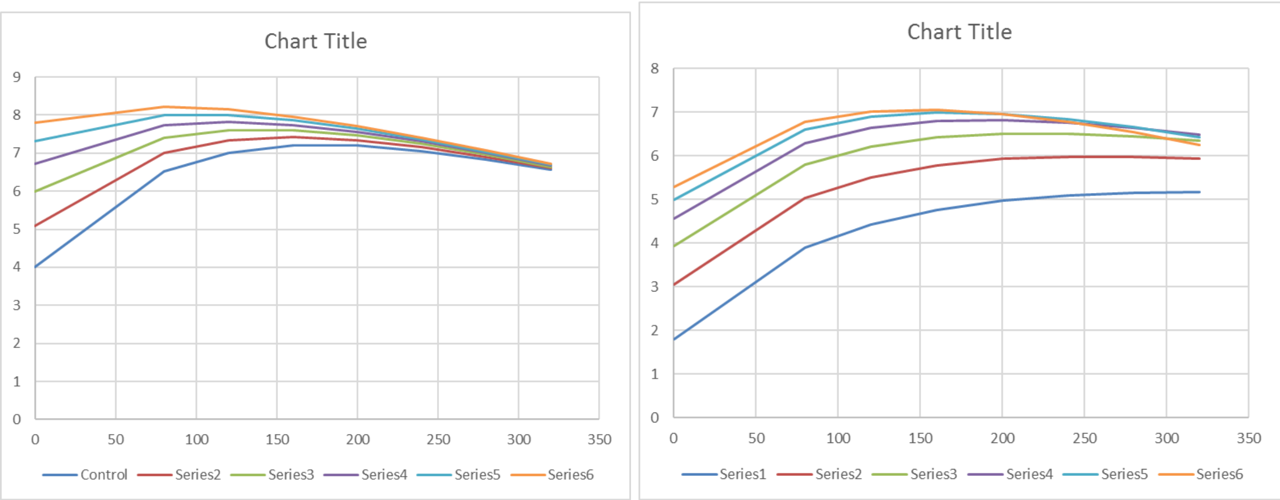

Figure 4.14.1. Test of curves of the response to N at different rates of organic amendment using (a) Eq. [1b] and (b) Eq. [2b] (Section 3.8). In both cases increasing series number is associated with increasing levels of amendment i.e. *O* in Eqs [1b] and [2b]

Figure 4.14.1 plots responses calculated with Eq [1b] and [2b] and the increasing effect on yield of hypothetically increasing levels of organic matter input can be seen relative to a control in both cases. Neither form is completely appropriate however. Compare with Figs. 4.1.1 to 4.1.4, for example. It is likely that an interaction of some kind exists between the N and the OM applied as in [1b]. Although this is a reasonable supposition, the Fosters and New Zealand experiments were not designed to test such an interaction and results from both experiments do not support the existence of an interaction in so far as the data be may be interpreted. Eq [2b] is preferred because of the tendency with Eq [1b] for the model to fit to lower and lower levels of application of N with increasing applications of OM. This extreme (to which [1b] tends) is unreasonable and consequently [2b] fits the available data better. Eq [2b] has problems too. It is quite likely that Yopt does shift to the left sufficiently with applied OM: partly because of the N in the amendment, partly because of the increase in native fertility with continued application and partly because of the other effects hypothesised in this project: that OM enables roots to acquire nutrients and water more easily because of better structure. It may be possible to test interactions more closely in the ongoing SARIC project. In the current study [2b] is used to compute trends in Yopt in relation to applications of both N and amendment. This means that yield optima in relation to OM and to N are independent and can be calculated as follows where Copt is the optima rate of application of OM expressed as its carbon content and where ß1 and ß2 are the break-even ratios for applying N and OM, taken here as 0.003 as before and 0, respectively.

$$Nopt = \frac{\ln((-ß1 - C1)/(B1 * \ln(r1)))}{\ln(r1)} \quad \text{3a}$$

$$Copt = \frac{\ln((-ß2 - C2)/(B2 * \ln(r2)))}{\ln(r2)} \quad \text{3b}$$

4.15. **Economics**

Table 4.15.1. Economics of applying amendments.

	AD	Compost	FYM	Straw	units
Optimum annual rate of application[1]	2.1	2.1	2.1	2.1	C t/ha
OM C content[2]	0.32	0.20	0.33	0.46	
OM dry matter[2]	0.43	0.25	0.22	0.80	
Fresh matter needed	15.3	42.0	29.1	5.8	t/ha
Price per tonne	6.0	6.0	2.0	2.0	£/t
Cost acquisition (and spreading)	90	249	58	12	£/ha
Spreading[3]			50	50	£
Price N Fertiliser per kg	0.5	0.5	0.5	0.5	£
N value amendment assuming 50% available	28	19	38	8	£/ha
During foursubsequent years[4]	9	6	13	3	£/ha
sum N value[5]	37	25	51	10	£/ha
Assuming four years of application					
Sand[6]	**670**	**-30**	**669**	**662**	£/ha
Silt[6]	**541**	**-159**	**540**	**532**	£/ha
Clay[6]	**282**	**-418**	**281**	**273**	£/ha

[1]Based on the WOM data (section 3.1.1.3). On Fosters there was no clear maximum rate

[2]From chemical analyses

[3]Spreading is included in acquisition of AD & Compost. FYM and Straw are assumed to be obtained informally and therefore the cost of spreading must be borne. An arbitrary cost of £2 per tonne is assumed. In practice, this may in fact be zero or in-kind

[4]Supply of N in years subsequent to application taken to be 1/3 of that in the first year

[5]Value of P not included. Likely to be about £5-10

[6]Difference in benefits to texture taken from Hijbeek at al., (2016). No significant differences were found in our pot experiments. The silt soil is equivalent to the Fosters site and so this value might be more appropriate to UK generally if the differences found by Hijbeek et al. for the European continental climates do not apply here.

Plough draught is reckoned to improve by 10% for the duration of the benefits - £1.25 ha^{-1}.

Data on the costs of acquiring amendments are difficult to come by. Within the current research, it was generally the price of haulage that determined the price that we paid for relatively small amounts of material. The price in Table 4.15.1 of £6 t^{-1} applied is based on the delivery of large amounts (10, 000 tonnes). Pricing may be subject to individual negotiation and so a firm price is difficult to come by. A recurring view was that the cost of the amendment should reflect that value of the nutrients contained (mainly N and P). On this basis, the (admittedly anecdotal) costs of around £5-6 t^{-1} would seem realistic.

Based on the above data, the calculations in the last three rows are as follows:

(£g+£s+£p)*(Yr_app+Yr_dur)+£N*Yr_app+£N*sum(Yr_dur)/3- £app*Yr_app

Where £g is the value of the extra grain, £s is the value of the extra straw, £p is the saving in fuel through plough draught reduction, Yr_app is the number of years of application (4) and Yr_dur is the number of years the benefit persists after application (4), £N is value of the N available in the amendment in the year of application and sum (Yr_dur) combines all the separate benefits from multiple years of application and £app is the cost of acquiring and spreading the specified amount of amendment. The end result is scaled by a factor derived from Hijbeek et al. (2016) for texture.

Table 4.15.1 calculates the value of amendments including both N (but not P) and yield benefits. It makes a number of assumptions on the basis of the analysis of amendments made in this research, the increases in productivity of crops, the number of years of application that might be needed for such increases to be seen and the number of years such increases might be expected to continue after application ceases. However, the duration of the application changes the magnitude of the profit or loss but not the break-even point of whether an amendment is profitable or not.

Haulage appears to be the main determinant of whether the use of these materials is economic or not at least over the timescales and assumptions considered. All materials apart from compost appear economic to apply (but see below). Haulage costs have not been applied to FYM and straw on the assumption that a farmer will already have these materials or be able to source them locally rather than from a business whose focus is supplying these materials. The reason why compost does not appear economic in this research is because a large part of the material transported is not active. If compost were drier (it is 80% water in our analyses) it would be more economic to transport and apply. The AD we sourced contained much less water and much more carbon. Since carbon is the measure by which we have judged the efficaciousness of the materials, AD scores well. Clearly a different water or chemical analysis would give a different result. We suggest above (Figure 4.1.33, section 4.1.5) that carbon content may not be the most reliable guide to changes in structure, but that a quality parameter such as energy or cellulose content might sometimes better explain the effect of amendments on yield or soil. Compost also contains somewhat less cellulose than the other materials and thus would still score badly. On the other hand, the compost may have an effect for longer if it decomposes more slowly than the other materials. These questions remain to be answered, but as a rule of thumb the break-even point (as far as the yield increases in this project are concerned) is likely to be a cost of acquiring and spreading amendments at a price of about £100 t^{-1} dry C ha^{-1} and ideally substantially less (say £50 t^{-1} C), in order to return a worthwhile profit.

These calculations do not include any consideration of the amelioration of Take-All in 2nd or 3rd wheats nor any change in value attributed as to increases in TGW. In computer simulations, trafficability increased with amendment. A rough rule of thumb would be 1 d extra access to land for 1 t C ha^{-1} applied $year^{-1}$. This benefit has also not been included in the economic analysis presented in Table 4.15.1

5. Discussion

5.1. Yield

The amount of nitrogen yielding the optimum amount of grain at a break-even ratio of roughly 3:1 decreased in trials with organic amendments. The amount of grain produced generally increased, varied with crop but was of the order of 10% more. It took at least two consecutive years of application before the increases became statistically significant, but it also appears that benefits continue (at a reduced level) for at least two and perhaps as many as five years after applications cease. The carbon content, or perhaps energy or cellulose content, is a better guide to the magnitude of these benefits than total mass or even dry matter of the amendments. In some older experiments, there appeared to be an optimum rate of amendment equivalent to just over 2 t C ha^{-1} $year^{-1}$. However, this is assuming no cost of acquisition (BER=0) and it was apparent that the maximum was greater in new trials (2002 on, 6 t C ha^{-1}) than in older trials (1965-72, 1978-1984, 1 t C ha^{-1}). Modern varieties may be able to exploit the change in the root environment afforded by the use of organic amendments better than older varieties. Nitrogen content of grain was unaffected by amendment but thousand grain weight and oil concentration (osr) increased slightly. Oil content increased to the extent that it might attract an additional premium (45 to 48%).

There was some indication that sandy soils benefit more than clay-rich soils but that benefits persist longer in clay soils. Amending soils where the crops were established with reduced tillage also led to increases of yield but of a smaller magnitude. It seems likely that benefits of amending soil and of reducing the tillage are similar and perhaps operate at least partly by means of the same mechanism – improving structure in the surface of the soil where the crop germinates and establishes.

5.2. Microbiology

5.2.1. Fosters

Whilst there was a limited range of subtle and idiosyncratic effects of organic matter additions upon soil microbial parameters, the overarching finding in the Fosters study was that total microbial biomass was not affected by the addition of organic matter at any of the rates applied. However, there was a significant effect of rotation type upon microbial biomass, where biomass was apparently increased or decreased according to the rotational context as others have found (e.g. Gregory et al., 2007). The experimental design was not formulated to be able to identify specific effects in relation to such contexts, since this would require appropriate replication of these circumstances. This phenomenon was also apparent in relation to the phenotypic community structure of the soil microbes in the early stages of the study, but significant shifts in such structure in relation to organic matter started to be manifest in the later phases. Here, organic matter additions resulted in community shifts compared to the controls from spring 2015 (2 years after onset), but were not sensitive to organic matter type or application rate, and by spring 2016 coherent shifts in relation to application rate were emerging. Fungal biomass showed considerable but highly idiosyncratic variation across the experiment such that no coherent trends could be identified. Overall these results suggest that the microbial communities in the Fosters field were more sensitive to (specific) plant-related factors than to OM additions. We postulate that this could be underpinned by plant-derived carbon inputs in terms of gross amounts of available energy (i.e. a food source) and more subtle effects arising from the deposition of specific compounds. The other key finding is that apparently the effects of OM addition require time to be manifest, and here beyond the duration of this study. The overall insensitivity of the microbial communities to management interventions postulated to lead to a stimulation in Fosters could also suggest that the soil system here is actually compromised to such an extent that the biota are not in a state that makes them particularly capable of responding to such inputs. One arena where recovery is dependent on crossing abiotic and biotic barriers is restoration ecology; here, unless abiotic conditions are met, it is difficult to manage the biotic components to recovery (Hobbs and Harris, 2001). With constant cultivation, there may be little opportunity for suitable abiotic conditions to be established, permitting the re-establishment of an appropriate biotic community.

5.2.2. New Zealand

In New Zealand field, OM applications (irrespective of type or rate) generally increased microbial biomass, but not at all sampling times or in a notably consistent manner. There were additional interactions whereby mineral N increased microbial biomass, but again effects were not consistent - in some instances, mineral N increased biomass while in others there was no effect, with no obvious single interactive factor. Furthermore, such increases were only significant where organic matter was applied as there was no effect of mineral N where no OM was applied. The microbial community structure showed considerable temporal variation, but beyond this, significant interactions with OM rate and mineral N application were also manifest. Compost specifically had a notable effect upon microbial community structure, in terms of the overall structure (apparent via principal components), but specifically with respect to increasing the proportion of the indicator fatty acid relating to mycorrhizal fungi. Total fungal biomass showed considerable and highly idiosyncratic variation over time, and no relation to any treatment. The overarching conclusion from the New Zealand study is that OM addition of any form or rate increased microbial biomass by on average 22%, but with no significant further or cumulative increase over time. Microbial community structure was more consistently affected by rate, over and above significant temporal variation.

5.2.3. **Comparison of microbiology of New Zealand and Fosters**

Both total microbial and fungal (ergosterol) biomass were greater in the New Zealand experiment compared to Fosters (across all sampling times and treatments). The overall mean microbial biomass in the New Zealand experiment was 466 µg C/g (± SE 12) compared to 182 µg C/g (± SE 2) in the Fosters experiment. For fungal biomass, the overall mean in the New Zealand experiment was 7.3 µg ergosterol/g (± SE 0.5), compared to 3.3 µg ergosterol/g (± SE 0.1) in the Fosters experiment. In addition, although temporal variation was greater, there is an indication (Appendix XI) that microbial community composition was different between trials as PC1 separates the PLFA profiles of the New Zealand from the Fosters experiment at each sampling time. These differences between trials are indicative that where the soil is managed through reduced tillage (New Zealand), the microbial community is more responsive than soils under conventional tillage practice (Fosters).

5.3. **Earthworms**

The overarching and unequivocal results from both Fosters and New Zealand experiments were that there was no evidence for notable effects of organic amendments of any form, rate or formulation upon the population sizes, total biomass or biodiversity of earthworms. There were a few, largely idiosyncratic, exceptions which cannot be interpreted in any general sense as being of consequence. Where clear-cut interactions occurred in the New Zealand study, these essentially involved an inhibition of earthworm numbers in the circumstance of what could be construed as excess mineral N. There was however no evidence here for an inherent stimulation of worm populations by organic amendments.

New Zealand supported a greater frequency (38%) and biomass (18%) of earthworms than Fosters. This would be expected given the no-till circumstance in New Zealand. Van Groeningen et al. (2014) note that earthworm effects upon plant productivity tend to be variable but can be manifest at *any* frequency, however effects are generally more consistently pronounced at frequencies above 400 individuals m^2. These thresholds were exceeded occasionally in certain plots at certain times, but as the data show, not consistently in either experiment.

The lack of effects of organic matter amendment in both studies is outwardly paradoxical, since the energy inputs involved would be hypothesised to have stimulated worm numbers. However, this phenomenon was also observed for microbial biomass in these studies. This provides evidence that the biotic components of these systems are limited by factors other than basic energy supply. There may be some form of physical bottleneck in these systems, associated with soil structural (architectural?) features.

5.4. General synthesis

On the debate over the value of chemical versus organic fertility Cooke (1967) said 'It causes the needless division into a minority who believe only in "natural organic" farming and avoid fertilizers and the majority who recognise the use of fertilizers, but who often ignore the soil biology.' The same author also stresses earlier work by Jacks (1963) whose view was not only that organic manuring supplied nutrients but that the soil organisms derived the energy they needed to organise and structure the soil in such a way as to benefit all soil-dwelling organisms. Our reliance on the ease with which we can farm with chemical fertilisers has contributed to a tendency to forget the role of fresh organic amendments in supplying energy and given that they are much richer in energy than native soil organic matter, the stimulus they give to improving soil structure via the actions of soil organisms. This earlier work sought to clear up confusion about the benefits of amendments, arguing that still earlier work had not supplied enough mineral N (or other nutrients). When a full response curve to applied N is obtained and sufficient N is given, Cooke argued, the apparent benefits of manure disappeared. Later work (Jenkinson and Johnston, 1976) supports this view but noted a dramatic increase in the amount of straw produced on plots that had long received applications of FYM. It is only since 1976 that increases in grain yield have been seen on these FYM plots relative to plots receiving mineral N only (Min). Johnston et al (2009) document this change with yields from four varieties sown between 1968 and 2007. This implies that the conditions in the FYM plots allow the plants to disproportionately (relative to Min) exploit the changes in harvest index after 1975 that result from new varieties or the use of growth regulating chemicals. Thus to be clear: early data implied a benefit of manure but careful experimentation confirmed that crops receiving the same amounts of mineral N from whatever source, tended to yield similarly. Our research suggests that the response to applied N changes where FYM is applied and that crucially the potential yield response increases as a result. This has been amplified by breeding in favour of varieties that allocate more photosynthate to grain rather than straw. Since the fields were managed according to standard farm practice, other nutrients are not likely to be limiting, so it is hard to attribute this change in the response of crops to N in the presence of manure to any fertiliser effect of the manure. The improvement in penetration resistance with amendment on Great Knott and the increase in soil organisms in some soils on some occasions point to an improvement in structure and reduction in density but the precise mechanism whereby these benefits affect the response curve remains to be elucidated. These may be: the additional P, S or micronutrients in the amendments, take-up of organic N, even distribution through soil, availability of nutrients all winter or better establishment.

Across rotations, yields increase with amendment and perhaps with some parameter of the quality of the amendment. Pore structure improves in the silt size range with energy of amendment while earthworms grow better in pots in relation to the cellulose or energy content of the amendment. Plough draught forces are reduced by amendments again in relation to the energy content. Spring sown crops may benefit more than winter sown and these benefits have been greater in the drier parts of continental Europe. Amended soils have strikingly high levels of P. All soils have more than satisfactory levels of available P so that excess levels should not matter. Nonetheless, we cannot rule out the idea that surplus P is a factor in improving crops yields. There is no clear mechanism by which additional P might improve structure, however.

Organic matter amendments are not a miracle cure-all. Where other issues such as compaction are present, these other factors almost certainly need to be addressed before amending soil can be expected to have any benefit (Hobbs and Harris, 2001). This is especially so if feeding soil organisms are the mechanism by which amendments have their benefit. Few organisms can overcome compaction quickly; these are mostly (trees, moles) unwelcome in agriculture.

Structural details such as the number of pores and their total perimeter increased, and the average length of the largest dimensions of pores (ferret: down to silt size) declined significantly with the amount of energy of amendment, compared to without, as measured by Computer-assisted Tomography (CT) scans of soil. These results are consistent with the presence of more small pores within the range measured of the amended soils. No consistent change was found in the bulk density of the same soils, however. Exactly what this means is unclear and there were large differences between experimental blocks which may be the result of pre-existing soil condition and which may influence the results.

In contrast to the main trials on Fosters and New Zealand fields, adding very large amounts of straw to soil and staging the applications four times per year in the Great Knott III field at rates which were rather more than in the main experiments (8 t C ha^{-1}), decreased mechanical impedance (penetrometer measurements) and increased earthworm numbers. These findings are in agreement with our initial hypotheses. However, yield was depressed on these plots by the very treatment that fed the earthworms, possibly as a result of the increase in pests such as slugs. Given that some of the plots on which this effect was found appeared to suffer from prior compaction, we can have a reasonable degree of confidence that soil organisms – earthworms in particular - do respond to amending soil, despite the lack of convincing evidence in the main Fosters trial.

Amending soil is worthwhile provided the amendments can be acquired and spread at a cost of about £50 t C^{-1} ha^{-1} yr^{-1} for at least two years. This assertion is supported by or needs to take account of (i) the increases in yield of grain and straw, (ii) the changes in the quality of the grain, (iii) the reduction in draught forces associated with amending soil, (iv) with the time (number of years of application) needed to see these benefits, (v) the effect of different years of weather on the results, (vi) the cost of acquisition and spreading of amendments and (vii) preliminary estimates of the value of the nutrient supply and the duration of benefit. We provide guidance on the price needed, because costs of acquisition vary depending on quantities of amendment taken, haulage costs (distance from the source) and the quality of the material. Fuller guidance, especially on duration, nutrient benefits and nutrient loss will be reported as part of the SARIC project (BYOSOLID, NE/M016714/1) at the end of 2017.

Experimentation designed to establish the mechanism behind the empirically observed and statistically significant increases in yield as a result of changes in the form of the response of crops to applied N did not produce conclusive results. Yields were expected to increase as a result of improvements to structure. Both yields and structure have been shown to improve in this research but there is little definitive evidence that associates the improvements in structure with the improvements in yield. Nonetheless, yields and structure were both found to improve with amendment. So, if the evidence that the structure causes increases in yield is weak, is there another mechanism that might explain why yields increase with amendment? Because if there is not, we may reasonably attribute the yield increases to the observed structural improvements.

Certainly, the addition of nutrients (chiefly N and P) need to be considered. The response curves measure response to mineral N applied in spring. Amendments supply N throughout the year, so crop response might be different if plants are well supplied at all times. Anecdotally, record yields in the UK in the summer of 2015 were partly attributed to regular feeding of soil with nutrients – especially N. All soils investigated were well supplied with P, but it may be that the regular release of soluble P from the amendments was more available to crops than soil P. If an increase in continuous nutrient supply were the mechanism by which yields increase, losses might also be expected to increase. However, there was no increase in the associated emissions of N_2O from amended compared to unamended plots (unpublished SARIC results) nor was there any significant difference in mineral N in any of the plots sampled between controls and plots receiving amendments.

Using a computer model, it was possible to track the decline in influence of OM on yield once amendment is withheld. Data from Rothamsted (silty clay loam) and Woburn (sandy loam) suggest that benefits decline over 5-7 years but this may be related to the number of years that amendments were previously added. It seems a reasonable rule however, to propose that if soil is amended for at least 5 years and benefits are seen, it will be a further 5 years before the benefits disappear altogether, although a steep decline of 30-50% is likely in the first year the amendments are withheld.

There are reports in the literature of greater resistance to disease in crops growing in soil with amendments or at least greater amounts of soil organic matter – possibly through encouraging the growth of a diversity of organisms some of which are antagonistic soil disease causing organisms or beneficial to a crop in some other way (Zou et al, 2015; Roper et al., 2012). Take-All reduces yield and increases the amount of N needed for maximum yield in the Broadbalk wheat experiment. A metric, GperN, can be calculated which is the amount of grain produced at optimum level of N divided by this amount of N. GperN was not related to take-all rate for any of the series of wheats: 1st 2nd or 3rd on Broadbalk. However, 1st and 3rd GperNs were negatively correlated with measured take-all rates on 1st and 3rd wheats that received mineral N only. Slopes of these relationships were negative and significantly different from zero for 1st and 3rd wheats. This suggests that wheats without FYM were more susceptible to take-all than those receiving FYM. Average levels of GperN on the FYM plots were significantly larger than levels on plots without – they were roughly double. There was no significant difference between the take-all scores on the FYM plots and other plots receiving mineral fertiliser only. This suggests that the FYM did not suppress disease but instead increased the uptake of N from the soil, either by increasing exploration by the root system or supplying more N than would otherwise be the case – or possibly via both mechanisms. These benefits were not investigated experimentally in the current project, although improvements in structure might be expected to benefit the micro-organisms dwelling in the soils.

Results from AFBI suggest that inorganic N is needed in the same season as application of the organic materials if recovery of nutrients from the organic material is to be achieved. Therefore, best practice will include use of both the organic materials and inorganic N.

Reduced tillage was associated with increased earthworm numbers: numbers and biomass were greater on New Zealand field than Fosters at Rothamsted, were greater at Hillsborough in comparison to Crossnacreevy in Northern Ireland and were greater in the reduced and zero till treatments at Mid Pilmore in Scotland. These increases are not always associated with decreases in bulk density and in some cases (New Zealand) there is more organic matter in the surface few cm of the soil as a result of the tillage regime or historical differences in the fields. Greater amounts of organic matter are also likely to be associated with greater numbers and biomass of earthworms. Addition of large amounts of straw to Great Knott III at Rothamsted increased earthworms but decreased yields. Yields on the Mid Pilmore experiment were slightly less under reduced compared with conventional tillage. Infiltration was significantly improved by amendment on the reduced tillage New Zealand field. The increase in organic matter in the surface soils under reduced tillage resulting from the concentration of crop residues in this zone, is very likely to have improved the environment of the germinating seedling.

In summary: amendments can improve yield, soil structure and the mass of soil organisms. We have no direct evidence of association between these factors apart from the fact that they all come about as a result of amending the soil. Taken together, however, improvements in the total mass or perhaps activity of soil organisms would be expected to improve structure which in turn would be expected to improve yield via effects in the rooting environment. Simulation modelling suggests a link between structure (reduction in density) and yield and the only plausible mechanism for this is via the soil organisms, but this is not contained within the model and so cannot be tested, even indirectly. There is no evidence of other mechanisms operating that might improve yield such as better nutrient supply or disease suppression. Where take-all is present, amendments improve yield in relation to N supply but this is likely to come about as a result of better exploitation of available soil N by the plant roots – in other words via improvements in soil structure. It seems unlikely that there is a strong increase in the amounts of nutrients available throughout the growing season and that this could account for improved yields, because increased losses of mobile N would also be expected; this has not been observed to date. Experimentation is continuing that might help to answer these questions. It does seem likely, however, that amending soil improves fertility in the broadest possible sense. It appears economic, depending on acquisition costs and the quality of the amendment, to amend soil and there seems to be little impact on the wider environment, at least over the timescales of amendment considered in this research (four years).

Porosity, plough draught, stability and biological activity may all be improved at the same time. It is possible that these are indicators of some common but unknown link, but this seems unlikely since no candidate mechanism springs to mind. It is possible that the improvements come about via separate mechanisms – additional nutrients and disease suppression improve yields whilst draught, stability and biological activity are improved by the changes in structure. Even if yields do benefit from nutrients it seems unlikely that the other changes would have no effect. It is unwise to multiply up hypotheses unnecessarily and given the consistent observations in this work it seems reasonable to regard the improvements in yield as being partly the result of improvements in structure until evidence arrives to the contrary and to act and advise accordingly. As more information becomes available from ongoing and perhaps new research, advice should be updated.

There were no significant differences in yields from experiments amending a loamy sand, silt clay loam and clay loam soils. The amendments on the Woburn Organic Manuring experiment on a loamy soil increased yields more than would be expected from the nutrients alone. Experiments at Gedgrave in Woodbridge as part of the grower's network also yielded better with amendments compared to without, but no N response curve was made at this site. A series of long-term trials in

Europe found a slight tendency for the additional yield as a result of amending soil and that is over and above any nutrient effect of that amendment, to decline slightly with increasing clay content. Experiments on soil from Saxmundham in this study on a clay soil confirmed the difficulty of getting macro-organisms to thrive and of ensuring that added OM becomes part of the native SOM and so is able to confer structural benefits. In conclusion, amending sandy or silty or silty soils will probably lead to increases in yield in excess of what might be expected from the nutrient content of the amendments. However, earthworm numbers in plots that had received FYM for many years at Saxmundham but on which application stopped were found to be larger in 2014 than without suggesting that organisms and perhaps benefits to yield persist longer in clays soils than lighter land. Although clay soils (>40%) may be less likely to see an immediate benefit, research might be directed to understanding the reasons why macro-organisms do not establish themselves easily in this soil and if this might be one reason why amendments have less benefit to yield.

5.5. Follow on – suggestions for future work

Modern crops appeared better able to exploit the benefits of organic matter amendment than older ones. Breeding and management in cereal production has exploited the use of the dwarfing gene and straw-shortening chemicals to increase the proportion of photosynthate allocated to grain. There are implications for rooting and for plant hormone signalling as a result of these changes but we know very little about the interaction between plant roots and soil that leads to such signalling. **Measure plant hormones, especially cytokinins in sap of plants growing in amended and unamended plots this spring to see if root-shoot signals are responsible for the differing above-ground growth.**

Two rotation sides of the experiment on Fosters field differed in draught forces. It is likely that they are not true replicates. In particular, the Southern block of the Eastern Rotation had a significantly larger specific draught. The southernmost two plots of both strips of our straw incorporation experiment on Great Knott III were similarly afflicted by large draught and appear to have been compacted during previous experimentation. Despite this, decreases in draught forces could be detected in relation to organic matter amendment. Scaling-up of this technology for on-farm use might best be achieved by research to interrogate the on-board tractor control system and develop and calibrate a piece of software using an implement like the frame developed here. Lower draught forces were associated with yield increases in this research. **Work with a tractor engineering company to derive relationships between outputs from the control system and draught forces**

Sow Fosters with contrasting crop lines – probably barley - to test the genetic pre-disposal towards yielding well in amended soils where germination and root exploration is expected to be better than non-amended soils

Maintain Fosters and New Zealand experiments in order to generate better data on the persistence of amendments after application has ceased. Further mathematical development of the models to do this provided by the AHDB Rotations Partnership managed by NIAB-CUF, but no resource is available to maintain these two field trials.

Evidence is presented in this report of a good relationship between the energy content of amendments and improvement in yield response and structure. Little consistent response in the numbers or mass of soil organisms was found. A mechanism consistent with these observations is that it is the activity rather than biomass of soil organisms that is responsible for shaping improvements in structure. Future work should **investigate the role of amendments in increasing activity of soil organisms** and the **relationships between this increase in activity and improvements in yield and structure**

6. Additional activities – KE

Videos

- Sustainable Waitrose http://www.sustainableagriculturewaitrose.org/research/waitrose-sponsored-research/rothamsted-research/andy-whitmore/
- Farm walks HGCA https://www.youtube.com/watch?v=tyxNj1Q1oaw&list=PLN17t0oDGVwVPnYVbZz34D3EEh7xH2JFB&index=1
- BBC shared Planet http://www.bbc.co.uk/programmes/p01jm6nt/p01jm4y0

Knowledge Exchange

- Farm Walk 6 March 2013 *Using organic matter to improve soil structure and crop yield*
- Badger Institute of Agricultural Management, Cambridge 2 December 2014 *Improvement of soil structure and crop yield by adding organic matter to soil*
- Association of Independent Crop Consultants 13 January 2016, Towcester. *Improvement of soil structure and crop yield by adding organic matter to soil*
- Oxford Real Farming conference 6 January 2016. *Building soil organic matter - what we know works*
- Demonstration @ Cereals 2013, 2014
- *Benefits of Soil Organic Matter*. talk at Cereals 2015
- Welsh Arable farmers 18 November 2014 *Does organic matter really matter?*
- Annual Science Meetings, Waitrose Agronomy Group
- NIAB alpha group July 2013
- Morley open day 20 June 2013
- Otley open day 9 July 2013

Articles in Popular Press

- Blake Arable Farming Magazine *A little organic matter goes a long way* September 2016
- Crops magazine July 2014 *What makes a resilient soil?*
- BBC Country file magazine 47-50. Joanna Carter. *What have worms ever done for us?*
- Crops Magazine June 2014 *Active soils function better*
- *Release the X Factor* Crop Production Magazine, October 2015 32-35
- Crop Production Magazine Supplement, Soil Matters, August 2013, *Unearthing Soils Secrets*, 4-6

MSc studentships

Full copies of these theses are available on request from the Cranfield Masters archive.

Grower Science: Soil moisture release characteristic determination by the freezing point depression method *Alexandra Cooke*

The moisture release characteristic (MRC) of a soil provides information about soil physical characteristics such as water-holding capacity and soil architecture. Consequently, it provides useful information to inform irrigation scheduling, soil monitoring, crop performance and effective land management. Traditional methods to obtain the MRC curve are expensive, time-consuming and restricted to a laboratory environment. Consequently, there is a need for a practitioner-level method which can provide equivalent results utilising accurate economical equipment. The freezing point depression (FDP) method enables the MRC to be determined by measuring the freezing temperature of a soil at a particular moisture content. Different FPD methods were explored and the results statistically analysed against each other and against results established by sand tension tables and pressure membrane cells for 5 agricultural soils. Agreement of resulting MRC curves was recognised. Results of the soil moisture adjustment method which involved the drying-down of soil from saturation is not statistically equivalent or practitioner-appropriate when compared to wetting-up the soil from an air dried condition.

These results have consequently validated the successful development of the FPD method for application by a practitioner in a domestic environment – producing equivalent results to the traditional lab-based methods with the production of statistically similar MRC curves across a range of soil types. This will enable practitioners to establish this key scientific information about their soil, thus enabling more informed judgements for irrigation and soil management, and aid long-term soil monitoring.

Grower Science: Feasibility of accurate on-farm measurement of nitrogen in organic amendments. *Oramabo Damiete Esther*

The ability to determine nutrient resource potential of organic amendments on-farm at low cost would better enhance its efficient use as a nitrogen (N) input to the soil. Consequently, the aim is to develop a low-cost quick test method for measuring available N as ammonium ($NH4^+$) and nitrate ($NO3^-$) in organic amendments. 14 samples comprising of Farm yard manure (FYM), compost and Anaerobic digestate (AD) were extracted in 5 replicates, using farmer accessible, low cost extractants (1.58mol NaCl and distilled water) and analysed with both a segmented flow analyser and commercially available micro paper analytical device (μPAD). Precise result of μPAD analysis was deduced from RGB (Red Green Blue) codes of its resultant colour using the μPAD reference scale as the standard curve. The results were compared with those of the Standard Operating Protocol (SOP) (2mol KCl extraction using a segmented flow analyser). NaCl and distilled water extraction were highly correlated with KCl extraction; R2= 0.9917 for 1.58mol NaCl and R2= 0.9893 for distilled water. SOP results correlated with RGB prediction with R2= 0.8685 for $NO3^-$ and R2= 0.8815 for $NH4^+$. μPAD provides a promising way to measure N in organic amendments in comparison to conventional method.

Grower Science: Comparison of organic and mineral nitrogen fertilisers on farmland bird food abundance. *Agnese Mancini*

Agricultural intensification has reduced farmland bird populations since the 1970s. One of the main drivers of this negative trend is the reduction of invertebrate, which are a fundamental food resource. Due to trophic interactions, agricultural practices that enhance invertebrate abundance are likely to support greater bird populations.

The project aim was to investigate whether the application of organic fertilisers, as compost and farmyard manure (FYM), are likely to support a greater farmland bird population than the application of mineral fertilisers through increasing invertebrate populations (earthworms and arthropods). In addition the effects of the fertilisers on the soil microbial community (microbial biomass and phenotypic community analysis using phospholipid fatty acid analysis) were investigated as a resource for the invertebrate population. The organic fertilisers were applied at 2.5 and 3.5 t C ha^{-1} and ammonium nitrate at 220 kg ha^{-1}. Increases in soil organic matter were also assessed. The study area was a winter oilseed rape field-trial located at Rothamsted Research (UK).

Soil organic matter and soil microbial biomass increased because of organic fertilisers compared to no organic fertilisers, being the effect of compost greater than FYM. Soil microbial biomass was greatest in the plots receiving compost and mineral N. Organic fertilisers increased earthworm biomass and density. Coleopteran biomass, mainly represented by Carabidae, was enhanced by mineral N fertilisers and by the combination between organic and mineral fertilisers, but not differences were founded between the solely use of ammonium nitrate and its combination with organic fertilisers. Compost, FYM and mineral N demonstrated to interact and therefore their combined use can not only provide a valuable crop yield in the long term but also support populations of invertebrates and likely farmland bird populations.

Grower Science: On-farm method to measure the rate of water infiltration. *Ana Moya Esparcia*
Numerous studies have been published looking at the characteristics of infiltration methods, but few have considered how efficient they are as a proposed practitioner-level tool. This project compares the most commonly used standard scientific methods alongside two proposed practitioner-level methods.

There is a need for farmers and land managers to monitor infiltration as a key physical property of their soil, for risk management and effective land use. Knowledge relating to infiltration allows costs in water utilisation, energy and soil amendments to be reduced, and can be used as an indicator of the impact of soil improvement measures over the long term. Traditionally, infiltration rates are determined by specialists using expensive and time consuming equipment. This project has considered the development of two practitioner-level applicable methods to measure the rate of water infiltration. The proposed on-farm methods, the Drain Pipe Method (DPM) and the Paint Can Method (PCM), measure the soils' hydraulic conductivity from which soil water infiltration can be established. These methods have been developed using economical equipment suitable to be applied by a practitioner in a farming environment.

DPM and PCM results were statistically compared against those determined by the most commonly utilised standard scientific methods: a) Tension disk infiltrometer; b) Double-ring infiltrometer; c) Decagon mini-disk infiltrometer; d) Guelph permeameter; and e) Rainfall simulator. The results have validated the successful development of the DPM and the PCM for on-farm application by a practitioner, producing equivalent results to the traditional scientific methods and statistically similar values of infiltration across a range of soil types and OM contents.

The two proposed practitioner methods are considered to be viable alternatives to the scientific methods and provide a more practical method for growers to use in a farming environment.

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Resources such as OPAL or national field council
https://www.opalexplorenature.org/earthwormguide
http://www.field-studies-council.org/publications/fold-out-charts.aspx#Invertebrates

8. Appendices

Appendix I. Mean grain/seed yield under different levels of organic amendments and fertilizer nitrogen in Fosters during 2013-2016

Grain/seed yield	OM Levels†	N levels‡	2013		2014		2015		2016	
			SB (E)	WW (W)	WOSR (E)	SB (W)	WW (E)	WO (W)	SB (E)	WW (W)
	Organic amendment levels + Fertilizer nitrogen at level 3									
Straw	1	3	8.5	10.2	5.94	8.1	12.5	10.0	9.7	10.3
	2	3	8.3	9.5	5.94	8.1	13.0	7.5	9.8	10.3
	3	3	8.6	9.5	5.93	9.6	12.9	10.0	9.8	9.8
	4	3	8.3	10.0	5.99	8.3	12.8	9.7	8.9	9.8
	Mean		**8.4**	**9.8**	**6.0**	**8.5**	**12.8**	**9.3**	**9.5**	**10.1**
Anaerobic digest	1	3	8.4	9.9	5.9	8.6	12.6	10.7	9.6	9.7
	2	3	8.3	9.5	5.1	9.1	12.4	10.7	10.2	10.2
	3	3	8.1	9.6	5.9	8.9	13.2	10.4	10.3	10.2
	4	3	8.7	9.9	6.2	9.8	14.0	11.1	10.4	10.7
	Mean		**8.4**	**9.7**	**5.8**	**9.1**	**13.0**	**10.7**	**10.1**	**10.2**
Anaerobic digest + straw	1	3	8.5	9.9	5.8	9.4	12.5	10.6	10.0	9.8
	2	3	8.7	9.8	6.2	8.5	13.4	10.0	9.7	10.4
	3	3	8.9	10.5	6.0	9.2	13.0	10.9	10.5	9.9
	4	3	8.8	9.1	5.6	8.0	13.4	10.0	9.5	10.3
	Mean		**8.7**	**9.8**	**5.9**	**8.8**	**13.1**	**10.4**	**9.9**	**10.1**
Farmyard manure	1	3	8.3	9.1	5.9	8.7	13.1	9.7	9.6	10.1
	2	3	9.3	9.6	6.1	8.0	13.8	10.4	10.2	10.4
	3	3	9.1	10.2	5.8	8.7	13.1	10.5	10.6	10.3
	4	3	8.8	10.6	6.0	8.4	13.7	10.8	11.1	10.4
			8.9	**9.9**	**5.9**	**8.4**	**13.4**	**10.3**	**10.4**	**10.3**
Farmyard manure + straw	1	3	8.8	9.7	5.5	9.1	13.0	10.3	9.7	10.3
	2	3	8.5	9.5	6.1	9.1	13.0	10.3	9.8	9.6
	3	3	8.2	10.2	6.1	9.3	12.3	10.8	9.9	10.0
	4	3	8.4	10.2	5.8	9.0	12.8	10.1	10.1	9.7
	Mean		**8.5**	**9.9**	**5.9**	**9.1**	**12.8**	**10.4**	**9.9**	**9.9**
Compost	1	3	8.6	9.0	5.6	8.9	13.5	9.9	9.5	10.2

	2	3	8.5	9.6	5.0	8.4	13.4	10.8	9.5	10.3
	3	3	8.1	9.8	5.3	9.2	12.7	10.8	10.2	10.2
	4	3	8.5	9.2	5.9	8.6	13.0	10.3	10.0	10.5
	Mean		**8.4**	**9.4**	**5.4**	**8.8**	**13.2**	**10.4**	**9.8**	**10.3**
Compost + straw	1	3	8.4	9.2	5.9	8.4	12.6	9.8	9.5	9.9
	2	3	8.5	9.4	5.2	8.9	12.9	9.8	9.3	10.1
	3	3	8.3	9.4	6.0	9.4	12.2	9.9	10.0	10.0
	4	3	8.0	10.0	5.7	8.3	12.7	10.5	9.8	10.1
	Mean		**8.3**	**9.5**	**5.7**	**8.7**	**12.6**	**10.0**	**9.6**	**10.0**
Unamended			**8.6**	**9.5**	**6.1**	**9.6**	**12.7**	**10.2**	**9.6**	**10.1**
Organic amendment level at 3 + Fertilizer N levels										
Straw	3	0	6.5	5.0	3.7	3.6	7.0	4.0	2.6	3.8
	3	1	8.1	7.8	4.8	7.46	10.0	8.3	6.4	8.2
	3	2	8.4	9.0	5.8	8.47	12.2	9.4	8.4	9.1
	3	3	8.1	10.0	5.9	8.81	12.2	9.7	9.4	9.9
	3	4	8.9	9.2	5.8	9.02	12.8	10.4	9.9	10.2
		Mean	**8.0**	**8.2**	**5.2**	**7.5**	**10.8**	**8.4**	**7.4**	**8.2**
Anaerobic digest	3	0	5.5	7.0	3.9	4.51	8.6	6.2	4.4	5.5
	3	1	7.9	8.3	5.39	8.19	11.8	10.9	8.0	9.8
	3	2	8.6	10.1	5.5	8.97	13.6	11.1	9.7	9.5
	3	3	8.7	10.5	6.0	8.74	12.9	10.9	10.1	10.5
	3	4	8.7	9.9	5.9	8.92	13.1	10.5	10.6	10.3
		Mean	**7.9**	**9.1**	**5.3**	**7.9**	**12.0**	**9.9**	**8.6**	**9.1**
Farmyard manure	3	0	6.4	5.7	4.6	5.59	8.5	7.6	4.8	5.6
	3	1	7.9	9.0	5.45	9.07	11.5	9.6	7.2	9.3
	3	2	8.6	10.5	5.9	8.12	13.1	9.8	8.8	10.4
	3	3	8.6	9.3	5.3	9.08	13.1	10.3	10.4	9.9
	3	4	8.8	9.9	5.8	8.86	12.9	11.1	10.0	9.5
		Mean	**8.0**	**8.9**	**5.4**	**8.1**	**11.8**	**9.7**	**8.3**	**8.9**
Compost	3	0	6.9	6.1	3.8	3.46	7.8	7.8	4.2	6.3
	3	1	8.4	8.8	5.18	8.59	11.7	9.7	7.4	8.4
	3	2	8.5	10.1	5.8	8.66	12.7	10.4	9.4	10.2
	3	3	8.8	9.7	5.6	8.90	14.1	10.4	10.3	10.3
	3	4	8.6	9.9	6.1	8.38	13.8	11.1	10.1	10.2
		Mean	**8.2**	**8.9**	**5.3**	**7.6**	**12.0**	**9.9**	**8.3**	**9.1**
No organic amendments	0	0	5.2	5.6	3.5	4.1	6.4	5.4	3.3	5.1

	0	1	7.9	7.9	4.7	7.5	10.2	9.0	7.3	8.4
	0	2	8.2	9.5	4.7	7.4	12.0	10.3	8.8	8.9
	0	3	8.8	9.6	4.8	7.6	11.6	10.0	9.4	10.0
	0	4	8.9	9.9	3.6	5.6	12.7	9.7	10.0	9.6
		Mean	**7.8**	**8.5**	**4.3**	**6.5**	**10.6**	**8.9**	**7.8**	**8.4**

SB: Spring barley; WW: Winter wheat; WOSR: Winter oilseed rape; WO: Winter oats

E: East; W: West

†0: Nil, 1: 1 t C ha^{-1}; 2: 1.75 t C ha^{-1}; 3: 2.5 t C ha^{-1}; 4: 3.5 t C ha^{-1}

‡:0: Nil, 1: 60 kg N ha^{-1}; 2: 100 kg N ha^{-1}; 3: 140 kg N ha^{-1}; 4: 180 kg N ha^{-1} (SB, 2013)

0: Nil, 1: 60 kg N ha^{-1}; 2: 120 kg N ha^{-1}; 3: 160 kg N ha^{-1}; 4: 200 kg N ha^{-1} (WW, 2013)

0: Nil, 1: 80 kg N ha^{-1}; 2: 150 kg N ha^{-1}; 3: 220 kg N ha^{-1}; 4: 260 kg N ha^{-1} (WOSR, 2014)

0: Nil, 1: 60 kg N ha^{-1}; 2: 90 kg N ha^{-1}; 3: 120 kg N ha^{-1}; 4: 150 kg N ha^{-1} (SB, 2014)

0: Nil, 1: 80 kg N ha^{-1}; 2: 150 kg N ha^{-1}; 3: 190 kg N ha^{-1}; 4: 220 kg N ha^{-1} (WW, 2015)

0: Nil, 1: 60 kg N ha^{-1}; 2: 90 kg N ha^{-1}; 3: 120 kg N ha^{-1}; 4: 150 kg N ha^{-1} (WO, 2015)

0: Nil, 1: 60 kg N ha^{-1}; 2: 100 kg N ha^{-1}; 3: 140 kg N ha^{-1}; 4: 180 kg N ha^{-1} (SB, 2016)

0: Nil, 1: 80 kg N ha^{-1}; 2: 150 kg N ha^{-1}; 3: 190 kg N ha^{-1}; 4: 220 kg N ha^{-1} (WW, 2016)

Appendix II. Mean straw yield under different levels of organic amendments and fertilizer nitrogen in Fosters during 2013-2016

Grain/seed yield	OM Levels†	N levels‡	2013		2014		2015		2016	
			SB (E)	WW (W)	WOSR (E)	SB (W)	WW (E)	WO (W)	SB (E)	WW (W)
	Organic amendment levels + Fertilizer nitrogen at level 3									
Straw	1	3	3.3	3.6	2.7	5.0	6.8	5.6	4.5	5.6
	2	3	3.2	3.0	3.5	5.2	7.2	6.6	4.9	4.9
	3	3	3.1	3.3	3.9	5.7	7.7	5.7	4.6	5.3
	4	3	3.1	3.3	3.8	5.5	7.5	5.2	4.3	4.8
	Mean		**3.2**	**3.3**	**3.5**	**5.3**	**7.3**	**5.8**	**4.5**	**5.2**
Anaerobic digest	1	3	3.3	3.5	2.6	5.7	7.1	6.8	5.2	4.4
	2	3	3.5	3.1	3.1	5.6	7.5	6.7	5.2	5.2
	3	3	3.6	3.0	3.1	5.2	7.7	6.0	4.5	5.3
	4	3	3.9	3.6	4.8	5.8	9.2	7.7	5.6	5.9
	Mean		**3.6**	**3.3**	**3.4**	**5.6**	**7.9**	**6.8**	**5.1**	**5.2**
Anaerobic digest + straw	1	3	3.1	3.2	3.4	6.0	7.4	7.3	5.1	4.7
	2	3	3.7	3.2	2.5	5.0	7.8	5.8	4.6	5.4
	3	3	3.8	3.6	2.4	5.5	7.4	6.9	5.7	4.9
	4	3	3.7	3.2	3.0	5.3	7.8	5.5	4.5	5.3
	Mean		**3.6**	**3.3**	**2.8**	**5.5**	**7.6**	**6.4**	**5.0**	**5.1**
Farmyard manure	1	3	3.4	3.1	3.5	4.9	7.8	5.9	4.9	5.1
	2	3	3.6	2.7	3.3	5.6	8.3	7.1	5.3	5.5
	3	3	3.9	3.7	3.5	5.8	8.2	6.8	5.7	5.2
	4	3	3.4	4.2	3.4	6.0	8.1	7.5	6.3	5.2
	Mean		**3.6**	**3.4**	**3.4**	**5.6**	**8.1**	**6.9**	**5.6**	**5.3**
Farmyard manure + straw	1	3	3.6	3.5	3.0	5.7	7.7	6.5	4.7	5.4
	2	3	3.0	2.6	3.0	5.8	7.5	6.1	4.7	4.9
	3	3	3.3	3.4	3.5	5.1	7.6	7.6	5.1	5.5
	4	3	3.5	3.5	2.8	5.3	7.2	5.5	4.7	5.0
	Mean		**3.3**	**3.2**	**3.1**	**5.5**	**7.5**	**6.5**	**4.8**	**5.2**
Compost	1	3	3.7	3.0	2.9	4.6	6.9	5.6	4.3	5.5
	2	3	3.5	3.1	2.6	5.6	8.1	6.8	5.0	5.6
	3	3	3.1	3.2	3.3	5.2	7.3	6.8	4.7	5.1

	4	3	3.4	2.6	3.5	5.4	7.8	6.4	5.1	5.3
	Mean		**3.4**	**3.0**	**3.1**	**5.2**	**7.5**	**6.4**	**4.8**	**5.4**
Compost + straw	1	3	3.2	3.0	2.8	4.4	7.2	5.5	4.3	5.1
	2	3	3.5	2.4	2.7	5.5	7.3	5.8	4.4	4.9
	3	3	3.3	2.7	3.4	5.1	6.9	5.8	4.9	5.2
	4	3	3.3	3.5	2.8	5.2	7.2	6.5	5.2	5.4
	Mean		**3.3**	**2.9**	**2.9**	**5.1**	**7.1**	**5.9**	**4.7**	**5.2**
Unamended			**3.3**	**2.8**	**3.0**	**5.4**	**7.4**	**6.2**	**4.5**	**4.8**
Organic amendment level at 3 + Fertilizer N levels										
Straw	3	0	1.9	0.7	1.5	1.53	4.0	1.4	2.9	1.3
	3	1	2.8	2.1	2.1	3.51	6.0	4.0	3.4	3.8
	3	2	3.3	3.0	2.9	4.77	6.3	5.4	4.0	4.4
	3	3	3.0	3.7	2.6	5.35	6.7	5.3	4.7	5.0
	3	4	3.6	2.7	2.6	4.91	6.7	6.4	5.0	5.2
			2.9	**2.4**	**2.3**	**4.0**	**5.9**	**4.5**	**4.0**	**3.9**
Anaerobic digest	3	0	1.2	1.4	1.4	1.84	5.3	3.5	1.8	2.0
	3	1	3.1	2.6	2.2	4.18	7.1	5.8	4.6	4.3
	3	2	3.7	3.5	2.6	4.73	8.5	6.3	5.5	4.4
	3	3	3.7	4.2	2.9	5.86	7.4	6.8	5.6	5.2
	3	4	3.5	3.7	3.2	5.27	7.4	7.3	5.5	5.4
			3.0	**3.1**	**2.5**	**4.4**	**7.1**	**5.9**	**4.6**	**4.3**
Farmyard manure	3	0	1.7	1.0	1.9	2.02	5.0	3.2	2.5	2.0
	3	1	2.7	2.6	2.6	4.36	6.9	4.9	4.0	4.4
	3	2	3.4	4.1	3.0	4.82	8.0	5.2	4.3	5.2
	3	3	3.4	3.3	2.9	4.91	8.1	6.0	5.4	5.2
	3	4	4.1	3.1	3.9	5.56	6.6	6.6	4.9	5.0
			3.0	**2.8**	**2.9**	**4.3**	**6.9**	**5.2**	**4.2**	**4.4**
Compost	3	0	1.7	1.1	1.8	1.86	4.0	3.5	1.9	2.4
	3	1	3.3	2.1	2.1	4.01	7.1	5.5	4.5	3.8
	3	2	3.4	3.4	2.7	5.57	7.6	6.4	5.0	4.9
	3	3	3.2	3.2	3.0	5.57	8.5	6.5	5.7	5.6
	3	4	3.2	3.1	3.8	5.31	8.0	7.6	4.9	5.4
			3.0	**2.6**	**2.7**	**4.5**	**7.0**	**5.9**	**4.4**	**4.4**
No organic amendments	0	0	1.3	0.7	1.5	1.9	2.9	2.2	1.5	1.7
	0	1	2.9	2.3	1.8	4.3	6.1	5.0	4.2	3.6
	0	2	3.1	3.1	1.7	4.1	7.3	6.6	4.4	4.0

	0	3	3.4	3.0	2.0	4.0	5.8	5.5	4.6	4.8
	0	4	3.5	2.7	1.3	3.1	6.7	5.1	5.0	5.1
		Mean	**2.8**	**2.4**	**1.7**	**3.5**	**5.7**	**4.9**	**3.9**	**3.9**

SB: Spring barley; WW: Winter wheat; WOSR: Winter oilseed rape; WO: Winter oats

E: East; W: West

†0: Nil, 1: 1 t C ha^{-1}; 2: 1.75 t C ha^{-1}; 3: 2.5 t C ha^{-1}; 4: 3.5 t C ha^{-1}

‡:0: Nil, 1: 60 kg N ha^{-1}; 2: 100 kg N ha^{-1}; 3: 140 kg N ha^{-1}; 4: 180 kg N ha^{-1} (SB, 2013)

0: Nil, 1: 60 kg N ha^{-1}; 2: 120 kg N ha^{-1}; 3: 160 kg N ha^{-1}; 4: 200 kg N ha^{-1} (WW, 2013)

0: Nil, 1: 80 kg N ha^{-1}; 2: 150 kg N ha^{-1}; 3: 220 kg N ha^{-1}; 4: 260 kg N ha^{-1} (WOSR, 2014)

0: Nil, 1: 60 kg N ha^{-1}; 2: 90 kg N ha^{-1}; 3: 120 kg N ha^{-1}; 4: 150 kg N ha^{-1} (SB, 2014)

0: Nil, 1: 80 kg N ha^{-1}; 2: 150 kg N ha^{-1}; 3: 190 kg N ha^{-1}; 4: 220 kg N ha^{-1} (WW, 2015)

0: Nil, 1: 60 kg N ha^{-1}; 2: 90 kg N ha^{-1}; 3: 120 kg N ha^{-1}; 4: 150 kg N ha^{-1} (WO, 2015)

0: Nil, 1: 60 kg N ha^{-1}; 2: 100 kg N ha^{-1}; 3: 140 kg N ha^{-1}; 4: 180 kg N ha^{-1} (SB, 2016)

0: Nil, 1: 80 kg N ha^{-1}; 2: 150 kg N ha^{-1}; 3: 190 kg N ha^{-1}; 4: 220 kg N ha^{-1} (WW, 2016)

Appendix III. Grain weight (1000) under different levels of organic amendments and fertilizer nitrogen in Fosters during 2013-2016

Grain/seed yield	OM Levels†	N levels‡	2013		2014		2015		2016	
			SB (E)	WW (W)	WOSR (E)	SB (W)	WW (E)	WO (W)	SB (E)	WW (W)
Organic amendment levels + Fertilizer nitrogen at level 3										
Straw	1	3	48.4	37.6	5.2	47.8	44.9	NC	44.8	41.4
	2	3	46.6	36.2	5.2	47.6	43.8	NC	43.8	42.3
	3	3	47.4	37.7	5.0	46.4	44.5	NC	43.6	43.0
	4	3	46.5	35.4	5.0	47.9	44.7	NC	44.1	41.8
	Mean		**47.2**	**36.7**	**5.1**	**47.4**	**44.5**	NC	**44.1**	**42.1**
Anaerobic digest	1	3	46.4	35.9	5.1	47.6	45.4	NC	43.8	41.6
	2	3	45.2	34.9	5.1	47.6	45.1	NC	45.3	41.4
	3	3	43.9	37.0	4.8	46.1	44.5	NC	44.0	40.5
	4	3	44.8	35.8	5.0	45.8	44.3	NC	43.0	40.9
	Mean		**45.1**	**35.9**	**5.0**	**46.8**	44.8	NC	**44.0**	**41.1**
Anaerobic digest + straw	1	3	45.6	36.7	5.0	47.8	46.2	NC	43.4	42.4
	2	3	45.6	36.7	5.0	47.8	44.7	NC	43.5	42.2
	3	3	45.6	36.7	5.0	47.8	45.9	NC	44.5	41.4
	4	3	45.6	36.7	5.0	47.8	44.2	NC	44.2	42.1
	Mean		**45.6**	**36.7**	**5.0**	**47.8**	45.2	NC	**43.9**	**42.0**
Farmyard manure	1	3	46.8	34.4	4.7	47.5	44.5	NC	44.6	41.9
	2	3	46.2	37.8	5.1	47.3	45.4	NC	43.2	41.8
	3	3	47.6	37.3	5.2	47.1	44.7	NC	45.1	41.7
	4	3	44.8	34.9	5.0	47.4	44.9	NC	44.2	42.4
	Mean		**46.3**	**36.1**	**5.0**	**47.3**	44.9	NC	**44.3**	**42.0**
Farmyard manure + straw	1	3	45.9	35.7	4.9	47.0	45.7	NC	44.4	40.8
	2	3	49.1	34.8	4.9	46.8	45.9	NC	44.5	42.2
	3	3	46.9	37.8	5.0	46.7	44.0	NC	44.0	42.3
	4	3	46.7	36.5	4.9	47.4	45.2	NC	44.5	43.0
	Mean		**47.1**	**36.2**	**4.9**	**46.9**	45.2	NC	**44.4**	**42.1**
Compost	1	3	45.9	34.9	5.0	48.3	45.2	NC	44.0	41.0
	2	3	44.5	35.7	4.8	47.5	45.7	NC	44.6	41.7
	3	3	47.2	35.5	4.9	47.8	44.4	NC	42.9	41.7

	4	3	43.9	35.7	5.0	47.8	44.3	NC	43.4	41.6
	Mean		**45.4**	**35.4**	**4.9**	**47.8**	44.9	NC	**43.7**	**41.5**
Compost + straw	1	3	46.1	36.9	4.9	46.6	44.2	NC	43.9	41.9
	2	3	46.2	35.5	5.0	47.5	44.8	NC	44.9	41.1
	3	3	49.3	36.8	5.0	47.5	45.4	NC	44.4	41.1
	4	3	44.0	35.5	5.0	46.2	44.5	NC	43.4	42.1
	Mean		**46.4**	**36.2**	**5.0**	**46.9**	44.7	NC	44.2	41.6
Unamended			**45.5**	**35.1**	**5.2**	**48.3**	**43.1**	NC	**45.1**	**41.2**
Organic amendment level at 3 + Fertilizer N levels										
Straw	3	0	49.9	40.9	5.3	49.3	44.5	NC	45.5	41.1
	3	1	48.0	38.1	5.0	48.2	44.0	NC	44.1	42.1
	3	2	44.1	36.3	4.8	47.3	44.7	NC	44.1	41.4
	3	3	45.8	36.1	5.0	46.8	45.0	NC	44.2	41.4
	3	4	43.9	34.3	4.9	44.8	44.1	NC	43.6	41.9
			46.3	**37.1**	**5.0**	**47.3**	**44.5**	NC	**44.3**	**41.6**
Anaerobic digest	3	0	49.3	39.8	5.2	47.9	46.1	NC	46.8	42.6
	3	1	47.9	37.7	5.1	48.4	47.0	NC	45.3	42.8
	3	2	46.9	36.6	5.1	46.6	45.2	NC	44.9	41.9
	3	3	46.7	37.3	4.9	46.4	44.4	NC	43.5	41.4
	3	4	45.8	37.9	4.9	45.2	44.9	NC	43.4	41.8
			47.3	**37.8**	**5.0**	**46.9**	**45.5**	NC	**44.8**	**42.1**
Farmyard manure	3	0	48.9	40.8	5.3	48.7	45.3	NC	47.0	41.0
	3	1	49.6	38.7	5.1	47.7	45.4	NC	45.8	41.3
	3	2	47.1	35.9	5.3	46.8	46.3	NC	45.5	41.6
	3	3	47.7	35.4	4.9	45.3	44.9	NC	44.4	41.8
	3	4	46.2	35.8	5.0	46.5	44.3	NC	45.3	41.7
			47.9	**37.3**	**5.1**	**47.0**	**45.2**	NC	**45.6**	**41.5**
Compost	3	0	50.8	40.6	5.1	47.8	45.1	NC	46.1	42.8
	3	1	47.0	39.7	5.3	49.2	45.9	NC	45.7	42.9
	3	2	46.4	35.7	5.3	47.6	45.6	NC	44.3	42.7
	3	3	45.3	36.6	4.8	45.5	45.6	NC	43.9	41.4
	3	4	47.0	36.0	5.1	42.2	45.5	NC	44.7	41.8
			47.3	**37.7**	**5.1**	**46.4**	**45.5**	NC	**44.9**	**42.3**
No organic amendments	0	0	49.2	39.4	5.0	48.8	43.9	NC	45.8	41.5
	0	1	47.9	38.5	5.0	47.6	45.7	NC	44.9	42.4
	0	2	47.2	35.7	5.1	47.9	44.9	NC	44.0	40.3

	0	3	46.8	36.3	4.9	44.8	44.2	NC	44.3	41.1
	0	4	44.8	39.7	5.2	46.5	44.0	NC	43.5	40.8
		Mean	**47.2**	**37.9**	**5.0**	**47.1**	**44.5**	NC	**44.6**	**41.2**

SB: Spring barley; WW: Winter wheat; WOSR: Winter oilseed rape; WO: Winter oats; NC: not counted

E: East; W: West

†0: Nil, 1: 1 t C ha^{-1}; 2: 1.75 t C ha^{-1}; 3: 2.5 t C ha^{-1}; 4: 3.5 t C ha^{-1}

‡:0: Nil, 1: 60 kg N ha^{-1}; 2: 100 kg N ha^{-1}; 3: 140 kg N ha^{-1}; 4: 180 kg N ha^{-1} (SB, 2013)

0: Nil, 1: 60 kg N ha^{-1}; 2: 120 kg N ha^{-1}; 3: 160 kg N ha^{-1}; 4: 200 kg N ha^{-1} (WW, 2013)

0: Nil, 1: 80 kg N ha^{-1}; 2: 150 kg N ha^{-1}; 3: 220 kg N ha^{-1}; 4: 260 kg N ha^{-1} (WOSR, 2014)

0: Nil, 1: 60 kg N ha^{-1}; 2: 90 kg N ha^{-1}; 3: 120 kg N ha^{-1}; 4: 150 kg N ha^{-1} (SB, 2014)

0: Nil, 1: 80 kg N ha^{-1}; 2: 150 kg N ha^{-1}; 3: 190 kg N ha^{-1}; 4: 220 kg N ha^{-1} (WW, 2015)

0: Nil, 1: 60 kg N ha^{-1}; 2: 90 kg N ha^{-1}; 3: 120 kg N ha^{-1}; 4: 150 kg N ha^{-1} (WO, 2015)

0: Nil, 1: 60 kg N ha^{-1}; 2: 100 kg N ha^{-1}; 3: 140 kg N ha^{-1}; 4: 180 kg N ha^{-1} (SB, 2016)

0: Nil, 1: 80 kg N ha^{-1}; 2: 150 kg N ha^{-1}; 3: 190 kg N ha^{-1}; 4: 220 kg N ha^{-1} (WW, 2016).

Appendix IV. Oil (%) and oil content (t ha^{-1}) of oilseed rape under different levels of organic amendments and fertilizer nitrogen in Fosters in 2014

Grain/seed yield	OM Levels†	N levels‡	2014	
			Oil %	Oil content (t ha^{-1})
Organic amendment levels + Fertilizer nitrogen at level 3				
Straw	1	3	48.0	0.28
	2	3	47.6	0.28
	3	3	48.6	0.29
	4	3	47.6	0.29
	Mean		**47.9**	**0.29**
Anaerobic digest	1	3	47.9	0.28
	2	3	46.6	0.24
	3	3	46.9	0.28
	4	3	47.1	0.29
	Mean		**47.1**	**0.27**
Anaerobic digest + straw	1	3	46.6	0.27
	2	3	46.3	0.29
	3	3	46.9	0.28
	4	3	47.2	0.27
	Mean		**46.8**	**0.28**
Farmyard manure	1	3	47.3	0.28
	2	3	47.9	0.29
	3	3	48.3	0.28
	4	3	48.5	0.29
	Mean		**48.0**	**0.29**
Farmyard manure + straw	1	3	48.1	0.26
	2	3	48.0	0.29
	3	3	47.7	0.29
	4	3	47.5	0.28
	Mean		**47.8**	**0.28**
Compost	1	3	46.7	0.26
	2	3	46.5	0.23
	3	3	46.5	0.25
	4	3	46.7	0.27
	Mean		**46.6**	**0.25**
Compost + straw	1	3	47.5	0.28
	2	3	47.3	0.25

	3	3	47.0	0.28
	4	3	46.7	0.26
	Mean		**47.2**	**0.27**
Unamended			47.7	0.29
Organic amendment level at 3 + Fertilizer N levels				
Straw	3	0	48.5	0.18
	3	1	48.1	0.23
	3	2	45.9	0.26
	3	3	49.0	0.29
	3	4	48.1	0.28
		Mean	**47.4**	**0.3**
Anaerobic digest	3	0	49.8	0.19
	3	1	49.6	0.27
	3	2	49.8	0.27
	3	3	50.2	0.30
	3	4	**50.8**	**0.30**
		Mean	**47.7**	**0.3**
Farmyard manure	3	0	49.6	0.23
	3	1	47.8	0.26
	3	2	48.3	0.29
	3	3	47.8	0.25
	3	4	**50.5**	**0.29**
		Mean	**47.9**	**0.3**
Compost	3	0	49.8	0.19
	3	1	49.4	0.26
	3	2	49.2	0.29
	3	3	48.8	0.27
	3	4	50.6	0.31
		Mean	**48.2**	**0.3**
No organic amendments	0	0	49.0	0.17
	0	1	46.6	0.22
	0	2	46.3	0.22
	0	3	48.3	0.23
	0	4	47.0	0.17
		Mean	**47.4**	**0.20**

SB: Spring barley; WW: Winter wheat; WOSR: Winter oilseed rape; WO: Winter oats

†0: Nil, 1: 1 t C ha^{-1}; 2: 1.75 t C ha^{-1}; 3: 2.5 t C ha^{-1}; 4: 3.5 t C ha^{-1}

‡:0: Nil, 1: 60 kg N ha^{-1}; 2: 100 kg N ha^{-1}; 3: 140 kg N ha^{-1}; 4: 180 kg N ha^{-1} (SB, 2013)

0: Nil, 1: 60 kg N ha^{-1}; 2: 120 kg N ha^{-1}; 3: 160 kg N ha^{-1}; 4: 200 kg N ha^{-1} (WW, 2013)

0: Nil, 1: 80 kg N ha^{-1}; 2: 150 kg N ha^{-1}; 3: 220 kg N ha^{-1}; 4: 260 kg N ha^{-1} (WOSR, 2014)

0: Nil, 1: 60 kg N ha^{-1}; 2: 90 kg N ha^{-1}; 3: 120 kg N ha^{-1}; 4: 150 kg N ha^{-1} (SB, 2014)

0: Nil, 1: 80 kg N ha^{-1}; 2: 150 kg N ha^{-1}; 3: 190 kg N ha^{-1}; 4: 220 kg N ha^{-1} (WW, 2015)

0: Nil, 1: 60 kg N ha^{-1}; 2: 90 kg N ha^{-1}; 3: 120 kg N ha^{-1}; 4: 150 kg N ha^{-1} (WO, 2015)

0: Nil, 1: 60 kg N ha^{-1}; 2: 100 kg N ha^{-1}; 3: 140 kg N ha^{-1}; 4: 180 kg N ha^{-1} (SB, 2016)

0: Nil, 1: 80 kg N ha^{-1}; 2: 150 kg N ha^{-1}; 3: 190 kg N ha^{-1}; 4: 220 kg N ha^{-1} (WW, 2016).

Appendix V. Subset of Fosters experimental plots sampled for microbial analysis

Rotation 1 Plot IDs	Rotation 2 plot IDs	OM Type	C Rate (t/ha)	N rate
43, 126	70, 215		0	0
4, 154	99, 196		0	RB209
5, 143	73, 193		1	RB209
42, 127	102, 203		1.75	RB209
37, 120	62, 167		2.5	RB209
36, 159	76, 210		3.5	RB209
54, 128	107, 169		1	RB209
23, 150	60, 202		1.75	RB209
11, 136	83, 179		2.5	RB209
19, 146	65, 214		3.5	RB209
13, 121	90, 208		1	RB209
26, 142	79, 192		1.75	RB209
20, 152	67, 199		2.5	RB209
44, 145	80, 204		3.5	RB209
6, 156	75, 216		1	RB209
50, 137	110, 220		1.75	RB209
49, 134	81, 219		2.5	RB209
15, 117	96, 188		3.5	RB209
40, 119	64, 213		1	RB209
53, 160	91, 205		1.75	RB209
48, 140	85, 175		2.5	RB209
55, 123	93, 185		3.5	RB209
33, 132	72, 217		1	RB209
8, 139	100, 194		1.75	RB209
46, 130	86, 186		2.5	RB209
3, 114	58, 174		3.5	RB209
31, 135	57, 173		1	RB209
35, 149	82, 183		1.75	RB209
18, 158	106, 187		2.5	RB209
17, 148	71, 209		3.5	RB209

Appendix VI. Mean numbers of earthworms (log10 [number m^2]) with respect to Crop x Amend x OMrate x Mixture treatment combinations (Fosters study).

Crop	OM rate	Untreated	+OM	
			Single	Mixture
	0	2.35	-	-
	2		2.32	
	4		2.42	2.18
	0	2.30	-	-
	2		2.30	
	4		2.30	2.34
	0	1.93	-	-
	2		2.33	
	4		2.22	1.82
	0	2.31	-	-
	2		2.40	
	4		2.34	2.55
	0	2.64	-	-
	2		2.55	
	4		2.71	2.50
	0	2.30	-	-
	2		2.41	
	4		2.45	2.44

For Untreated column, n=2; +OM single n=8; +OM mixture n=6.

SED: min.rep 0.27; max-min 0.22; max.rep 0.15

Appendix VII. Fosters Microbial Biomass

Appendix VII.A: Microbial biomass means (± SE; n=2) from Rotation 1

Organic Type	Rate (C-t/ha)	Autumn 2013	Spring 2014	Autumn 2014	Spring 2015	Autumn 2015	Spring 2016
		µg C/g					
	1.0	-	-	-	-	-	112 ± 5
	1.75	-	-	-	-	-	131 ± 42
	2.5	-	-	-	-	-	182 ± 13
	3.5	-	-	-	-	-	191 ± 12
	1.0	169 ± 22	265 ± 17	126 ± 14	192 ± 22	-	184 ± 8
	1.75	202 ± 13	132 ± 34	150 ± 32	230 ± 64	-	168 ± 26
	2.5	133 ± 42	348 ± 183	145 ± 3	210 ± 22	-	176 ± 34
	3.5	220 ± 30	215 ± 47	141 ± 20	245 ± 22	-	154 ± 18
	1.0	179 ± 8	177 ± 131	125 ± 4	203 ± 16	-	159 ± 10
	1.75	191 ± 9	188 ± 63	170 ± 74	229 ± 35	-	194 ± 10
	2.5	193 ± 32	285 ± 76	141 ± 21	207 ± 22	-	160 ± 11
	3.5	159 ± 25	223 ± 4	133 ± 40	183 ± 21	-	183 ± 22
	1.0	132 ± 42	204 ± 15	130 ± 40	195 ± 10	-	173 ± 9
	1.75	164 ± 2	234 ± 27	147 ± 35	187 ± 18	-	149 ± 34
	2.5	165 ± 16	153 ± 6	129 ± 11	180 ± 60	-	139 ± 16
	3.5	191 ± 14	245 ± 100	153 ± 54	232 ± 33	-	162 ± 13
	1.0	190 ± 10	305 ± 70	153 ± 16	218 ± 7	-	158 ± 17
	1.75	201 ± 1	249 ± 10	140 ± 32	191 ± 25	-	161 ± 21
	2.5	190 ± 5	269 ± 116	144 ± 30	222 ± 8	-	151 ± 38
	3.5	165 ± 18	220 ± 26	130 ± 10	163 ± 17	-	166 ± 25
	1.0	190 ± 3	250 ± 17	148 ± 12	226 ± 12	-	153 ± 18
	1.75	143 ± 40	224 ± 75	157 ± 3	176 ± 25	-	177 ± 32
	2.5	121 ± 33	218 ± 4	128 ± 11	221 ± 32	-	163 ± 5
	3.5	182 ± 11	203 ± 5	114 ± 20	236 ± 38	-	188 ± 21
	1.0	196 ± 3	200 ± 16	112 ± 25	193 ± 49	-	180 ± 4
	1.75	161 ± 27	301 ± 86	171 ± 10	210 ± 55	-	191 ± 18
	2.5	128 ± 46	201 ± 14	137 ± 15	219 ± 4	-	146 ± 23
	3.5	125 ± 34	281 ± 4	132 ± 5	188 ± 11	-	202 ± 1
	0*	184 ± 14	302 ± 31	142 ± 6	180 ± 43	-	141 ± 8
	0	193 ± 4	259 ± 110	98 ± 3	207 ± 41	-	144 ± 14
Overall Mean		172 ± 5	237 ± 12	138 ± 4	205 ± 5	-	165 ± 4

* = control plots without mineral nitrogen applied; AD anaerobic digestate, FYM farm yard manure. Dashes indicate no data available.

Appendix VII.B. Microbial Biomass means (±SE; n=2) from Rotation 2

Organic Type	Rate (C-t/ha)	Autumn 2013	Spring 2014	Autumn 2014	Spring 2015	Autumn 2015	Spring 2016
				µg C/g			
	1.0	-	-	-	-	178 ± 10	150 ± 7
	1.75	-	-	-	-	152 ± 34	125 ± 28
	2.5	-	-	-	-	166 ± 39	156 ± 16
	3.5	-	-	-	-	201 ± 50	168 ±30
	1.0	232 ± 40	236 ± 53	220 ± 13	179 ± 35	126 ± 1	182 ± 34
	1.75	213 ± 25	157 ± 16	170 ± 15	180 ± 9	115 ± 31	139 ± 33
	2.5	248 ± 21	207 ± 49	221 ± 8	251 ± 7	168 ± 3	188 ± 5
	3.5	165 ± 23	188 ± 26	158 ± 17	162 ± 5	128 ± 35	146 ± 27
	1.0	190 ± 51	180 ± 69	174 ± 49	174 ± 33	161 ± 33	130 ± 11
	1.75	223 ± 14	325±143	216 ± 15	191 ± 27	149 ± 5	177 ± 11
	2.5	212 ± 24	162 ± 33	188 ± 38	178 ± 76	162 ± 21	153 ± 51
	3.5	188 ± 41	195 ± 60	155 ± 45	190 ± 46	189 ± 12	154 ± 31
	1.0	223 ± 27	172 ± 33	183 ± 21	178 ± 18	141 ± 35	177 ± 46
	1.75	204 ± 7	245 ± 60	170 ± 9	169 ± 7	121 ± 28	180 ± 23
	2.5	180 ± 14	165 ± 4	182 ± 20	187 ± 85	131 ± 23	164 ± 12
	3.5	228 ± 6	183 ± 1	184 ± 56	206 ± 41	153 ± 19	188 ± 38
	1.0	185 ± 9	179 ± 34	166 ± 7	142 ± 1	92 ± 4	134 ± 4
	1.75	179 ± 1	188 ± 20	148 ± 0	147 ± 11	145 ± 3	128 ± 15
	2.5	250 ± 23	164 ± 6	192 ± 13	195 ± 9	123 ± 17	181 ± 24
	3.5	182 ± 25	162 ± 10	181 ± 9	171 ± 15	147 ± 35	152 ± 24
	1.0	266 ± 9	215 ± 11	214 ± 20	238 ± 35	186 ± 34	161 ± 8
	1.75	203 ± 8	227 ± 38	164 ± 3	158 ± 32	137 ± 34	163 ± 11
	2.5	225 ± 11	179 ± 38	189 ± 47	203 ± 1	177 ± 25	181 ± 3
	3.5	205 ± 5	404 ± 19	179 ± 36	136 ± 1	143 ± 47	221 ± 13
	1.0	230 ± 10	190 ± 29	188 ± 15	187 ± 5	193 ± 19	202 ± 49
	1.75	174 ± 26	223 ± 48	208 ± 5	214 ± 41	160 ± 17	165 ± 8
	2.5	174 ± 8	213 ± 3	249 ± 14	231 ± 20	138 ± 20	171 ± 25
	3.5	146 ± 83	167 ± 31	180 ± 52	173 ± 53	161 ± 72	160 ± 48
	0*	204 ± 31	164 ± 11	184 ± 10	161 ± 12	155 ± 7	118 ± 12
	0	228 ± 18	234 ± 8	188 ± 18	179 ± 28	155 ± 7	181 ± 1
Overall Mean		206 ± 6	205 ± 11	187 ± 5	184 ± 6	152 ± 4	163 ± 4

*= control plots without mineral nitrogen applied; AD anaerobic digestate, FYM farm yard manure. Dashes indicate no data available.

Appendix VIII. Fosters fungal biomass

Appendix VIII.A. Fungal (ergosterol) biomass means (±SE; n=2) from Rotation 1

Organic Type	Rate (t/ha)	Autumn 2013		Spring 2014		Autumn 2014		Spring 2015		Autumn 2015	Spring 2016	
		µg ergosterol/g										
	1.0	-		-		-		-		-	0.7	±0.1
	1.75	-		-		-		-		-	0.9	±0.2
	2.5	-		-		-		-		-	1.0	±0.1
	3.5	-		-		-		-		-	0.9	±0.1
	1.0	10.6	±4.7	7.0	±1.8	2.9	±0.3	0.7	±0.1	-	1.0	±0.1
	1.75	5.8	±0.6	7.8	±0.4	2.6	±0.1	0.7	±0.1	-	0.9	±0.1
	2.5	5.0	±0.2	5.9	±1.7	3.6	±1.3	0.8	±0.1	-	0.8	±0.1
	3.5	11.8	±4.1	8.4	±0.7	2.6	±0.6	0.8	±0.1	-	1.1	±0.1
	1.0	6.0	±0.7	10.4	±5.1	2.3	±0.6	0.6	±0.1	-	0.8	±0.0
	1.75	8.0	±3.8	9.1	±0.4	2.2	±0.1	0.8	±0.1	-	0.9	±0.1
	2.5	7.0	±0.3	9.5	±0.9	2.2	±0.3	0.8	±0.0	-	1.0	±0.2
	3.5	6.0	±0.1	8.6	±0.4	2.6	±0.4	0.9	±0.1	-	0.8	±0.0
	1.0	3.4	±0.1	9.4	±1.7	2.2	±0.9	0.8	±0.1	-	0.9	±0.2
	1.75	9.3	±0.9	8.5	±3.6	3.5	±0.6	0.8	±0.1	-	1.2	±0.1
	2.5	7.7	±1.1	5.9	±1.0	4.3	±0.6	0.8	±0.1	-	1.1	±0.2
	3.5	4.9	±1.1	7.2	±0.1	3.2	±0.8	0.8	±0.1	-	0.9	±0.1
	1.0	5.8	±0.3	6.2	±0.2	3.9	±0.4	0.9	±0.0	-	1.0	±0.1
	1.75	8.4	±3.1	8.2	±1.5	2.1	±0.0	0.8	±0.0	-	1.0	±0.1
	2.5	5.2	±0.9	7.0	±1.8	3.6	±0.4	0.9	±0.1	-	1.0	±0.1
	3.5	4.4	±0.1	6.9	±2.4	3.0	±1.1	0.8	±0.0	-	1.0	±0.2
	1.0	8.1	±0.5	9.3	±1.8	2.5	±0.6	0.8	±0.1	-	1.0	±0.1
	1.75	7.1	±1.0	5.6	±1.9	2.0	±0.4	0.8	±0.1	-	1.0	±0.1
	2.5	3.8	±0.2	5.0	±0.2	3.4	±1.3	0.8	±0.1	-	0.8	±0.1
	3.5	9.4	±2.7	5.7	±0.8	2.1	±0.5	0.8	±0.1	-	1.3	±0.1
	1.0	5.0	±0.4	7.0	±0.4	2.7	±0.3	0.7	±0.0	-	0.9	±0.1
	1.75	6.2	±2.4	8.3	±1.6	3.0	±0.1	0.8	±0.1	-	0.8	±0.1
	2.5	7.3	±0.3	10.0	±1.1	2.6	±0.4	0.7	±0.1	-	1.1	±0.1
	3.5	5.9	±0.7	5.1	±0.9	2.7	±0.6	0.8	±0.1	-	1.1	±0.4
	0*	6.6	±1.6	5.1	±1.2	2.0	±0.2	0.7	±0.0	-	0.8	±0.1
	0	5.9	±0.2	10.2	±2.1	2.0	±0.2	0.7	±0.0	-	0.8	±0.1

* = control plots without mineral nitrogen applied; AD anaerobic digestate, FYM farm yard manure. Dashes indicate no data available.

Appendix VIII.B. Fungal (ergosterol) biomass means (± SE; n=2) from Rotation 2.

Organic Type	Rate (t/ha)	Autumn 2013		Spring 2014		Autumn 2014		Spring 2015		Autumn 2015		Spring 2016	
		µg ergosterol/g											
	1.0	-		-		-		-		0.6	±0.2	0.8	±0.0
	1.75	-		-		-		-		0.6	±0.1	0.7	±0.0
	2.5	-		-		-		-		1.0	±0.2	1.0	±0.3
	3.5	-		-		-		-		0.8	±0.2	0.9	±0.0
	1.0	8.1	±0.7	5.3	±0.3	5.2	±0.6	0.7	±0.1	1.0	±0.1	0.9	±0.1
	1.75	6.3	±0.3	4.4	±0.1	3.7	±0.7	0.7	±0.1	0.9	±0.1	0.9	±0.1
	2.5	10.0	±0.1	6.0	±1.0	3.7	±1.0	0.8	±0.1	0.9	±0.1	1.0	±0.1
	3.5	4.0	±0.3	2.9	±0.3	4.9	±1.3	0.7	±0.1	1.1	±0.1	1.0	±0.1
	1.0	6.8	±1.0	4.6	±1.3	5.4	±0.9	0.8	±0.1	0.8	±0.4	0.9	±0.0
	1.75	6.1	±1.5	4.9	±0.4	5.6	±0.5	0.8	±0.1	0.9	±0.1	0.9	±0.0
	2.5	7.0	±0.4	4.9	±0.9	4.8	±1.0	0.8	±0.1	0.5	±0.0	0.8	±0.1
	3.5	5.4	±0.9	4.8	±0.9	5.1	±0.2	0.7	±0.1	0.8	±0.3	0.6	±0.2
	1.0	6.4	±0.0	5.2	±0.5	5.6	±1.2	0.8	±0.0	0.9	±0.3	1.0	±0.1
	1.75	4.5	±1.0	5.3	±0.2	4.5	±1.0	0.7	±0.1	0.7	±0.1	1.1	±0.2
	2.5	6.7	±0.7	5.7	±0.2	4.2	±0.1	0.7	±0.1	0.9	±0.5	0.8	±0.0
	3.5	5.8	±1.1	5.2	±0.3	5.1	±0.7	0.8	±0.0	1.2	±0.2	0.9	±0.1
	1.0	5.5	±0.8	5.0	±0.9	4.2	±1.2	0.7	±0.1	0.6	±0.1	0.8	±0.1
	1.75	6.0	±0.7	3.7	±0.5	3.2	±0.2	0.8	±0.1	0.7	±0.1	0.8	±0.1
	2.5	8.8	±0.1	4.0	±0.8	5.2	±0.4	0.9	±0.1	1.0	±0.1	1.3	±0.3
	3.5	6.0	±0.6	3.8	±0.1	5.4	±0.1	0.7	±0.0	0.7	±0.1	0.9	±0.1
	1.0	6.2	±1.0	5.3	±1.2	5.2	±0.9	0.9	±0.1	1.0	±0.1	1.1	±0.0
	1.75	6.8	±2.4	4.0	±1.6	4.9	±0.3	0.9	±0.2	0.9	±0.6	1.0	±0.3
	2.5	6.1	±0.3	5.0	±0.2	4.2	±0.1	0.8	±0.1	0.9	±0.3	1.0	±0.3
	3.5	5.4	±1.0	8.3	±0.3	4.2	±0.3	1.0	±0.2	1.0	±0.1	1.0	±0.1
	1.0	7.0	±0.5	6.1	±0.9	4.3	±0.6	0.8	±0.2	0.7	±0.0	1.1	±0.0
	1.75	6.1	±0.6	4.2	±0.4	5.1	±0.3	0.8	±0.0	1.0	±0.4	1.0	±0.1
	2.5	4.7	±0.4	4.5	±0.6	7.0	±0.8	0.9	±0.1	1.2	±0.5	0.9	±0.2
	3.5	4.3	±0.4	5.2	±0.5	4.6	±1.1	0.8	±0.2	1.2	±0.3	0.9	±0.2
	0*	5.9	±0.2	4.3	±0.1	4.2	±0.3	0.7	±0.0	1.2	±0.4	0.8	±0.1
	0	6.4	±0.1	5.5	±0.3	5.5	±0.2	0.9	±0.2	1.1	±0.3	0.8	±0.0

* = control plots without mineral nitrogen applied; AD anaerobic digestate, FYM farm yard manure. Dashes indicate no data available.

Appendix IX. New Zealand Microbial Biomass

Appendix IX.A. Microbial biomass means (±SE: n=3)

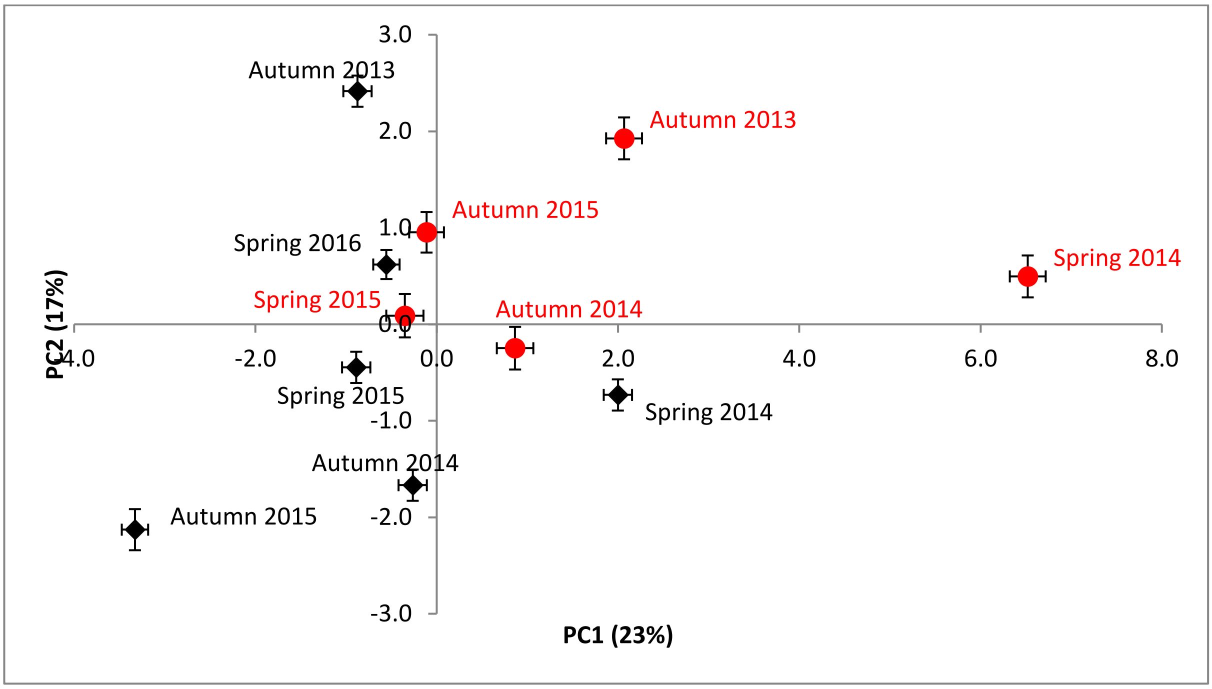
Organic Amendment	Organic Rate (t/ha)	Nitrogen Rate (kgN/ha)	Autumn 2013		Spring 2014		Autumn 2014		Spring 2015		Autumn 2015	
					µg C/g							
	0	0	348	±16	482	±23	601	±14	328	±20	224	±16
	0	180	337	±33	449	±64	517	±129	391	±72	324	±83
		0	357	±32	505	±30	631	±50	479	±78	395	±30
		180	425	±43	610	±55	702	±62	425	±77	366	±40
		0	379	±21	581	±22	580	±67	461	±89	382	±69
		180	414	±31	686	±80	779	±46	453	±2	387	±99
		0	328	±22	467	±21	407	±58	463	±70	404	±111
		180	408	±16	666	±210	574	±90	371	±30	276	±68
		0	428	±20	548	±39	700	±41	474	±29	394	±62
		180	356	±29	565	±53	632	±114	425	±44	395	±55
		Total	378	±10	556	±26	612	±27	427	±18	355	±21

Appendix X. New Zealand Fungal Biomass

Appendix X.A. Fungal (ergosterol) biomass (means ±SE: n=3)

Organic Amendment	Organic Rate (t/ha)	Nitrogen Rate (kg N/ha)	Autumn 2013		Spring 2014		Autumn 2014		Spring 2015		Autumn 2015	
			µg ergosterol/g									
	0	0	1.9	±0.4	12.1	±0.5	15.1	±1.5	2.9	±0.1	2.2	±0.2
	0	180	1.7	±0.1	11.8	±1.8	15.3	±0.4	3.0	±0.3	2.6	±0.3
		0	1.6	±0.3	12.4	±1.0	16.7	±2.2	3.1	±0.3	2.4	±0.4
		180	2.0	±0.0	13.2	±1.0	14.5	±2.8	3.0	±0.2	2.2	±0.1
		0	1.5	±0.6	14.0	±0.5	17.3	±2.8	3.2	±0.2	2.6	±0.6
		180	2.2	±0.3	17.3	±1.0	14.9	±0.9	2.7	±0.7	3.3	±0.4
		0	1.3	±0.4	15.7	±2.7	13.4	±1.2	2.7	±0.8	2.2	±0.1
		180	2.4	±0.1	13.5	±2.4	14.2	±1.2	3.7	±0.2	2.3	±0.1
		0	1.6	±1.1	16.7	±4.2	14.4	±1.7	2.6	±0.2	2.2	±0.1
		180	1.0	±0.1	18.7	±2.2	14.5	±1.4	2.7	±0.3	2.6	±0.3
		Total	1.7	±0.1	14.5	±0.7	15.0	0.5	3.0	0.1	2.5	±0.1

Appendix XI. Comparison of the microbial community composition (phenotype-PLFA) of the New Zealand to the Fosters experiment



Comparing the microbial community (phenotypic) profiles of the New Zealand to the Fosters experiment within each sampling time. Fosters are black diamonds, New Zealand red circles.