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WHY ARE LONG-TERM EXPERIMENTS IMPORTANT?

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Well-managed, well-documented long-term experiments and the archived samples from them are valuable resources that can be used to investigate the effects of land management and global change on soil quality; soil fertility and yield. For example, modifications to the Broadbalk Wheat experiment at Rothamstedhave ensured that it still remains relevant to modern science after more than 160 years. These changes, which include the introduction of modern, higher yielding cultivars, larger rates of nitrogen, pesticides etc mean that grain yields on some treatments are now more than three times greater than they were in earlier years. Data from Broadbalk, and other long-term experiments on different soil types and in different climatic zones, are the only way we have of studying the long-term sustainability of agricultural systems.

Key words: long-term experiments, sustainable harvests, global changes, soil organic matter, data archive.

НАУЧНАЯ ЦЕННОСТЬ ДЛИТЕЛЬНЫХ ПОЛЕВЫХ ОПЫТОВ

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Методика и техника ведения научной документации при оформлении результатов исследований длительных полевых опытов, а также соблюдение требований по проведению длительного полевого опыта являются основой для получения экспериментальных данных о влиянии систем земледелия и глобальных изменений на свойства почвы, почвенное плодородие и урожайность культур с целью изучения устойчивости агроэкосистем во времени.

Ключевые слова: длительные опыты, получение устойчивых урожаев, глобальные изменения, органическое вещество почвы, архив данных.

In a changing world, with increasing concentrations of $C0_2$, increasing temperatures and a rapidly rising global population, maintaining food production is essential. In this context, the value of long-term experiments should not be overlooked. Although they do have limitations they are often the only way by which the long-term sustainability of a particular farming system can be assessed.

The purpose of the experiments started by I.B. Lawes and I.H. Gilbert at Rothamsted in the mid-19th century was to identify the best way of using organic manures and more recently introduced inorganic fertilizers to maximise the yield of the major crops grown in Great Britain at that time. They were not, originally, intended to be long-term experiments. However, Lawes and Gilbert soon realised that the climatic character of the different seasons had a considerable effect on yield from year-to-year and on the effect of one treatment compared to another. They realised the need for better meteorological data and for further yield measurements over a longer run of years to help explain their results. Crucially, they also realised that there needed to be a greater understanding of the physical and chemical properties of the soil and that significant advances in the analysis of soils were required. Several of the experiments begun by Lawesand Gilbert therefore continued and more were started in the 20th century. Rothamsted also assumed responsibility for experiments at Woburn, Bedfordshire (started in 1876), and at Saxmundham, Suffolk (started in 1899). Thus, Rothamsted Research now has about 20 long-term experiments ranging from 16 to 170 years old on three contrasting soil types. Management includes continuous arable cropping and permanent grassland with various combinations of organic manures, inorganic fertilizers and lime, ley-arable cropping, bare fallows and areas of woodland.

One of the potential problems with long-term experiments is that they can become "fossilised' i.e. treatments and management practices that were put in place at the start of the experiment may no longer be relevant. It is important therefore that any long-term experiment should be reviewed regularly and changes made if necessary. However, it is equally important that there should be strong scientific reasons for any change and that these should be fully discussed and documented. Frequent changes should usually be avoided. Many of the experiments at Rothamsted have been modified to a greater or lesser extent over the years to ensure their continued relevance (as far as possible) to modem agriculture and to environmental concerns, whilst retaining their long-term integrity. Plant samples (grain, straw, herbage) have been taken from many of the experiments every year since they began; soils have been sampled less frequently. With great foresight Lawes and Gilbert retained many of the samples once they had been analysed creating a unique archive of material. Successive generations of scientists have added to this archive which now totals c. 300,000 samples. Thus, the experimental sites can be used to study how soil quality and fertility can be maintained and at the sustainability, or otherwise, of crop yield over many years whilst the retrospective analysis of archived samples allows us to look back over 170 years at many aspects of soil function, plant nutrition and pollution that could not have been anticipated 50 or a 100 years ago. In this paper we will look at some of the factors affecting crop production and changes in soil organic matter (SOM) and how archived samples have been used to further our understanding of e.g. plant physiology and the turnover of SOM.

It is important to recognize that all long-term experiments are being conducted against a background of increasing concentrations of $C0_2$ in the atmosphere (Keeling & Whorf, 2005) and, in many parts of the world, increasing temperatures; at Rothamsted, for example, mean annual temperature has increased by about 1°C in the last 20-30 year, mainly as a result of higher winter minima (Poulton, 2006).

Also, in many developed and developing countries there are, or have been, significant atmospheric inputs of nitrogen (N) and sulphur (S). At Rothamsted N inputs, in rainfall and as dry deposition, totalled about 45 kg N/ha in the 1980's but have since declined to about 30-35 kg N/ha whilst S inputs peaked at about 25 kg S/ha in the 1970's but then decreased dramatically, to about 5kgS/ha, by late 1990's as a result of the decline in heavy industry in the UK and the clean-up of coal-fired power stations (Goulding et al.; 1998). In contrast, atmospheric inputs of N and S are still high in many countries, e.g. in North-East China inputs of N, as dry deposition, totalled 55 kgN/ha, mainly as a result of the growth in heavy industry and power stations (Shen et al.; 2009). Finally, although population growth in much of Europe and North America is fairly slow this not the case in much of Africa, the Indian sub-continent and China (Evans, 1998). In these countries, increasing food production is of major concern.

Sustainability of yield

The Broadbalk Wheat experiment is perhaps the best known of the long-term experiments at Rothamsted. Its development over more than 160 years provides us with examples of how these experiments can be used to study both agronomic and environmental issues. It was started in autumn 1843 on a site that had probably been in arable cropping for several centuries; the soil was regarded as "average" wheat growing soil. Winter wheat has been grown on all, or part, of the experiment every year since the first harvest in 1844. The experiment covers 3 ha; each treatment strip is about 6 x 300m.In one of their early papers Lawes and Gilbert (1864) gave reasons for why they started the experiment. They wanted to know what the grain yielding potential of the land was, what nutrients were soonest exhausted and how the results obtained on Broadbalk might be applicable to a large proportion of arable land in the UK. To answer these questions the yields of wheat grown with various combinations of inorganic fertilizers (N, P, K, Mg, Na) were compared with organic manures (farmyard manure [FYM] and castor meal) and a control treatment, receiving no inputs. Some treatments, particularly the amounts of N that were tested, changed markedly in the first few years before Lawes and Gilbert adopted a set of treatments in 1852 which remained largely unaltered for many years. Figure 1 shows the yields of wheat grain on a few selected treatments and can be used to explain how the experiment has been modified over the years. It reflects the changes in management that have been introduced on Broadbalk, and on many other arable farms in the UK, particularly since the 1950s/1960s, and the effect that these changes have had on yield. Before the 1960s the data points are (mainly) 10 year means, since then they are means of different cultivars.

Until the First World War, the experiment had been weeded by hand but the subsequent shortage in manpower allowed weed competition to become so severe that yields on all treatments had declined by the 1920's. The experiment was therefore divided

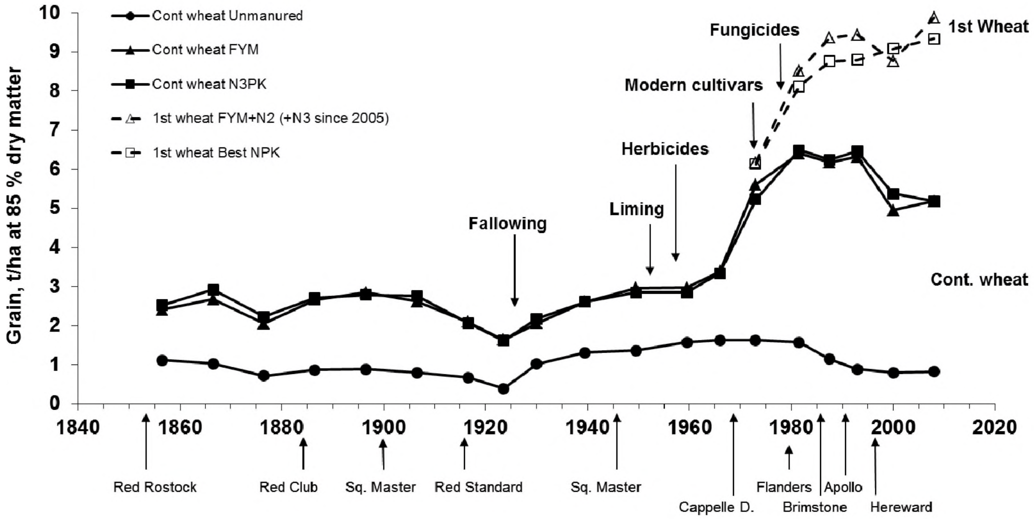

Fig. 1- Broadbalk. Mean yields of wheat grain and changes in management

into five sections and one section was bare-fallowed each year to control weeds. Yields recovered to their previous level and, during the period of rotational fallowing, important information on diseases was obtained. Herbicides have been used to control weeds on most of the experiment since 1964, allowing a return to continuous wheat. Soil acidification had become a problem on some treatments by the early 1950's so corrective chalk dressings have been applied, as necessary to maintain soil pH such that yield is not limited. By the mid-1960's most farmers in the UK were growing modem, short-strawed cultivars of wheat and most were using calcium ammonium nitrate fertilizer rather than ammonium sulphate. This prompted considerable discussion about what further changes were needed to ensure that Broadbalk remained as relevant to modem agriculture as possible without losing its long-term continuity.

In 1968, the experiment was divided into 10 sections (c. 200 plots), short-strawed cultivars were introduced and the form of N changed to calcium ammonium nitrate. Some sections remained in continuous wheat. On others a rotation of crops was grown, allowing us to compare the yield of wheat grown continuously with that of a 1st wheat grown after a 2-year break where the effects of soil-bome pests and disease, particularly *Gaeumamomyces graminis,* are minimised. The change to short-strawed cultivars also meant that the top rate of N fertilizer tested could be increased from 144 to 192 kg N/ha. The use of fungicides on all except one section since 1979 protected the yield potential of the modem varieties and this lead to a further increase in the maximum amount of N tested; to 288 kg N/ha. The best yields of wheat grain are now about 11 t/ha where a 1st wheat has been grown with FYM plus extra N in spring or with PKMg plus 240 or 288 kg N/ha. Thus, on this soil type, yields have been maintained for more than 160 years with inorganic fertilizers alone or with FYM, or increased with higher fertilizer inputs or with FYM plus extra N. But, to achieve this, soil pH, weeds, pests and disease must be controlled and new cultivars introduced when necessary.

Although it was possible to maintain the yields of wheat (and barley) on the silty-clay loam at Rothamsted this was not the case on the sandy soil at Wobum. Here, the yields of wheat and barley declined as the soil became acid (Russell &Voelcker, 1936) but this decline was probably confounded by the presence of soil-bome pests, particularly cereal cyst nematodes on the lighter, sandy soil. Although soil acidity was corrected, yields did not recover (fig. 2). Similarly, Lawes and Gilbert were unable to maintain the yields of continuous root crops or legumes at Rothamsted, almost certainly because of soil-bome pests with which they were not familiar.

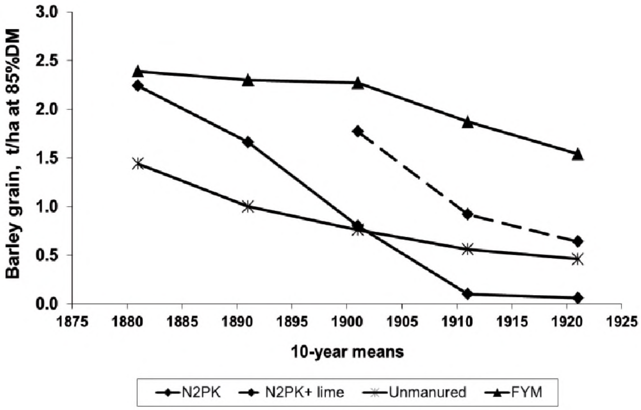

Fig. 2. Woburn Intensive Cereals Experiment; mean yields of barley grain

The role of soil organic matter

Soil is a major sink for $C0_2$ in the form of soil organic matter (SOM). SOM plays a vital role in soil fertility, crop production and sustainable agricultural systems; the issue is discussed in detail by Johnston et al. (2009).

Microbial activity will release N and P which is available to the growing crop, but may also be lost from the crop: soil system. But, SOM also influences water holding capacity (Blair et al. 2006), the supply of trace elements (Johnston, 2004), and the ease and timing of cultivations (Watts et al. 2006). The amount of SOM depends on the input of organic matter, the rate at which it decomposes, the rate at which existing organic matter is mineralized, soil texture and climate. All of these factors interact such that an equilibrium value is established for a particular soil type and farming system. Any changes in organic matter input, farming practice (e.g. a change from ploughing to direct drilling) or, potentially, increasing $C0_2$ concentrations in the atmosphere and global warming, will result in a change towards a new equilibrium value. It is important to realise that the amount of organic matter in the soil will not increase (or decrease) indefinitely; it will reach an equilibrium. In temperate climates SOM changes may be very slow and it is only in long-term experiments that these changes can be monitored reliably.

Effect on yield

On Broadbalk, yields of wheat given PKMg and either 240 or 288 kgN/ha exceed those of wheat grown on soil receiving 35 t/ha FYM each year. Adding extra N to wheat grown on soils receiving FYM results in a yield similar to the best yield that can be obtained with inorganic fertilizers alone (see fig. 1). On the Hoosfield experiment at Rothamsted (on the same soil type as Broadbalk), yields of spring barley given PKMg or FYM and four rates of N have been compared since the experiment was modified in the 1960's. Initially, yields on plots given FYM for many years could be matched by applying sufficient N to soils receiving PKMg. However, over the last 20 years, with the introduction of higher yielding cultivars, this is no longer the case.

On average, yields on soil given FYM for many years now exceed those of yields on soils given PKMg+N (fig. 3). Spring sown barley has to establish a good root system as quickly as possible to exploit the soil for nutrients and reach maximum yield. Results suggest that better soil physical structure and the extra N mineralized from the SOM and available to the crop at times and positions throughout the soil profile not mimicked by fertilizer N helps to achieve this. In contrast, autumn sown wheat on Broadbalk has a much longer period, up to 4-5 months longer, in which to establish a good root system before the crop starts into rapid growth in spring; in this case the extra SOM does not always result in a yield increase.

In both experiments however it is worth noting that the losses of *inorganic N* from soils with a history of *organic* manure applications can be as great as those receiving the largest amount of *inorganic N* fertilizer (Powlson et al. 1989).

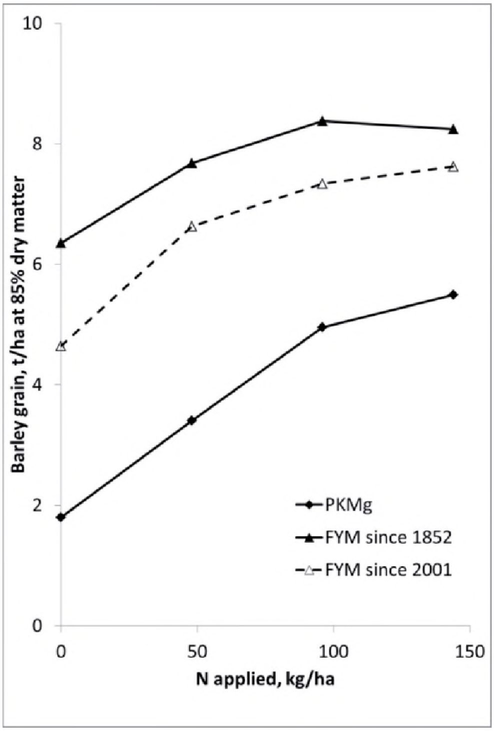

Fig.3. Hoosfield Barley experiment, 2008-11; mean yield of spring barley

Modelling SOM

Given the importance of SOM, understanding how the amount held in the soil changes over time, and predicting how it might change in the future is of great interest. The development of computer models that simulate the turnover of organic matter has been key to improving our understanding of soil carbon dynamics. Data from long-term experiments has been essential in developing and validating these models, including those at Rothamsted (Coleman & Jenkinson, 2008; Jenkinson & Coleman, 2008).

Figure 4 shows the measured and modelled amount of organic C in topsoil (0-23 cm) for three treatments in the Hoosfield Barley experiment which started in 1852 (Johnston et al, 2009). The fit of the model to the observed values is good with the exception of the first few years where SOM was declining after additions of FYM ceased after 20 years.

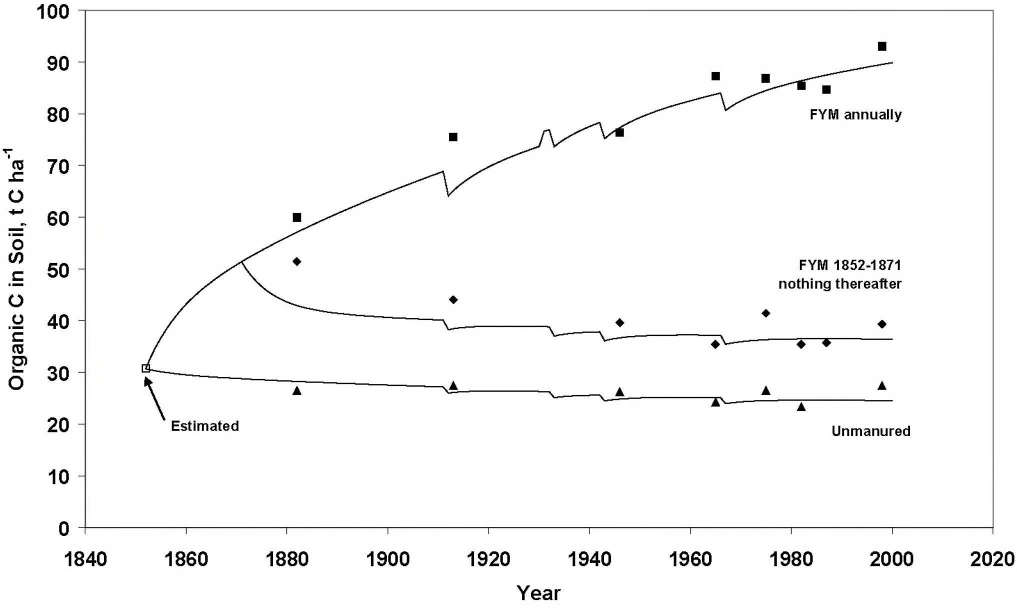

Fig. 4. Hoosfield Barley experiment. Organic carbon in soil (0-23cm). Data modelled by RothC-26.3 (solid lines)

Where no fertilizers or manure have been applied since the start of the experiment, yields have been poor and organic matter inputs (as stubble, roots, root exudates etc) have been low; nonetheless SOM has been in equilibrium on this silty clay loam at about 27 t C/ha (0.94%C).Where FYM (35 t/ha/yr) has been applied since 1852 inputs have been much larger and the soil now contains three times as much organic C as the control treatment.

Figure 5 shows the fit of the model to changes in SOM in two different situations. At Geescroft, arable cropping was abandoned in 1883and SOM accumulated as the site reverted to woodland (Poulton et al. 2003).

In contrast, on Highfield, SOM declined when a soil that had been in grass for more than 100 years was ploughed in 1959 and subsequently maintained as a "Bare Fallow". On both

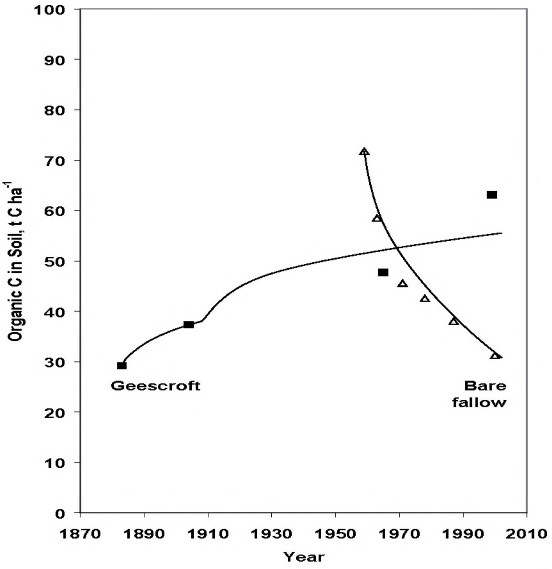

Fig. 5. Organic carbon on Geescroft Wilderness and Highfield Bare Fallow. Data modelled by RothC-26.3 (solid lines)

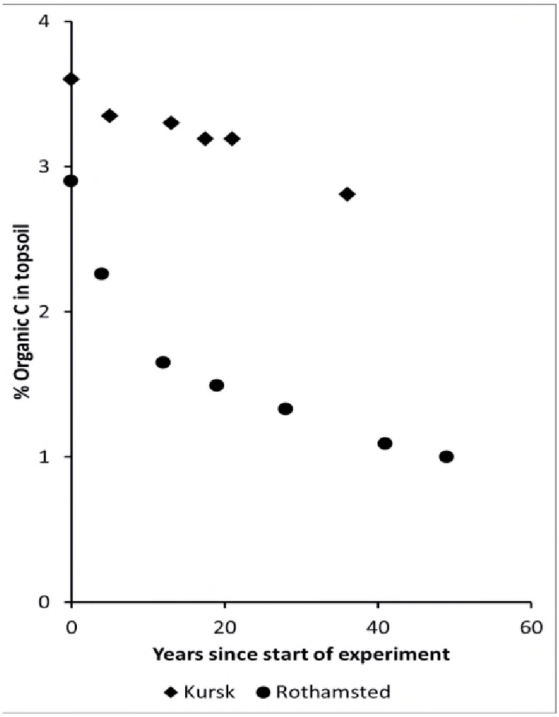

Fig. 6. Changes in %C in the topsoil of two Bare Fallow experiments

sites the model describes the changes in organic C very well (Johnston et al. 2009). On both sites (and for the FYM treatment shown in fig. 5) the data points have been corrected for changes in bulk density.

At Rothamsted we are fortunate in being able to compare long-term changes in e.g. soil C and N, on the several different soil types found on our three experimental farms. Even so, the number of soil types is limited and the three farms all experience similar climatic conditions. Whenever possible it is therefore useful to compare data across sites with a wider range of soil types and climates. A recent example of this has been to bring together scientists from a number of countries who are responsible for the management of six "Bare Fallow” experiments. The objectives were to establish a network of sites and to develop a model which could be used to determine the amount of stable (recalcitrant) carbon in the soil and the time it would take before the amount of carbon remaining in a bare fallow soil was predominantly stable C. The results are given by Barre et al. (2010, 2011). Figure 6 shows the raw data from just two of the sites, the Highfield Bare Fallow at Rothamsted and the Kursk Bare Fallow in Russia. At Rothamstedthe climate is cool, temperate; mean annual temperature is about 9.5°C and precipitation c. 710 mm. The experiment at Kursk is in the forest steppe climatic zone - temperate, moderately cold; mean annual temperature is 5.4°C and precipitation c. 570mm. The main difference between the two sites however, is soil type. The soil at Rothamsted is a silty clay loam overlying Clay-with-fiints with chalk at depth and is classified as a Chromic Luvisol. At Kursk the soil is a deep heavy loam chernozem on loess, classified as a Haplic Chernozem. At Rothamsted the site was ploughed out of long-term grass; % organic C declined significantly over the next 49 years, particularly in the first few years as the more labile material was decomposed. Compared to Rothamsted the soil at Kursk contained a higher concentration of organic C at the start of the bare fallowing period even though it had been in cultivation for more than 200 years. After almost 40 years bare fallow there has been a gradual decline in % C. It will be interesting to see whether the current rate of decline on these, and the other Bare Fallow experiments within the network, is affected as global temperatures and $C0_2$ concentrations continue to rise; these scenarios are currently being modelled.

Most of the models developed to simulate SOM turnover were designed for use in top soils, typically 0-20 or 0-25 cm. However, as half of the world's organic C held in the top metre of soil is in the 25-100cm layer (Jobbagy& Jackson, 2000) any effect of global warming on this subsoil C could be important. Archived soils, sampled in layers to a depth of 91cm in the 1870's together with fresh samples were analysed for organic C and ^{14}C (Jenkinson et al. 2008). Using this data a new model, Roth PC-1, was developed by Jenkinson and Coleman (2008) to simulate the turnover of subsoil C.

Roth C-26.3 has been incorporated into the Global Change Model (Jones et al.; 2005) developed by the Hadley Centre (UK Meteorological Office). Simulations using the combined models predict large losses of soil carbon due to increased temperature and changes in rainfall. This will increase $C0_2$ emissions to the atmosphere and make climate change worse.

Unexpected uses of long-term experiments and archived material

We continue to measure yield on most of our long-term experiments and this is still of great interest and relevance. Equally important, we also continue to look at the turnover of carbon in soil and the cycling of nitrogen (Jenkinson etal.; 2004) and phosphorus (Syers et al.; 2008) etc. However, long-term experimental sites and archived plant, soil and fertilizer samples present opportunities for research that could not have been anticipated when the experiments started or when samples were first kept.

For example, research has been done on the soil's ability to act as a sink for methane (CH_4), an important greenhouse gas. Hutsch et al. (1993) showed that on Broadbalk, less CH_4 was oxidised in soil where fertilizer N had been applied, compared with soil receiving FYM or the control soil receiving neither fertilizer nor manure. In the adjacent woodland CH_4 was taken up 6 times faster than on the FYM treated soil. However, in the acid soil of the Geescroft woodland there was no CH_4 uptake. Similarly, on the permanent grass experiment, Park Grass, CH_4 oxidation was inhibited on soils with a pH of c.5, or less (Hutsch et al. 1994). Methane oxidising bacteria in soil are responsible for removing CH_4 from the atmosphere but their activity is clearly influenced by management practice and soil conditions. Recently, Maxfield et al. (2011) used PLFAs to identify different populations present in the soils of various long-term experiments and Stiehl-Braun et al. (2011) used autoradiography to identify their physical location with respect to depth and soil pores.

Sulphur dioxide ($S0_2$) was an important atmospheric pollutant in the UK for much of the 20* Century. Inputs peaked at about 25 kgS/ha in the 1970's but have since declined to less than 5 kgS/ha (Goulding et al.; 1998). Zhao et al. (1998, 2003) measured the stable sulphur isotope ratio ($\delta^{34}S$) of archived samples of herbage from Park Grass and grain and straw from Broadbalk. They showed that $\delta^{34}S$ was correlated strongly and negatively with anthropogenic UK $S0_2$ emissions. Later, the DNA of two important wheat pathogens, *Phaeosphcteria nodorum* and *Mycosphcterell agraminicola*, was extracted from archived wheat straw samples from Broadbalk by Bearchell et al. (2005). They found that the relative abundance of these two pathogens reflected the relative importance of the two diseases they cause in the UK. Over the long-term, changes in the dominance of the two species was very strongly correlated with changes in atmospheric pollution, as measured by $S0_2$ emissions in the UK.

Conclusions

Well-managed, well-documented long-term experiments and the archived samples from them are valuable resources that can be used to investigate the effects of land management and global change on soil quality, soil fertility and yield. They are the only way we have of studying the long-term sustainability of agricultural systems.

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