ROTHAMSTED RESEARCH

# The Woburn Ley-arable experiment, 1938-2020: its management, the issues and problems that arose, and their resolution to maintain the continuity and relevance of the experiment.

**DOI:** 10.23637/wrn3-manag1938-2020-01

**Cite as:** Johnston, A.E., Poulton, P.R., Macdonald, A.J. and Glendining, M.J. (2022). The Woburn Ley-arable experiment, 1938-2020: its management, the issues and problems that arose, and their resolution to maintain the continuity and relevance of the experiment. *Rothamsted Research, Harpenden, UK.* 28pp https://doi.org/10.23637/wrn3-manag1938-2020-01

**Published by:** Rothamsted Research, Harpenden, UK

**Date:** June 2022

**Description:** The Woburn Ley-arable Experiment was started in 1938 to test and compare crop yields in all-arable and ley-arable crop rotations. It is a complicated experiment, with many changes over the years to cropping, fertilizer and manure applications. It is now an important resource for investigating long-term changes in soil organic matter (SOM). This paper describes the management of the experiment, 1938-2020 and details the important changes that have been made to ensure that it remains relevant to current issues of soil fertility, crop yield and carbon storage.

**Site:** W/RN/3. Stackyard field, Woburn Experimental Farm, Husborne Crawley, Woburn, Bedfordshire, UK. Geographic location: 51.99906, -0.61673

**Supplemented by:**

- Poulton et al, (2022). Woburn Ley-arable experiment fertilizer and lime applications 1938-2020. https://doi.org/10.23637/wrn3-fert1938-2020-01
- Poulton et al, (2022). Woburn Ley-arable experiment cropping sequence 1938-2020. https://doi.org/10.23637/wrn3-cropping1938-2020-01

**Funding:** Rothamsted Research receives strategic funding from the UK Biotechnology and Biological Sciences Research Council (BBSRC). The Rothamsted Long-term Experiments National Capability is supported by the BBSRC Grant BBS/E/C/000J0300 and the Lawes Agricultural Trust.

https://doi.org/10.23637/wrn3-manag1938-2020-01

June 2022

# The Woburn Ley-arable experiment, 1938-2020: its management, the issues and problems that arose, and their resolution to maintain the continuity and relevance of the experiment.

A. E. Johnston [a], P. R. Poulton [a], A. J. Macdonald [a] and M. J. Glendining [b]

[a] Sustainable Crops and Soils, Rothamsted Research, Harpenden, UK,

[b] Research Data and Systems, Rothamsted Research, Harpenden, UK

Contacts for this experiment: A. S. Gregory [a] (current sponsor) and M. J. Glendining (electronic Rothamsted Archive curator)

## Summary

The Woburn Ley-arable experiment is the oldest of its type in the UK, and data from it has been used widely. It is a complicated experiment, and there have been many changes over the years to cropping, fertilizer and farmyard manure (FYM) applications, to ensure its continued use and relevance to agricultural practice. It was designed initially to test the effects of rotations with or without leys (short-term herbage) on the yield of arable test crops. It is now an important resource for investigating long-term changes in soil organic matter (SOM) due to different cropping systems. It consists of 40 pairs of main plots, half of which are in 'Continuous Rotations', and half originally in 'Alternating Rotations'. The Alternating Rotation plots gave little additional information, so they were replaced by longer term leys in 1973. Changes to the treatment rotations, test crops and lime, FYM and fertilizers applied over the years, are described here. This paper attempts to detail the important changes that have been made in the management of the Woburn Ley-arable experiment to ensure that it remains relevant to current issues in soil fertility, crop yield and carbon storage. A list of the major changes, in chronological order, is given in Appendix Table 3.

## Introduction

Johnston *et al*. (2017) published changes in the SOM content in the different crop rotations tested in the Woburn Ley-arable experiment over a 70-year period (1938-2007). The data were a contribution to the question about the possibility of sequestering carbon from atmospheric carbon dioxide into soil organic carbon (SOC) by changes in agricultural cropping patterns.

That this data exists is remarkable because in summer 1955 it was decided to terminate the experiment after the crop on each plot had been harvested in autumn that year. This decision was reversed because, at harvest 1955, there was a large difference in potato yields on differently treated plots which needed to be explained and confirmed (as discussed later); thus, the experiment continued. It is also worth noting that the original purpose of the experiment was *not* to look at changes in SOM. Rather, it was to study the effect of different continuous arable and ley-arable rotations ('Treatment' crops) on the yield of two following arable 'Test' crops.

Managing the experiment to ensure the sustainability of the rotations required many changes in the crops grown and nutrient inputs and it was not possible in the SOM paper (Johnston *et al*, 2017) to list all of the changes needed to ensure that the experiment continued to provide useful information applicable to current issues in soil fertility, crop production and carbon sequestration.

For each year, details of the treatments and the yields are available in Yields of the Field Experiments (Anon. 1939-1986; 1987-2000) and Results of the Classical and Other Long-term Experiments (Anon. 2001-2002; 2003-2020); available from the electronic Rothamsted Archive, e-RA (www.era.rothamsted.ac.uk/eradoc). For the Woburn Ley-arable experiment, the treatment headings in the tables of test crop yields refer to the treatment in previous years, not to the current treatment as listed. Here we aim to collate this available annual information by periods in which the yield of a crop was adversely affected and the way in which this was remedied. We hope that summarising the information in this way will let others better understand and make use of the data. We hope that the changes listed here will provide extra background information for a proposed presentation of the yields of the cereal test crops from 1981 to 2001 (Johnston *et al.* 2022; in preparation).

## Historical background

The evolution of agriculture in England and changes to the farming landscape have been discussed elsewhere (Johnston & Garner, 1969; Poulton & Johnston, 2021). By the 1930s, many farms in England were 'mixed' farms comprising some fields in permanent arable crops and others in permanent pasture providing grazing and forage for animals.

However, scientists at the Welsh Plant Breeding Institute in Aberystwyth, had, over a number of years, bred improved strains of grasses and clovers, which, together with improved cultivation techniques, made it possible to get better germination, establishment and yields of both. Such improvements led to the suggestion that to increase soil fertility, and thus crop yields, the pattern of cropping on individual fields should be changed with arable crops alternating with short periods in herbage crops, the latter often called leys; hence ley-arable cropping. It was thought that such a change would increase the yields of the arable crops due to increased amounts and availability of nutrients and/or improved soil structure from SOM accumulated during the period in leys. The leys could be grasses and/or clovers or forage legumes like lucerne, which could be grown for three or four years without needing to be re-sown. But there were many questions about which crops to grow, their management and which rotation to follow. In response, Rothamsted decided to start an experiment on the sandy loam soil at Woburn in 1938 where it was generally considered that the arable crops would benefit from the “fertility” (not defined) accumulated in the soil from growing leys for three to four years, together with the return of nutrients by grazing animals. In addition, any FYM produced when the animals were housed during the winter was applied to fields growing arable crops. Rothamsted started two further ley-arable experiments on the farm at Rothamsted in 1949 (Boyd, 1968), and similar experiments were set-up by ADAS (Eagle, 1975) and ICI (Lowe, 1975). However, ley-arable cropping gradually fell out of favour in the 1960s and 1970s for financial and management reasons as more farms became either predominantly arable or animal based; the ADAS and ICI experiments were stopped for these reasons. Those at Woburn and Rothamsted have continued and now form part of the Rothamsted Long-term Experiments National Capability (Macdonald *et al*., 2018).

## Structure and purpose of the Woburn Ley-arable experiment

This comprehensive, complicated experiment was started in 1938 to test and compare crop yields in all-arable and ley-arable crop rotations. The term ‘ley’ means grasses, clovers or forage legumes grown for a short period (e.g., 1-5 years) as part of a rotation. The experiment at Woburn was established in Stackyard Field where the soil is a sandy loam classified as a Cambic Arenosol (FAO, 1990) comprising three closely related soil series with about 11-16% clay in the topsoil (Catt *et al.*, 1980). The site has a slight slope of about $2^{o}$.

An initial and continuing component of this experiment is a comparison of four contrasted 5-year rotations which are repeated on the same plots (the “Continuous Rotation” plots; see Table 1 and Appendix Table 1) on half of the total of 40 pairs of main plots; each main plot is 19.66 x 8.53m.

**Table 1**. Cropping on the Continuous Rotation plots, Woburn Ley-arable, 1938-1950s

| Rotation (and Code) | Treatment crops | Test crops |
|---|---|---|
| Arable with roots (Ar) | Potatoes, rye, sugar beet | Potatoes, spring barley |
| Arable with hay (Ah) | Potatoes, rye, hay (sown grass seed) | Potatoes, spring barley |
| Ley (L) | 3-yr grass/clover ley with *c*. 25 kgN/ha, grazed | Potatoes, spring barley |
| Lucerne (Lu) | 3-yr lucerne ley, cut for conservation | Potatoes, spring barley |

The experiment has five blocks (Appendix Figure 1) and was phased-in over a 5-yr period so that each year of the rotation is present each year. Each rotation has three years of the different “treatment” crops followed by two years of the same “test” crops the yields of which measured the effect of the preceding treatment cropping. The treatment crops in two of the rotations were arable crops, in the other two they were leys; these initial crops are shown in Table 1. Although there have been changes in the crops grown in each rotation (see later) the “structure” of these rotations has remained unchanged throughout the 80+ years of the experiment.

Details of the cropping on block III (the block on which the experiment started with first year treatment crops) are in Appendix Table 1; details of the cropping on all five blocks can be found in e-RA (DOI: 10.23637/wrn3-cropping1938-2020-01). Later changes in cropping and manuring have usually been phased-in but with some exceptions. The first was when lucerne, and subsequently sainfoin, failed because of disease and it was expedient to replace them immediately to maintain a leguminous herbage crop in the rotation. The second was to stop applying FYM which had been applied to one in each pair of plots for the 1st Test crop (details of FYM applications are given in Appendix Table 2).

On the other 40 plots in the experiment there was an additional test, mimicking what (at that time) a farmer might consider doing in commercial practice; the same four rotations were grown but the 5-year ley rotations alternated with the 5-year arable rotations; these were designated the "Alternating Rotation" plots (see Appendix Table 1). For example, using the rotation code letters in Table 1, the ley and arable rotations alternated, e.g. Ar, L, Ah, Lu; each of these cycles would take 20 years to complete. Having the comparison of Continuous and Alternating rotations saved this experiment from being stopped in 1955; see next section. However, in terms of measuring the effects of alternating the rotations on the yields of the two test crops it gave little additional information and was stopped in the 1970s so that the plots could be used to test 8-yr leys and compare their effects with 3-yr leys as discussed later.

It is worth noting that early reports refer to the experiment as having 40 main plots, each divided into two sub-plots testing without and with FYM. However, for many years we have tended to refer to 40 *pairs* of main plots, *i.e.* 80 main plots with each pair testing without and with FYM. On experimental plans the plots have always been numbered consecutively, 1 to 80 (see Appendix Figure 1). Detailed experimental plans can be found in the e-RA document archive (http://www.era.rothamsted.ac.uk/eradoc/books/3).

## An early major problem

The role, purpose and results of each field experiment at Rothamsted were discussed at an annual, on-site visit of the Field Plots Committee (FPC[c]). In summer 1955, and in response to a question from the Director (F.C. Bawden) about the results during the 17 years of the Ley-arable experiment, the Head of the Chemistry Department (G. W. Cooke) said that when small amounts of fertilizer N were applied to the test crops the yields were better after the leys than after the arable crops but on the FYM plots, with the additional N mineralised from the FYM,

[c] Most researchers at Rothamsted do not have the appropriate technical knowledge or equipment to do field experiments, and consequently, the farm management and staff conduct the experiments on their behalf. As the number of experiments increased in the 1930s, the Director appointed a Field Plots Committee (FPC; originally comprising mainly Heads of Departments) to vet all proposed experiments. Once an experiment is agreed by the FPC (later the Working Party for Field Experiments; WPFE: now the Farm and Field Experiments Committee; FFEC), the "sponsor(s)" are responsible for organising agreed scientific observations and measurements. The sponsors names appear on the field plans and in the annual Yields of the Field Experiments books (Anon. 1939-2020) where the treatments, field operations and yields are recorded. As the complexity of many experiments increased, staff from several scientific disciplines became involved and they became sponsors also. For many long-term experiments, the sponsors have necessarily changed over time, as they have with the Ley-arable experiment at Woburn.

the difference between the four rotations was smaller but the yields following the leys were still larger than those following the arable treatment crops (see Figure 1). As these results *seemed* to suggest that the difference could be further lessened by applying more N to the test crop and that there was no "unique" benefit from growing the leys it was decided to stop the experiment after harvest that autumn.

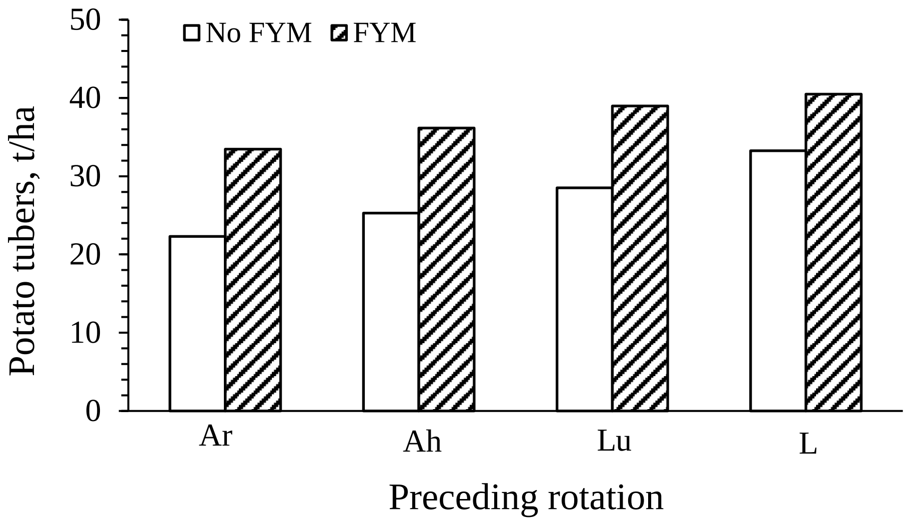



**Figure 1** Mean yield of potato tubers, t/ha, 1950-54 either without or with FYM. Woburn Ley-arable.

In 1955 potatoes were grown as the first crop on Block I in the two continuous arable rotations and following the leys in two alternating rotations (see Cropping Table in e-RA 10.23637/wrn3-cropping1938-2020-01). There was a very considerable difference in the yields (Table 2).

**Table 2** Yields of potatoes and rye when grown as the 1st and 2nd Test crops in 1955 and 1956 respectively, Block I, Woburn Ley-arable.

| | Previous 3-yr treatment cropping | | | |
|---|---|---|---|---|
| | Continuous rotation | | Alternating rotation | |
| Test crop | Arable hay | Arable roots | Ley | Lucerne |
| Potato tubers, t/ha | 4.8 | 3.8 | 19.4 | 14.7 |
| Rye grain, t/ha | 4.29 | 4.15 | 4.54 | 4.07 |

These potatoes, grown in 1955, were the seventh and fifth potato crops, respectively, since the start of the experiment 18 years previously (see 10.23637/wrn3-cropping1938-2020-01). A preliminary inspection of the potato crop suggested that the small yields on the Continuous Rotation plots was due to the presence of potato cyst nematode (*Globodera rostochiensis* then called *Heterodera rostochiensis*) where potatoes were being grown more frequently (Mann, 1956). The FPC then reversed their decision to stop the experiment to examine in more detail the problem of potato cyst nematode because any loss of yield like that at Woburn would be devastating for many farmers growing potatoes on similar textured soils in England. As part of this research, potatoes continued as the first *treatment* crop in the arable rotations and these results and those of the treatments subsequently tested to control potato cyst are given later. But, to maintain the continuity/sustainability of the experiment, the decision taken was to have sugar beet as first *test* crop instead of potatoes (Appendix Table 1).

***The first and most obvious lesson to be learnt from the experiment was that when crops are to be grown in rotation, they should be chosen to minimise the risk of the build-up of soil-borne pests and diseases.***

## Unexpected effects with the leys

The initial decision by the FPC to stop the experiment after harvest in 1955 was disappointing to some of us because we were beginning to see some totally unexpected effects with the leys, especially the lucerne. For example, in 1951-52, the yields of first test crop potatoes following lucerne (25.2 t/ha) were less than those following a grazed ley (31.6 t/ha) and only a little better than those in the all-arable rotation (21.8 t/ha). There was little benefit from the ploughed-in lucerne ley, which was expected to supply additional N, to that applied as a basal dressing to all the potato plots and thus give the largest yield.

It was also observed that when lucerne was grown for three years as a treatment crop, yields in the first and second year were larger where FYM had been applied to the potato test crop three and four years previously. Table 3 summarises the lucerne yields for the four rotations from 1943 – 1963.

This effect of the FYM residues on the yields of lucerne was unlikely to be an effect of a residue of available N from the FYM, especially for a leguminous crop, and subsequently crop and soil analysis showed that the increase in yield with FYM residues was due to the extra K added in the FYM. Large amounts of K were being removed in the lucerne and soil K reserves were being depleted, particularly where FYM was not applied. Later measurements suggest that much K was also leached, particularly on plots growing continuous arable crops. To correct this, supplementary applications of K fertilizer were applied to the plots growing lucerne and basal K applications were increased. For the method of calculating the corrective K applications see Section on Page 15-17 and for the increased basal dressings see Fertilizer Application Tables in e-RA (DOI: 10.23637/wrn3-fert1938-2020-01).

***This work on potassium status of the soil led to much debate on how to manage soil nutrient status in other Rothamsted experiments which is discussed in more detail on page 15-17.***

**Table 3.** Yields of the 1st and 2nd year lucerne on soils without and with FYM residues. Yields are t/ha dry matter, mean of the Continuous and Alternating rotations, meaned over the five blocks, Woburn Ley-arable.

| Periods | Soils without FYM | | Soils with FYM residues | |
|---|---|---|---|---|
| 1st year, 2nd year | 1st year | 2nd year | 1st year | 2nd year |
| 1943-47, 1944-48 | 1.00 | 5.61 | 0.99 | 5.89 |
| 1948-52, 1949-53 | 2.00 | 6.68 | 2.73 | 7.99 |
| 1953-57, 1954-58 | 2.32 | 6.01 | 3.06 | 7.56 |
| 1958-62, 1959-63 | 3.06 | 5.66 | 4.02 | 6.84 |

Note: yields of lucerne in the 3rd year of the ley are not given because of the adverse effect of stem eelworm; see later.

## Continuing problems with nematodes.

Nematodes (eelworms) can be introduced into a soil via plant material or on seed. Free-living nematodes become more of a problem on light-textured rather than clayey soils because they move readily through the larger pores within sandy soil. This was clearly seen in the problems with nematodes in the Woburn Ley-arable experiment on the sandy loam soil but not in the Rothamsted experiments on sandy clay loam soil.

### Stem eelworm

Table 4 shows the yield of lucerne in the first, second and third year on the same plot, and the three-year total yield for four 5-year periods starting in 1938, where lucerne was grown on the same plot in the continuous rotations. With improving management practices, the total yield in three years increased during the first three 5-year cycles but then began to decline especially as yield in the third, and to some extent in the second year was appreciably less than previously.

The lower yields were due to damage by stem eelworm *(Ditylenchus dipsaci)*, probably introduced on infected seed; this problem was not resolved by fumigation of the soil and the use of fumigated seed which was tested in 1960-62 (Rothamsted Experimental Station, 1970). Lucerne was replaced by another, but less well known, leguminous forage crop, sainfoin. Subsequent changes in the leys are discussed later.

### Free-living nematodes

Sugar beet was grown by many farmers on the lighter textured soil like the sandy loam at Woburn and was a natural choice for inclusion as the third treatment crop in the "arable roots" rotation. However, in 1956 when sugar beet replaced potatoes as first test crop, carrots replaced sugar beet as the third arable treatment crop. For three 5-year rotations sugar beet was the first test crop and there was a test of four rates of N to identify the optimum N for each rotation. The rates of N tested and the average sugar yields in 1965-67 are in Table 5.

**Table 4.** Yields of lucerne in five 5-year periods where lucerne was grown in a 'Continuous Rotation'. Yields are t/ha of dry matter meaned over the five blocks *i.e.* five years, Woburn Ley-arable.

| | Yield, t/ha, in each year of the ley | | | Total yield |
|---|---|---|---|---|
| Period | 1st | 2nd | 3rd | t/ha |
| 1938/42 - 1940/44 | 1.19 | 4.05 | 6.07 | 11.30 |
| 1943/47 - 1945/49 | 1.14 | 5.75 | 7.27 | 14.16 |
| 1948/52 - 1950/54 | 2.01 | 6.85 | 7.66 | 16.52 |
| 1953/57 - 1955/59 | 2.33 | 6.01 | 5.51* | 13.85 |
| 1958/62 - 1960/64 | 3.06 | 5.65 | 3.06* | 11.77 |

* No crop in third year in 1959 and 1960 because of stem eelworm

The largest yields of sugar were on plots receiving fertilizer N following three years in lucerne, and this increase was thought to be a benefit from N mineralised from lucerne residues late in the growing season, thus keeping the beet leaves green and actively photosynthesising for longer. This benefit was despite the fact that there was no additional SOM in the plots growing lucerne leys compared to the arable rotations (Fig. 2). Unexpectedly, yields of sugar after the grazed grass-clover ley were also little different to those in the arable rotations although these ley-treated soils contained more SOM than the soils growing arable crops. This suggested that there was little benefit from the SOM accumulated in these grazed ley plots. However, it is more probable that the yields following the grazed ley were decreased by the presence of the free-living nematodes *Longidorus* and *Trichodorus* which were particularly numerous in the 3-year grazed ley plots.

**Table 5.** Responses of sugar beet to fertilizer N following different continuous rotations, mean of with and without FYM, 1965-67, Woburn Ley-arable.

| | Sugar, t/ha | | | | | |
|---|---|---|---|---|---|---|
| Continuous | N applied, kg/ha | | | | | |
| Rotation | 44 | 88 | 132 | 176 | 220 | 264 |
| Arable with roots | - | - | 7.43 | 8.13 | 8.24 | 8.33 |
| Arable with hay | - | - | 8.40 | 8.74 | 8.31 | 8.53 |
| Ley | 7.70 | 8.30 | 8.21 | 8.26 | - | - |
| Lucerne | 8.33 | 8.86 | 8.85 | 8.95 | - | - |

**Controlling potato cyst nematode**

Following the change to sugar beet as the first *test* crop in 1956, potatoes continued as the first *treatment* crop during the next four 5-yr arable rotations (Appendix Table 1). During this time much research was being done on various chemicals as soil fumigants to kill nematodes and there was some discussion as to whether some potato varieties were more resistant to cyst nematode than others. With the problem of free-living nematodes affecting the yields of the first test crop sugar beet in the ley rotation, it was decided in 1971 to again grow potatoes as the first crop in all rotations testing cultivars considered susceptible and resistant to potato cyst nematode on soils with and without fumigation.

In the first year, the yields of "susceptible" and "resistant" varieties were very similar and this component of the experiment was abandoned. Potato yields were small in 1975 due to little rainfall; the average yields in 1971-74 are in Table 6. The effect of fumigation with chloropicrin and/or aldicarb was consistent in all four rotations and ranged from 6.6 to 10.5 t/ha tubers. More interestingly, with and without fumigation there was a small increase in tuber yield, 4.6 to 6.1 t/ha, where the potatoes were grown following three years of ley. This was one of the first examples from Rothamsted and Woburn field experiments of an increase in yield that could be attributed to extra organic matter in the sandy loam soil at Woburn.

**Table 6.** Yields of potato tubers, 1971-74, following different continuous rotations, without and with fumigation, Woburn Ley-arable.

| | Total tubers, t/ha | | With fumigation |
|---|---|---|---|
| Rotation | Without fumigation | With fumigation | *minus* without fumigation |
| Arable with roots | 50.7 | 57.6 | 6.9 |
| Arable with hay | 51.5 | 62.0 | 10.5 |
| Ley | 57.6 | 64.2 | 6.6 |
| Sainfoin* | 56.8 | 64.7 | 7.9 |
| Mean of tuber yields following arable crops in a continuous arable rotation | 51.1 | 59.8 | 8.7 |
| Mean of tuber yields following leys in a ley-arable rotation | 57.2 | 64.4 | 7.2 |
| Mean following leys *minus* mean following arable | 6.1 | 4.6 | - |

*Sainfoin had replaced lucerne in the years before these potatoes were grown.

## Changes in the leys and their management, and the test of 8-year leys

Initially, the leys were either lucerne (Lu) or grass/clover (L) given a small amount of N and grazed by sheep. There were increasing problems with both; eelworm on lucerne and using sheep to graze the small plots of grass/clover, and various changes were proposed, and some were implemented. Sainfoin (S) replaced lucerne in 1964) (see Cropping Table for all five blocks in e-RA, DOI: 10.23637/wrn3-cropping1938-2020-01). In 1969 the first- and second-year leys were not grazed and from 1970 the produce of all the leys was cut and carted off (removed from) the plots, yields of the leys were not taken from 1969 to 1983. Yields of sainfoin were variable and it was replaced by red clover, grown alone, from 1971 on blocks I, II and IV; this treatment was called "clover ley" (Cl). These changes were not entirely satisfactory and there was much discussion about appropriate ley treatments in the early 1970s.

The outcome of the discussion was to make changes that would simplify both management and establish two ley treatments, both lasting three years that should grow on the sandy loam soil at Woburn. One would be an all-grass ley (a mixture of Timothy and meadow fescue) with fertilizer N (Ln3) to replace the grazed grass/clover ley (L); the other would be a grass/clover ley (Timothy and meadow fescue with white clover, about 10% of the seeds mixture) without fertilizer N (Lc3) to replace the lucerne/sainfoin/clover ley.

To make these changes as quickly as possible, rather than phase them in, it was decided to plough those plots that were in the 1$^{st}$, 2$^{nd}$ and 3$^{rd}$ year grazed grass/clover and clover leys in the three blocks in late summer 1975, cultivate them, and sow them with the appropriate seeds mixture in spring 1976 and establish the new leys. Unfortunately, summer 1976 was very dry and the seeds failed to grow, and the plots were re-sown in October 1976, except the 1$^{st}$ year ley which was re-sown the following spring (Appendix Table 1).

As noted in the Introduction, half the plots in each block were in "Continuous" and half in "Alternating" rotations; for example, in the latter a 5-year *arable* rotation alternated with a 5-year *ley* rotation. The results from these alternating rotations gave little additional useful information and they were stopped in 1973 after 35 years. It was decided to replace the 3-year leys on these plots with leys lasting eight years followed by the two test crops. The leys were sown with the same seeds mixture as used for the three-year leys and were identified as Ln8 and Lc8 (sometimes Lln8 and Llc8, or LLn8 and LLc8, in the Yield Books). The first "cycle" of these 8-year leys were phased in during 1973-1977 and a second "cycle" between 1978-1982. Thus, by 1981 on Block III it was possible to compare the effects of continuous arable treatment crops, 3-yr leys and 8-yr leys on the yield of the following test crops. By 2007, each cycle had completed three periods of 8-year leys (Appendix Table 1 and Cropping Table in e-RA; DOI: 10.23637/wrn3-cropping1938-2020-01).

The produce of these leys was harvested, usually twice per year, and was removed from the plots. Yields of the leys, including the number of days that the grass/clover (L) leys were grazed by sheep, in the early years of the experiment were given by Mann & Boyd (1958). Yields of the treatment crops were not taken between 1969 and 1983 but since 1984 yields of all treatment crops have been recorded and samples retained for chemical analysis (see Anon., 1939-1986; 1987-2000; 2001-2002; 2003-2020). Table 7 gives the yields of the 3-yr and 8-yr leys between 1984 and 2006. The grass leys given a small amount of fertilizer N yielded, on average, more than the grass/clover leys. It was difficult to maintain a productive 8-year ley, especially the grass/clover ley, on the sandy loam soil and for these reasons it was decided to stop testing the 8-year leys, see later. The longer leys increased % OC more than the 3-year leys (Johnston *et al*., 2017) but resulted in little or no extra increase in the yield of the first or second cereal test crop compared to that following the 3-year leys (not shown here).

**Table 7** Mean total yield (t/ha) for each year of the 3-yr and 8-yr grass and grass/clover leys, 1984-2006.

| Grass ley+N | t/ha | Grass/clover ley | t/ha |
|---|---|---|---|
| Ln1 | 5.21 | Lc1 | 2.98 |
| Ln2 | 8.77 | Lc2 | 6.20 |
| Ln3 | 7.56 | Lc3 | 6.47 |
| LLn1 | 5.64 | LLc1 | 3.29 |
| LLn2 | 9.02 | LLc2 | 6.61 |
| LLn3 | 8.02 | LLc3 | 6.39 |
| LLn4 | 7.95 | LLc4 | 6.14 |
| LLn5 | 8.04 | LLc5 | 6.18 |
| LLn6 | 8.41 | LLc6 | 6.15 |
| LLn7 | 8.37 | LLc7 | 5.78 |
| LLn8 | 7.95 | LLc8 | 5.49 |

## Introduction of fallow years and their later replacement

Before the mid-70s changes in the arable treatment and test crops were made to minimise the build-up of pests and diseases as shown above. Another example was the change in the cropping in the arable rotations. From 1978 to 1998, treatment crops in the AB rotation (previously Ah) were spring barley, spring barley, beans, and in the AF rotation (previously Ar) bare fallow, bare fallow, beans, to see whether there was less risk of take all (*Gaeumannomyces graminis*) and sharp eyespot (*Rhizoctonia solani*) in the test crops of wheat and barley in the AF rotation compared to their incidence in the AB rotation in which there were more cereal crops (Salt, 1959).

Having two years without a crop in five cropping years in the AF rotation was the only way in which Salt could get the information he required but, unfortunately, monitoring the incidence of the diseases ceased when Salt retired in 1980/1. The two years of fallow did however, have a measurable effect on % OC which declined relative to that in the AB rotation. (Johnston *et al.*, 2017). In 1998 it was decided to have arable crops in all five years of the AF rotation and the decline in % OC had been stopped by 2000/04 (Fig 2).

The same three arable crops, winter rye (R), maize (M) and beans (BE), were now grown in the AB and AF rotations but in the sequence R, M, BE in the AB (now ABe) rotation and R, BE, M in the AF (now AM) rotation to compare the effects of a legume and a non-legume on the yield of the subsequent 1st Test crop (Appendix Table 1). From 2009, oats replaced maize in the arable rotations, which were then designated ABe (as before) and AO (replaced AM).

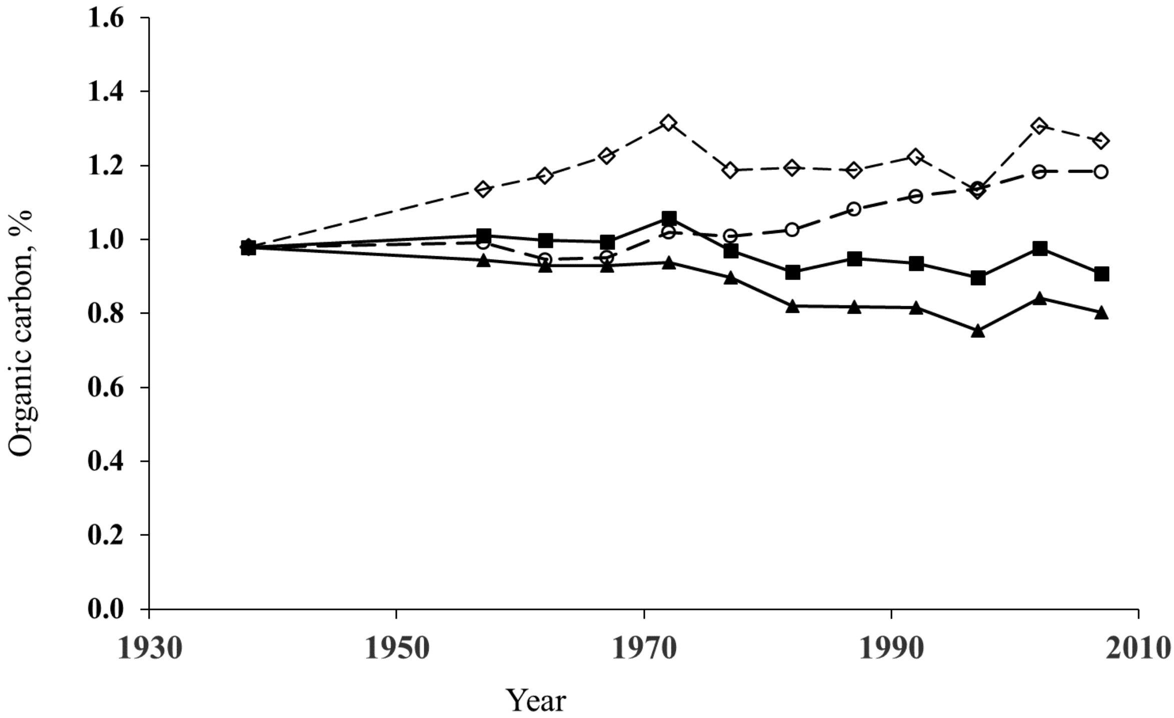



**Figure 2** Changes in % Org C on soils which did not receive FYM: ▲, Ar/AF; ■, Ah/AB; ○; Lu/Lc3; ◊, L/Ln3 (see Appendix Table 1 for complete description of treatment codes).

Another notable aspect of the data shown in Figure 2 is the lack of effect on SOM of the 3-yr lucerne leys (replaced by sainfoin in 1965). That these legume leys did not increase SOM compared to the arable rotations is perhaps because they were drilled in rows 25 cm apart and had deep tap roots with little fibrous root. It was not until they were replaced in the early 1970s (see Appendix Table 1) by clover, then grass/clover leys which had a much denser root mass in the topsoil that SOM increased (Johnston *et al.*, 2009). A similar effect was observed in the Highfield and Fosters Ley-arable experiments at Rothamsted.

## Major changes to the rotations in 2007

Testing 8-year leys stopped in 2006, and, to further simplify the management of the experiment, changes were made in 2007 on these plots. The four treatments then being followed in the 'Continuous Rotation' plots (see section above, '**Introduction of fallow years and their later replacement**'), *i.e.* the continuous arable rotations and the 3-year grass or grass/clover rotations were now imposed on those treatments which had grown 8-year leys since the 1970s; the changes were not 'phased-in' (see Appendix Table 1 and DOI: 10.23637/wrn3-cropping1938-2020-01). Thus, these four treatments, AO, ABe, Ln3 and Lc3 are now duplicated, *but on soils with a greater concentration of organic C* (Table 8). For example, the two continuous arable rotations which started in 1938 with c. 1.0 % C now contain c. 0.8 - 0.9 % C; the same all-arable rotations are now being replicated on soils which contained c. 1.3 %

C in 2005-9 (see Johnston *et al.* 2017). The effect of the extra SOM on the yield of the Test crops is being assessed.

**Table 8** Organic C in topsoil, 2005-9. Revised rotations started 2007 on plots previously in Alternating Rotations and then 8-year leys; the new rotations were not phased-in.

| Previous treatment codes | Treatment code 2007-2020 | Org C* % |
|---|---|---|
| Continuous Rotations | | |
| (Ar) (AF) (AM) AO | AO | 0.80 |
| (Ah) (AB) (ABe) ABe | ABe | 0.91 |
| (L) Ln3 | Ln3 | 1.27 |
| (Lu) (S) (CL) Lc3 | Lc3 | 1.24 |
| Previously Alternating Rotations, then:- | | |
| 1st Cycle 8-yr grass leys (LLn8) | LLn/AO | 1.30 |
| 1st Cycle 8-yr grass/clover leys (LLc8) | LLc/ABe | 1.28 |
| 2nd Cycle 8-yr grass leys (LLn8) | LLn/Ln3 | 1.38 |
| 2nd Cycle 8-yr grass/clover leys (LLc8) | LLc/Lc3 | 1.43 |

* Mean of plots with and without FYM residues on all five blocks

## Change of the first and second test crops to winter wheat and spring barley (then winter rye)

As part of the need to simplify the cropping in this experiment it was decided that from 1976 the first test crop would be winter wheat and from 1977 the second test crop would be spring barley (replaced by winter rye in 1992). With the phasing in of the 8-year leys from 1973 it was not until 1981 and 1982 that the effects of the two continuous arable rotations, the two 3-year leys and the two 8-year leys on the yield of the 1st test crop and the 2nd test crop, respectively, could be compared (see Appendix Table 1). The yields of these three test crops are being summarised for publication.

For both the 1st and 2nd test crops the response to N is determined by dividing each main plot into four subplots to test four rates of fertilizer N (N0, N1, N2 and N3). The four rates have changed periodically as the newer cultivars grown have responded to increasing amounts of N. For wheat, the amount tested in 1981 was 0, 63, 126, 189 kg N/ha, from 1982-2000 it was 0, 70, 140, 210 kg N/ha and since 2006 it has been 0, 80, 160, 240 kg N/ha.

With some evidence that fertilizer N could be used more efficiently if the total application was divided and applied in more than one application at different times, this was tested on the first test crop of winter wheat on all five blocks from 2001 to 2005, as shown in Table 9. The split application was tested on that plot in each pair of main plots which had not received FYM, while the single application was tested on the plot that had received FYM (until the mid-1960s);

by this time there was little or no effect of the FYM residues on yield. On average there was little benefit from splitting the fertilizer N applications. At best, there was an increase of 0.73 t/ha, but, following the 8-yr leys, yields of wheat given most N were surprisingly less with split dressings compared to a single application; it is not clear why. All sub-plots reverted to testing N applied as single dressings in 2006, but, since 2007, all of the sub-plots in wheat receive their N as split applications (in line with the recommendations in RB209; AHDB, 2020; see DOI: 10.23637/wrn3-fert1938-2020-01). From 1977 to 1991 the 2nd Test crop was spring barley; the amount tested in 1981 was 0, 50, 100 and 150 kg N/ha, from 1982-91 the rates of N tested were 0, 60, 120, 180 kg N/ha. In 1983, following very heavy rainfall soon after N application a further 60 kg N/ha was applied to those sub-plots receiving N (*i.e.* not to the N0 sub-plots). With hindsight this was a mistake as it hindered later comparisons of the results with other years.

**Table 9** Yields of the 1st Test crop, winter wheat given fertilizer N as two dressings or as a single application. Mean yield of grain, t/ha at 85% dry matter, 2001-2005 (i.e. from each of the five blocks)

| | Grain, t/ha at 85% DM | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Split N, kg/ha | | | | Single N, kg/ha | | | |
| Rotation | 0 | 40+30 | 40+100 | 40+170 | 0 | 70 | 140 | 210 |
| AB | 2.28 | 4.75 | 6.38 | 6.43 | 2.34 | 4.60 | 5.80 | 6.24 |
| AM | 1.55 | 4.31 | 5.89 | 6.26 | 1.75 | 4.49 | 5.72 | 6.25 |
| Ln3 | 3.53 | 5.35 | 6.35 | 6.73 | 3.70 | 5.27 | 6.13 | 6.38 |
| Lc3 | 4.43 | 6.27 | 7.55 | 7.30 | 4.64 | 6.40 | 6.82 | 7.03 |
| LLn8 | 2.82 | 4.79 | 5.06 | 4.99 | 3.53 | 4.78 | 5.66 | 5.89 |
| LLc8 | 4.66 | 5.95 | 6.59 | 6.68 | 3.79 | 5.12 | 6.43 | 7.15 |
| Mean | 3.21 | 5.24 | 6.30 | 6.40 | 3.29 | 5.11 | 6.09 | 6.49 |

In the period between 1981 and 1991 there was a significant increase in the yield of grain where wheat followed a 3-year or 8-year grass ley compared to wheat following the all-arable (AB) rotation and a further increase where wheat followed 3-year or 8-year grass/clover leys *i.e.* there was an additional benefit from the leguminous residue. However, there was no similar effect of the ley residues on the yields of spring barley. It was considered that any residual mineralized N from the ley residues was probably lost between the harvest of the wheat and the drilling of the spring barley but that there may still be a "N benefit" to a second *autumn* sown crop. Consequently, in 1992, the 2nd test crop was changed to winter rye, a crop that grows well on sandy, light-textured soils with modest amounts of applied N and where available water may restrict yields in some years. Initially the amounts of N tested were 0, 30, 60, 90 kg N/ha, but, after five years it was realised that this was not sufficient for yields to reach the top of the yield/N applied response curve so in 1997 the rates were increased to 0, 40, 80 and 120 kg N/ha. The amounts tested were increased again in 2007 to 0, 50, 100, 150 kg N/ha. With this second *autumn* sown crop there was a small N effect (*c.* 0.5 t/ha) where rye was the second crop after beans compared to after oats; but little or no effect where rye was the second crop after grass/clover leys compared to grass leys.

For the two test crops, N0, N1, N2, N3 applied to the sub-plots for the 1st test crop are followed by N0, N1, N2, N3, respectively, to the 2nd test crop (barley or rye). However, when the same blocks/plots are in test crops 5, 10, 15 years later the N rates to the sub-plots are rotated in the order N3>N2>N1>N0>N3, so that, over time, the whole plot receives the same amount of fertilizer N, has hopefully grown similar yielding crops and therefore will have had similar amounts of root and stubble incorporated, thus attempting to ensure that organic inputs have been similar on all plots over time.

## Correcting and maintaining soil nutrient status

One of the most important early lessons in this experiment was how to manage the nutrient status of the soil so that the major plant nutrients and soil acidity (pH) would not prevent the crop achieving its optimum yield potential; examples are discussed here.

In general, when the Woburn Ley-arable experiment started in 1938, the accepted statistical/experimental practice was to apply the same total amount of each nutrient not being tested (*i.e.* basal nutrients) to each plot. Thus, the same amount of potassium (K) and phosphorus (P) was applied to all plots with no account of the amounts removed in harvested crops or the effect of the K balance (K applied minus K removed) or the P balance on plant-available K and P in the soil. This approach led to a major and unexpected problem, and its solution resulted in a major change in the use of P, K and magnesium (Mg) fertilizers, and the maintenance of soil pH and soil nutrient status in this and other Rothamsted experiments.
In 1951-52, the yields of potatoes following lucerne (25.2 t/ha) were less than those following a grazed ley (31.6 t/ha) and only a little better than those in the all-arable rotation (21.8 t/ha). That there was little benefit from the ploughed-in lucerne ley, expected to supply additional N, was unexpected.

Yields of 1st and 2nd year lucerne grown on the same plot in the four 5-year periods starting between 1943 and 1958 are shown in Table 3 above. Yields were larger on plots where FYM had been applied for the preceding potato test crop, *i.e.* three and four years previously, respectively, before the lucerne was sown.

This effect of the FYM residues was unlikely to be a "residual N effect", especially for a leguminous crop, and subsequently crop and soil analysis showed that the increase in yield with FYM residues was due to the extra K added in the FYM. Large amounts of K were being removed in the lucerne and soil K reserves were being depleted, particularly where FYM was not applied. Later measurements suggest that much K was also leached, particularly on plots growing continuous arable crops. To correct this, supplementary applications of K fertilizer were applied to the plots growing lucerne and basal K applications were increased (see below).

To monitor the effect of the K balance on readily-soluble soil K all plots were sampled in 1956, 1957 and 1960. Those sampled in 1957 to a depth of 25.4 cm (10 inches) were analysed for Exchangeable K. Averaged over the five blocks, soils in Continuous Rotations growing continuous arable crops or with lucerne leys contained 57-60 mg/kg exchangeable K and 80-87 mg/kg where FYM was being applied every five years. Where grazed leys were grown the soils contained, on average, 94 and 166 mg/kg exchangeable K on plots without and with FYM respectively. In the current Nutrient Management Guide, RB209 (AHDB, 2020) soils containing < 60 mg/kg exchangeable K are classified in K Index 0 and a strong response to added K would be expected. Soils with 61-120 mg/kg are in K Index 1 and a response to added K would still be expected. Between 121-180 mg/kg (K Index 2-) some crops would still be responsive to added K. A test of additional K fertilizer applied to the 1st Test crop of sugar beet (1956-61) increased the yields of sugar (Rothamsted Experimental Station, 1966).

To avoid a repeat of this confounding deficiency, and similar problems, the decision was taken to maintain an adequate level of plant-available P and K and soil pH (see below) in the top 25 cm (plough depth) of soil in each plot. Starting in autumn 1961, regular sampling and analysis of the soil in the block at the end of the third treatment year was established. Initially, sufficient 'Corrective K' fertilizer was applied to raise the level of exchangeable K in each plot in the sampled block to that of the highest measured value. In addition, from 1962-1967, to balance the amount of K added in the FYM, an equivalent amount of fertilizer K was added to those plots not receiving FYM (see Appendix Table 2). The balancing dressings stopped in 1967 when FYM applications stopped. However, the 'Corrective K' dressings have continued although, since 1988, rather than raising the level of exchangeable K to that of the highest analysed value that year, they are now raised to 250 mg/kg exchangeable K (K Index 3; AHDB, 2020). Although the amounts of basal fertilizer have increased over the years corrective K is always required on some plots, often the all-arable rotations where K might be easily leached (see e-RA, DOI: 10.23637/wrn3-fert1938-2020-01).

Details of the fertilizers applied in the earlier years of the experiment are given in *Details of the Classical and Long-term experiments up to 1962* (Rothamsted Experimental Station; 1966), *Details of the Classical and Long-term experiments up to 1967* (Rothamsted Experimental Station; 1970) and *Details of the Classical and Long-term experiments, 1968-73* (Rothamsted Experimental Station; 1978). In the late-1990s, when it became apparent that atmospheric inputs of sulphur (S) had declined significantly (Zhao *et al.*, 2003) it was decided that potassium sulphate ($K_2SO_4$), which had previously been used from 1938-1943, rather than potassium chloride (KCl), which had been used since 1944, should again be used for some of the basal K applications, and thus some S was also applied. For 2003, applications were revised again so that part of the $K_2SO_4$ requirement was applied in early spring; amounts applied were further increased for 2007 (see Fertilizer Application tables in e-RA DOI: 10.23637/wrn3-fert1938-2020-01). Basal applications of fertilizer P have been sufficient to maintain Olsen P at 26-45 mg/kg (P Index 3; AHDB, 2020); a level at which no further response to fertilizer P would be expected.

For many years, Mg was not applied to the experiment. In 1962 and 1963 applications of magnesium sulphate ($MgSO_4$) were tested on the 1st Test crops of sugar beet. Basal $MgSO_4$ was applied to some crops from 1965 to 1970. After magnesian limestone was introduced in 1971 to maintain soil pH, exchangeable Mg in the soil began to increase rapidly, and by 2003 when calcitic limestone replaced magnesian limestone, (see e-RA; DOI: 10.23637/wrn3-fert1938-2020-01) exchangeable Mg was well in excess of crop requirement. No Mg fertilizer has been required since the magnesian limestone dressings stopped.

**Nitrogen**

The arable treatment crops and the leys receive fertilizer N at an appropriate rate (see Rothamsted Experimental Station 1966; 1970; 1978 and Mann & Boyd, 1958). For many years, the test crops also received N at a rate appropriate to the crop. However, the plots were often split to test an additional factor, e.g. Mg, the effect of additional K, soil fumigants to control stem eelworm, and rates of N. Since 1976, four rates of N (N0, N1, N2, N3) have been tested on the test crops, on quarter plots, at rates appropriate to the crop, the amounts being increased as the yield potential of the crop increased (see section above: '**Change of the first and second test crops to winter wheat and spring barley'**; pages 13-14).

**Liming**

It is thought that occasional dressings of chalk had previously been applied to that part of Stackyard Field on which the Ley-arable experiment was sited in 1938. None was applied to the experiment itself until 1947 when basal applications of chalk were phased in (see e-RA DOI: 10.23637/wrn3-fert1938-2020-01). Soil pH in the 1956 samples ranged from 5.5-7.2. Chalk dressings were gradually increased, and additional chalk was sometimes applied to some plots. In most years between 1971 and 1996, magnesian limestone (Dolomite), rather than chalk, was applied to supply Mg rather than adding Mg as soluble kieserite. After six years when no liming material was applied, basal dressings of chalk were resumed for 2003 (see e-RA DOI: 10.23637/wrn3-fert1938-2020-01). To maintain soil pH ~7, chalk is currently applied at a rate of 5 t/ha in the autumn before the second test crop is sown.

## Monitoring changes in the level of organic matter in the soil of the different rotations

Details of how the soil samples were analysed for their organic carbon (OC) content over a 70-year period has been reported by Johnston (1973) and Johnston *et al*. (2017) The data were a contribution to the question about the possibility of sequestering carbon from atmospheric carbon dioxide into soil organic carbon (SOC) by changes in agricultural cropping patterns (see also Poulton *et al.*; 2018) Sampling soil from the different treatments started in 1956 to determine plant-available K and once this was measured the samples were archived along with site samples that had been taken from each block in 1938. In the 1960s, at a time when it was possible to respond to scientific curiosity and not be constrained by project funding, it was decided to determine % OC in the soils. After four 5-year rotations, *i.e*. after 20 years of contrasted cropping, on the Continuous Rotation plots the data showed that, compared to the all-arable soils, there was more organic matter in the soils with the grazed grass-clover leys, but unexpectedly there was no increase where the lucerne leys had been grown (see above and Fig 2). These observations on SOM in the different cropping systems undoubtedly contributed further to the decision to continue the experiment and monitor the changes in SOC. Subsequent changes in the species composition and duration of the leys and to some of the arable crops grown were made to ensure the sustainability of the experiment and the relevance of the results to farming practice, and these provided additional data for inclusion in the SOM story. Details of the methods of sampling and soil analysis are given in detail by Johnston *et al*. (2017).

## Conclusions

Started in 1938, the Woburn Ley-arable is the oldest experiment of its type in the UK. This paper attempts to detail the important changes that have been made in the management of the experiment to ensure that it remains relevant to current issues in soil fertility, crop yield and carbon storage. In Appendix Table 3 some of these changes are set out in chronological order.

Some of the key findings from the experiment include:

- the importance of the correct crop rotation to minimise soil-borne pests and diseases
- the benefit of fumigation to control nematodes
- the effect of different crops on soil K status in a sandy loam soil prone to leaching
- the need to maintain soil pH and plant-available nutrients such that yield is not limited other than by factors being tested
- the effect of rotations on the response to N and yield of subsequent arable crops
- the effects of leys and FYM on the maintenance or build-up of SOM in a sandy loam soil

In their paper detailing crop yields from 1938-1956, Mann & Boyd (1958) acknowledged that, by the mid-1950s, it was becoming apparent that the amounts of nutrients being applied were inadequate and also, that nematodes were becoming a problem. This led to regular reviews of many aspects of the management of the experiment and to the changes that were made over the next 15-20 years. Consequently, it was not until the 1970s that the original purpose of the experiment *i.e.* to look at the effects of continuous arable or ley-arable rotations on the yield of two following arable "Test" crops, could be re-addressed. By that time significant differences in SOM were becoming apparent; highlighting the need for long-term trials to study trends in those soil factors affecting crop yield which may take decades to become clear.

The Woburn Ley-arable, like other long-term experiment at Woburn and Rothamsted, also provides a platform for additional research. For example, Macdonald *et al.* (1989) used $^{15}$N-labelled fertilizer to look at the source of nitrate in soil at harvest, while Murphy *et al.* (2007) measured microbial biomass, gross N mineralisation and $CO_2$ production on contrasted rotations. All of the publications that use data from the experiment can be found in the e-RA Bibliography (http://www.era.rothamsted.ac.uk/e-RApubs.php). The hope is that this paper will provide background information on the management of the experiment which will be useful to scientists in the future.

## Acknowledgements

We would like to thank farm staff at both Woburn and Rothamsted who have managed the experiment over >80 years, the many scientific staff involved with sample processing and members of the Analytical Unit, the Statistical departments and of e-RA who helped to curate the accumulated data. We also thank the Lawes Agricultural Trust and Rothamsted Research.

The Rothamsted Long-term Experiments National Capability is supported by the UK Biotechnology and Biological Sciences Research Council (BBS/E/C/000J03000).

## References

AHDB (2020) Nutrient Management Guide (RB209) https://ahdb.org.uk/rb209

Anon. 1939-1986. *Yields of the Field Experiments*. Rothamsted Experimental Station, Lawes Agricultural Trust, Harpenden. http://www.era.rothamsted.ac.uk/eradoc/books/2

Anon. 1987-2000. *Yields of the Field Experiments*. IACR-Rothamsted, Lawes Agricultural Trust, Harpenden. http://www.era.rothamsted.ac.uk/eradoc/books/2

Anon. 2001-2002. *Results of the Classical and Other Long-term Experiments*. IACR-Rothamsted, Lawes Agricultural Trust, Harpenden. http://www.era.rothamsted.ac.uk/eradoc/books/2

Anon. 2003-2020. *Results of the Classical and Other Long-term Experiments*. Rothamsted Research, Lawes Agricultural Trust, Harpenden. http://www.era.rothamsted.ac.uk/eradoc/books/2

Boyd, D.A. 1968. Experiments with ley and arable farming systems. *Rothamsted Experimental Station Report for 1967*, 316-331. DOI: 10.23637/ERADOC-1-58947

Catt, J.A, Weir, A.H, Norrish, R.E, Rayner, J.H, King, D.W, Hall, D.G.M et al. (1980) The soils of Woburn experimental farm. III. Stackyard. *Rothamsted Experimental Station Report for 1979*, Part 2, pp. 5-40. DOI: 10.23637/ERADOC-1-34287

Eagle, D.J. (1975) ADAS ley fertility experiments. In: *Soil Physical Conditions and Plant Growth*, MAFF Technical Bulletin 29. pp. 344-360. HMSO, London

F.A.O. (1990) F.A.O.-UNESCO Soil Map of the World: revised Legend. World Soil Resources Report 60. Rome.

Johnston, A.E. (1973) The effects of ley and arable cropping systems on the amounts of soil organic matter in the Rothamsted and Woburn Ley-arable experiments. *Rothamsted Experimental Station. Report for 1972*, Part 2, 131-159. DOI: 10.23637/ERADOC-1-34692

Johnston, A.E. and Garner, H.V. (1969). The Broadbalk Wheat Experiment: Historical Introduction. *Rothamsted Experimental Station Report for 1968*, Part 2, 12-17. DOI: 10.23637/ERADOC-1-34916

Johnston, A.E., Poulton, P.R. & Coleman, K. (2009) Soil organic matter: its importance in sustainable agriculture and carbon dioxide fluxes. *Advances in Agronomy*, **101**, pp.57 DOI: 10.1016/s0065-2113(08)00801-8

Johnston, A.E., Poulton, P.R., Coleman, K., Macdonald, A.J. & White, R.P. (2017) Changes in soil organic matter over 70 years in continuous arable and ley-arable rotations on a sandy loam soil in England. *European Journal of Soil Science*, **68**, 305-316. DOI: 10.1111/ejss.12415

Lowe, A.J. (1975) Ley fertility experiments at Jealott's Hill. In: *Soil Physical Conditions and Plant Growth*, MAFF Technical Bulletin 29, pp.360-388. HMSO, London.

Macdonald, A., Poulton, P., Clark, I., Scott, T., Glendining, M., Perryman, S., Storkey, J., Bell, J., Shield, I., McMillan, V. and Hawkins, J. (2018) Guide to the Classical and Other Long-term experiments, Datasets and Sample Archive. Rothamsted Research, pp57. DOI: 10.23637/ROTHAMSTED-LONG-TERM-EXPERIMENTS-GUIDE-2018

Macdonald, A.J., Powlson, D.S., Poulton, P.R. & Jenkinson, D.S. (1989) Unused fertiliser nitrogen in arable soils – its contribution to nitrate leaching. *Journal of the Science of Food and Agriculture*, **46**, 407-419.

Mann, H.H. (1956) Potato root eelworm at Woburn. *Rothamsted Experimental Station Report for 1956*, 206-207. DOI: 10.23637/ERADOC-1-59486

Mann, H.H., & Boyd, D.A. (1958) Some results of an experiment to compare ley and arable rotations at Woburn. *Journal of Agricultural Science*, **50**, 297-306. DOI: 10.1017/S002185960003149X

Murphy, D.V., Stockdale, E.A., Poulton, P.R., Willison, T.W. & Goulding, K.W.T.G. (2007) Seasonal dynamics of carbon and nitrogen pools and fluxes under continuous and ley-arable rotations in a temperate environment. *European Journal of Soil Science*, **58**, 1410-1424. DOI: 10.1111/j.1365-2389.2007.00946.x

Poulton, P.R. & Johnston, A.E. (2021) Can long-term experiments help us understand and, and manage, the wider landscape – examples from Rothamsted, England. In: *Exploring and Optimizing Agricultural Landscapes.* Eds. L. Mueller, V.G. Sychev, N.M. Dronin, F. Eulenstein. Innovations in Landscape Research. Springer Nature, Switzerland, 233-252. DOI: 10.1007/978-3-030-67448-9_9

Poulton, P., Johnston, J., Macdonald, A., White, R. & Powlson, D. (2018) Major limitations to achieving "4 per 1000" increases in soil organic carbon stock in temperate regions: Evidence from long-term experiments at Rothamsted Research, United Kingdom. *Global Change Biology*, **24**, 2563-2584. DOI: 10.1111/gcb.14066

Rothamsted Experimental Station (1966) *Details of the Classical and Long-term experiments up to 1962.* Lawes Agricultural Trust, Harpenden. pp. 87. DOI: 10.23637/ERADOC-1-191

Rothamsted Experimental Station (1970) *Details of the Classical and Long-term experiments up to 1967.* Lawes Agricultural Trust, Harpenden. pp. 128. DOI: 10.23637/ERADOC-1-192

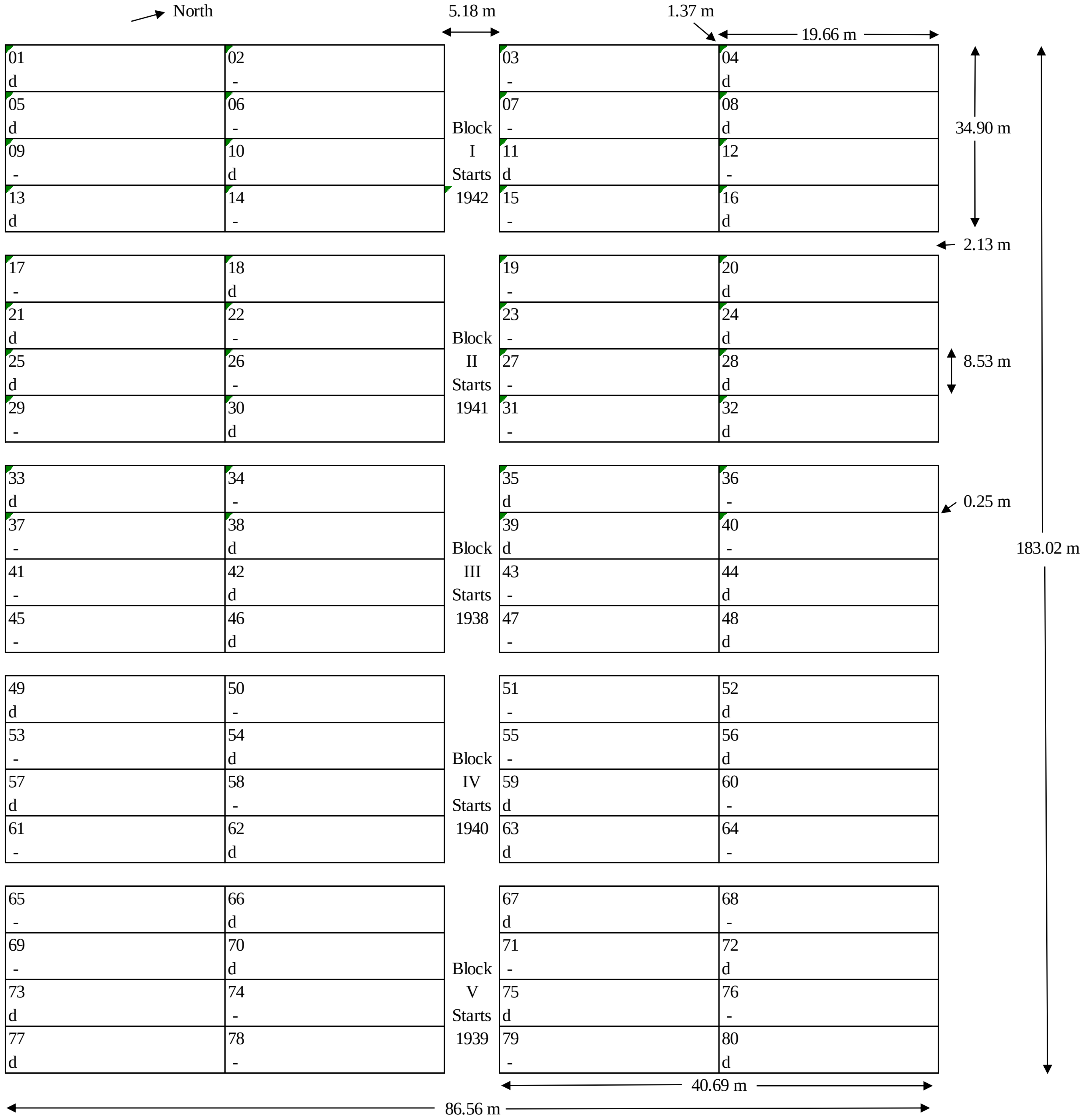
Rothamsted Experimental Station (1978) *Details of the Classical and Long-term experiments 1968-73.* Lawes Agricultural Trust, Harpenden. pp. 77. DOI: 10.23637/ERADOC-1-193

Salt, G.A. (1959). Eyespot in wheat in ley-arable experiments at Rothamsted, 1952-58. *Plant Pathology*, 8, 59-62. DOI: 10.1111/j.1365-3059.1959.tb00875.x

Zhao, F. J., Knights, J. S., Hu, Z. Y. and McGrath, S. P. (2003) Stable sulfur isotope ratio indicates long-term changes in sulfur deposition in the Broadbalk experiment since 1845, Journal of Environmental Quality, 32, (1), 33-39. DOI: 10.2134/jeq2003.3300

## See Appendix Figure 1 and Appendix Tables 1, 2 & 3 below

**Appendix Figure 1** Plan of the Woburn Ley-arable experiment




d = plots receiving dung (FYM) every five years until the mid-1960s.

**Appendix Table 1** Treatment crops and test crops[a], 1938–2020, Block III[b], Woburn ley–arable experiment.

| | Continuous rotations | | | | Alternating rotations[g] then 8–year leys[h] | | | |
|---|---|---|---|---|---|---|---|---|
| | Arable | | Ley–arable | | 1st cycle | | 2nd cycle | |
| Year | AB[c] | AF[d] | LN3[e] | LC3[f] | LN8[i] | LC8[j] | LN8[k] | LC8[l] |
| 1938 | P | P | L1 | Lu1 | P | P | Lu1 | L1 |
| 1939 | W | W | L2 | Lu2 | W | W | Lu2 | L2 |
| 1940 | H | K | L3 | Lu3 | K | H | Lu3 | L3 |
| 1941 | P | P | P | P | P | P | P | P |
| 1942 | B | B | B | B | B | B | B | B |
| 1943 | P | P | L1 | Lu1 | Lu1 | L1 | P | P |
| 1944 | W | W | L2 | Lu2 | Lu2 | L2 | W | W |
| 1945 | H | SBe | L3 | Lu3 | Lu3 | L3 | SBe | H |
| 1946 | P | P | P | P | P | P | P | P |
| 1947 | B | B | B | B | B | B | B | B |
| 1948 | P | P | L1 | Lu1 | P | P | L1 | Lu1 |
| 1949 | R | R | L2 | Lu2 | R | R | L2 | Lu2 |
| 1950 | H | SBe | L3 | Lu3 | H | SBe | L3 | Lu3 |
| 1951 | P | P | P | P | P | P | P | P |
| 1952 | B | B | B | B | B | B | B | B |
| 1953 | P | P | L1 | Lu1 | L1 | Lu1 | P | P |
| 1954 | R | R | L2 | Lu2 | L2 | Lu2 | R | R |
| 1955 | H | SBe | L3 | Lu3 | L3 | Lu3 | H | SBe |
| 1956 | SBe | SBe | SBe | SBe | SBe | SBe | SBe | SBe |
| 1957 | B | B | B | B | B | B | B | B |
| 1958 | P | P | L1 | Lu1 | P | P | Lu1 | L1 |
| 1959 | R | R | L2 | Lu2 | R | R | Lu2 | L2 |
| 1960 | H | C | L3 | Lu3 | H | C | Lu3 | L3 |
| 1961 | SBe | SBe | SBe | SBe | SBe | SBe | SBe | SBe |
| 1962 | B | B | B | B | B | B | B | B |
| 1963 | P | P | L1 | Lu1 | Lu1 | L1 | P | P |
| 1964 | R | R | L2 | Lu2 | Lu2 | L2 | R | R |
| 1965 | H | C | L3 | S | S | L3 | C | H |
| 1966 | SBe | SBe | SBe | SBe | SBe | SBe | SBe | SBe |
| 1967 | B | B | B | B | B | B | B | B |
| 1968 | P | P | L1 | S1 | P | P | L1 | S1 |
| 1969 | R | R | L2 | S2 | R | R | L2 | S2 |
| 1970 | H | C | L3 | S3 | C | H | L3 | S3 |
| 1971 | P | P | P | P | P | P | P | P |
| 1972 | W | W | W | W | W | W | W | W |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 1973 | P | P | Ln1 | Lc1 | Ln1 | Lc1 | P | P |
| 1974 | B | B | Ln2 | Lc2 | Ln2 | Lc2 | B | B |
| 1975 | H | B | Ln3 | Lc3 | Ln3 | Lc3 | H | B |
| 1976 | W | W | W | W | Ln4 | Lc4 | W | W |
| 1977 | B | B | B | B | Ln5 | Lc5 | B | B |
| 1978 | B | F | Ln1 | Lc1 | Ln6 | Lc6 | Ln1 | Lc1 |
| 1979 | B | F | Ln2 | Lc2 | Ln7 | Lc7 | Ln2 | Lc2 |
| 1980 | O | O | Ln3 | Lc3 | Ln8 | Lc8 | Ln3 | Lc3 |
| 1981 | W | W | W | W | W | W | Ln4 | Lc4 |
| 1982 | B | B | B | B | B | B | Ln5 | Lc5 |
| 1983 | B | F | Ln1 | Lc1 | Ln1 | Lc1 | Ln6 | Lc6 |
| 1984 | B | F | Ln2 | Lc2 | Ln2 | Lc2 | Ln7 | Lc7 |
| 1985 | BE | BE | Ln3 | Lc3 | Ln3 | Lc3 | Ln8 | Lc8 |
| 1986 | W | W | W | W | Ln4 | Lc4 | W | W |
| 1987 | B | B | B | B | Ln5 | Lc5 | B | B |
| 1988 | B | F | Ln1 | Lc1 | Ln6 | Lc6 | Ln1 | Lc1 |
| 1989 | B | F | Ln2 | Lc2 | Ln7 | Lc7 | Ln2 | Lc2 |
| 1990 | BE | BE | Ln3 | Lc3 | Ln8 | Lc8 | Ln3 | Lc3 |
| 1991 | W | W | W | W | W | W | Ln4 | Lc4 |
| 1992 | R | R | R | R | R | R | Ln5 | Lc5 |
| 1993 | B | F | Ln1 | Lc1 | Ln1 | Lc1 | Ln6 | Lc6 |
| 1994 | B | F | Ln2 | Lc2 | Ln2 | Lc2 | Ln7 | Lc7 |
| 1995 | BE | BE | Ln3 | Lc3 | Ln3 | Lc3 | Ln8 | Lc8 |
| 1996 | W | W | W | W | Ln4 | Lc4 | W | W |
| 1997 | R | R | R | R | Ln5 | Lc5 | R | R |
| 1998 | R | R | Ln1 | Lc1 | Ln6 | Lc6 | Ln1 | Lc1 |
| 1999 | M | BE | Ln2 | Lc2 | Ln7 | Lc7 | Ln2 | Lc2 |
| 2000 | BE | M | Ln3 | Lc3 | Ln8 | Lc8 | Ln3 | Lc3 |
| 2001 | W | W | W | W | W | W | Ln4 | Lc4 |
| 2002 | R | R | R | R | R | R | Ln5 | Lc5 |
| 2003 | R | R | Ln1 | Lc1 | Ln1 | Lc1 | Ln6 | Lc6 |
| 2004 | M | BE | Ln2 | Lc2 | Ln2 | Lc2 | Ln7 | Lc7 |
| 2005 | BE | M | Ln3 | Lc3 | Ln3 | Lc3 | Ln8 | Lc8 |
| 2006 | W | W | W | W | Ln4 | Lc4 | W | W |
| 2007 | R | R | R | R | R | R | R | R |
| 2008 | R | R | Ln1 | Lc1 | R | R | Ln1 | Lc1 |
| 2009 | O | BE | Ln2 | Lc2 | BE | O | Ln2 | Lc2 |
| 2010 | BE | O | Ln3 | Lc3 | O | BE | Ln3 | Lc3 |
| 2011 | W | W | W | W | W | W | W | W |
| 2012 | R | R | R | R | R | R | R | R |
| 2013 | R | R | Ln1 | Lc1 | R | R | Ln1 | Lc1 |
| 2014 | O | BE | Ln2 | Lc2 | BE | O | Ln2 | Lc2 |
| 2015 | BE | O | Ln3 | Lc3 | O | BE | Ln3 | Lc3 |
| 2016 | W | W | W | W | W | W | W | W |
| 2017 | R | R. | R | R | R. | R | R | R |
| 2018 | R | R | Ln1 | Lc1 | R | R | Ln1 | Lc1 |
| 2019 | O | BE | Ln2 | Lc2 | BE | O | Ln2 | Lc2 |
| 2020 | BE | O | Ln3 | Lc3 | O | BE | Ln3 | Lc3 |

P, potatoes: W, winter wheat: H, 1–year hay: K, kale: B, spring barley: SBe, sugar beet: R, winter rye: C, carrots: F, fallow: O, winter oats: BE, winter beans: M, maize: L1–L3, grazed grass+clover: Lu1–Lu3, lucerne: S1–S3, sainfoin: Ln1–Ln8, grass: Lc1–Lc8, grass+clover.

Each of the eight rotations (AB, AF *etc.* ) were grown on pairs of plots in each of five blocks. One plot in each pair received FYM; 38 t ha$^{-1}$ applied every fifth year to the first test crop of potatoes or sugar beet. Applications of FYM stopped when sugar beet was replaced as the first test crop in the mid-1960s. The last applications of FYM were to Blocks IV, II, I, III and V in 1963, 1964, 1965, 1966 and 1967 respectively.

[a] Test crops are highlighted. Plots were divided to test four rates of N when test crops were grown. The rates of N rotated so that, over time, the C inputs on the four subplots were similar.

[b] Treatment cropping started in 1938 on Block III, and in 1939, 1940, 1941, 1942 on Blocks V, IV, II and I respectively.

[c] AB treatment crops: potatoes, cereal, 1–year hay from 1938–75; barley, barley, beans (or oats) from 1978–95; rye, maize, beans since 1998; rye, oats beans since 2008.

[d] AF treatment crops: potatoes, cereal, root crop from 1938–75; fallow, fallow, beans from 1978–95; rye, beans, maize since 1998; rye beans oats since 2008.

[e] LN3 treatment crop: 3–year grazed grass+clover leys with N from 1938–70; 3–year grass leys with N since 1973.

[f] LC3 treatment crop: 3–year lucerne or sainfoin leys from 1938–70; 3–year grass+clover leys since 1973.

[g] On four pairs of plots treatment crops alternated between arable and ley rotations.

[h] The alternating rotations were replaced by 8–year grass leys with N or 8–year grass+clover leys. The 1st cycle of these longer leys started in 1973 on Block III and in 1974, 1975, 1976, 1977 on Blocks V, IV, II and I respectively. The 2nd cycle of 8-yr leys started in 1978 on Block III and in 1979, 1980, 1981, 1982 on Blocks V, IV, II and I respectively. The delay in starting the 2nd cycle of 8–year leys meant that the effects of all of the different treatment rotations on the yield of the following test crops could be measured every five years.

[i] LN8 treatment crop: alternating treatment crops from 1938–70; 8–year grass leys with N since 1973 (1st cycle); Ln8/AO from 2008 i.e. 8-yr leys stopped and replaced with rye, beans, oats as treatment crops.

[j] LC8 treatment crop: alternating treatment crops from 1938–70; 8–year grass+clover leys since 1973 (1st cycle). Lc8/ABe from 2008 i.e. 8-yr leys stopped and replaced with rye, oats, beans as treatments crops.

[k] LN8 treatment crop: alternating treatment crops from 1938–75; 8–year grass leys with N since 1978 (2nd cycle). Ln8/Ln3 from 2008 i.e. 8-yr leys stopped and replaced with 3-yr grass ley with N as treatment crop.

[l] LC8 treatment crop: alternating treatment crops from 1938–75; 8–year grass+clover leys since 1978 (2nd cycle). Lc8/Lc3 from 2008 i.e. 8-yr leys stopped and replaced with 3-yr grass/clover leys as treatment crops.

**Appendix Table 2** FYM[a] applications and K content[b], Woburn Ley-arable experiment.

| | Harvest year and K content | | | | | |
|---|---|---|---|---|---|---|
| Block III | 1941 | 1946 | 1951 | 1956 | 1961 | 1966 |
| K content, kg/ha | (334) | (334) | (334) | 440 | 257 | 500 |
| Block V | 1942 | 1947 | 1952 | 1957 | 1962 | 1967 |
| K content, kg/ha | (334) | (334) | (334) | 332 | 279 | 202 |
| Block IV | 1943 | 1948 | 1953 | 1958 | 1963 | - |
| K content, kg/ha | (334) | (334) | (334) | 343 | 333 | |
| Block II | 1944 | 1949 | 1954 | 1959 | 1964 | - |
| K content, kg/ha | (334) | (334) | (334) | 241 | 386 | |
| Block I | 1945 | 1950 | 1955 | 1960 | 1965 | - |
| K content, kg/ha | (334) | (334) | (334) | 222 | 340 | |

[a] FYM, 37.7 t/ha, applied every 5 years for the 1st Test crop (potatoes or sugar beet). Until 1966 the manure was from pigs; in 1967 from bullocks. Average dry matter of the manure was 21.5%

[b] The K content of the manure was used to calculate the balancing fertilizer K dressing applied for harvest years 1962-67 to those plots not receiving FYM. The actual amount of balancing fertilizer K applied can be found 'Details of the Classical and Long-term experiments up to 1967' p.112 (DOI: 10.23637/ERADOC-1-192) and in the Corrective K and Balancing dressings table (DOI: 10.23637/wrn3-fert1938-2020-01).

Note: The manures were not analysed between 1941 and 1955; the values shown above in parentheses are the mean K content of those analysed between 1956 and 1966 *i.e.* excluding 1967 which was made from bullocks rather than pigs.

**Appendix Table 3** Significant developments in the Woburn Ley-arable experiment.

| Year | Changes in management |
|---|---|
| 1938 | Experiment established on Stackyard Field at Woburn on a site that had been in arable cropping, probably since the 1820s. It comprises 40 pairs of main plots in five blocks which were phased in over a 5-yr period. On half of the plots four "Continuous" rotations compared the effects of a 3-yr grazed grass/clover ley (L), a 3-yr lucerne ley (Lu), a 3-yr arable rotation which included a 1-yr hay crop (Ah) and a 3-yr arable rotation which included root crops (Ar), the "Treatment" crops, on the yield of two arable "Test" crops. On the other plots the ley and arable "Treatment" crops alternated; the "Alternating" rotations. A test of FYM, applied to the 1st "Test" crop, was also included on one of each pair of main plots. The "Test" crops were potatoes followed by spring barley. The layout of the experiment is shown in Appendix Figure 1 above. |
| 1947 | Calcium carbonate applications started. |
| 1955 | Plots in 1st “Test" crop, potatoes, divided to test additional N and K. |
| 1956 | Sugar beet replaced potatoes as the 1st "Test" crop. The two arable treatment rotations were also altered to minimise the effects of soil-borne pathogens. |
| 1959 | Combine harvester used for the first time. |
| 1960-62 | Various fumigants tested for control of stem eelworm (*Ditylenchus dipsaci).* |
| 1962 | Corrective K and Balancing applications started. |
| 1965 | Sainfoin (S) replaced lucerne. |
| 1967 | FYM applications to the 1st "Test" crop stopped; Balancing applications also stopped. |
| 1968 | Spring barley replaced sugar beet as the 1st "Test" crop. |
| 1968-73 | Various fumigants tested for control of potato cyst nematodes. |
| 1968-96 | Magnesian limestone (to supply Mg) replaced calcium carbonate in most years. |
| 1971 | Clover (Cl) replaced sainfoin. |
| 1973-78 | After much discussion major changes were made to the experiment.<br>Grazed grass/clover leys (L) became grass leys + N (Ln) and leys previously in lucerne (Lu), sainfoin (S) or clover (Cl) became grass/clover leys (Lc). The "Alternating" rotations were stopped and two cycles of 8-yr leys followed by the 2-yr "Test" crops were introduced; the first cycle started (retrospectively) in 1973, the second cycle in 1978. The 8-yr leys were either grass + N (LLn) or grass/clover (LLc). Plots in "Test" crops routinely divided to test four rates of N. |
| 1976-77 | The two "Test" crops changed to winter wheat and spring barley. |

| | |
|---|---|
| 1978 | The treatment crops in the arable with roots rotation (Ar) was replaced by a rotation which included two fallows (AF) and the arable with hay rotation (Ah) was replaced by a rotation with only arable crops (AB). |
| 1981-82 | First comparison of the two "Test" crops after 8-yr leys, 3-yr leys and arable "Treatment" crops. The plots in "Test" crops were divided to test four rates of fertilizer N. |
| 1992 | Winter rye replaced spring barley as the second "Test" crop. |
| 1998 | The arable treatment crops changed. Fallow, fallow, beans (AF) became rye, beans, maize (AM) and barley, barley, beans (ABe) became rye, maize, beans (ABe); *i.e.* the same three crops grown in a different order such that the following "Test" crop of wheat followed either a non-legume or a legume. |
| 2002 | Calcium carbonate replaced Magnesian limestone (after six years without liming). |
| 2006/7 | In 2006 it was decided to end the 8-yr leys after both cycles had completed three 10-yr rotations. Thus, in 2008 plots previously in the 1st cycle of 8-yr leys started to follow the same rotations as the two continuous arable rotations, whilst those in the 2nd cycle went into a 3-yr grass + N or 3-yr grass/clover rotation *i.e.* the same four rotations as the "Continuous" plots but on soils with more SOM. |
| 2009 | Maize in the arable rotations replaced by oats. AM becomes AO, ABe remains the same code. |

Note: not all changes are given; for more detail see Rothamsted Experimental Station (1966; 1970; 1978) and DOI 10.23637/wrn3-cropping1938-2020-01 and DOI: 10.23637/wrn3-fert1938-2020-01