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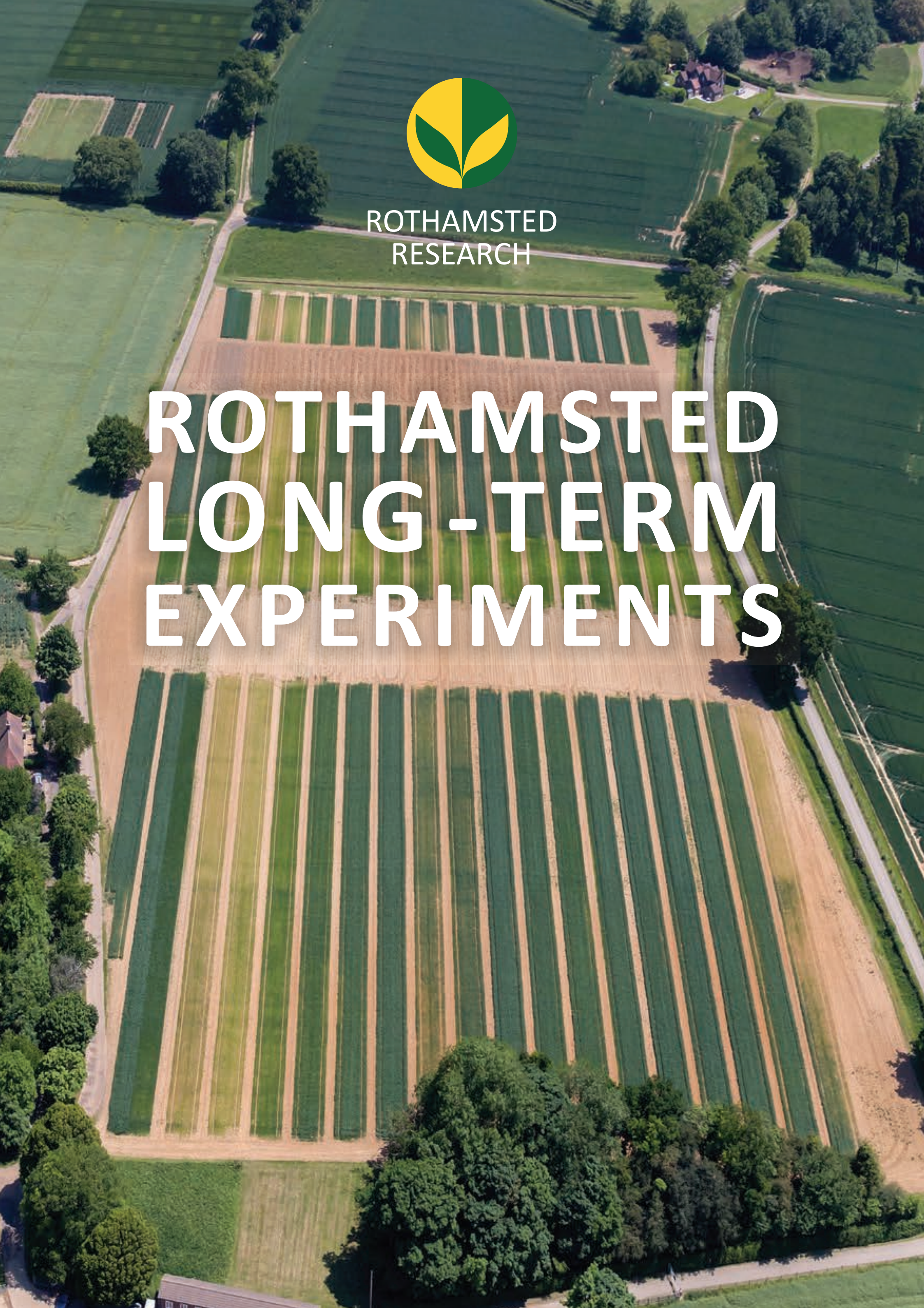

ROTHAMSTED RESEARCH

# ROTHAMSTED LONG-TERM EXPERIMENTS

ROTHAMSTED
RESEARCH

# Guide to the Classical and other Long-term experiments, Datasets and Sample Archive


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**Front cover**
Broadbalk from the air, 2015

**Back cover**
Park Grass from the air, 2015




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# FOREWORD

It is a testament to the foresight and commitment of Sir John Lawes and Sir Henry Gilbert, as well as others who have come after them, that field experiments established as long as 175 years ago continue to reveal new insights and important findings of relevance to today's agriculture and its interactions with our ever-changing environment. At Rothamsted, our tradition has been to not only make these unique resources available to researchers from all over the world, but also use them for answering new questions, with new scientific methods and techniques. Hence, the classical experiments and other long-term studies provide a vital reservoir for advancing science and we hope that this will continue for many more decades to come.

Managing and documenting these experiments and their associated data and archives is not a trivial task. It requires funding, rigour, adaptation, and – most importantly – people who are dedicated to them. I am grateful to Andy Macdonald and his colleagues for assembling this much revised summary of Rothamsted's long-term experiments which, I am sure, will be of great value to the scientific community and the public at large.

**ACHIM DOBERMANN**

**Director**
**April 2018**

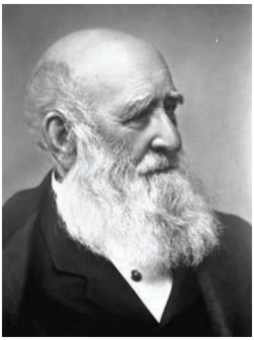
By reaper-binder in 1935


Harvesting wheat on Broadbalk by small-plot combine, 2017

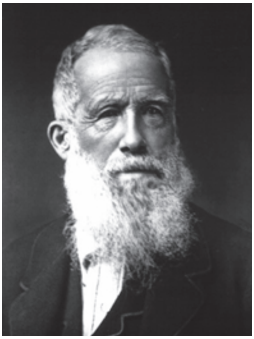
# INTRODUCTION

The Classical experiments is the name now given to those experiments started by Lawes and Gilbert between 1843 and 1856, and which still continue. Although they were not intended to be long-term, Lawes and Gilbert realised that much useful information could be gained by continuing them over many growing seasons. Nine experiments were continued of which they abandoned only one, in 1878. Some treatments were changed during the first few years and, later, further changes were made to answer specific questions raised by the results. In particular, two Wilderness studies were established in the 1880s to examine the effects of abandoning arable land. When Lawes died in 1900, the eight remaining experiments were continuing more or less as originally planned. Modifications have been made to the experiments since Lawes died, in some cases discontinuing the original treatments. Seven of the Classical experiments continue today. They are the oldest, continuous agronomic experiments in the world.

Their main objectives were to measure the effects on crop yields of inorganic compounds containing nitrogen, phosphorus, potassium, sodium and magnesium (N, P, K, Na and Mg), elements known to occur in considerable amounts in crops and farmyard manure (FYM), but whose separate actions as plant nutrients had not been studied systematically. The materials used were superphosphate (first made at Rothamsted by treating bones with sulphuric acid), the sulphates of K, Na and Mg (often referred to then, and in this Guide, as minerals), and ammonium salts and sodium nitrate (as alternative sources of nitrogen). The effects of these inorganic fertilisers were compared with those of FYM and rape cake in most of the experiments. The inorganic fertilisers were tested alone and in various combinations. Nitrogen was often applied at two or more rates.



Sir Joseph Henry Gilbert



Sir John Bennet Lawes

Growing the same crop each year on the same land was a feature of many of the experiments. Considered bad farming in the nineteenth century, Lawes and Gilbert reasoned that it was the best way to learn about individual crop nutrient requirements. Lawes and Gilbert recorded the yields of all produce harvested from each plot and samples were kept for chemical analyses. These results, together with details of the quantity and composition of each fertiliser applied, enabled a balance sheet for the major nutrients to be compiled for each plot. Analyses of soil samples showed how N, P and K accumulated or diminished in soil depending on fertiliser or manure applications, offtakes in crops and losses in drainage water.

The results were of immediate importance to farmers, showing which nutrients had the largest effects on different crops. However, the value to farmers of later results diminished as the contrasted processes of depletion and enrichment of nutrients went on. In addition, the annual applications of FYM caused the soil organic matter contents of fertiliser- and FYM-treated soils to become increasingly different. Until *c*.1939 the best yields on each experiment were similar to the average yields of the same crops grown on English farms. After 1939, with the introduction of higher yielding cultivars and increased use of fertilisers, farm yields in England exceeded those of the Classicals until changes to the latter were made in the 1960s.

The Classical experiments have been modified occasionally since Lawes's death. Daniel Hall, in 1903–06, added a few plots to Broadbalk, Park Grass and Barnfield; mainly to test the effects of P in the presence of NKNaMg, which had been omitted from these experiments. Hall also instigated the first regular liming scheme on Park Grass; the only Classical experiment not sited on a neutral or slightly calcareous soil. Most of the arable experiments are on fields that had received the traditional heavy dressings of locally-dug chalk, a practice not followed on grassland.

By the late 1940s there was increasing concern that the soils in a number of plots receiving ammonium sulphate in the Classical experiments were becoming so acid that yields were adversely affected. Thus, comparisons of ammonium sulphate and sodium nitrate as N sources were no longer possible. In the Agdell rotation experiment, acidity became so severe on the NPK plots that the fungal disease club root (*Plasmodiophora brassicae*) so decreased yields of turnips that the experiment had to be extensively modified in 1951. Over the next few years, soil acidity on the arable experiments was corrected by differential lime (chalk) applications, and a schedule of liming was started to prevent acidity developing again. Following these changes it was decided to assess the value of the reserves of soil P and K accumulated in the Agdell and Exhaustion Land experiments by both soil analysis and crop yield. On Barnfield, not only was the value of the P and K reserves tested but also the benefit of the extra soil organic matter (SOM) in the FYM-treated soils. These tests were made by sub-dividing the original large plots into sub-plots to test fresh applications of N, P and K as appropriate.

These changes provided much new and valuable information. Consequently, in the mid-1960s, discussions started about modifications to the Broadbalk, Hoosfield Barley and Park Grass experiments to make the treatments and the results more relevant to farming practice at that time. The management, cropping and treatments on these experiments were reviewed and modifications introduced to ensure that, as far as possible, the experiments remained relevant to farming practice but without losing their long-term integrity. One important change, made on all the cereal experiments, was the replacement of long-strawed cultivars with modern, short-strawed varieties that had greater potential grain yield. Another major change, introduced in 1968, except on Park Grass, was the replacement of ammonium sulphate and sodium nitrate by ammonium nitrate, initially as 'Nitro-Chalk' (calcium ammonium nitrate), now as 'Nitram' (ammonium nitrate). More recent changes are detailed later.

In addition to the Classical experiments started by Lawes and Gilbert, there are (or were) several other long-term experiments on the flinty silty clay loam (Avery & Catt, 1995) at Rothamsted and at two other sites, Woburn and Saxmundham, on contrasting soil types. On the sandy loam soil (Catt *et al*. 1975, 1977, 1980) at Woburn Experimental Farm, the Royal

Agricultural Society of England (RASE) started experiments in 1876 to compare different animal feeds, and assess the residual values of the dungs as sources of plant nutrients (to test the validity of Lawes and Gilbert's findings). In addition, RASE started other experiments on wheat and barley grown continuously. On a heavy sandy clay loam soil at Saxmundham, Suffolk (Hodge, 1972), two long-term rotation experiments were started by East Suffolk County Council in 1899. These were extensively modified when Rothamsted took over the site in 1964 and have provided much valuable data on crop responses to P and K on a heavier soil. Rothamsted relinquished the lease on the Saxmundham site in 2010. Although now discontinued, samples and data from these and other discontinued experiments are retained for future use.

With remarkable prescience, Lawes and Gilbert retained samples of crops and soils taken for chemical analysis once the initial analyses had been completed. Successive generations of scientists at Rothamsted have continued to add to the collection and the resulting Rothamsted Sample Archive (RSA) now comprises > 300,000 samples. This unique resource is of immense value; analyses of archived material allow us to generate new data stretching back more than 175 years.

The collection of long-term datasets is not confined to the Classical and other long-term field experiments. Meteorological measurements have been made since the 1850s, when Lawes and Gilbert first collected and analysed rain-water. With current concerns over climate change the long-term weather records provide invaluable information about the climatic conditions under which the crops have been grown. Rothamsted has also been monitoring insect populations since 1964. The Rothamsted Insect Survey comprises national networks of light traps, to record moths, and suction traps, principally to monitor migrating aphids. It provides the most extensive long-term quantitative datasets on insect populations in the world.

Sample archive, 1930s

Rothamsted (and North Wyke Research, which merged with Rothamsted Research in 2009) are two of the lead sites within the Environmental Change Network (ECN), which comprises 11 terrestrial sites and > 40 freshwater sites across the UK. The ECN sites monitor a large number of pollutants and climate change variables and the associated effects on soil, vegetation, insects and mammals.

The Electronic Rothamsted Archive (e-RA) is being continually updated to increase the amount of numerical and descriptive data included from the long-term experiments and ECN. In time this will allow ready access to the large volume of data that has been accumulated at Rothamsted since 1843.

## Broadbalk Winter Wheat

Broadbalk field is thought to have been in arable cropping for many centuries prior to 1843. The first experimental crop of winter wheat was sown in autumn of that year and harvested in 1844 (by convention, when we refer to a year it is the harvest year unless stated otherwise). Every year since then, wheat has been sown and harvested on all or part of the field. Inorganic fertilisers supplying the elements N, P, K, Na and Mg in various combinations were compared with organic manures (FYM and rape cake, later replaced by castor bean meal) and a control treatment that received no fertiliser or manure inputs. For the first few seasons these treatments were varied a little but in 1852 a scheme was established that remained largely unaltered until 1968 (Table 1). In the early years the field was ploughed in 'lands' by oxen (later by horses) and all the crop from each plot was cut with scythes, bound into sheaves and carted into the barns to await threshing. Yields of grain and straw were recorded and samples kept for chemical analysis. Broadbalk is now ploughed by a tractor-mounted five-furrow reversible plough and harvested by a small plot combine harvester; only the central area (2m wide) located along the length of each plot is cut for yield and samples.

Weeds were initially controlled by hand-hoeing. When this became impracticable, five 'Sections', (I–V on plan), crossing all the treatment strips (initially called plots) at right angles, were made and bare fallowed sequentially (Plan 1). Fallowing was mainly in a 5-year rotation of fallow with four successive crops of wheat, with each phase present each year. Herbicides have been used since 1964 on all of the experiment, except for half of Section V (now Section 8; see later).

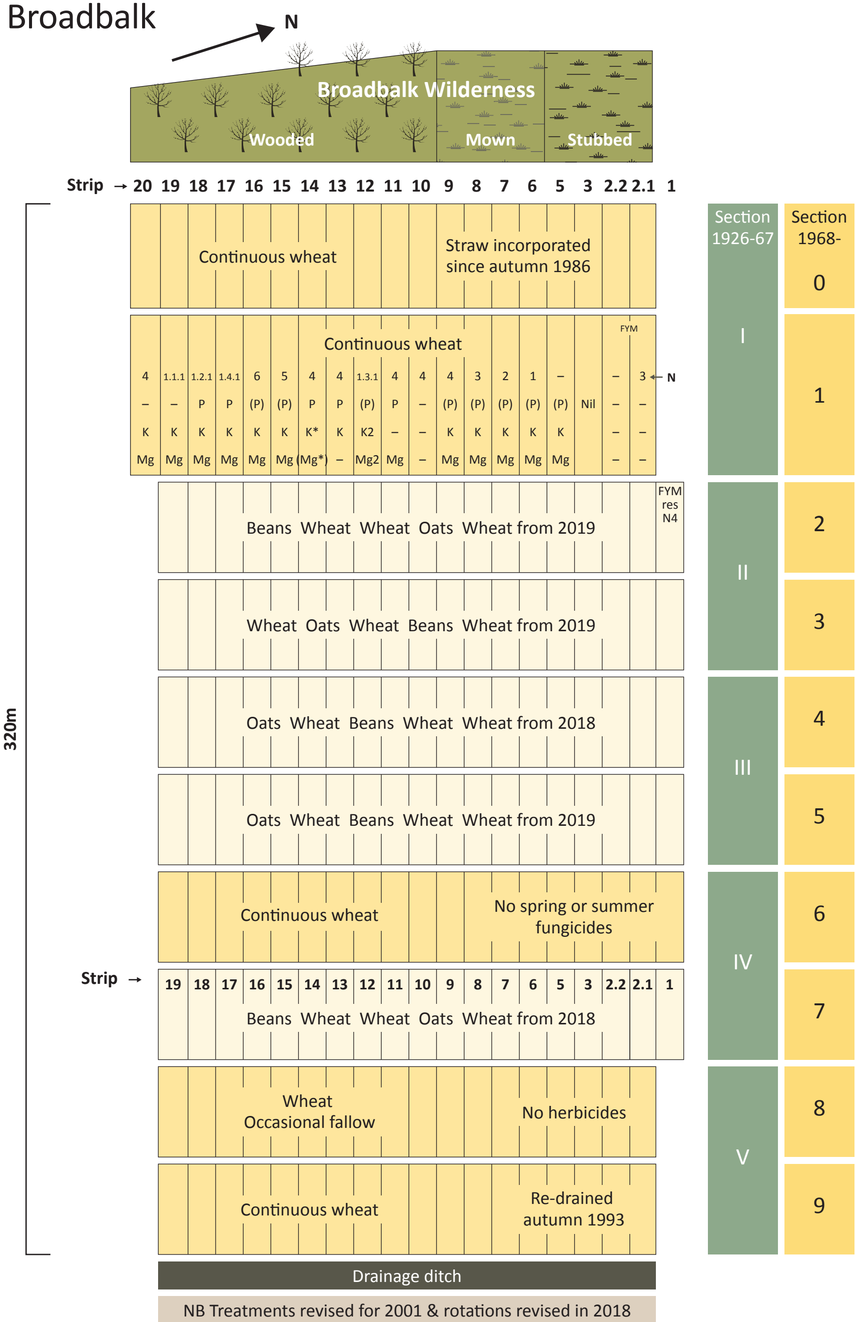
Chalk has been applied intermittently since the 1950s to maintain soil pH at a level at which crop yield is not limited.

Details of, and results from the experiment, up to 1967 can be found in the Report for Rothamsted Experimental Station for 1968, Part 2 (1969).

After correction of soil acidity on parts of the experiment in the 1950s, a review of the treatments and management led to modifications being introduced in 1968. The most significant of these were i) the change from long-strawed to modern, short-strawed cultivars of wheat with a greater grain yield potential and ii) the division of Sections I – V to create 10 new Sections 0 – 9 (Plan 1 and Table 1), so that the yield of wheat grown continuously could be compared with that of wheat grown in rotation after a two-year break. We continue to review the experiment regularly and to make changes, but only when there is a strong scientific case for doing so. An important change, made for the 2000 season, was to withhold P fertiliser from selected plots. This will allow plant-available P (Olsen P) to decline to a level which is suitable for achieving maximum yield whilst reducing the chance of P being lost in drainage water. Also in 2000, treatments on four strips were changed such that a test of split N applications could be included and applications of sulphur-containing fertilisers on strip 14 were stopped. Most of the treatment changes are shown in Table 1 that accompanies the plan of the experiment.

Sections 0, 1, 8 and 9 continued to grow wheat only, with occasional fallows to control weeds on Section 8 which does not receive herbicides. Sections 2, 4, 7 and Sections 3, 5,

# Broadbalk


N
Broadbalk Wilderness
Wooded
Mown
Stubbed
Strip → 20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 3 2.2 2.1 1
Continuous wheat
Straw incorporated since autumn 1986
Continuous wheat
FYM
4 – K Mg
1.1.1 – K Mg
1.2.1 P K Mg
1.4.1 P K Mg
6 (P) K Mg
5 (P) K Mg
4 P K* (Mg*)
4 P K –
1.3.1 (P) K2 Mg2
4 P – Mg
4 – – –
4 (P) K Mg
3 (P) K Mg
2 (P) K Mg
1 (P) K Mg
– (P) K Mg
Nil
– – – –
3 – – – ← N
FYM res N4
Beans Wheat Wheat Oats Wheat from 2019
Wheat Oats Wheat Beans Wheat from 2019
Oats Wheat Beans Wheat Wheat from 2018
Oats Wheat Beans Wheat Wheat from 2019
Continuous wheat
No spring or summer fungicides
Strip → 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 3 2.2 2.1 1
Beans Wheat Wheat Oats Wheat from 2018
Wheat Occasional fallow
No herbicides
Continuous wheat
Re-drained autumn 1993
320m
Drainage ditch
NB Treatments revised for 2001 & rotations revised in 2018
Section 1926-67
I
II
III
IV
V
Section 1968-
0
1
2
3
4
5
6
7
8
9

## Table 1. Broadbalk fertiliser and organic manure treatments

| Strip | Treatments until 1967 | Treatments from 1968 | Treatments from 1985 | Treatments from 2001 |
|---|---|---|---|---|
| 01 | - | FYM N2 PK | FYM N4 PK | (FYM) N4 |
| 2.1 | FYM since 1885 | FYM N2 | FYM N2 | FYM N3[(1)] |
| 2.2 | FYM | FYM | FYM | FYM |
| 03 | Nil | Nil | Nil | Nil |
| 05 | PKNaMg | PK(Na)Mg | PKMg | (P)KMg |
| 06 | N1 PKNaMg | N1 PK(Na)Mg | N1 PKMg | N1 (P)KMg |
| 07 | N2 PKNaMg | N2 PK(Na)Mg | N2 PKMg | N2 (P)KMg |
| 08 | N3 PKNaMg | N3 PK(Na)Mg | N3 PKMg | N3 (P)KMg |
| 09 | N*1 PKNaMg | N4 PK(Na)Mg | N4 PKMg | N4 (P)KMg |
| 10 | N2 | N2 | N2 | N4 |
| 11 | N2 P | N2 P | N2 P | N4 P Mg |
| 12 | N2 P Na | N2 P Na | N2 P Na | N1+3+1(P)KMg(2) |
| 13 | N2 PK | N2 PK | N2 PK | N4 PK |
| 14 | N2 P Mg* | N2 PK Mg* | N2 PKMg* | N4 PK*(Mg*) |
| 15 | N2 PKNaMg | N3 PK(Na)Mg | N5 PKMg | N5 (P)KMg |
| 16 | N*2 PKNaMg | N2 PK(Na)Mg | N6 PKMg | N6 (P)KMg |
| 17 | N2(A) | N2 ½[PK(Na)Mg] | N0+3 ½[PKMg](A) | N1+4+1 PKMg |
| 18 | PKNaMg(A) | N2 ½[PK(Na)Mg] | N1+3 ½[PKMg](A) | N1+2+1 PKMg |
| 19 | C | C | (C) | N1+1+1 KMg |
| 20 | N2 KNaMg | N2 K(Na)Mg | N2 KMg | N4 KMg |

(A) Treatment to strips 17 & 18 alternating each year. From 1968 both strips received N2 and ½-rate PK(Na)Mg; from 1980 wheat on strips 17 & 18 received N1+3 i.e. autumn N1 in alternate years plus N3 in spring.

### Annual treatment per hectare

| | |
|---|---|
| FYM : | Farmyard manure at 35t |
| (FYM) : | Farmyard manure at 35t 1968-2000 only |
| P : | 35kgP as triple superphosphate |
| (P) : | 35kgP as triple superphosphate until 2000; to be reviewed in 2021 |
| K : | 90kgK as potassium sulphate |
| K2 : | 180kgK as potassium sulphate, 2001-2005. (plus 450 kgK in autumn 2000 only) |
| K* : | 90kgK as potassium chloride |
| Mg : | 12kgMg as Kieserite.Was 35kgMg every 3rd year 1974-2000.Previously 11kgMg as magnesium sulphate until 1973 |
| Mg2 : | 24kgMg as Kieserite, 2001-2005. (plus 60 kg Mg in autumn 2000 only) |
| (Mg*) : | 30kgMg as Kieserite 1974-2000.Previously 31kgMg as magnesium sulphate until 1973 |
| (Na) : | 16kgNa as sodium sulphate until 1973; 55kgNa on strip 12 only until 2000 (57kgNa until 1973) |
| (C) : | Castor meal to supply 96kgN until 1988 |

N to wheat as single applications (mid-April)
N1, N2, N3, N4, N5, N6 : 48, 96, 144, 192, 240, 288 kgN

Split N to wheat (mid-March, mid-April, mid-May)
N1+1+1 : 48+48+48 kgN (strip 19)
N1+2+1 : 48+96+48 kgN (strip 18)
N1+3+1 : 48+144+48 kgN (strip 12)
N1+4+1 : 48+192+48 kgN (strip 17)

N to oats at ½-rate, as a single application (mid-April)
½N1, ½N2, ½N3, ½N4, ½N5, ½N6 : 24, 48, 72, 96, 120, 144 kgN
Oats on strips 19, 18, 12 and 17 also receive N as a single application; ½N3, ½N4, ½N5, ½N6 respectively

No N or FYM to beans from 2018

N as ammonium nitrate (Nitram, 34.5% N) since 1986; calcium ammonium nitrate (Nitro-chalk, c.26% N) 1968-85; ammonium sulphate or sodium nitrate (N*) until 1967.

(1) : FYM N2 from 1968-2004

(2) : N1+3+1 (P)K2Mg2 from 2001-2005

Note : S has been added, by default (except on strip 14 since 2001), as part of the potassium sulphate, magnesium sulphate, Keiserite, FYM and ammonium sulphate applications. S last applied to strip 14 in 2000.

In 2018 the rotation on five sections of the experiment changed to Wheat, Wheat, Oats, Wheat, Beans. The oats will receive N at half of the normal rate (see above); the beans will not receive N or FYM.

In the previous rotation, Wheat, Wheat, Wheat, Oats, Maize from 1996-2017, oats did not receive N or FYM.
In earlier rotations from 1968-1995, beans did receive N, FYM (and PK etc.); fallows in the rotations (and on Section 8) did receive FYM, PK etc. but no N was applied. Between 1926-1967 no fertilisers or manures were applied to those sections which were fallowed to control weeds. For detailed information on treatments and management until 1967, see Rothamsted Report for 1968, Part 2, pp215.

6 went into two different 3-course rotations in 1968. Section 6 reverted to continuous wheat in 1978 and the other five Sections went into a 5-course rotation; initially fallow, potatoes, wheat, wheat, wheat and from 1997-2017, oats (without N), forage maize, wheat, wheat, wheat. In autumn 2017 winter beans replaced maize and a new rotation of beans (without N), wheat, wheat, oats, wheat began. Beans were grown on Broadbalk from 1968-1978, but they received fertiliser N so their residual nutrient value without fertiliser N has not been tested. Winter oats, now given N as a single dose at half the usual rates applied to wheat on Broadbalk, were kept as a break crop to help control soil borne pests and diseases, especially take-all (*Gaeumannomyces graminis* var. *tritici*). The inclusion of two first wheats in the new rotation is designed to enhance the overall productivity of the rotation and examine its longer-term sustainability (Plan 1 and Table 1). Pesticides continue to be applied when necessary, except for Section 6 which does not receive spring or summer fungicides and Section 8 which has never received herbicides. On Section 0, the straw on each plot has been chopped after harvest and incorporated into the soil since autumn 1986; on all other Sections, straw is baled and removed.

In his first Rothamsted paper, published in 1847, Lawes described the Broadbalk soil as a heavy loam resting upon chalk, capable of producing good wheat when well manured (Lawes, 1847). Similar land in the neighbourhood, farmed in rotation, typically yielded *c.*1.2 t $ha^{-1}$. Figure 1 shows yields from selected treatments since the 1850s. The changes reflect the improved cultivars, cultivations and control of pests, diseases and weeds that have been introduced on Broadbalk (and on English farms generally), especially since the 1960s.

Until the First World War, the experiment had been hand-weeded but the subsequent shortage of labour allowed weed competition

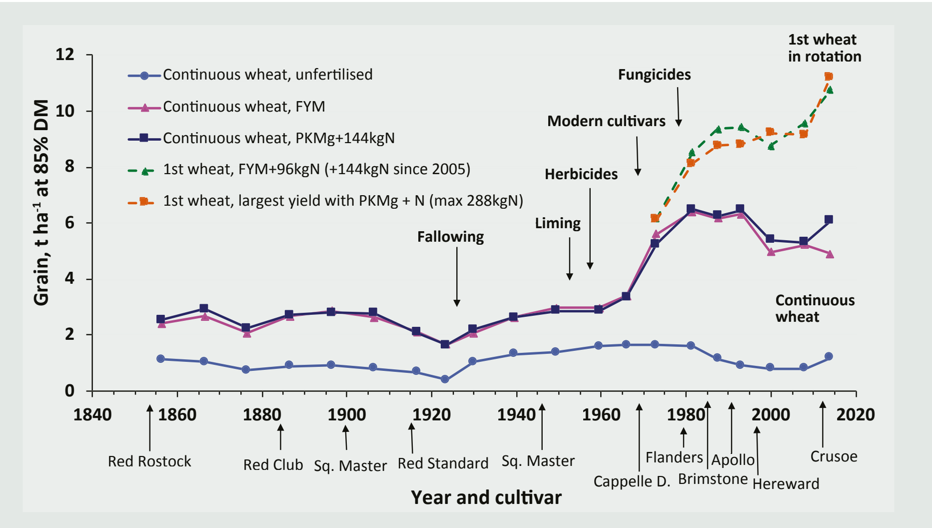



Fig. 1 Broadbalk: Mean yields of wheat grain and changes in husbandry (1852-2016)

to become so severe that yields on all treatments had declined by the 1920s. To control weeds, the experiment was divided into five sections (see plan) and one section bare-fallowed each year; yields recovered. Yields of wheat (mean of the four sections where wheat was grown) given no fertiliser or manure were *c*.1.4 t ha$^{-1}$ y$^{-1}$ (Figure 1), slightly larger than yields in earlier years. Mean yields of wheat given PKNaMg+144 kg N ha$^{-1}$ were similar to those of wheat given FYM. After the change from Squarehead's Master to the shorter-strawed cultivar Cappelle Desprez in 1968, mean yields of grain on these two treatments doubled to about 5.4 t ha$^{-1}$. Since 1968 we have been able to compare the yields of wheat grown continuously and as the first wheat after a two-year break (Dyke *et al.*, 1983). In the 10 years in which Cappelle Desprez was grown, foliar fungicides were not applied and foliar diseases, particularly powdery mildew, were common, and most severe on plots given most nitrogen. Since 1979, summer fungicides have been used, when necessary (except on Section 6), and this has allowed us to exploit the greater grain yield potential of modern cultivars. The increased responses to N fertiliser in 1979-84 suggested that yields might be greater if larger rates of N were applied, and since 1985 rates of 240 and 288 kg N ha$^{-1}$ have been tested. Yields of wheat grown after a two-year break can be over 2 t ha$^{-1}$ larger than yields of continuous wheat, almost certainly because the effects of soil borne pests and diseases, particularly take-all (*Gaeumannomyces graminis* var. *tritici*), are minimised (see later). With *cv*. Crusoe, the largest yields exceeded 13 t ha$^{-1}$ for winter wheat in rotation and yields were on average greater than with the previous variety (*cv.* Hereward), especially at the higher N rates (Figure 2). Withholding P fertiliser since 2000 has had no detrimental effect on yields as plant-available P in the soil still exceeds crop requirements (>Index 3; Defra 2010). Withholding S reduced the average grain

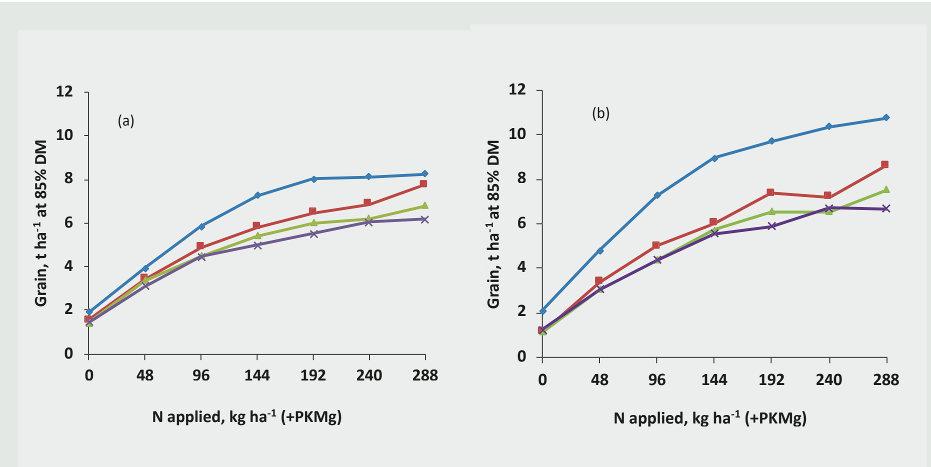



Fig. 2 Broadbalk; mean yields of wheat grain for (a) cv. Hereward, 2009-2012, and (b) cv. Crusoe, 2013-2017 (excluding 2015). Data are for: (x) continuous wheat; (◆) 1st wheat after a two-year break; (■) 2nd wheat; (▲) 3rd wheat.

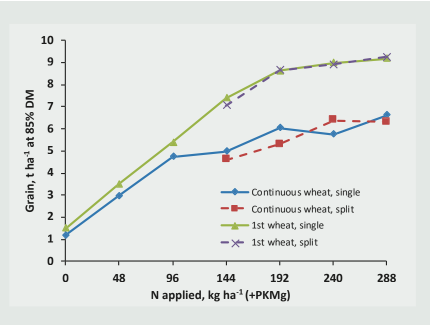



Fig. 3 Broadbalk; mean yields of wheat grain, 2002-11; where N fertiliser was given as single or split applications.

yields of first and continuous wheats by 0.6 and 0.2 t ha$^{-1}$, respectively. Compared to single applications of N, applying the same amount of N as three split dressings did not increase grain yield on this soil type (Figures 3).

The main purpose of the various crops that have been grown in rotation with wheat on Broadbalk since 1968 is to provide a "disease break" (see above and later). However, they also provide useful additional information. From 1997 to 2017 oats and maize were the two break crops; yields on selected treatments are shown in Table 2. The oats were not given fertiliser N or FYM. Thus, on plots where P and K is not limiting, any differences in yield between treatments were due to residues of inorganic N from previous applications or from differing amounts of N being mineralised from the soil organic matter (see next section). Forage maize was grown because it is a C4 plant (*i.e.* it has a different photosynthetic pathway than C3 plants) and has a different $^{13}C$ "signature" than the C3 plants which have been grown previously on Broadbalk. Thus, we can distinguish maize-derived organic matter from that of organic matter already in the soil.

**Table 2. Broadbalk; mean yield of oat grain (2011-2015) and forage maize (2008-2012)**

| Strip | Treatment[(1)] | Oat grain t ha$^{-1}$ 85% DM | Forage maize t ha$^{-1}$ total DM |
|---|---|---|---|
| 3 | Nil | 1.9 | 1.7 |
| 5 | (P)KMg | 2.1 | 3.9 |
| 6 | N1 (P)KMg | 2.3 | 6.2 |
| 7 | N2 (P)KMg | 2.5 | 8.8 |
| 8 | N3 (P)KMg | 3.2 | 8.8 |
| 9 | N4 (P)KMg | 3.2 | 8.9 |
| 15 | N5 (P)KMg | 4.5 | 9.1 |
| 16 | N6 (P)KMg | 5.5 | 8.3 |
| 2.2 | FYM | 6.6 | 12.0 |
| 2.1 | FYM N3 | 7.0 | 14.6 |
| 1 | (FYM) N4 | 5.7 | 12.6 |

[(1)] See Table 1 for details
Note; No N fertiliser or FYM was applied for the winter oat crops.

## Organic matter in the Broadbalk soil

The amount of Organic C (t ha$^{-1}$) in topsoil (0-23cm) on selected treatments is shown in Figure 4. The C content of some soils has changed little in more than a century after they were first measured in 1865. By 1865, soil in plots receiving N3PKMgNa fertilisers had a little more C than soil in the nil and minerals-only plots because the better-fertilised crop gave not only more yield, but also more stubble, and probably roots, to be ploughed-in. Soil C in plots receiving larger amounts of fertiliser N (192, 240 and 288 kg ha$^{-1}$) in recent years,

Broadbalk, soil sampling, 1944

The Broadbalk experiment

and where larger crops have been grown is still tending to increase. On the FYM treatments, soil C increased rapidly at first, by about 1 t $ha^{-1} yr^{-1}$, then more slowly, and now contains more than double that present in the nil or fertiliser-only soil. The decline in soil C on the FYM plots in the 1920s was because, to control weeds, all sections were fallowed for two or four consecutive years before regular fallowing started; FYM was not applied in 1925-1968 when the plots were fallowed, but fallow sections have received FYM from 1968.

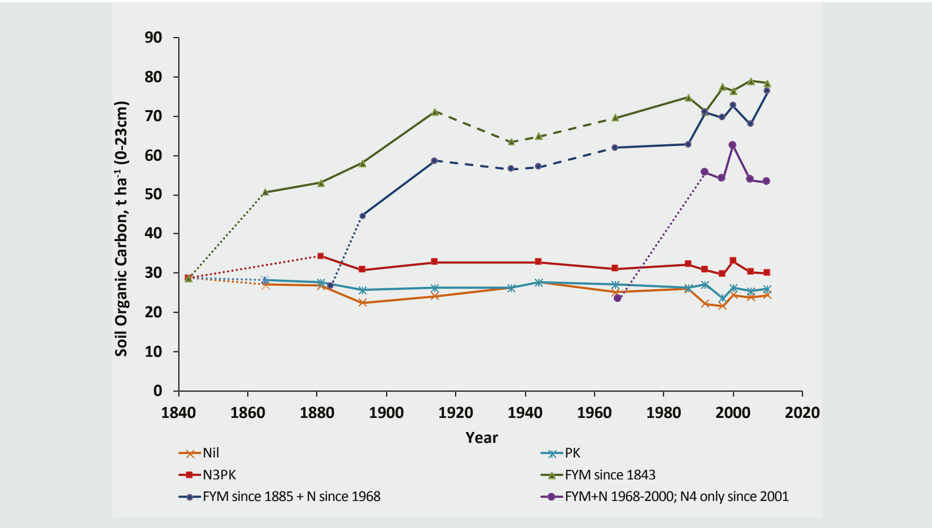



Fig. 4 Broadbalk; long-term changes in soil organic carbon, 1843-2010. Data is from soils where wheat is grown continuously, except that between 1926 and 1967 one or more sections were bare fallowed each year to control weeds; FYM was not applied to the fallow sections. Data has been adjusted for changes in bulk density.

Most soils have a C:N ratio of about 10:1; so % Organic C can be used to calculate % N. The soil %N on Broadbalk closely follows % Organic C, and N balances, *i.e.* N input *vs* N offtake in the crop and N retained in soil, can be calculated for different periods. In the early years of the experiment, about 100 kg of the 225 kg N $ha^{-1}$ applied in the FYM could not be accounted for even though much N was accumulating in the soil and N offtakes by the crop were small. More recently (1990s), inputs of N in FYM and atmospheric deposition have been greater and although offtakes have been larger, N accumulation in the soil has been much less and *c*.200 kg N $ha^{-1}$ cannot be accounted for. Much N is lost by leaching as nitrate (see later).

### The microbiology of Broadbalk

The various treatments on Broadbalk (including the Wilderness) provide an opportunity to examine the effects of contrasting agricultural management practices on soil microbial populations and the processes mediated by the soil microbial biomass. The microbial biomass of the FYM plots is approximately twice that of the plots given either NPK or no fertilisers (Jenkinson & Powlson, 1976). Estimates of the total numbers of microbial cells in soil vary depending on the methods used; directly by microscopy (around $10^9$ cells $g^{-1}$ soil), indirectly by quantitative PCR (around $10^{10}$ cells $g^{-1}$ soil) (Clark *et al.*, 2012) or by culturing bacteria (around $10^5$ – $10^6$ cells $g^{-1}$ soil; Clark *et al.*, 2008). All methods however show a similar trend of increasing microbial abundance with increased biomass. Approximatively 1% of bulk soil bacteria are currently culturable. The relative numbers of specific groups of bacteria that can grow varies according to the selective media used and the environmental conditions at the time of sampling. The recovery of cells by culture on agar may reflect their physiological status when sampled, resulting in apparently lower numbers at times of stress.

Currently, there are no direct estimates of bacterial populations responsible for methane oxidation on Broadbalk. However, measurements of this process, indicate lower activity of methane-oxidizing bacteria in the soils receiving N fertilisers with much higher emissions in the Broadbalk Wilderness, indicating that soil cultivation or amount of biomass may have major disruptive effects on these microbial populations. Fertiliser treatments also impacts on microbial populations involved in N-cycling and hence the utilisation of N by crops or it's loss to the environment. The population of ammonia oxidizing bacteria has been estimated from the amount of DNA specific to this group in the soil. It is around $10^4$ $g^{-1}$ in unfertilised soil with 10- to 50-fold more in the soils receiving N fertilisers. The potential for nitrification activity is likewise higher in the N fertilised soils. After application of ammonium nitrate fertiliser, populations of ammonia oxidizing bacteria increase 10- to 100-fold after six weeks, then slowly decline over the rest of the year. Another major group of ammonia oxidizers belong to the domain archaea (AOA). Their abundance in soil constitutes ~1% of total DNA, considerably higher than ammonia oxidizing bacteria. Their role in nitrification in agricultural systems is however still unclear. Results from Zhalnina *et al.*, 2013 indicated that long term agricultural management significantly increased AOA abundance when compared to the wilderness and grassland on Broadbalk. Abundance of the different bacterial genes involved in denitrification varied depending on the treatment.

Measurement of bacterial genes involved in denitrification in Broadbalk soil indicated that, in general, the genes responsible increased in abundance with increasing N fertiliser, consistent with the increased $N_2O$ emissions from soils receiving large amounts of N. However, the woodland soil, which does not receive fertiliser N, had much higher emissions when fertiliser was applied in laboratory studies. It also had a relatively lower abundance of the denitrification genes indicating that the woodland soil harbours a distinctly different microbiome compared to the plots remaining under arable management (Clark *et al.*, 2012). A survey of soil sampled monthly over the growing season from plots with a range of N fertiliser inputs, as well as the grassland and woodland sections of the Broadbalk Wilderness, confirmed the difference in community structure (Zhalnina *et al.*, 2013).

## Weeds on Broadbalk

Weeds were controlled on Broadbalk by hand-hoeing until shortly after the First World War when a shortage of labour resulted in increasing yield losses from weed competition. In response, the experiment was sub-divided into five sections in 1926 (Plan 1) that were sequentially fallowed to help control weeds. Herbicides have been used on all plots since 1964 except for half of section IV (new Section 8). No other form of weed control is used on this Section except for occasional fallowing when the weeds become too much of an impediment to harvesting the wheat crop.

By comparing the yields from Section 8 with equivalent plots on Section 9, that have the same fertiliser treatments but are kept free of weeds, the effect of the fertilisers on potential yield loss from weeds can be estimated. On plots that do not receive any N fertiliser, leguminous weeds, such as black medick (*Medicago lupulina*), that can fix N from the atmosphere, are very abundant. Some of this fixed N becomes available to the crop, resulting in increased grain yields on the weedy plots compared to the weed-free Section. The weeds become more competitive as the rate of N

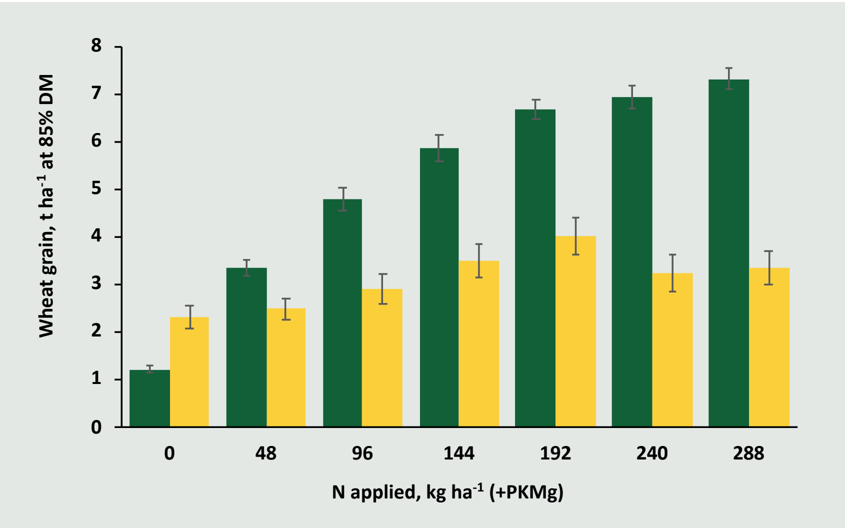



Fig. 5 Broadbalk; mean yields of grain, 1985-2014; where wheat was grown continuously or with occasional fallows, without herbicides (section 8; yellow histograms) or with herbicides (section 9; green histograms).

fertiliser increases and the percentage yield losses increase (Figure 5). Consequently, the yield benefits of increasing fertiliser application observed on Section 9 are not realised in the presence of weeds, emphasising the importance of good weed control to protect potential yield in modern cropping systems. The largest yield loss (92%) was recorded on Plot 17 (N1+4+1 PKMg) in 2006 following a five-year period without a fallow.

The differences in the yield losses between the fertiliser treatments are largely a result of changes in the weed communities on the different plots, with competitive weed species becoming more abundant as fertiliser application rates increase. The relative frequencies of different weed species have been recorded annually on all plots in Section 8 since 1991; over this period, 55 weed species have been recorded. Because winter wheat is grown in Section 8, the weed flora is largely made up of species adapted to germination in the autumn. There are striking differences in the weed floras between the fertiliser treatments largely resulting from differences in amounts of added N. Plot 3, which has never received any fertilisers, is the most diverse plot (with up to 19 species recorded each year), and species richness declines as the rate of N fertiliser increases; as few as seven species have been recorded in a given year on Plot 16, which receives most N (288 kg N $ha^{-1}$). The decline in species richness is explained by the loss of species such as corn buttercup (*Ranunculus arvensis*) on plots with high N application rates. These species have tended to also decline nationally, in contrast to nitrophilous species like chickweed (*Stellaria media*) which have remained common.

Broadbalk now provides an invaluable reserve for seven plant species that are rare, uncommon or declining nationally. These are: corn buttercup (*Ranunculus arvensis*), corn

Broadbalk, weeds on Section 8, July 2017

cleavers (*Galium tricornutum*), fine-leaved sandwort (*Minuartia hybrida*), narrow-fruited cornsalad (*Valerianella dentata*), prickly poppy (*Papaver argemone*) and shepherd's needle (*Scandix pecten-veneris*). Corn cleavers deserves a special mention as it is one of Britain's rarest plants and Broadbalk is the only site where this species has been recorded in recent years. Between 1991 and 2002 no more than four plants were seen in any one year but Rothamsted's weed conservation policy has meant that Broadbalk now supports a healthy population of this species.

The revised atlas of British and Irish Flora includes a list of species which have shown the greatest relative decrease nationally between the 1930-69 and 1987-99 national recording periods. Seven weeds on Broadbalk are among the 50 species that have shown the greatest decline, and three of them are in the top 10 species in the list (corn buttercup, corn cleavers and shepherd's needle).

## Pests and diseases on Broadbalk

The continuity of cropping and manurial treatments has made Broadbalk a valuable experiment for studying the effects of both plant nutrition and weather on the incidence of wheat pests and diseases.

Before insecticidal seed dressings were used, wheat bulb fly (*Delia coarctata* ) often caused severe damage to wheat after fallow. Bulb fly eggs are laid during the summer on bare soil, and damage is caused by larvae burrowing into the young wheat shoots in the early spring. Yield losses on Broadbalk differed greatly with season and were related to the ratio of number of plants to number of larvae, to the time of attack and to the suitability of conditions for plant growth. Plants on soils deficient in K usually suffered most because they were less well tillered, and damage to the primary shoot often killed the whole plant. The damage was minimised by sowing wheat earlier. However, this has resulted in occasional problems with gout fly (*Chlorops pumilionis*). Other insect pests (cereal aphids, cutworms, wheat-blossom midges and the saddle-gall midge) have caused damage only sporadically.

Foliar diseases such as yellow rust (*Puccinia striiformis*), brown rust (*Puccinia triticina*), septoria leaf blotch (*Zymoseptoria tritici*) and powdery mildew (*Blumeria graminis*) are common on the no fungicide Section of Broadbalk (Section 6), and differ between years depending on the resistance profile of the wheat cultivar being grown and the weather conditions. The winter wheat cultivar grown on Broadbalk since 2013, *cv.* Crusoe, has good resistance against yellow rust, powdery mildew and septoria, but is susceptible to brown rust. Brown rust symptoms are commonly seen towards the end of grain filling and when weather conditions are favourable this can reach epidemic proportions. In some years, this can result in yield losses in the no fungicide section of 18-56% compared to the fungicide-treated areas of the experiment.

Broadbalk, brown rust on fungicide treated (left) vs. untreated (right) wheat (cv. Crusoe)

Both eyespot (*Oculimacula* spp) and take-all root disease (*Gaeumannomyces graminis var tritici*) are common on Broadbalk. Comparisons of yields and of differences in amounts of take-all between continuous wheat on Broadbalk and that in other fields, growing shorter sequences of cereals, lead to the development of the hypothesis of 'take-all decline'. This natural form of biocontrol, where take-all disease becomes less severe in continuously grown wheat compared to its severity in shorter sequences of wheat, is thought to be due to the build-up of antagonistic microflora in the soil. Take-all disease has been regularly assessed in selected plots since the introduction of rotations on Broadbalk in 1968. This very valuable long term dataset is currently being used to explore the impact of climatic and agronomic factors on take-all disease severity with the aim of improving our understanding and forecasting of disease outbreaks.

## Broadbalk drains

In 1849, a tile drain was laid down the centre of each treatment strip. The tiles, of the 'horseshoe and sole' type, 5 cm internal diameter, were laid 60 cm below the surface, and led to a 10 cm cross main, which took the water to waste. The drains were not intended for experimental use, but in 1866 they were opened, and drainage water collected and analysed; the forerunner of the ditch we see today was built in 1896. Although ammonium ($NH_4$), K, Mg and Na salts were all added to the soil, the biggest losses were of calcium (Ca) and these increased with increasing amounts of $NH_4$ salts applied. This observation confirmed the theory of ion exchange developed by Thomas Way. Losses of nitrate ($NO_3$) were also considerable, and also increased with the amount of $NH_4$ salts added. The original drains were still running in the 1990s and were used to make measurements of $NO_3$-N and P losses. However, because the experiment had been divided into Sections, and because some drains ran intermittently it was no longer possible to know where the drainage water was coming from. The drains on Section 9 (nearest the drainage ditch) were, therefore, replaced in autumn 1993. The old drains, draining Sections 0-8, were intercepted and taken to waste. The ends of the old drains on Section 9 were plugged with clay and new perforated 8 cm plastic pipes installed 50 cm to one side of the old drain at 75 cm depth.

Measurements of N leached to groundwater plus losses via the drains indicated that even where no N fertiliser had been applied for more than 150 years on average about 10 kg $ha^{-1}$ of $NO_3$-N was lost each year (1990-1998). Most N was lost where the amount of fertiliser N applied exceeded that needed for "optimum" yield or where FYM was applied for many years. The EU limit for the maximum

Drain outlets at eastern end of Broadbalk, 2010

concentration of N allowed in potable waters (11.3 mg N $l^{-1}$) was often exceeded where the larger amounts of fertiliser N or FYM were applied. However, in years when through drainage was less than average, the EU limit was sometimes exceeded even where little or no N had been applied (Goulding *et al.*, 2000).

Losses of P from agricultural land to water courses can result in eutrophication. Because many soils have the capacity to retain P, vertical movement of P through the soil profile is generally considered to be of little importance. On Broadbalk, the soil now contains between 5 and 120 mg $kg^{-1}$ of available-P (Olsen P) depending on the treatment. As noted earlier, fertiliser P is being withheld on some treatments (see Broadbalk plan) until concentrations of Olsen P decline to a more sensible agronomic level. Measurements of P (mainly dissolved reactive P) in drainage showed that the critical level, above which the P concentration in the drainage water increased rapidly, was *c*. 60 mg $kg^{-1}$ Olsen P on this soil type (Heckrath *et al.*, 1995).

## Broadbalk and Geescroft Wildernesses

Although not experiments in the usual sense, these two areas of regenerating woodland are of great value, especially now, when the sequestration of carbon in soils and vegetation is much debated. Both sites had grown arable crops for many years. On Broadbalk, the surface soil had been heavily chalked and is still calcareous; Geescroft had not been heavily chalked and topsoil pH fell from 7.1 in 1883 to 4.4 in 1999.

In 1882, at the west end of Broadbalk field about 0.2 ha of the wheat crop on land unmanured for many years was left unharvested and the land was no longer cultivated. The wheat did not compete well with the weeds, and after only four years the few self-sown wheat plants that could be found were stunted and barely recognisable as cultivated wheat. One half of the area has remained untouched; it is now woodland dominated by ash, sycamore and hawthorn; the ground is covered with ivy in the densest shade, and with dog's mercury and other species present where shade is less dense. On the other half, woody species have been removed (stubbed) annually since about 1900 to allow open-ground vegetation to develop. This consists mainly of coarse grasses, hogweed, agrimony, willow-herb, nettles, knapweed and cow parsley, with smaller numbers of many other species.

In 1957 the stubbed section was divided into two parts; one part continues to be stubbed each year. On the other part, the herbage was mown several times during each of the next three years and the produce removed to encourage grasses as a preparation for grazing. Although the hogweed and cow parsley gave place to ground ivy, the grasses did not increase substantially until the site was grazed by sheep. By 1962, perennial ryegrass and white clover had appeared, and they are now widely distributed. The ground ivy has almost gone, and the growth of other species is much restricted. The appearance of nettles in this area in 1986 has necessitated occasional applications of herbicides. Since 2001, this area has been mown.

The Geescroft Wilderness covers 1.3 ha. It is sited on part of what had been an experiment that grew beans from 1847 to 1878. After subsequent years in fallow and clover the experimental site was abandoned in 1886 and the area of the wilderness-to-be left untouched. The area now has a relatively uniform stand of

Broadbalk Wilderness, July 2017

Geescroft Wilderness, 1933

trees, dominated by oak and ash. An understory of holly has become increasingly dense since the 1960s. Because the soil has become so acid, there are few ground cover species.

On both sites, much C has been sequestered in trees and soil since cultivation ceased in the 1880s (Poulton *et al.*, 2003). By the end of the 20th Century, Geescroft had gained, on average, 2.00 t C $ha^{-1}$ $yr^{-1}$ (0.38 t in litter and soil to a depth of 69cm, plus an estimated 1.62 t in trees, including their roots); corresponding gains of N were 22.2 kg N $ha^{-1}$ $yr^{-1}$ (15.2 kg in soil, plus 6.9 kg in trees). Broadbalk has gained 3.39 t C $ha^{-1}$ $yr^{-1}$ (0.54 t in soil, plus an estimated 2.85 t in trees), 49.6 kg N $ha^{-1}$ $yr^{-1}$ (36.8 kg in soil, plus 12.8 kg in trees). Much of the N required for plant growth will have come from inputs in rain and dry deposition. The faster accumulation of C and N in the wooded part of Broadbalk compared to Geescroft is probably because, as it is relatively narrow, there is a large edge effect and greater light interception per unit area, perhaps more scavenging of atmospheric N, and thus more growth. However, additional atmospheric N could have come from nearby covered yards in which bullocks were housed during the winter.

## Park Grass

Park Grass, 1941

Park Grass is the oldest experiment on permanent grassland in the world. Started by Lawes and Gilbert in 1856, its original purpose was to investigate ways of improving the yield of hay by the application of inorganic fertilisers or organic manures (Plan 2 and Table 3).

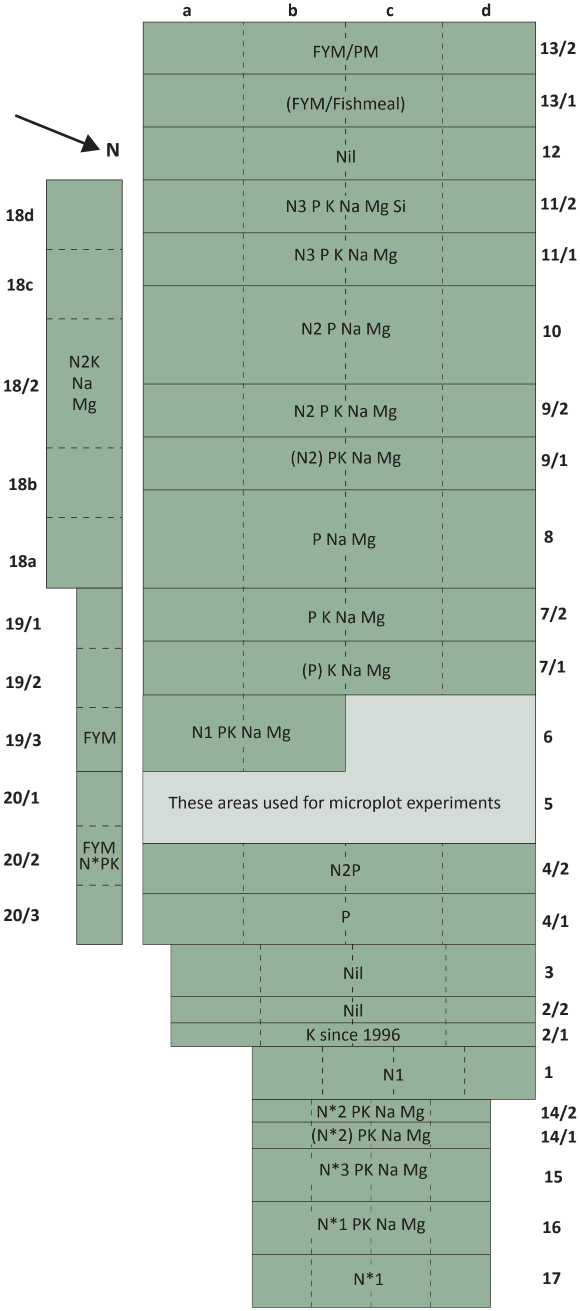
Within 2-3 years it became clear that these treatments were having a dramatic effect on the species composition of what had been a uniform sward comprising about 50 species. The continuing effects on species diversity and on soil function of the original treatments, together with later tests of liming and interactions with atmospheric inputs and climate change, has meant that Park Grass has become increasingly important to ecologists, environmentalists and soil scientists (Silvertown *et al.*, 2006). It is a key Rothamsted site within the UK Environmental Change Network (see later).

The experiment was established on *c.* 2.8 ha of parkland that had been in permanent pasture for at least 100 years. The uniformity of the site was assessed in the five years prior to 1856. Treatments imposed in 1856 and subsequently included controls (Nil - no fertiliser or manure), and various combinations of P, K, Mg, Na, with N applied as either sodium nitrate or ammonium salts (Table 3). FYM was applied to two plots but was discontinued after eight years because, when applied annually to the surface in large amounts, it had adverse effects on the sward. FYM, applied every four years, was re-introduced on three plots in 1905.

The plots are cut in mid-June and made into hay. For 19 years the re-growth was grazed by sheep penned on individual plots but since 1875 a second cut, usually carted green, has been taken. The plots were originally cut by scythe, then by horse-drawn and then tractor-drawn mowers. Yields were originally estimated by weighing the produce, either of hay (1st harvest) or green crop (2nd harvest), and dry matter determined from the whole plot. Since 1960, yields of dry matter have been estimated from strips cut with a forage harvester. However, for the first cut the remainder of the plot is still mown and made into hay, thus continuing earlier management and ensuring return of seed. For the second cut the whole plot is cut with a forage harvester.

Park Grass probably never received the large applications of chalk that were often applied to arable fields in this part of England. The soil (0-23cm) on Park Grass probably had a pH (in water) of about 5.5 when the experiment began. A small amount of chalk was applied to all plots during tests in the 1880s and 1890s. A regular test of liming was started in 1903 when most plots were divided in two and 4 t $ha^{-1}$ $CaCO_3$ applied every four years to one half. However, on those plots receiving the largest amounts of ammonium sulphate this was not enough to stop the soil becoming progressively more acid, making it difficult to disentangle the effects of N from those of acidity. It was decided to extend the pH range on each treatment and, in 1965, most plots were divided into four: sub-plots "a" and "b" on the previously limed halves and sub-plots "c" and "d" on the previously unlimed halves. Sub-plots "a", "b" and "c" now receive different amounts of chalk, when necessary, to achieve and/or maintain soil (0-23cm) at pH 7, 6 and 5, respectively. Sub-plot "d" receives no lime and its pH reflects inputs from the various treatments and the atmosphere. Soils on the unlimed sub-plots of the Nil treatments are now at *c*. pH 5.0 whilst soils receiving 96 kg N $ha^{-1}$ as ammonium sulphate or sodium nitrate are at pH 3.4 and 5.9, respectively. For the latter two treatments, between 1965 and 2015, 74 and 22 t $ha^{-1}$ $CaCO_3$, respectively, were required to increase the soil pH and maintain it at pH 7.

# Park Grass



a
b
c
d
N
FYM/PM
13/2
(FYM/Fishmeal)
13/1
Nil
12
N3 P K Na Mg Si
11/2
N3 P K Na Mg
11/1
N2 P Na Mg
10
N2 P K Na Mg
9/2
(N2) PK Na Mg
9/1
P Na Mg
8
P K Na Mg
7/2
(P) K Na Mg
7/1
N1 PK Na Mg
6
These areas used for microplot experiments
5
N2P
4/2
P
4/1
Nil
3
Nil
2/2
K since 1996
2/1
N1
1
N*2 PK Na Mg
14/2
(N*2) PK Na Mg
14/1
N*3 PK Na Mg
15
N*1 PK Na Mg
16
N*1
17
18d
18c
N2K
Na
Mg
18/2
18b
18a
19/1
19/2
FYM
19/3
20/1
FYM
N*PK
20/2
20/3

### Table 3 Park Grass fertiliser and organic manure treatments.

**Treatments (per hectare per year unless indicated)**

| | |
|---|---|
| **Nitrogen (applied in spring)** | |
| N1, N2, N3 | 48, 96, 144 kg N as ammonium sulphate |
| N*1, N*2, N*3 | 48, 96, 144 kg N as sodium nitrate |
| (N2) (N*2) | last applied 1989 |
| **Minerals (applied in winter)** | |
| P | 17 kg P as triple superphosphate since 2017, previously 35 kg P |
| K | 225 kg K as potassium sulphate |
| Na | 15 kg Na as sodium sulphate |
| Mg | 10 kg Mg as magnesium sulphate |
| Si | 450 kg of sodium silicate |
| Plot 20 | 30 kg N*, 15 kg P, 45 kg K in years when FYM is not applied |
| **In 2013, plot 7 was divided into 7/1 and 7/2; P applications on 7/1 stopped** | |
| **Since 2013, plot 15 has also received N*3 (previously PKNaMg but no N)** | |
| **Organics (applied every fourth year)** | |
| FYM | 35 t $ha^{-1}$ farmyard manure supplying c.240 kg N, 45 kg P, 350 kg K, 25 kg Na, 25 kg Mg, 40 kg S, 135 kg Ca |
| PM | Pelleted poultry manure (replaced fishmeal in 2003) supplying c.65 kgN |
| **On plot 13/2 FYM and PM (previously fishmeal) are applied in a 4-year cycle i.e.:** | |
| FYM in 2017, 2013, 2009, 2005 etc. | |
| PM in 2015, 2011, 2007, 2003, fishmeal in 1999, 1995 1991 etc. | |
| **(FYM/Fishmeal) FYM and fishmeal last applied in 1993 and 1995 respectively** | |
| **Lime (applied every third year)** | |
| Ground chalk applied as necessary to maintain soil (0-23 cm) at pH 7, 6 and 5 on sub-plots "a", "b" and "c". | |
| Sub-plot "d" does not receive any chalk | |

In 1990, plots 9 and 14, which received PKNaMg and N as either ammonium sulphate or sodium nitrate respectively, were divided so that the effects of withholding N from one half of all the sub-plots could be assessed. Similarly, plot 13, which received FYM and fishmeal (now poultry manure), was divided, and, since 1997, FYM and fishmeal has been withheld from one half. In 1996, plot 2, a long-term Nil treatment, was divided and K has been applied to one half each year to give a "K only" treatment. In 2013, plot 7 was divided in two to test the effects of withholding P on herbage production and botanical diversity. The effects have been negligible so far, almost certainly because of the large amounts of available P that had built up in the soils from past inputs; in 2014 available P on plots receiving P fertiliser was 60-290 mg plant-

Park Grass, plots 11/2d (left) and 12d (right)

available (Olsen)P $kg^{-1}$. Consequently, in 2016, the P application to these plots was decreased from 35 to 17 kg P $ha^{-1}$, so that it more closely matches P offtakes. Since 2013, plot 15 has received sodium nitrate at 144 kg N $ha^{-1}$, in addition to PKNaMg, to provide a comparison with plot 11, which receives the same rate of N as ammonium sulphate.

Yields of total dry matter (both harvests) for 2012-16 are shown in Table 4. The largest yields were on limed sub-plots given PKNaMg and 144 kg N $ha^{-1}$ (11/1 and 11/2). Yields with 96 kg N $ha^{-1}$ as either ammonium or nitrate (and PKNaMg) are similar (9/2 and 14/2); where P or K are not applied yields are less (18, 4/2 and 10). Similarly, yields on plots given N only (1 and 17) are no better than on the Nil plots (3, 12 and 2/2) because lack of P and K limits yield. On soil receiving PKNaMg but no N fertiliser (7/2), yields are as good as those on plots receiving PKNaMg plus 96 kg N $ha^{-1}$ (plots 9/2 and 14/2) because of the large proportion of legumes in the sward (Table 4). Where no lime is applied legumes are less common and yields

**Table 4. Park Grass; mean annual yield of dry matter, t $ha^{-1}$ (2012-2016)**

| Plot | Treatment [1] | Sub-plot a | b | c | d |
|---|---|---|---|---|---|
| **No nitrogen group** | | | | | |
| 3 | Nil | 3.3 | 3.6 | 1.8 | 2.7 |
| 12 | Nil | 4.0 | 3.3 | 2.7 | 2.6 |
| 2/2 | Nil | 3.8 | 3.7 | 2.6 | 2.9 |
| 2/1 | K | 3.4 | 3.8 | 2.3 | 2.0 |
| 4/1 | P | 4.8 | 5.2 | 4.1 | 3.9 |
| 8 | P Na Mg | 4.6 | 4.7 | 4.1 | 4.3 |
| 7/1 [2] | (P) K Na Mg | 6.5 | 7.2 | 6.6 | 4.4 |
| 7/2 [2] | P K Na Mg | 6.7 | 6.8 | 6.6 | 5.0 |
| **Ammonium N group** | | | | | |
| 1 | N1 | 3.6 | 3.1 | 2.3 | 1.7 |
| 18 | N2 K Na Mg | 3.9 | 3.9 | 3.6 | 2.4 |
| 4/2 | N2 P | 3.9 | 4.3 | 4.4 | 2.8 |
| 10 | N2 P Na Mg | 4.8 | 5.0 | 5.3 | 3.6 |
| 6 | N1 P K Na Mg | 6.9 | 7.2 | - | - |
| 9/1 | (N2) P K Na Mg | 7.0 | 7.3 | 5.8 | 1.7 |
| 9/2 | N2 P K Na Mg | 7.1 | 7.4 | 6.3 | 5.1 |
| 11/1 | N3 P K Na Mg | 8.0 | 7.2 | 7.0 | 6.0 |
| 11/2 | N3 P K Na Mg Si | 8.6 | 8.2 | 7.5 | 7.0 |
| **Nitrate N group** | | | | | |
| 17 | N*1 | 3.6 | 3.9 | 2.9 | 3.3 |
| 16 | N*1 P K Na Mg | 6.9 | 7.0 | 6.9 | 5.6 |
| 14/1 | (N*2) P K Na Mg | 6.8 | 7.1 | 7.0 | 6.9 |
| 14/2 | N*2 P K Na Mg | 6.5 | 6.6 | 6.7 | 6.7 |
| 15 [3] | N*3 P K Na Mg | 7.3 | 7.4 | 7.3 | 7.1 |
| **FYM group** | | | | | |
| 13/1 | (FYM/fishmeal) | 5.6 | 5.6 | 4.9 | 4.5 |
| 13/2 | FYM/PM | 5.8 | 6.9 | 6.9 | 6.4 |
| | | /1 | /2 | /3 | |
| 19 [4] | FYM | 6.9 | 7.2 | 6.3 | |
| 20 [4] | FYM/N* P K | 7.1 | 7.3 | 6.8 | |

[1] See Table 3 for details
[2] Plot 7 split in 2013 and P withheld from 7/1; yields given for 7/1 are for 2013-16
[3] N*3 applied since 2013 (yields given are for 2013-16)
[4] Plots 19 and 20 are not part of the liming scheme

are smaller. For all treatments, yields on unlimed sub-plots are less than those on soils maintained at pH 6 or above. However, even on the very acid soils (pH 3.4 – 3.7) dominated by one or two species, mean yields can still be as large as 6-7 t $ha^{-1}$ (*e.g.* "d" sub-plots of 11/1 and 11/2).

### Botanical composition

Vegetation surveys have been carried out on Park Grass on more than 30 occasions since the experiment began. The most recent, comprehensive surveys of botanical composition, made just before the first cut, were done annually from 1991 to 2000 and from 2010 to 2012. Table 5 shows soil pH and those species comprising 5% or more of the above ground biomass, and the total number of species identified on each sub-plot (selected treatments, mean 2010-2012). The striking contrasts between the plots, in botanical diversity and composition, are a result of complex interactions between fertiliser and manure treatments and pH. Without exception, all the original treatments imposed at the start of the experiment resulted in a decline in species number; the fertilisers have acted on the community by selecting out species that are poorly adapted to those treatments. When the effect of increasing soil fertility is analysed separately from the effect of pH, the steepest declines in species richness have been observed on plots that receive both inorganic N and P in combination.

The most diverse flora, including many broad-leaved species, is on the Nil plots (plots 3, 2/2 and 12), with about 35-42 species in total. These swards are probably the nearest approximations to the species composition of the whole field in 1856, although gradual impoverishment of the plant nutrients soon caused decreases in perennial ryegrass (*Lolium perenne*) and Yorkshire fog (*Holcus lanatus*) and later increases in common bent (*Agrostis capillaris*), red fescue (*Festuca rubra*), rough hawkbit (*Leontodon hispidus*) and common knapweed (*Centaurea nigra*). Species characteristic of poor land *e.g.* quaking grass (*Briza media*) and cowslip (*Primula veris*) are also present in small amounts, on these plots. Lime alone does not greatly alter the absence/presence of individual species but it decreases the contribution of common bent and red fescue, and increases that of some broad-leaved species.

Applying N as ammonium sulphate or as sodium nitrate has resulted in the most spectacular contrasts. In the absence of applied chalk, soil pH on the "d" sub-plots ranges from 4.1 to 3.6 where ammonium sulphate has been applied and from 5.4 to 6.0 with sodium nitrate. The effect of soil acidification on the total number of species in the sward is dramatic; 1-4 species with ammonium sulphate, but 22-35 with sodium nitrate (Table 5). Grasses are dominant on the "d" sub-plots, where the soil pH ranges from 4.0 to 3.6. Species that dominate on these plots, such as sweet vernal grass (*Anthoxanthum odoratum*), are restricted to those able to tolerate the increased concentration of aluminium ions in the soil associated with low pH. Figure 6 summarises, for three contrasting treatments,

Sorting herbage samples from Park Grass, 2010

## Table 5. Park Grass; species comprising at least 5% of herbage, mean 2010-2012; and total number of species observed

| Treatment[(1)] | Plot | Soil pH in 2011 | Percentage of dry matter (Species names are listed below) AC | AP | AO | AE | BM | DG | FR | HL | LP | LO | TP | TR | AM | CN | HS | HR | LH | PL | RA | SM | No. of species observed |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Nil | 3a | 7.2 | + | + | + | + | 5 | + | 10 | + | + | 15 | 5 | + | + | 10 | - | - | 10 | 5 | + | 10 | 37 |
| | b | 6.3 | 5 | + | + | + | 5 | + | 10 | 5 | + | 10 | 5 | + | 5 | 5 | - | - | 15 | 10 | + | 10 | 35 |
| | c | 5.2 | 10 | - | + | - | 5 | + | 30 | + | + | 5 | 5 | - | + | 5 | + | + | 20 | 5 | + | + | 37 |
| | d | 5.3 | 15 | - | + | + | 5 | + | 25 | + | + | + | + | + | 5 | 5 | - | + | 10 | 5 | + | - | 35 |
| Nil | 2/2b | 6.2 | + | + | + | + | 5 | + | 10 | 5 | + | 10 | 5 | + | + | 10 | + | - | 20 | 5 | + | 5 | 42 |
| | d | 5.1 | 15 | - | + | + | 5 | + | 30 | + | - | + | + | - | 5 | 5 | - | + | 5 | 10 | + | - | 35 |
| K (since 1996) | 2/1b | 6.0 | + | + | + | + | 10 | + | 10 | 5 | + | 5 | 15 | + | 5 | 5 | + | - | 25 | 5 | + | + | 39 |
| | d | 4.8 | 20 | - | + | - | + | + | 30 | + | - | - | + | - | 5 | 5 | - | 5 | 10 | 5 | + | - | 28 |
| PKNaMg | 7b | 6.2 | + | + | + | 25 | - | 5 | + | + | 5 | - | 25 | + | + | + | 5 | - | - | 10 | + | - | 29 |
| | d | 4.9 | 10 | + | 5 | + | - | + | 15 | 5 | 5 | + | 15 | 5 | 5 | 10 | + | + | 5 | 20 | + | - | 33 |
| (FYM/ Fishmeal) | 13/1b | 6.2 | 10 | 5 | 5 | 15 | - | 5 | 5 | 5 | 10 | + | 10 | - | + | + | + | + | 5 | 10 | 5 | - | 33 |
| | d | 4.8 | 20 | + | 5 | - | - | + | 10 | 5 | + | + | 15 | + | 10 | + | - | 10 | 5 | 10 | 5 | - | 33 |
| FYM/PM | 13/2b | 6.1 | 5 | 10 | + | 20 | - | 10 | 5 | 10 | 15 | - | + | - | - | - | 5 | - | + | 5 | 5 | - | 33 |
| | d | 5.0 | 30 | 5 | 10 | 5 | - | + | 10 | 10 | - | - | 10 | - | 10 | + | + | - | 5 | 5 | 5 | - | 30 |
| N*1 | 17b | 6.3 | 5 | + | + | + | 20 | 5 | 5 | 5 | - | - | + | + | 5 | 5 | + | - | 25 | 10 | + | + | 36 |
| | d | 5.7 | 5 | + | 5 | + | 10 | + | 5 | 5 | - | - | + | - | + | 5 | + | - | 35 | 10 | + | - | 35 |
| (N*2) PKNaMg | 14/1a | 6.9 | + | + | + | 15 | - | 5 | 5 | + | + | + | 25 | 15 | + | + | 15 | - | - | 5 | 5 | - | 29 |
| | b | 6.0 | + | 5 | + | 10 | - | + | 5 | + | 15 | - | 25 | + | + | + | 10 | - | - | 10 | 5 | - | 29 |
| | c | 5.3 | 5 | + | 5 | 5 | - | 10 | 5 | 5 | 10 | + | 25 | 5 | - | + | 5 | - | + | 10 | 5 | - | 31 |
| | d | 5.4 | 10 | 5 | 5 | 10 | - | 5 | + | 5 | 5 | - | 20 | 10 | + | + | + | - | + | 10 | 5 | + | 26 |
| N*2 PKNaMg | 14/2a | 7.0 | - | + | + | 35 | - | 5 | 5 | 10 | + | - | 5 | + | + | - | 20 | - | - | + | 5 | - | 25 |
| | b | 6.2 | + | 20 | + | 25 | - | + | 5 | 10 | + | - | 5 | + | - | + | 10 | - | + | 5 | 5 | - | 28 |
| | c | 5.9 | + | 25 | + | 25 | - | 5 | 5 | 10 | + | - | 5 | + | - | + | 5 | - | + | 5 | 10 | - | 25 |
| | d | 6.0 | + | 25 | + | 15 | - | 5 | 5 | 10 | - | - | + | + | - | - | 5 | - | - | 5 | 10 | - | 22 |
| N1 | 1b | 6.3 | 5 | - | + | + | 30 | 5 | 5 | + | - | + | + | - | + | 5 | - | - | 25 | 10 | + | - | 28 |
| | d | 4.0 | 65 | - | 30 | - | - | - | + | - | - | - | - | - | - | - | - | - | + | - | - | - | 5 |
| N2P NaMg | 10b | 6.3 | 10 | + | 10 | + | - | - | 40 | 20 | - | + | - | - | - | - | - | - | - | 15 | + | - | 18 |
| | d | 3.7 | 5 | - | 90 | + | - | - | - | 5 | - | - | - | - | - | - | - | - | - | - | - | - | 4 |
| (N2) PKNaMg | 9/1a | 7.1 | + | + | + | 10 | - | 5 | + | + | 15 | - | 20 | + | + | - | 5 | - | + | 10 | + | - | 30 |
| | b | 6.4 | + | 5 | + | 10 | - | + | + | + | 5 | + | 45 | + | + | 5 | + | - | + | 15 | + | - | 34 |
| | c | 5.2 | 5 | + | + | 5 | - | + | 10 | 5 | 5 | + | 25 | 5 | 5 | 10 | + | - | + | 10 | + | - | 31 |
| | d | 4.1 | 45 | - | 45 | - | - | - | + | + | - | - | + | - | - | - | - | - | - | + | - | - | 11 |
| N2 PKNaMg | 9/2a | 7.1 | - | 10 | + | 35 | - | 10 | + | 5 | 10 | - | 15 | - | - | - | 5 | - | - | + | + | - | 23 |
| | b | 6.2 | + | 5 | + | 40 | - | 5 | + | 5 | 5 | - | 15 | - | - | - | 5 | - | - | 5 | + | - | 24 |
| | c | 5.1 | 20 | 5 | + | 10 | - | 5 | 30 | 10 | 5 | + | 5 | - | - | - | + | - | - | + | + | - | 28 |
| | d | 3.7 | + | - | 55 | - | - | - | - | 40 | - | - | - | - | - | - | - | - | - | - | - | - | 3 |
| N3 PKNaMg | 11/1b | 6.4 | - | 20 | + | 30 | - | 20 | + | 10 | - | - | + | - | - | - | 5 | - | - | + | + | - | 17 |
| | d | 3.6 | - | - | - | - | - | - | - | 100 | - | - | - | - | - | - | - | - | - | - | - | - | 1 |
| N3 PKNaMgSi | 11/2b | 6.1 | - | 20 | + | 45 | - | 15 | - | 5 | - | - | + | - | - | + | 5 | - | - | + | + | - | 17 |
| | d | 3.6 | 5 | - | + | + | - | - | - | 95 | - | - | - | - | - | - | - | - | - | - | - | - | 4 |

(1) See Table 3 for treatment details.
Data are from surveys immediately before hay harvest; mean 2010-2012 rounded to the nearest 5% of dry matter (selected plots only).
Note; +, species present at less than 5%; -, species not present on that plot.
Species that do not occur at 10%, or more, on any one plot are not shown.

| | | |
|---|---|---|
| **Grasses** | *Agrostis capillaris* | Common Bent |
| | *Alopecurus pratensis* | Meadow Foxtail |
| | *Anthoxanthum odoratum* | Sweet Vernal Grass |
| | *Arrenatherum elatius* | False Oat Grass |
| | *Briza media* | Quaking Grass |
| | *Dactylis glomerata* | Cock's-foot |
| | *Festuca rubra* | Red Fescue |
| | *Holcus lanatus* | Yorkshire Fog |
| **Forbs** | *Achillea millefolium* | Yarrow |
| | *Centaura nigra* | Common Knapweed |
| | *Heracleum sphondylium* | Hogweed |
| | *Hypochaeris radicata* | Cat's-ear |
| | *Leontodon hispidus* | Rough Hawkbit |
| | *Plantago lanceolata* | Ribwort Plantain |
| | *Ranunculus acris* | Meadow Buttercup |
| | *Sanguisorba minor* | Salad Burnet |
| **Legumes** | *Lathyrus pratensis* | Meadow Vetchling |
| | *Lotus corniculatus* | Common Bird's-foot-trefoil |
| | *Trifolium pratense* | Red Clover |
| | *Trifolium repens* | White Clover |

effects over time on the numbers of species comprising 1%, or more, of the above-ground biomass. Even on the Nil plots, the number of species has decreased since the start of the experiment, possibly as a consequence of atmospheric inputs and/or changes in the management of the sward. Applying either form of N decreased species number further in the absence of chalk, much more so with ammonium sulphate than with sodium nitrate. Raising soil pH, by adding chalk, has had bigger effects on the Nil and ammonium sulphate treatments than on those given sodium nitrate.

Since 2000 an increase in legumes, as a percentage of herbage dry matter, has been observed on plots 9/1 and 14/1, where fertiliser N has been withheld since 1989, and on other treatments (Table 5). Over the same period a marked decrease in atmospheric N deposition has been observed, indicating that grassland species diversity can recover following a decrease in atmospheric pollution

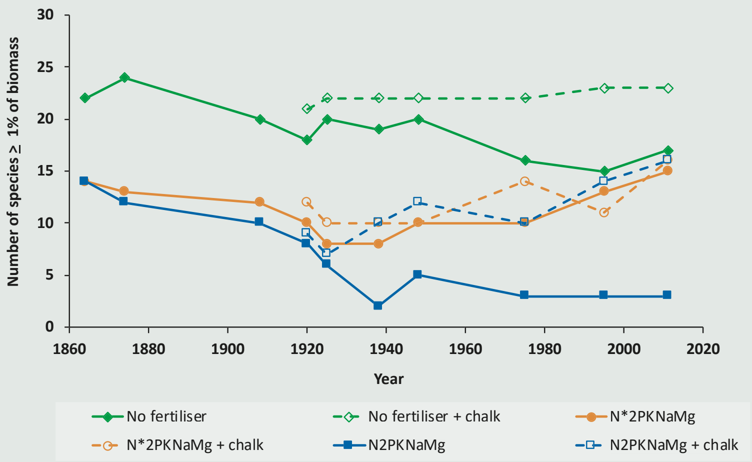
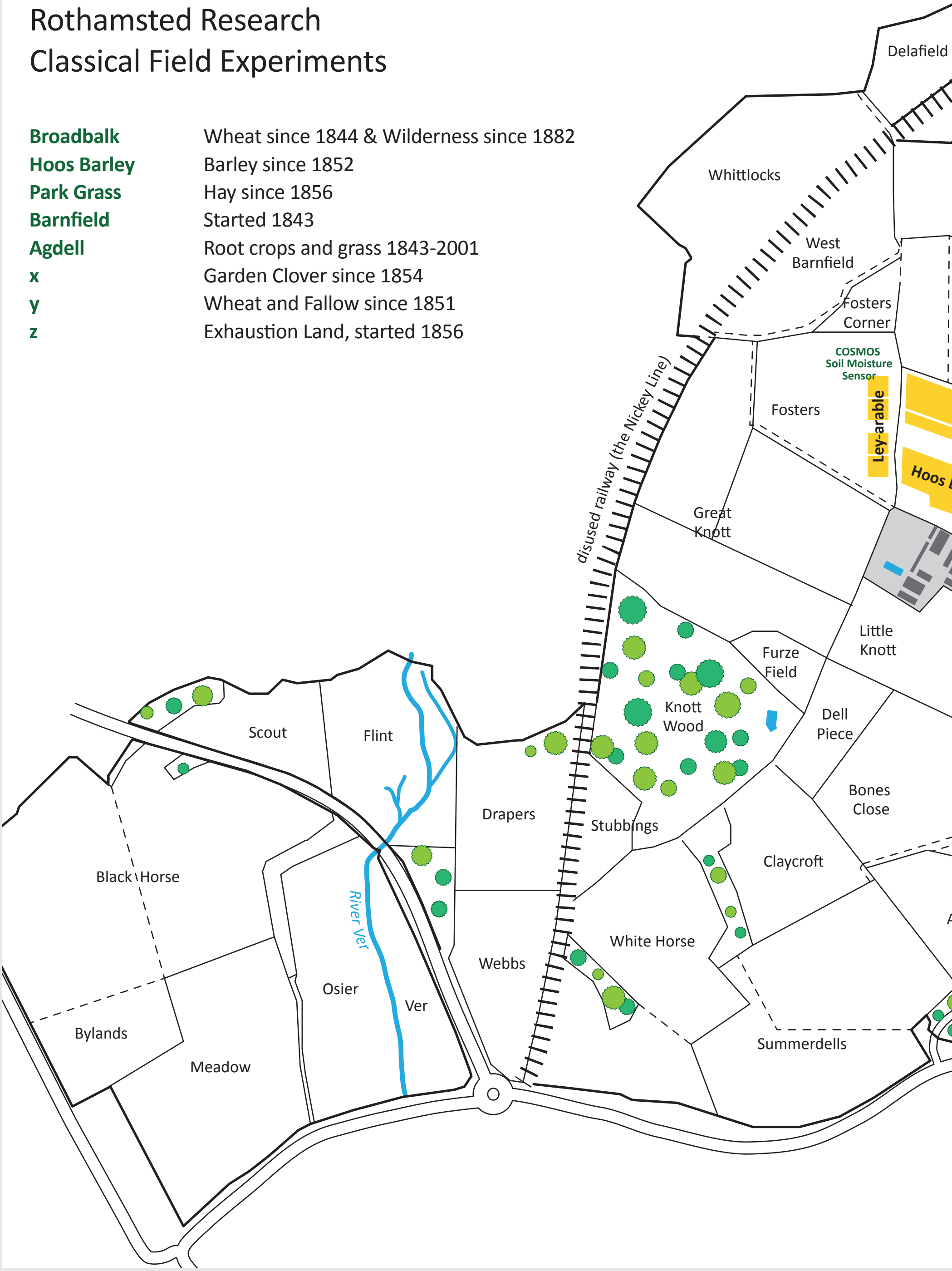



Fig. 6 Park Grass; changes in the number of species comprising 1% or more of the above-ground biomass over time, 1864-2011.

# Rothamsted Research
# Classical Field Experiments

| | |
|---|---|
| **Broadbalk** | Wheat since 1844 & Wilderness since 1882 |
| **Hoos Barley** | Barley since 1852 |
| **Park Grass** | Hay since 1856 |
| **Barnfield** | Started 1843 |
| **Agdell** | Root crops and grass 1843-2001 |
| **x** | Garden Clover since 1854 |
| **y** | Wheat and Fallow since 1851 |
| **z** | Exhaustion Land, started 1856 |



| | |
|---|---|
| Area: | 330ha (813 acres) |
| Elevation: | 95-134m (310-440ft) abive sea level |
| Rainfall: | 1971-2000 mean, 704mm per year |
| | 1981-2010 mean, 733mm per year |
| Extremes: | 380mm in 1921, 1059mm in 2012 |
| Soil: | Well drained or moderately well drained flinty loams on clay-with-flints and/or chalk<br>Aquic Paleudalf (USDA), Chromic Luvisol (FAO) |

and N fertiliser inputs. This provided the first evidence of the impact of anthropogenic stress on biodiversity in an agricultural system followed by recovery after removal of that stress (Storkey *et al*., 2015).

Applying P alone (plot 4/1) and PNaMg (plot 8) has decreased the total number of species a little but no more than any other treatment when soils are maintained at pH 5 and above. P applications had relatively minor effects on species composition, compared to the Nil plots (data not shown), but giving K with P (plot 7), has increased the amount of dry matter from legumes, especially red and white clover (*Trifolium pratense* and *Trifolium repens*) and meadow vetchling (*Lathyrus pratensis*), thus greatly increasing yield.

## The microbiology of Park Grass

The international TerraGenome consortium (Vogel *et al.*, 2009) produced the first soil metagenome from the Park Grass untreated control plot (3d) in 2009 to examine the microbial diversity and genetic potential of the total soil microbiota. Key aims of this work were to establish the effects of different sampling approaches (spatial, temporal, depth) on variability in the soil metagenome and the application of different DNA extraction methods. The DNA extracted revealed that 89% of the DNA that could be assigned belonged to Bacteria, 1.4% to the Archaea and 1.0 % to Eukarya. The DNA extraction method was the most important factor in establishing which groups were detected and their relative abundance; the depth, season and spatial separation were less significant. The relatively low contribution of Eukarya to the metagenome, compared to Bacteria, was surprising because fungal activity is often reported to be an important component of grassland soil ecosystems. However, such comparisons are not straightforward as soil fungi differ from bacteria in scale and growth habits, with cytoplasm-depleted hyphae connecting the actively growing tips where cytoplasm and nuclei are located.

Following the publication of the Park Grass metagenome from the control plot, different molecular approaches have been applied to study how different treatments influence the soil microbiome. A survey of 16S rRNA amplicons in community DNA collected from across the pH gradient on Park Grass plots with different N and P fertilisation regimes and controls showed that soil pH correlated most strongly with microbial diversity (H’) and that the soil C/N ratio and concentration of ammonia-N also played a significant role (Zhalnina *et al.*, 2015). A study using a nested sampling strategy on plots with and without mineral fertilisation (NPK) showed that the long-term treatments had decreased both plant and microbial α diversity (the number of different species detected) when compared to the control treatment, indicating that long-term fertilisation may magnify existing divergent spatial patterns of both plants and microorganisms.

# Hoosfield Spring Barley

Spring barley has been grown continuously on this experiment since 1852. It offers interesting contrasts to Broadbalk; being spring-sown it has only needed to be fallowed four times to control weeds and it tests not only nitrogen, minerals and FYM but also sodium silicate (Table 6).

The design of the experiment is of a factorial nature (Warren & Johnston, 1967) with strips 1-4 (Plan 3), originally testing four combinations of nutrients: 0 v P v KMgNa v PKMgNa, crossed by four Series, originally testing no N or three forms of N, applied (usually) at 48 kg N $ha^{-1}$ (Series 0, no N; Series A, ammonium sulphate; Series AA, sodium nitrate; Series C, rape cake, later castor meal).

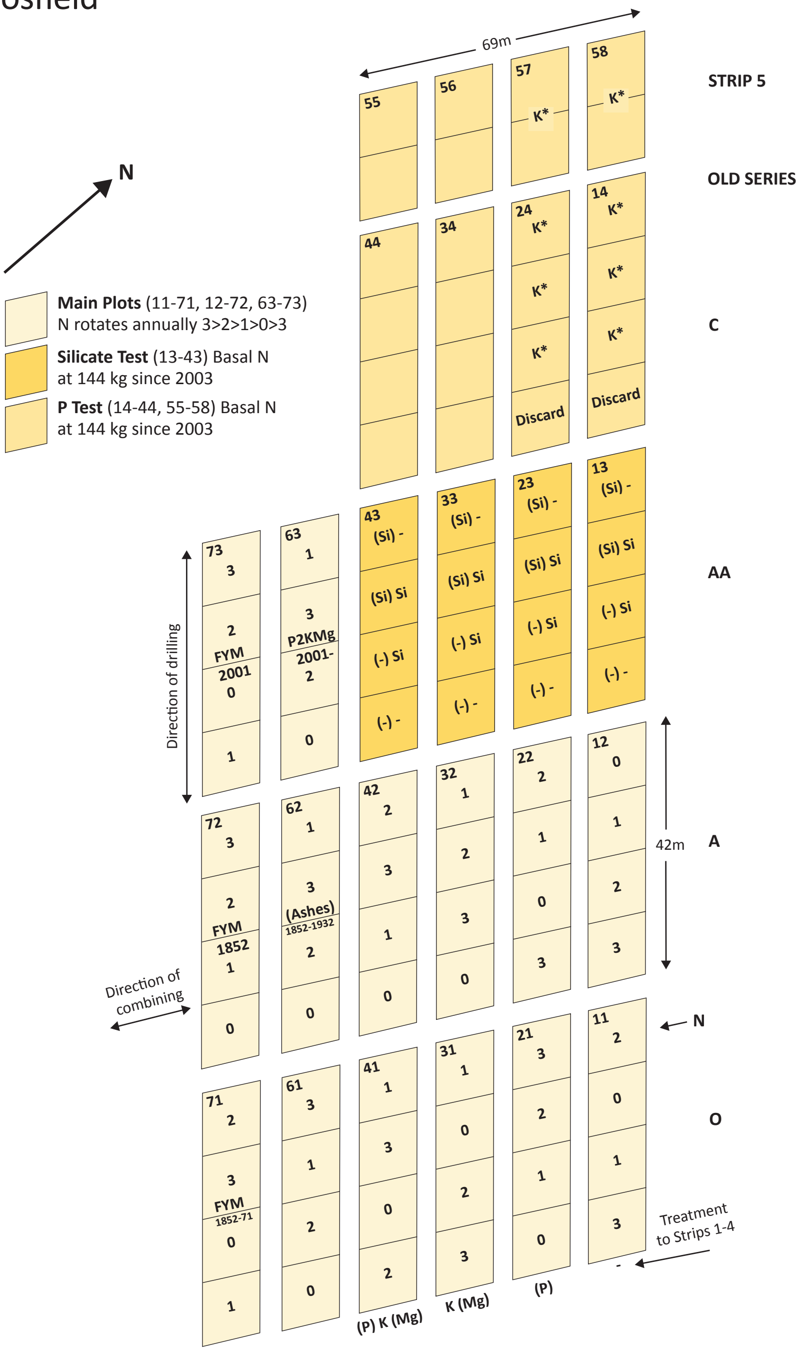
The sodium nitrate Series was divided in 1862 for a test of 0 *v* sodium silicate; this was modified in 1980 to test: 0 v silicate 1862-1979 v silicate since 1980 v silicate since 1862. Additional plots, on the south side, test: unmanured (plot 61); ashes, 1852-1932 (plot 62); residues of FYM applied 1852–71 (plot 71); FYM since 1852 (plot 72). Ashes were tested because in the early years of the experiment they were used to bulk up the different fertilisers to the same volume for ease of spreading. Thus, ashes alone were tested to ensure that no additional nutrients were being added. Two new plots, started in 2001, test: P2KMg (plot 63) and FYM (plot 73). Strip 5 tested various other combinations of N, P, K and Mg.

Short-strawed cultivars have been grown on the whole experiment since 1968 when most of the existing plots were divided and a four-level N test started, replacing the test of different forms of N. Growing barley in rotation with potatoes and beans was tested on parts of Series AA and C. The effects of the two-year break on the yield of barley were small, and barley has been grown each year on the whole experiment since 1979.

In 2003, several major changes were made to the experiment. On the "Main" plots (see Plan), the four-level N test continued but P and Mg are being withheld on some plots (and on parts of Series AA) until levels of plant-available P and Mg decline to more appropriate agronomic levels. Series C and Strip 5 are now used to test responses to plant-available P; basal N is applied and some plots receive K fertiliser to ensure that K is not limiting yield. The silicate test on Series AA has been simplified by stopping the four-level N test and applying basal N.

Until the 1980s, PK with appropriate amounts of N, gave yields as large as those from FYM (Figure 7). More recently, yields have increased on the long-term FYM soil such that, on average, they are not now matched by fertilisers alone. The difference in yield on these soils, with very different levels of SOM in the top 23cm (1.0% and 3.8% organic C in NPK and FYM plots respectively), is probably due to the improved soil structure and improved water-holding capacity, and to additional N being mineralized and made available to the crop at times in the growing season, and in parts of the soil profile, not mimicked by fertiliser N applied in spring. The purpose of the new FYM treatment, which started in 2001, is to see how quickly yields can be increased and how long it takes for yields comparable with those on the long-continued FYM treatment to be achieved. Yields on the new FYM treatment are now about 2 t $ha^{-1}$ larger than on the NPK plots but are still about 1.0 t $ha^{-1}$ less than those on the long-continued FYM plots (Figure 8). This implies that much of the difference in yield is due to the mineralization of extra N, but there may be further benefits as soil structure gradually improves. However, much of the N mineralised from the extra SOM on the FYM-

# Hoosfield



69m
N
Main Plots (11-71, 12-72, 63-73) N rotates annually 3>2>1>0>3
Silicate Test (13-43) Basal N at 144 kg since 2003
P Test (14-44, 55-58) Basal N at 144 kg since 2003
STRIP 5
OLD SERIES
C
AA
A
O
55
56
57
58
K*
44
34
24
14
Discard
43
33
23
13
(Si) -
(Si) Si
(-) Si
(-) -
73
63
3
1
2
FYM
2001
0
P2KMg
2001-
Direction of drilling
72
62
(Ashes)
1852-1932
1852
Direction of combining
42
32
22
12
42m
71
61
41
31
21
11
1852-71
Treatment to Strips 1-4
(P) K (Mg)
K (Mg)
(P)
-

## Table 6. Hoosfield fertiliser and organic manure treatments.

**Annual treatment per hectare**

**Nitrogen (applied in spring)**

| | |
|---|---|
| N 0, 1, 2, 3 | 0, 48, 96, 144 kg N as calcium ammonium nitrate (Nitro-chalk)<br>N rates rotate in the order: N3 > N2 > N1 > N0 |

**Organics (applied before ploughing in autumn)**

| | |
|---|---|
| FYM 1852 | Farmyard manure at 35 t since 1852 |
| FYM 2001 | Farmyard manure at 35 t since 2001 |
| FYM 1852-71 | Farmyard manure at 35 t, 1852-1871 only |

**Minerals (applied before ploughing in autumn)**

| | |
|---|---|
| P2 | 44 kg P as triple superphosphate since 2001 |
| (P) | 35 kg P until 2002 (to be reviewed for 2020) |
| K | 90 kg K as potassium sulphate |
| K* | 180 kg K, 2004-8 (450 kg K in 2003) |
| (Mg) | 35 kg Mg as Kieserite every 3 years until 2002 (to be reviewed for 2020) |
| Mg | 35 kg Mg as Kieserite since 2001 |
| Si | 450 kg sodium silicate since 1980 |
| (Si) | 450 kg sodium silicate 1862-1979 |

Note: Na as sodium sulphate discontinued in 1974 (applied with K and Mg),
P, K and Mg last applied to Series C for 1979

**Series treatments (last applied 1966; 1967 for parts of Series C)**

| | |
|---|---|
| 0 | None |
| A | 48 kg N as ammonium sulphate |
| AA | 48 kg N as sodium nitrate |
| C | 48 kg N as castor bean meal |

Note: Old Series C and Strip 5 used as a "P" Test since 2003. These plots and those on the Silicate Test (on old Series AA) receive 144 kg basal N

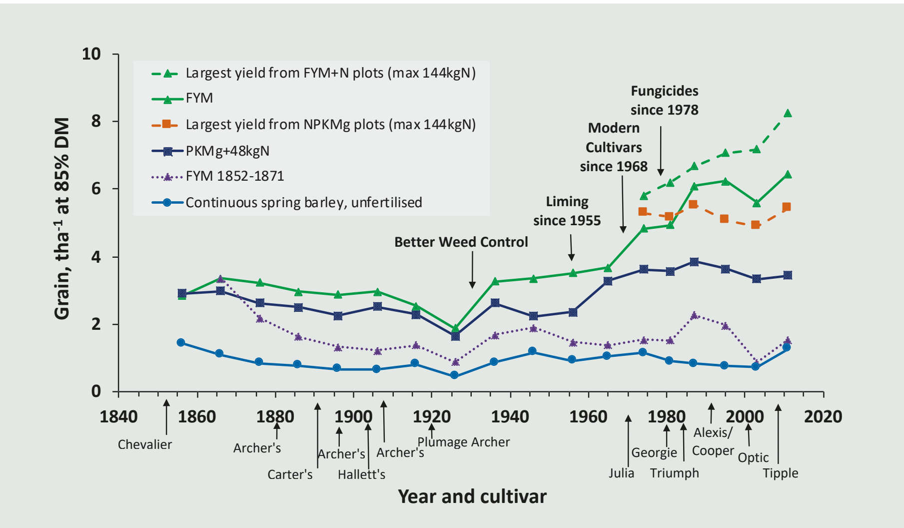



Fig. 7 Hoosfield; mean yields of spring barley grain and changes in husbandry, 1852-2015.

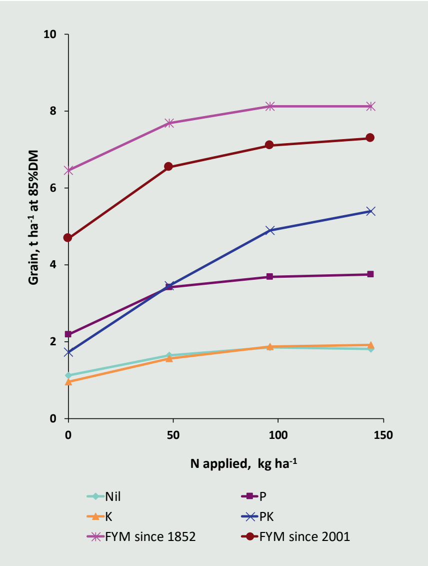



Fig. 8 Hoosfield; mean yields of spring barley grain (cv. Tipple), 2008-2015.

treated soils will be released at a time when it *cannot* be used by the crop and much will be lost by leaching as nitrate.

Sodium silicate, both as a fresh application and as a residue, continued to give substantial yield increases in the period 2008-15 on plots lacking P or K but had little effect on plots receiving these nutrients (Table 7). The mechanism for this is still not fully understood but is thought to be a soil rather than a crop effect.

**Table 7. Hoosfield; effects of silicate on the mean yield of spring barley, 2008-15**

| Treatment[1] | (-)- | (Si)- | (-)Si | (Si)Si |
|---|---|---|---|---|
| | Mean yields of grain, t ha$^{-1}$ at 85% DM | | | |
| N3 | 2.26 | 2.60 | 3.07 | 3.21 |
| N3 K | 2.07 | 3.41 | 3.18 | 3.84 |
| N3P | 4.43 | 4.94 | 4.51 | 4.32 |
| N3PK | 6.15 | 6.57 | 6.46 | 6.43 |

[1] See Table 6 for details

## Exhaustion Land

Unlike some Classical experiments, which have been modified without losing the continuity of many of their treatments, this experiment has had several distinct phases since it started in 1856.

From 1856 to 1901 annual dressings of N, P, K or FYM (from 1876 only) were applied, initially to wheat (1856-1875) then to potatoes (1876-1901). There were 10 plots from 1876 to 1901.

From 1902 to 1939 no fertilisers or manures were applied and, with a few exceptions, cereals were grown. Yields were recorded in some years; residual effects of the previous treatments were very small in the absence of fresh N fertiliser.

From 1940, fertiliser N was applied to all plots. Nitrogen not only increased yields, but also demonstrated the value of P and K residues remaining in the soil from the first period of the experiment. From 1940 to 1985, spring barley was grown and N fertiliser applied to all plots every year, initially at a single rate, but in 1976 the 10 main plots were divided to test four rates of N. The residual effects of the P and K were initially large but declined as amounts of available P in the soil declined. However, even in recent years (1992-2012) residues from P applied in FYM or as fertiliser more than 100 years ago, still supply more than twice as much P as the soil that has received no P input since 1856 (Table 8).

In 1986, after a long period when the P residues, in particular, were being "exhausted" it was decided to see how quickly this decline in soil fertility could be reversed. Annual, cumulative dressings of 0 v 44 v 87 v 131 kg P ha$^{-1}$, as triple superphosphate, were tested on five of the original plots (each divided into four sub-plots). Basal N and K were

**Table 8. Exhaustion Land; phosphorus removed from 1856 to 2012 by arable crops growing on soils without P since 1856 or on soils with residues of P applied as fertiliser from 1856-1901 or in FYM from 1876-1901 and none since.**

| | | Amounts of P removed, kg ha$^{-1}$ | | | | | |
|---|---|---|---|---|---|---|---|
| | | Plots 1 & 5 No P since 1856 | | Plots 7 & 9 Residues of P fertiliser 1856-1901 | | Plot 3 Residues of FYM 1876-1901 | |
| Period | Crop | Total | per year | Total | per year | Total | per year |
| 1856-75 | W. wheat | 80 | 4.0 | 121 | 6.0 | 66 | 3.3 |
| 1876-01 | Potatoes | 47 | 1.8 | 138 | 5.3 | 159 | 6.1 |
| 1902-40[(1)] | S. barley | 102 | 2.6 | 207 | 5.3 | 200 | 5.1 |
| 1941-85[(2)] | S. barley | 189 | 4.2 | 394 | 8.8 | 478 | 10.6 |
| 1986-91[(3)] | S. barley | 28 | 4.7 | 51 | 8.5 | 60 | 10.1 |
| 1992-2012[(4)] | W. wheat | 75 | 3.6 | 175 | 8.3 | 200 | 9.5 |

[(1)] Mainly spring barley grown during this period; no fertilisers or manure applied
[(2)] Fertiliser N has been applied at various rates since 1941; fallow in 1967 and 1975
[(3)] Basal K applied since 1986
[(4)] Spring wheat in 2001

applied such that these nutrients did not limit yield. Responses to fresh P were rapid. After just three years, where P applications had increased available-P (Olsen P) above a critical level, a yield "plateau" was reached . Although further applications of fresh P increased soil P these did not increase yield. Applications of the three fixed rates of P were stopped after seven years and since 2000 were replaced by maintenance dressings, equivalent to offtakes by the crop. (not to the no-fresh-P sub-plots). Wheat has been grown since 1992. Typically, it showed the same response to available-P as spring barley *i.e.* above a critical level, *on this soil*, of about 10-14 mg kg$^{-1}$ there is no further increase in yield, even though that maximum yield may be quite different (Figure 9) (Poulton *et al.*, 2013). In autumn 2015, maintenance P dressings on plots previously given 44 kg P ha$^{-1}$ (see above) ceased.

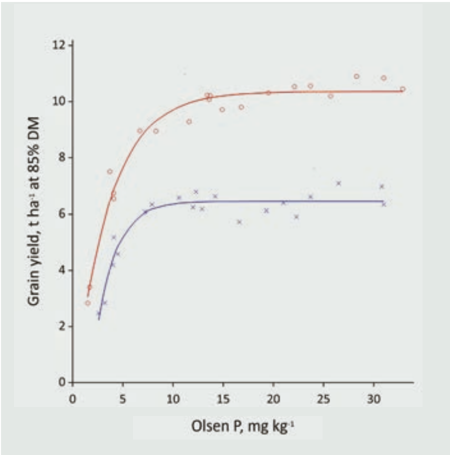



Fig. 9 Exhaustion Land; responses in the yield of wheat grain to concentrations of plant-available P (Olsen P) in the soil in contrasting years: 2003 (x) and 2008 (o).

On the other half of the experiment, the effects of K residues (in the presence of basal P and N) on yield are investigated (the "K Test" plots). Since 2007, annual cumulative applications of 0, 62.2 and 124.5 kg K ha$^{-1}$ as muriate of potash have been applied (K0, K1 and K2). On average, grain yields are increased by 0.7 t ha$^{-1}$ with K1, but show little further benefit from additional K inputs and in some years there is no response to K fertiliser.

## Garden Clover

Garden Clover experiment, 2008

Garden Clover is the simplest of the Classical experiments, with (until 1956) only one, unmanured plot. Lawes and Gilbert were successful in growing wheat, barley and turnips each year on the same land but found that red clover, although a perennial, seldom survived through the winter when sown on farmland. Even when re-sown annually it soon failed to give an acceptable yield. To see whether red clover could be grown continuously on a "richer" soil Lawes and Gilbert laid down this small plot in the Manor's kitchen garden in 1854. Yields were very large for the first 10 years, averaging about 10 t dry matter $ha^{-1}$, probably because the soil was rich in nutrients and because soil-borne pests and diseases of clover were absent. Reasonable yields were obtained over the next 30 years but thereafter yields showed a marked decline and there were several complete failures.

Between 1956 and 1972 the plot was sub-divided and a sequence of tests made of K, molybdenum (Mo), formalin, N and Mg. N, K and Mg all increased yields, Mo and formalin did not. With N, P, K and Mg yields of about 6 t dry matter $ha^{-1}$ were obtained in the year of sowing. The crop was usually severely damaged during the winter by clover rot (*Sclerotinia trifoliorum*) and was re-sown each spring. Since 1973 basal N, P, K, Mg and chalk have been applied.

Between 1976 and 1978 aldicarb was tested as a control for clover cyst nematode, *Heterodera trifolii*, which was known to be present, and the cultivar Hungaropoly, believed resistant to clover-rot, was compared with the standard susceptible cultivar S.123. The combination of aldicarb and Hungaropoly gave yields up to 8 t dry matter $ha^{-1}$ but winter survival remained poor (McEwen *et al.*, 1984).

The plot was then sown with *cv.* Hungaropoly only, with basal aldicarb (until 1988), and tested the fungicide benomyl from 1980-90. Initially, there was a benefit from applying benomyl but averaged over the 11 years in which it was tested there was none. Between 1979 and 2018 the experiment was re-sown eight times. The mean yield of the cultivar Milvus for the period 2007-2012 was 11t $ha^{-1}$

Clover nodule bacteria and their bacteriophages are abundant. Nodule bacteria for *Vicia* spp. are sparse and those for *Lotus* and medicks absent. Other than Park Grass, with its mixed herbage, this is the only remaining Classical site where only a non-graminaceous crop has been grown. In terms of microbial diversity, its soil provides a potentially valuable contrast with that of Broadbalk and Hoosfield.

The rich kitchen garden soil on which the experiment was established had received much FYM. In 1857 the top soil (0-23cm) contained 10.8 t N $ha^{-1}$; by 2011 this had declined to 4.5 t N $ha^{-1}$.

# OTHER LONG-TERM EXPERIMENTS

In addition to the Classical experiments started by Lawes and Gilbert, there are several other long-term experiments at Rothamsted and at Woburn on contrasting soil types. Some of these are described below.

## At Rothamsted

### Highfield and Fosters Ley-arable Experiments

The Ley-arable experiments at Rothamsted, on Highfield and Fosters fields, started in 1949 (Johnston, 1973). Their purpose was to look at the effects of different cropping systems on yield and soil organic matter. The two sites have the same soil type but very different cropping histories. Highfield had been in permanent grass since 1838; on this site some plots stayed in permanent grass, others went into continuous arable cropping and some alternated between leys and arable. Fosters had been in arable cropping for several centuries; on this site some plots stayed in continuous arable, some went into permanent grass and others alternated between leys and arable. Although we no longer measure yields we continue to monitor SOM. Figure 10 shows that, it has taken about 60 years for soils to approach a stable equilibrium following changes in the cropping systems. Thus, in soils ploughed out of permanent grass or put into permanent grass after arable cropping the SOM is now relatively constant.

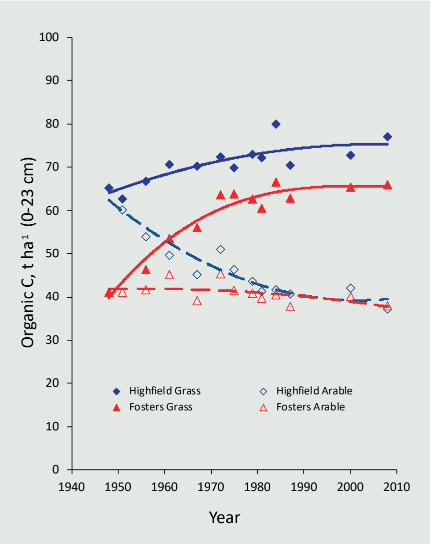



Fig. 10 Highfield and Fosters Ley-arable; changes in the amount of soil carbon in the top-soil (0-23 cm), 1949-2008. Data has been adjusted for changes in bulk density.

### The Long-term Miscanthus Experiment

Other work at Rothamsted has focussed on non-food crops, including Miscanthus, a perennial grass originating mainly from east Asia. *Miscanthus* x *giganteus* is a naturally occurring hybrid between *M. sinensis* and *M. sacchariflorus* thought to have originated in Japan. It was first recorded in European botanical gardens in the 1930s but it wasn't until 50 years later that researchers interested in renewable energy began to take an interest in its suitability as an energy crop.

Miscanthus utilises the C4 pathway for photosynthesis but unusually amongst C4 grasses shows good low temperature adaptation. For cooler northern areas of Europe this introduced the possibility of capitalising on the advantages of the C4 pathway, namely; lower nitrogen requirement, greater water use efficiency and greater ability to utilise high light intensities, when compared to C3 grasses. As a perennial, *M.* x *giganteus* offered savings on cultivation costs plus the potential for increasing soil carbon content, giving the crop a favourable Life Cycle Analysis compared to annual crops. When research work began, it became evident that the perennial cycle also involved nutrient

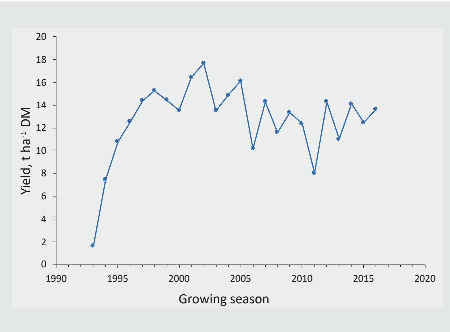



Fig. 11 Rothamsted; yield of *Miscanthus x giganteous*, 1993-2016.

remobilisation between the rhizome and shoots and *vice versa*. The nett effect being efficient utilisation of nutrients, especially N, and, if harvested when fully senesced (early spring of the year following growth) a biomass fuel low in contaminants such as N, K, S and Cl.

Rothamsted Research first planted *M.* x *giganteus* in spring 1993. The belief at that time was that a crop may remain productive for 20 years. As Figure 11 shows, following an establishment phase of 3 years the Rothamsted crop has remained productive for a total of 24 years. Seasonal variation is clear, but there is no sign of a yield decline. Very few of the experimental crops planted around Europe between 1988 (the earliest known planting as a crop) and 1993 remain in place. The Rothamsted crop is certainly one of the oldest stands in the world, if not the oldest. This experiment is maintained to determine how long a single planting may remain productive and to monitor for pests and diseases that may threaten that productivity.

## The Large-scale Rotation Experiments (LSREs): new long-term experiments

The Rothamsted long-term experiments have proved to be a unique resource for understanding the behaviour of agricultural systems over decadal time scales. However, the potential to use the existing experiments to answer new questions is sometimes limited by the need to maintain the original treatment structure, the lack of replication and plot size. To address these constraints, a new long-term experiment, supported by the Lawes Agricultural Trust, has been set up on the Rothamsted farm at Broom's Barn (Suffolk). The new experiment compares contrasting farming systems with multiple interacting factors. Treatments were chosen that would impact on a wide range of agronomic and environmental response variables as well as addressing issues relevant to modern farming systems. The experiment was established at Broom's Barn in autumn 2017 and a similar experiment started at Harpenden in autumn 2018.

The main treatment is crop rotation with large 24 x 24m plots in one of three rotations: a three-year rotation aiming at short-term economic return, a five-year rotation with a greater diversity of crops (including cover crops) and a seven-year rotation designed for increased environmental sustainability (also including cover crops and a two-year ley). A second treatment of contrasting soil cultivation is also included: either annual ploughing or zero tillage (using a direct drill). The main plots are also split with half receiving organic amendments. Each phase of each rotation is present in every year in all treatment combinations. The design also includes the flexibility to test contrasting crop protection strategies. These new LSREs will serve as valuable experimental platforms in the coming years for integrating the breadth of science covered by Rothamsted Research and informing the design of future farming systems with the aim of increasing yields while reducing the impact on the environment.

## At Woburn

Experiments at Woburn began in 1876 under the auspices of the Royal Agricultural Society of England. The principle aim was to test the residual manurial value of two contrasting feedstuffs fed to animals in covered yards or on the land. Rothamsted took over the management of the farm in the 1920s. In contrast to the silty clay loam at Rothamsted, which, typically, contains 20-40% clay, much of the soil at Woburn is a sandy loam containing about 8-14% clay (Catt *et al*,1977, 1980). It is much more difficult to maintain or increase SOM on this soil, and several of the long-term experiments at Woburn were established to study the effects on yield and SOM of including grass leys and applying organic amendments in arable rotations.

### The Woburn Ley-arable Experiment

The Ley-arable experiment was started in 1938 to compare the effects of rotations with or without grass or grass-clover leys on the yield of two arable test crops and on SOM. Soils at Woburn that have been in continuous arable cropping since 1876 contain about 0.8-0.9 % C, and % C is still declining, slowly; soils which have alternated between 3-year leys and 2-years arable since 1938 contain about 1.2 % C (Figure 12).

Changes in the amounts of C in the soil over > 70 years have been modelled. In the rotation where the ley was originally grazed (Ln3), only about 5% of the estimated C input was retained in the soil; in the other rotations > 98% of the input was lost (Johnston *et al*.,2017). Typically, where no fertiliser N is applied, yields of test crops are greater following the grass leys than

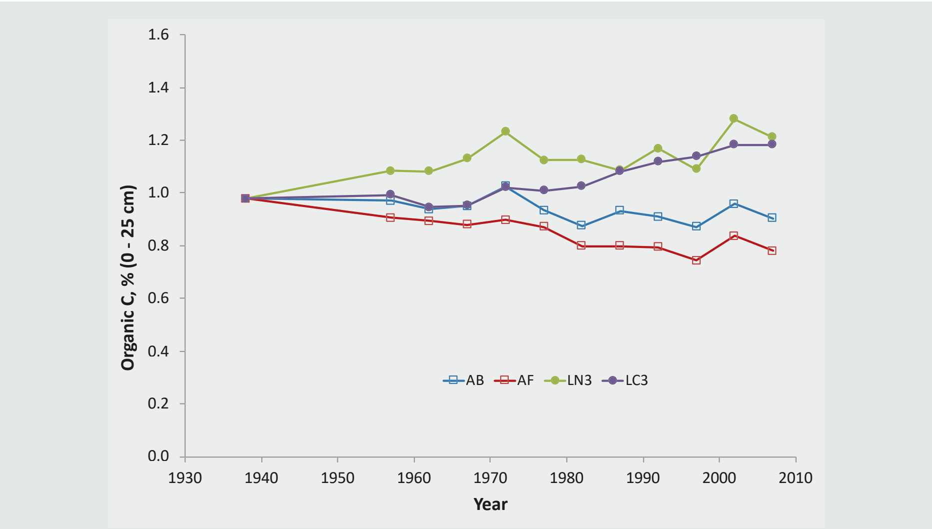



Fig. 12 Woburn Ley-arable; changes % organic C in the top-soil (0-25 cm), 1938-2009. Treatments are: (AB) continuous arable; (AF) continuous arable with root crops or fallows; (LN3) 3-year grazed grass/clover (later grass + N) leys + 2-years arable; (LC3) 3-year lucerne (later grass/clover) leys + 2-years arable.

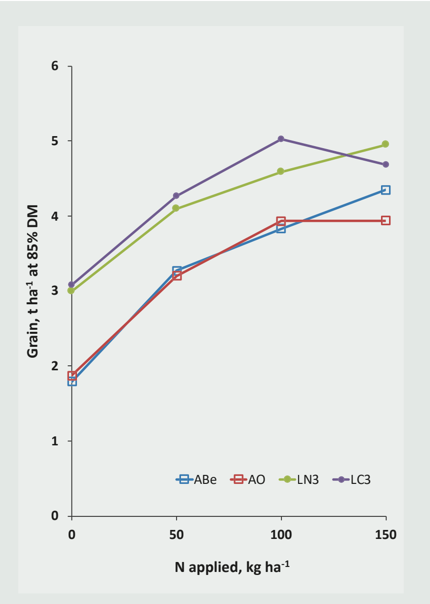



Fig. 13 Woburn Ley-arable; mean yields of winter rye, 2011-2015. Data are yields of the 2nd Test crop after: (ABe) beans in continuous arable rotation [previously AB]; (AO) oats in continuous arable rotation [previously AF]; (LN3) 3-year grass ley + N; (LC3) 3-year grass/clover ley.

in the continuous arable sequence because more N is available from the mineralisation of SOM. Following grass-clover leys, yield is increased further because of the extra N being made available from the breakdown of the leguminous residues. Even in the second cereal after the leys have been ploughed-in a larger yield is often achieved, with less fertiliser N, compared with continuous arable cropping (Figure 13).

## The Woburn Organic Manuring Experiment

The Woburn Organic Manuring experiment was started in 1964 to test the effects of different types of organic matter inputs on crop yields and SOM. Initially, six organic treatments (grass or grass/clover leys and arable crops with FYM, peat, straw or green manures) were compared with arable crops receiving fertilisers only. Arable crops were then grown in rotation with an eight-level N test from 1973 to 1980, to assess the effects of the organic amendments. During this period, no organic manures were applied. There was another treatment phase from 1981-1986, when further organic manures were applied. Again, SOM increased with the organic treatments and the grass leys but continued to decline slowly where only fertilisers were applied. This treatment phase was followed by another test phase, 1987-1994, when six rates of N were tested on arable crops, and no further organic manures were applied. From 1995-2002 arable test cropping continued but only two rates of N were tested. In 2003 another treatment phase started. All plots, except for the permanent grass-clover leys (and beans when grown) were split to test six rates of N on arable crops grown in rotation. Currently, the experiment contains 32 plots divided into four blocks. Of these, 28 are in a five-course arable rotation (Wheat, Maize/Cover Crop, Rye, S. Barley/Cover Crop, Beans) with different organic amendments (FYM, Straw, Compost, None). The remaining four plots continue in permanent grass/clover, without N. The arable plots are split so that N can be applied in spring at six rates for all crops, except beans which receive no N. Yields are recorded each year and soils are taken every 5 years.

## Barnfield

This was the first of what became the "Classical" experiments, with treatments applied in spring 1843 for a crop of turnips sown in July. The treatments and cropping, although mainly roots, differed until 1876 when a period of continuous cropping with mangolds was started that lasted until 1959 (sugar beet were also grown, on half-plots, from 1946).

Treatments during the first two years were on long narrow plots, as on Broadbalk. However, the design was modified in 1856 when strips testing minerals and FYM, including FYM + PK, were crossed at right angles by series comparing no N fertiliser with both inorganic and organic forms of N supplying 96 kg ha$^{-1}$ (Warren & Johnston, 1962). Before 1968 this was the only Classical in which N was applied in combination with FYM and FYM + PK fertiliser.

Because yields of continuous roots were declining, perhaps because of increasing amounts of cyst nematodes (*Heterodera schachtii*), the cropping has been progressively modified since 1959 and has included a range of arable crops, with an increased range of N dressings, and grass. From 1977 to 1983 the series that had never received N fertiliser was kept fallow. It was sown to a grass-clover ley in 1984. The remainder has been in grass since 1975.

A feature of the continuous roots and subsequent arable crops was the larger yields on soils given FYM, even where large rates of N were applied in combination with the minerals. This may have been because the extra organic matter had greatly improved soil structure on this field, which is one of the most difficult on the farm to cultivate. Yields of the grass, grown more recently, were also larger on FYM-treated soils, although no FYM was applied after sowing the grass. This was perhaps because more of the N applied to grass on minerals-treated soils was being used to increase soil organic matter. Accordingly, from 1983 to 2000 a range of N dressings (75, 100, 125, 150 kg N ha$^{-1}$ per cut) was tested on the grass. The yields with minerals plus optimum N nearly equalled those from FYM. With neither minerals nor FYM there was no benefit from increasing N above 75 kg ha$^{-1}$.

No treatments have been applied and no yields measured since 2001, but the soil within the different plots still contain different nutrient concentrations, reflecting their past inputs. Consequently, the site is a useful resource for studies on plant nutrient dynamics and was used recently to investigate the responses of wheat roots to supplies of soil P.

## Hoosfield Alternate Wheat and Fallow

From 1856 to 1932, this 0.4 ha area, which has received no applications of fertiliser or manure since 1851, was divided into two strips that alternated between wheat and fallow in successive years. From 1934 to 1982, a modification allowed a yearly comparison of a one-year and a three-year fallow but the effects were small and, in 1983, the experiment reverted to the original design. It does receive chalk, when needed, and pesticides.

The cultivar grown has usually been the same as on Broadbalk and the effects of fallowing may be roughly estimated by comparing yields of wheat on Hoosfield with continuous, unmanured wheat on Broadbalk. In the first 10 years of the experiment the one-year fallow gave an extra 0.6 t ha$^{-1}$, but, over the next

60 years the difference was smaller at only 0.14 t ha$^{-1}$. With modern cultivars, and since its reversion to the original design in 1983, average yields of the wheat after a one-year fallow have been 1.6 t ha$^{-1}$. When expressed on the basis of the whole area (*i.e.* wheat plus fallow), the yield of 0.8 t ha$^{-1}$ is slightly less than the 1.0 t ha$^{-1}$ for continuous wheat on Broadbalk. Since autumn 2015, the whole experiment (both plots) has been sown to winter wheat. A small amount of N fertiliser (50 kg N ha$^{-1}$) is applied in spring (mid-April), but, to maintain the low soil P and K status, no other fertilisers are applied. No yields or crop samples have been taken since harvest 2015. It was in this field, in 1935, that symptoms caused by *Gibellina cerealis* were first recorded in the UK (Glynne *et al*., 1985).

## Woburn Market Garden

The Market Garden experiment started in 1942, originally to look at the effects on crop yield and SOM of various organic inputs; namely FYM, compost and sewage sludge (Johnston & Wedderburn, 1975; Johnston, 1975). The experiment was in grass from 1974 to 1982. When concerns were expressed in the late 1970s about the heavy metal content of sewage sludges being applied to agricultural land, the experiment was "re-activated" to examine the fate of metals that had been applied in the sewage sludge between 1942 and 1961. Archived samples of soils and sewage sludges from the earlier phase of the experiment made it possible to compile, for various metals, a budget of the amount applied and the amount remaining in the soil (McGrath, 1984). Total zinc (Zn) and cadmium (Cd) concentrations in the topsoil were much higher in sludge-amended plots than in those testing other treatments. Calculations suggest that about 80% of the metal load applied between 1942 and 1961 remained in the soil, predominantly in the top 27cm. From 1983, crops potentially sensitive to heavy metals were grown and analysed, as was the soil. Uptakes of Zn and Cd by these crops were minimal, although concentrations of *e.g.* Cd in barley grain could exceed current guidelines when grown on soils with high Cd content. The heavy metals applied in the sludge also affected the soil microbial biomass; more than 20 years after the last application, the total amount of biomass in sludge-amended soils was half that in low-metal soils. It was also found that a strain of *Rhizobium* (*R. leguminosarum* biovar *trifolii*) involved in symbiotic $N_2$ fixation in clover (*Trifolium repens*) was ineffective in sludge-amended soils, but remained effective in FYM and control soils. Clover grown on the metal-contaminated plots yielded 60% less dry matter than clover grown on uncontaminated plots. Permitted levels of metals in sludges are now much lower than those used in the Market Garden experiment, but results from the experiment were used to help formulate EU legislation to prevent heavy metal contamination of soil.

## Agdell

This was the only Classical in which crops were grown in rotation. From 1848 to 1951, three different manurial combinations (none, PKNaMg and NPKNaMg plus rape cake, castor meal) were applied to the root crops of two four-course rotations. The rotations differed only in their third course – roots, barley, fallow or legume, wheat. There were only six large plots and only one course of the rotation was present each year. The root crop was turnips or swedes, the legume clover or beans. From 1920, club-root (*Plasmodiophora brassicae*) became progressively more damaging to the root crop, especially on the NPKNaMg plots as a result of increasing soil acidity. By 1948 the produce was too small to weigh, and the four-course rotation ceased in 1951. Soil acidity was corrected and the plots were then used to evaluate the P and K reserves accumulated up to 1951. During this period the original six plots were halved and two levels of soil organic matter were established by growing leys on one half (Johnston & Penny, 1972). Subsequently, the plots were further sub-divided to build up different amounts of P and K in the soil. Crop yields were then related to the reserves of P and K in the soil and the effect of adding fresh P and K. The experiment ended in 1990 but data relating yield to plant-available P is still useful and has been used recently in several papers (Johnston *et al*., 2013).

## The Woburn Intensive Cereals Experiments

The Intensive Cereals experiments (winter wheat and spring barley grown continuously to mirror those at Rothamsted) started in 1876. Unlike most of the arable soils at Rothamsted, those at Woburn contain little or no free calcium carbonate and the soil pH at the start of the experiment was probably *c*.6. Consequently, within 20 years, the experiments ran into problems with soil acidification where ammonium sulphate was applied, and yields declined markedly. Tests of liming on these experiments, started in 1897, were the first in the UK, but yields did not recover to their former level. Conceivably, yields were also affected by cereal cyst nematodes which can be a problem with continuous cereals on these lighter textured soils. For many years the yields remained poor and the site was used for a number of other experiments. One tested the effects of growing grass-clover leys for one to six years on the yield of subsequent arable crops. Yields of up to 9.0 t $ha^{-1}$ of wheat grain and 75 t $ha^{-1}$ of potato tubers were achieved following the longer leys (Johnston *et al*., 1994).

## Saxmundham Rotations I & II

The soil at Saxmundham is a heavy sandy clay loam, which can be difficult to cultivate; it provides a further contrast to the soils at Rothamsted and Woburn. Two long-term experiments were started at Saxmundham in 1899 by the East Suffolk County Council. Each consisted of four blocks so that a typical Norfolk four-course rotation could be grown, with each crop present in each year. On the Rotation I experiment, there was a factorial test of N, P and K plus bone-meal and FYM treatments (Williams & Cooke, 1971). Rotation II sought to determine how limited amounts of FYM, sodium nitrate and superphosphate could best be used over the four-course rotation. When Rothamsted assumed responsibility for the site in 1965 the experiments were reviewed and modified. Data from the Rotation II experiment have been used extensively to look at the responses by various crops to fresh and residual P (Johnston *et al*., 2013), and the decline in plant-available P when fertiliser P is withheld (Johnston *et al*., 2016). The critical level, above which there is no further response to fresh P, is higher and more variable on this heavier soil than on the better soil at Rothamsted (see Exhaustion Land above). The Rotation I experiment has been used to look at crop responses to both P and K and their interactions with N, particularly where much fertiliser N was applied in recent years to high yielding cultivars of wheat with the aim of achieving bread-making quality. Rothamsted relinquished the site in 2010.

## Amounts of Straw and Continuous Maize Experiments (Rothamsted & Woburn)

Other more recent long-term trials were established to examine the effects of repeatedly incorporating the straw of continuous wheat or continuous maize on the contrasting soils at Rothamsted and Woburn (silty clay loam v sandy loam). The former, were established on the contrasting soils at Rothamsted (Great Knott III; silty-clay loam), and Woburn (Far Field I; sandy loam) in 1987; both were sown to continuous winter wheat. At Rothamsted sixteen plots were established in four replicate blocks with different rates of straw incorporation (0, 1, 2 & 4 times normal straw yield). The same treatments were tested at Woburn in three blocks of four plots. Yields of grain and straw were taken each year, and soil was sampled from all treatments after 7, 11 and 22 years of contrasting straw treatments. Incorporating just the amount of straw produced per unit area had only a small and not significant effect on soil organic C (SOC) even after 22 years. SOC was increased by incorporating greater amounts of straw, but only at the largest rate was the effect significant. (Powlson *et al*, 2011). The experiments were discontinued in 2016.

The Continuous Maize Experiments began in 1997, one was on silty clay loam at Rothamsted (Hoosfield) and the other on the sandy loam at Woburn (Stackyard). The experiments included six cropping treatments: 1. Continuous maize with stubble incorporated; 2. Continuous maize with stubble plus 10t maize tops incorporated; 3. Maize after three years of spring barley with straw removed; 4. Spring barley after five years of maize with stubble incorporated; 5. Continuous spring barley with straw removed plus 10 t maize tops

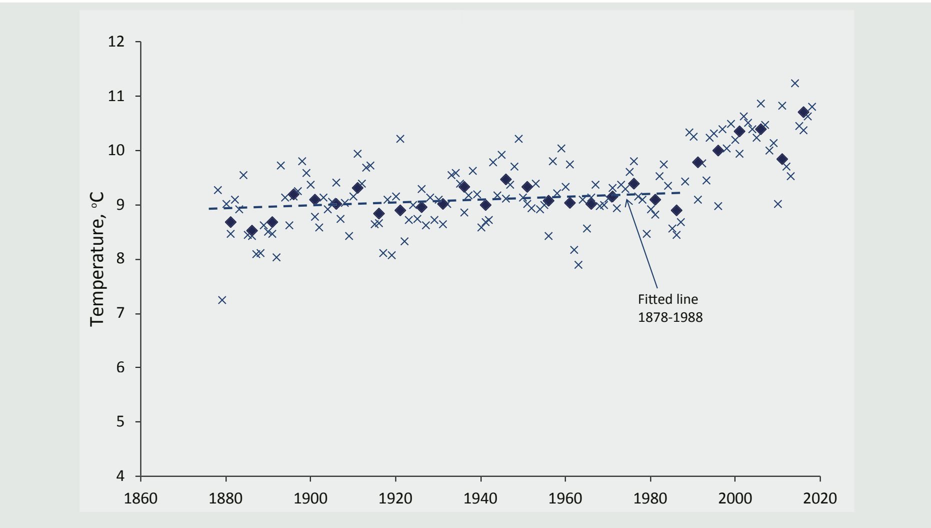



Fig. 14 Rothamsted; average temperature (°C), 1878-2018. Annual mean (x); 5-year mean (♦).

incorporated; 6. Continuous spring barley with straw removed. In treatments with rotations only one phase was present each year. Crop yields were taken each year and soils were collected in 1997, 2008 and 2015. Maize and spring barley were chosen as crops with contrasting $\delta^{13}C$ enrichment in their residues to provide an opportunity to follow the fate of the C incorporated in the maize crop residues. The experiments were discontinued in 2015.

## METEOROLOGICAL DATA

Because of climate change it is important when interpreting data from long-term experiments that changes in temperature, rainfall (amount and distribution), chemical inputs (in rainfall and as dry deposition) *etc.*, are all taken into account. Total rainfall has been measured at Rothamsted since 1853 and temperatures since 1873; other meteorological data have been collected subsequently. Annual rainfall averages 704mm (mean 1971-2000) but ranges

Rothamsted Meteorological Station, 2017

widely from 380mm in 1921 to 973mm in 2000. Increases in temperature in many parts of the world are well documented (Hansen & Sato, 2016) and Rothamsted data (Figure 14) show that the average (1989-2018) annual mean air temperature was approximately 1.1°C warmer than the long-term mean of 9.04°C (1878 to 1988). There has been a similar rise in average annual temperature at Woburn. Much of that rise is accounted for by increases during the autumn and winter months. Average soil temperatures have also risen.

Since the 1850s, chemical inputs in rain have changed considerably. Inputs of acidity ($H^+$ ions) are small; less than 0.1 kg $ha^{-1}yr^{-1}$ up to the 1950s. They reached a maximum of 0.4 kg $ha^{-1}yr^{-1}$ in the 1970s and are now about 0.2 kg $ha^{-1}yr^{-1}$. Inputs of sulphate-S were about 5 kg $ha^{-1}yr^{-1}$ in the 1850s and reached a maximum of 65 kg $ha^{-1}yr^{-1}$ by 1980. After a dramatic decline, associated with decreasing emissions from power stations and a decline in heavy industry they are now about 5 kg $ha^{-1}yr^{-1}$. Inputs of nitrate- and ammonium-N in rainfall were 1 and 3 kg $ha^{-1}yr^{-1}$, respectively, in 1855, and increased to 8 and 10 kg $ha^{-1}yr^{-1}$ in 1980. In 1996, N in dry deposition amounted to 34 kg N $ha^{-1}yr^{-1}$; about three times that in rainfall. The total N input for wet and dry deposition at that time was about of 43 kg $ha^{-1}yr^{-1}$. Since then, atmospheric inputs have declined to about 21 kg N $ha^{-1}$ $yr^{-1}$ (Storkey *et al.*, 2015) compared with about 10 kg N $ha^{-1}yr^{-1}$in the mid-1850s.

## LONG-TERM EXPERIMENTS AS A RESOURCE

Changes in agricultural practices or other factors influencing soil quality and soil processes can take decades to have any measurable effects. Effects of agriculture on the wider environment may also take many years to become apparent. In this context long-term experiments are an invaluable resource that can be used to quantify changes that are impossible to detect in short term experiments.

Thus, Broadbalk, Hoosfield and Park Grass have been used for detailed work on N cycling using the stable isotope, $^{15}N$, applied to microplots within the experiments. Results show that, in our temperate climate, recoveries, by cereals, of fertiliser N greater than 60% can be achieved (Powlson *et al*., 1986; Glendining *et al*., 1997) and that most of the nitrate present in the soil profile in the autumn, and therefore at risk of loss by leaching, is derived from SOM, not from unused fertiliser N. Exceptions are where excessive amounts of N are applied, in relation to potential crop yield, or where a crop fails. On Park Grass labelled N, as either $^{15}NH_4$ or $^{15}NO_3$, was applied in 1980 and 1981. After 18/19 years, 67% of the $^{15}NH_4$-N had been removed in successive grass harvests (mostly in the first year) but a further 17% still remained, in organic forms, in the soil. Less of the $^{15}NO_3$-N was recovered; 60% in the herbage plus 14% in the soil (Jenkinson *et al*., 2004). Labelled N has also been used to assess losses of N by denitrification and leaching, and to measure gross N mineralisation.

Other work has focussed on the soil's ability to act as a sink for methane ($CH_4$), an important greenhouse gas. For example, on the arable plots on Broadbalk, less $CH_4$ is oxidised in the soil where fertiliser N has been applied, compared with soil receiving FYM or soil receiving neither fertiliser nor manure (Hutsch *et al*., 1993). In the adjacent woodland (Broadbalk Wilderness) the rate at which $CH_4$ was taken up was 6 times faster than on the FYM soil. However, in the acid soil of the Geescroft Wilderness there was no $CH_4$ uptake. Similarly, on Park Grass, $CH_4$ oxidation was inhibited on soils with a pH of *c*.5 or less.

Recent work on Park Grass has examined how the differing nutritional statuses of the plots has affected the intrinsic water-use efficiency of the different swards. By measuring the $\delta^{13}C$ enrichment of archived herbage samples from selected plots on Park Grass from 1915 to 2009 Köhler *et al.* (2012) were able to examine the effects of different fertilisers and manures on changes in the intrinsic water-use efficiency of the plant communities over a period of nearly 100 years, under conditions of increasing atmospheric $CO_2$. The $CO_2$-responsiveness of the plant communities was found to be related to their grass content. This may have been due to the greater $CO_2$ responsiveness of stomatal conductance in grasses relative to forbs and the greater $CO_2$ response found in the fertilised swards may be related to the effects of N supply on botanical composition.

Broadbalk has been used to investigate the influence of both amount and form of N on gene expression in wheat grain (Lu *et al*., 2005). Clustering of gene expression profiles separated high and low N treatments. In addition, where the crop was accessing N derived from an organic source (FYM) there was a unique gene expression pattern and separate clustering. Analysis of this profile indicated the presence of genes encoding N assimilation components, seed storage proteins and several unknowns. These patterns were confirmed in successive years on Broadbalk and on the Woburn Ley-arable experiment where gene expression differed between wheat receiving fertiliser N and that receiving N derived from the mineralisation of grass ley residues. The most recent studies are combining both transcriptome and metabalome profiling to gain insights into processes relating to nitrogen use efficiency in wheat. In addition, Broadbalk and Hoosfield have been used to test and develop remote sensing techniques using drones fitted with multispectral cameras for mapping soil C.

Data from 16 long-term experiments was evaluated to see whether the "4 per 1000 initiative: Soils for Food Security and Climate", launched at the Paris Climate Conference in 2015 and aimed at increasing soil organic matter, thus mitigating global warming is achievable (Poulton *et al.,* 2018). Whilst the target of 4‰ per year for 20 years can often be reached by increasing inputs of manure or by changes in management, for example the introduction of grass or legume leys into arable cropping, such options are not always available to the farmer or desirable. The reasons for this include lack of resources or possible impacts on food security. However, any initiative which seeks to increase soil organic matter, and thus soil quality and functioning, should be welcomed.

New sample archive

## THE ROTHAMSTED SAMPLE ARCHIVE

The unique Rothamsted Sample Archive was established by Lawes and Gilbert in 1843 and its scientific value has been, and continues to be, immense. The Archive comprises, predominantly, soil and plant samples from the long-term field experiments at Rothamsted, Woburn and Saxmundham described in this guide. Plant samples consist of oven-dried, unground wheat and barley grain and straw and herbage from Park Grass, as well as finely ground material from many other crops. Soils (air-dried) have been taken from top-soils/plough layer (generally 0-23 cm) and occasionally from sub-soils, some to > 200 cm. They are usually stored as either 6.35mm, 2mm or more finely ground samples. There are also dried samples of organic manures and fertilisers that have been applied to the experiments, and several thousand soils from different locations in the UK and from other countries. Samples are stored in sealed glass bottles or jars, airtight tins, glass vials or card boxes. The samples were re-located in 2009.

The Sample Archive has been used extensively by Rothamsted staff and by scientists from other research institutes and universities in


Archived soil samples

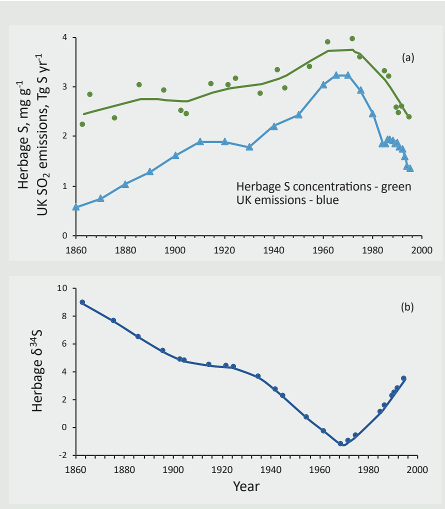



Fig. 15 Park Grass; the effect of changes in emissions of $SO_2$ in the UK on herbage S (a) and herbage $\delta^{34}S$ (b).

the UK and abroad. The retrospective analysis of archived material allows us to look back more than 175 years at, for example, many aspects of plant nutrition and soil fertility, and pollution that could not have been anticipated when the samples were taken. This is particularly true with respect to organic pollutants and environmental issues. Thus, archived samples have been analysed for their heavy metal content following the application of sewage sludge, for cadmium following applications of phosphate fertilisers and for poly-aromatic hydrocarbons and dioxins, which have increased in the atmosphere since the early 1900s.

Sulphur dioxide ($SO_2$) was an important atmospheric pollutant in the UK for much of the 20th century, but one that supplied much of agriculture's sulphur needs. Inputs have declined markedly since the 1970s (see section on Meteorological Data). Soil and herbage samples from Park Grass were used to assess the impact of the changing inputs of $SO_2$ on S cycling in the plant:soil system. While concentrations of S in herbage were positively correlated with annual $SO_2$ emissions (Figure 15), the trend in the stable S isotope ratio, $\delta^{34}S$, was negatively correlated with $SO_2$ emissions, reflecting the more negative $\delta^{34}S$ values associated with anthropogenic S sources (Zhao *et al*., 1998). Calculations suggest that up to 50% of the herbage S uptake came from anthropogenic sources at the peak of $SO_2$ emissions in 1970.

The plant material in the Rothamsted Sample Archive also contains fungal pathogens and it is possible to isolate and analyse the pathogen DNA. Pyrosequencing of this DNA was used to examine the development of resistance to triazole fungicides in the barley pathogen *Rhynchosporium commune* (leaf blotch fungus) conferred by the presence of CYP51A, a paralogue of the target site encoding gene CYP51 (Hawkins *et al.,* 2014). Spring barley has been grown since 1852 on Hoosfield, and *R. commune* DNA was successfully amplified from the archived barley samples collected in 33 separate years between 1892 and 2012. The pyrosequencing assay revealed that, for most of the 20th century, the majority of the *R. commune* population on Hoosfield lacked the azole fungicide resistance conferring gene, but in 1985, following the introduction of azole fungicides in the UK, levels rapidly increased and subsequently the majority of the *R. commune* population possessed the resistance gene.

Data from the analyses of soils for their organic carbon and $^{14}C$ content was used to develop and validate RothC, a computer model that simulates the turnover of soil organic matter, a key component of soil quality (Jenkinson, 1990). RothC is widely used by researchers worldwide and is now linked to the global climate model developed by the Hadley Centre.

Scientists at Southampton Oceanography Centre analysed samples of herbage from the Park Grass experiment over a 50-year period to measure concentrations of plutonium and uranium. They were able to detect the effects of, and distinguish between, nuclear bomb tests carried out by the US, USSR, UK and France, and show that plutonium contamination from weapons testing in the Nevada Desert in 1952/3 reached Northern Europe (Warneke *et al.*, 2002). Such measurements have only become possible in recent years with the development of more sophisticated analytical techniques.

There are written and electronic records of samples that have been archived and, increasingly, information on the samples is being stored electronically in the Electronic Rothamsted Archive (see below).

## ELECTRONIC ROTHAMSTED ARCHIVE (e-RA)

Data from the most important Classical experiments are accessible from the electronic Rothamsted Archive (e-RA), which is a permanent managed database for secure storage and dissemination of data, plus accompanying meteorological records and associated documentation. Users can query the password-protected database, via an internet application, http://www.era.rothamsted.ac.uk/.

e-RA currently holds records of yields, species composition, weeds, diseases, crop nutrient contents, grain quality and soil properties for four 'Classical' experiments: Broadbalk (both wheat and other crops in the rotations); Hoosfield Spring Barley; Park Grass; Hoosfield Alternate Wheat and Fallow, and also the two Wilderness Sites (Broadbalk and Geescroft). Daily meteorological data are held for Rothamsted (since 1853), Woburn (since 1928) and Broom's Barn (since 1982). Importantly, e-RA also contains a wealth of background information about the experiments, including plans, soil maps, details of fertiliser and manure treatments, management, photos, methods of analysis, site details and case studies. These metadata are vital to fully understanding the experiments, and ensuring that the results are correctly interpreted. The e-RA curators assist users by providing support in data selection, and ensuring they have all necessary background information.

Commonly requested data, published with a Creative Commons Licence and citable with DOIs, are available from the e-RA website as Open Access summary charts and tables; no password is required. These include mean long-term crop yields (Figures 1 and 7), long-term changes in soil organic carbon (Figure 4) and Park Grass species numbers (Figure 6). There is also a dedicated section for schools, with simple sub-sets of meteorological data.

A comprehensive searchable bibliography is included, containing over 1500 references relating to the long-term experiments, including details of over 500 publications by Lawes and Gilbert. Many of Rothamsted's historical documents are being made available through eRAdoc, an online repository for documents relating to the LTEs http://www.era.rothamsted.ac.uk/eradoc. These include Annual Reports, Yield Books, Guides and plans containing important information about the LTEs. These are being given DOIs so that they can be readily accessed and cited and many are available as searchable pdfs, with manually curated Tables of Contents.

Requests for e-RA data from the scientific community have been increasing steadily, with over 800 requests from 30 different countries since monitoring began in 2010. Data from the long-term experiments, both current and historic, has been used in over 170 publications since 2010.

Future developments include the addition of data from other Rothamsted long-term experiments; including the Highfield Ley-arable Experiment. In addition, the increased adoption of FAIR data principles (Wilkinson *et al*, 2016) with persistent identifiers, structurally improved metadata, vocabularies and visualisation tools, will enable this unique resource to be discovered and even more widely used by the international scientific community. For more details, see Perryman *et al.* (2018).

## THE ROTHAMSTED INSECT SURVEY (RIS)

Between 1933 and 1937 and again between 1946 and 1950 the larger (macro) moths were recorded in a light trap run at the edge of Barnfield, one of Rothamsted's Classical experiments. In 1960 a trap of identical design was placed at the same site, immediately producing information on long-term changes in farmland moth populations. This provides the only quantitative insect data that compares populations before and after the important period around the Second World War, when many agricultural practices were changing rapidly. Between 1960 and 1970 a national network of Rothamsted-style light traps was developed that has continued ever since.

Light trap on edge of Barnfield

Suction trap

Currently, there are about 80 such traps in operation, most of which are run by volunteers throughout the UK, from which all macro-moths are identified and counted on a daily basis. The light trap dataset, including records derived from decommissioned traps, now includes information from 500 sites, many of which have moth record data that extend to a decade or more.

In 1965, a 12.2m high suction trap was designed and set up at Rothamsted to monitor migrating aphid populations, and over the next few years a network of such traps was also installed across the UK. Currently there are 16 traps in operation in England and Scotland with the English sites being coordinated from Rothamsted and the Scottish sites from the Scottish Agricultural Science Agency in Edinburgh. These traps are emptied daily and all aphids are identified and counted along with other key pests, according to need. Currently, recorded pests include, but are not limited to, the cabbage stem flea beetle, pollen beetle, pea and bean weevil, spotted-winged *Drosophila* and also beneficial insects like lacewings and ladybirds. Forecasts of aphid phenology and abundance, in addition to weekly bulletins on population levels of key pest species, continue to be provided to growers, crop consultants and levy boards. We also communicate changes in the non-aphid fraction in a weekly summary called *RIS Remarks* which provides qualitative changes in abundance.

Since its conception the RIS has promoted the adoption of suction trap technology; currently 128 suction traps are in operation across the world and more are anticipated. Together, the national light and suction-trap networks are known as the Rothamsted Insect Survey (RIS) and provide the most extensive long-term quantitative datasets on insect populations anywhere in the world. The data are held in a database named 'Paul' which currently holds 45 million UK and some European insect records and is used to service data requests.

RIS data have been used for a wide range of research purposes from applied pest forecasting to fundamental studies on insect population dynamics and the effects of climate change on insect populations (Bell *et al*, 2015). For example, understanding the relationship (Figure 16) between winter temperatures and the times of the first flights of *Myzus persicae*,

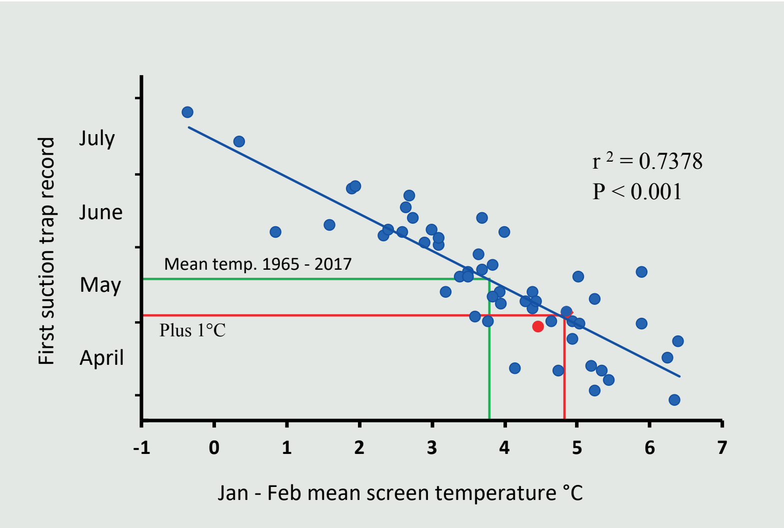



Fig. 16 Rothamsted; relationship between winter temperature and the times of the first flights of *Myzus persicae* (peach-potato aphid). Data for 2017 shown in red.

the peach–potato aphid (which is responsible for the transmission of potato and sugar beet viruses), has helped us to facilitate optimal timing of control measures and avoid their unnecessary use. It also aids assessment of the likely impact of warmer winters on the flight phenology of this important pest. Data from light traps show that there is a long-term trend towards earlier flight times for some moths. Data from the Rothamsted estate also suggest that there was a big decline in moth populations during the 1950s. An analysis of the national RIS moth dataset also suggests a more recent decline in moth populations across the UK, particularly in southern Britain where declines are dramatic (Fox *et al*, 2013). An update of those trends is being prepared with Butterfly Conservation for the *State of Britain's Larger Moths* report due to be published in 2019 (https//insectsurvey.com/trends).

In 1999, a vertical looking insect radar (VLR) was installed at Rothamsted with a second one in operation at Chilbolton (Hampshire). These are operated by the Rothamsted Radar Entomology Unit in close collaboration with the RIS and are providing important additional long-term data on high-altitude insect behaviour.

## UK ENVIRONMENTAL CHANGE NETWORK (ECN)

Rothamsted Research, at its research facilities in Harpenden, Hertfordshire (ECN Rothamsted) and North Wyke, Devon (ECN North Wyke), has been part of the Environmental Change Network (ECN) since its inception in 1992. It manages two of the eleven terrestrial sites (twelve initially) that constitute the ECN. The ECN is supported by fourteen independent government departments and agencies and was established to identify, assess and research environmental change nationally, and provide a basis for European and international collaboration. Its specific objectives are:

- To maintain a selected set of terrestrial and freshwater sites within the UK from which comparable long-term datasets are obtained by means of measurement, at regular intervals, of variables identified as being of major environmental importance.
- To compile, validate and archive datasets for use in identifying environmental change and develop an improved understanding of the causes of change.
- To make these long-term datasets available to researchers.
- To provide, for research purposes, a range of representative sites where there is good instrumentation and reliable information.

All of the ECN sites have well defined monitoring areas but within each there is a designated Target Sampling Site (TSS). At ECN Rothamsted, monitoring is done across the whole of the farm, but focusses on the Park Grass experiment (the designated TSS),

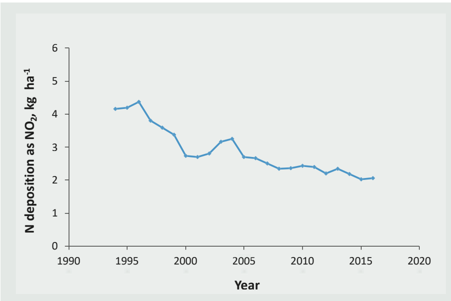



Fig. 17 Rothamsted; mean annual N deposition as $NO_2$ at Rothamsted Meteorological Station, 1994-2016.

especially on Plot 3d which has received no fertiliser inputs since the experiment was established in 1856. At North Wyke, the ECN monitoring is split between two areas, the Farm Platform (Figure 18) and Rowden Moor. The North Wyke TSS is a 0.66 ha paddock of permanent grassland on Rowden Moor where no nitrogen fertiliser has been applied since 1984.

The ECN uses well defined and agreed protocols (Sykes *et al*., 1996) for the sampling, measurement and analyses of key physical, chemical and biological variables, indicative of the causes and effects of environmental change; especially atmospheric pollution and climate variables. They are monitored using automated weather stations, bulk rain water collectors and $NO_2$ diffusion samplers, amongst other things. At ECN Rothamsted we have seen a decrease in the annual mean amount of $NO_2$ of around 50% (Figure 17); from a maximum of 11.6 µg N $m^{-3}$ (4.4 kg N $ha^{-1}$) in 1996 to 5.9 µg N $m^{-3}$ (2.2 kg N $ha^{-1}$) in 2012 (Scott *et al*, 2015). The wet and dry N deposition data from ECN Rothamsted was used to show that the reductions in atmospheric N deposition in recent decades have had positive effects on recovery of some plant species (especially legumes), on the Park Grass experiment (Storkey *et al* 2015; see above).

Further details of the Rothamsted and North Wyke ECN sites together with results from the first 20 years of monitoring can be found in two recent booklets (Scott *et al*., 2015 and Beaumont *et al*., 2016). The ECN network (www.ecn.ac.uk) and resulting datasets (http://data.ecn.ac.uk) are managed and collated by the Central Coordinating Unit, Centre for Ecology and Hydrology.

Rothamsted also hosts environmental monitoring equipment at the Harpenden and North Wyke sites on behalf of the United Kingdom Acidifying and Eutrophying Atmospheric Pollutants (UKEAP) project (http://www.pollutantdeposition.ceh.ac.uk/ukeap) and COSMOS-UK (http://cosmos.ceh.ac.uk/). The latter is a new long-term network monitoring changes in soil moisture using cosmic-ray measurement technologies. Both projects provide freely available data on-line.

## NORTH WYKE FARM PLATFORM

Establishment of the North Wyke Farm Platform (NWFP) began in 2010. It is located to the north of Dartmoor National Park, Devon on a ridge at 120 – 180 m above sea level, where the land slopes down on the west to the River Taw and on the east to one of its tributaries, the Cocktree stream. Over a 30-year period from 1982, the mean annual precipitation at the North Wyke site was 1044 mm. A significant feature of the site is the presence of clay-rich subsoils beneath the sub-surface horizons. Below the topsoil layer, the subsoil is highly impermeable to water and is seasonally waterlogged with most excess water leaving by surface and sub-surface lateral flow across the clay layer. This pattern in the movement of water allows for interception by a bounded drainage system and was a key factor in making this farm-scale experiment viable.

The NWFP comprises three farming systems in “farmlets”, each consisting of five component catchments totalling approximately 21 ha per farmlet. The farmlets test, through life cycle analysis, the productivity and environmental sustainability of contrasting temperate grassland beef and sheep systems at appropriate farm and land management scales (Figure 18). These approaches are:

1. Permanent pasture: managed using inorganic fertilisers (Green farmlet).

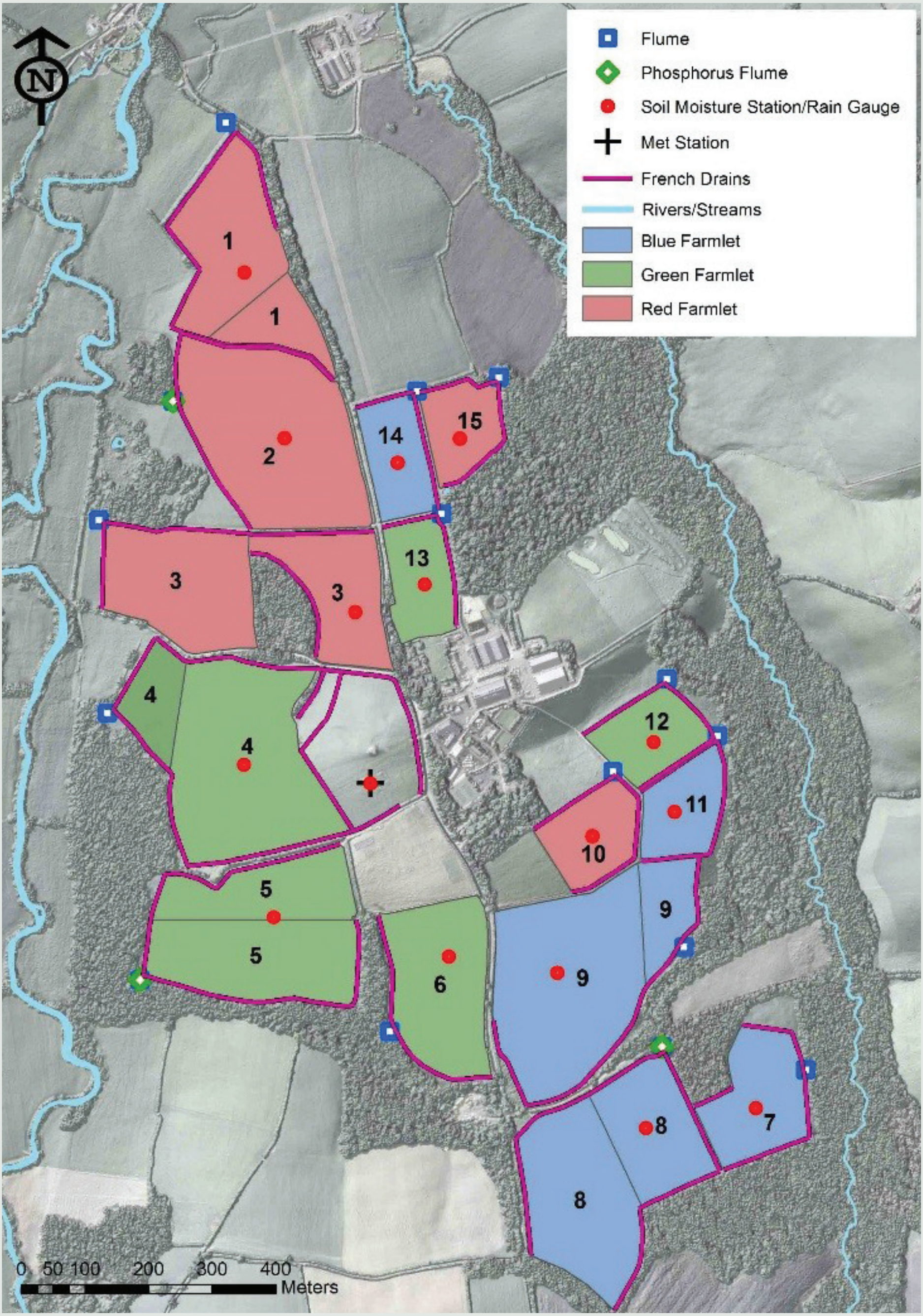



Fig. 18 North Wyke; aerial view of North Wyke showing location of farmlets etc.

2. Increased use of legumes: nitrogen fertilisers replaced with biological fixation using sown legume and grass mixtures (Blue farmlet).

3. Planned reseeding: regular renewal of swards, providing opportunities for introducing innovative cultivars with desirable traits. Currently, high sugar and deep rooting grasses are studied (Red farmlet).

Each of the 15 catchments is hydrologically isolated through a combination of topography and a network of 9.2 km of drains constructed around the perimeters of each catchment. The drainage network is made up of 800 mm deep trenches containing perforated drainage pipes and backfilled to the surface with 20-50 mm clean, carbonate-free granite chips. The trench bed and outer face are lined with plastic damp-proof-plastic membrane. This type of construction is commonly referred to as a French drain. Surface and sub-surface lateral flow from the drainage network for each catchment is directed though H-flumes, each sized according to the catchment characteristics and based on a predicted 1 in 50-year flood event.

At each flume, a cabin houses a range of *in-situ* state-of-the-art instruments that record water flow and water chemistry. Each catchment also has a centrally-located soil moisture station to record soil moisture, soil temperature and precipitation. In addition, meteorological variables are collected at a single NWFP site. All water flow, water chemistry, soil moisture and meteorological data are recorded at a fine-scale (15 minute) temporal resolution. Gaseous emissions of nitrous oxide, carbon dioxide, and methane are measured at strategic locations across the NWFP at differing temporal resolutions.

Catchment flumes and instrumentation cabin

Livestock performance and all agricultural operations such as tractor operations, spreading inorganic fertilisers and organic manures, spraying agrochemicals, ploughing, drilling seeds and silage making that occur on the NWFP fields are also recorded. The data collected are made publicly available via the NWFP data portal: https://nwfp.rothamsted.ac.uk/.

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