Rothamsted

Long-term Experiments

ROTHAMSTED
RESEARCH

Guide to the Classical and other Long-term Experiments, Datasets and Sample Archive.

2006

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Rothamsted Research: Guide to the Classical and other Long-term Experiments, Datasets and Sample Archive.

Front cover: Broadbalk from the air.
Back cover: Park Grass from the air.

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FOREWORD

It is a testament to the foresight of Sir John Lawes and Sir Henry Gilbert, as well as others who have come after them, that experiments established decades ago continue to reveal new insights and important findings of relevance to today's agriculture and its interactions with our ever-changing environment. This has been particularly evident through the application of novel molecular techniques that have enabled studies on historical fluctuations in pathogen populations and pointed to intriguing differences in gene-expression associated with sources of crop nutrients.

I am grateful to Paul Poulton and his colleagues for assembling this much revised summary of Rothamsted's long-term experiments which, among other new sections, includes reference to the Insect Survey and e-RA (Electronic Rothamsted Archive).

Ian Crute
Director
March 2006

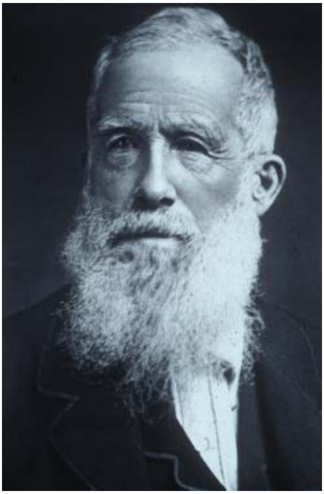
Harvesting wheat on Broadbalk

By reaper-binder in 1935

By small plot combine in 2005, with forage maize in the background.

INTRODUCTION

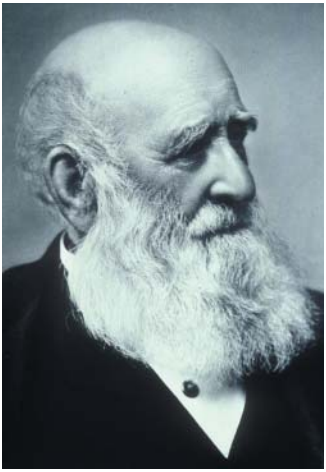
Between 1843 and 1856, Lawes and Gilbert started nine long-term field experiments, of which they abandoned only one, in 1878. Some treatments were changed during the first few years and, later, further changes were made to answer specific questions raised by the results. When Lawes died in 1900, the eight remaining experiments were continuing more or less as originally planned; these are now known as the "Classical" experiments. They are the oldest, continuous agronomic experiments in the world.



Sir John Bennet Lawes

Their main objects 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.

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 realised 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 applications, offtakes in crops and losses in drainage water.



Sir Joseph Henry Gilbert

The results were of immediate importance to farmers, showing which nutrients had the largest effects on different crops. However, the value of later results to farmers 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.*1950 the best yields on each experiment were similar to the average yields of the same crops grown on English farms. After 1950, with 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 started 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 were 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 getting 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 compromised. In the Agdell experiment, acidity was so severe on the NPK plots that the disease club root 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 the value of the P and K reserves but also the benefit of the extra soil organic matter (SOM) in the FYM-treated soils was tested. 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 further 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 critically and modifications introduced to ensure that, as far as possible, the experiments remained relevant without losing their long-term integrity. One important change, made on all the cereal experiments, saw the replacement of long-strawed, with modern, short-strawed cultivars that had greater potential grain yield. Another change, introduced in 1968 except on Park Grass, was the replacement of ammonium sulphate and sodium nitrate by ammonium nitrate, initially as 'Nitro-Chalk', now as 'Nitram'. Recent changes are detailed later.

In addition to the Classical experiments started by Lawes and Gilbert, there are several other long-term experiments at Rothamsted and at two other sites, Woburn and Saxmundham, on contrasting soil types. On the sandy loam soil at Woburn Experimental Farm, the Royal Agricultural Society of England started experiments in 1876 comparing different animal feeds, and their residual value to crops (to test the validity of Lawes' and Gilbert's findings), and on wheat and barley grown continuously. On a heavy sandy clay loam soil at Saxmundham, Suffolk, 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.

With remarkable prescience, Lawes and Gilbert retained samples of crops and soils once the initial analyses were completed. Successive generations of scientists at Rothamsted have continued to add to the collection and the resulting Archive now comprises > 300,000 samples. This unique resource is of immense value; new analyses of archived material continue to provide insights into changes occurring over more than 160 years.

The collection of long-term datasets is not confined to the 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 also has a long history of monitoring insect populations. The Rothamsted Insect Survey comprises national networks of light traps, to record moths, and suction traps, to monitor migrating aphids. It provides the most extensive long-term quantitative datasets on insect populations in the world and is used for a range of research purposes.

Archived samples

Rothamsted is one of the lead sites within the Environmental Change Network (ECN), which comprises 12 terrestrial sites and > 40 freshwater sites across the UK. The ECN sites monitor a large number of pollutants and climate change variables and associated effects on soil, vegetation, insects and mammals.

The Electronic Rothamsted Archive (e-RA) is being developed to hold meta-data and data from the long-term experiments, the Insect Survey and the ECN. In time this will allow ready access to the large volume of data that has been accumulated at Rothamsted since 1843.

THE CLASSICAL EXPERIMENTS

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 year of harvest). 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. 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 analyses. Broadbalk is now ploughed by a tractor-mounted reversible plough and harvested by a combine harvester; only the central strip of each plot is taken 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 at right angles, were made and bare fallowed sequentially. 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).

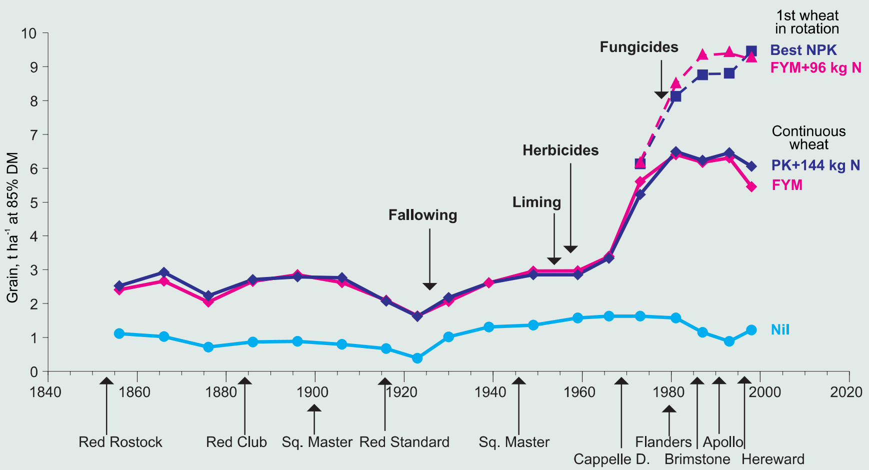
Chalk has been applied intermittently since the 1950s to maintain soil pH at a level at which crop yield is not limited.

Following the correction of soil acidity on parts of the experiment in the 1950s a review of the treatments and management led to a number of 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) 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 more appropriate agronomic levels. 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 detailed in the legend that accompanies the plan of the experiment.

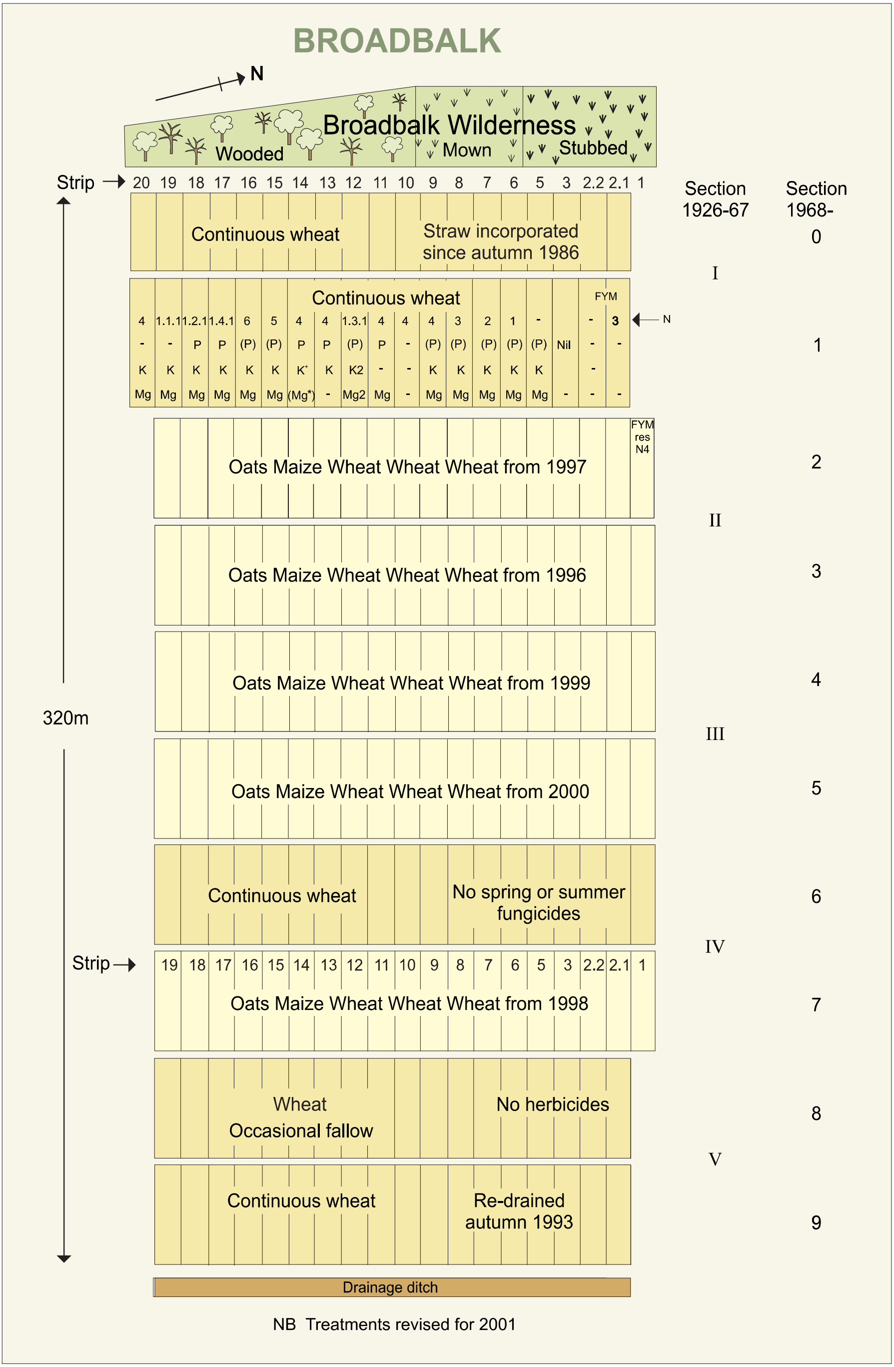
After the 1968, changes Sections 0, 1, 8 and 9 continued to grow wheat only, whilst Sections 2, 4, 7 and Sections 3, 5, 6 went into two different 3-course rotations. In 1978, Section 6 reverted to continuous wheat and the other five Sections went into a 5-course rotation; currently, oats, forage maize, wheat, wheat, wheat. Pesticides are applied when necessary, except on 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. Similar land in the neighbourhood, farmed in rotation, typically yielded *c.*1.2 t ha^{-1}. Figure 1 shows yields from selected treatments. 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.

Fig.1 Broadbalk. Mean yields of wheat grain, and changes in husbandry



Until the First World War, the experiment had been hand-weeded but the subsequent shortage of labour allowed weed competition 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 continuous wheat given no fertiliser or manure (but with pesticides) are now *c.*1 t ha^{-1}, similar to yields earlier in the experiment. Mean yields of wheat given PKNaMg+144 kg N ha^{-1} are 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 on these two treatments doubled to about 5 t ha^{-1}. Since 1968 we have been able to compare the yields of wheat grown


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
Section 1926-67
Section 1968-
0
I
Continuous wheat
Straw incorporated since autumn 1986
Continuous wheat
FYM
4 1.1.1 1.2.1 1.4.1 6 5 4 4 1.3.1 4 4 4 3 2 1 - - 3
- - P P (P) (P) P P (P) P - (P) (P) (P) (P) (P) Nil - -
K K K K K K K* K K2 - - K K K K K -
Mg Mg Mg Mg Mg Mg (Mg*) - Mg2 Mg - Mg Mg Mg Mg Mg - - -
N
1
FYM res N4
Oats Maize Wheat Wheat Wheat from 1997
2
II
Oats Maize Wheat Wheat Wheat from 1996
3
Oats Maize Wheat Wheat Wheat from 1999
4
320m
III
Oats Maize Wheat Wheat Wheat from 2000
5
Continuous wheat
No spring or summer fungicides
6
IV
Strip
19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 3 2.2 2.1 1
Oats Maize Wheat Wheat Wheat from 1998
7
Wheat
Occasional fallow
No herbicides
8
V
Continuous wheat
Re-drained autumn 1993
9
Drainage ditch
NB Treatments revised for 2001

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 N2(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)K2Mg2(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 1/2[PK(Na)Mg]	N0+3 1/2[PKMg](A)	N1+4+1 PKMg
18	PKNaMg(A)	N2 1/2[PK(Na)Mg]	N1+3 1/2[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 1/2-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. Maize did not receive autumn N.

<u>Annual treatment per hectare</u>

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 2011
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 until1988

N 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)

Split N to forage maize (seedbed and post-emergence)
N2+1 : 96+48 kgN (strip 19)
N2+2 : 96+96 kgN (strip 18)
N2+3 : 96+144 kgN (strip 12)
N2+4 : 96+192 kgN (strip 17)

No N or FYM to oats

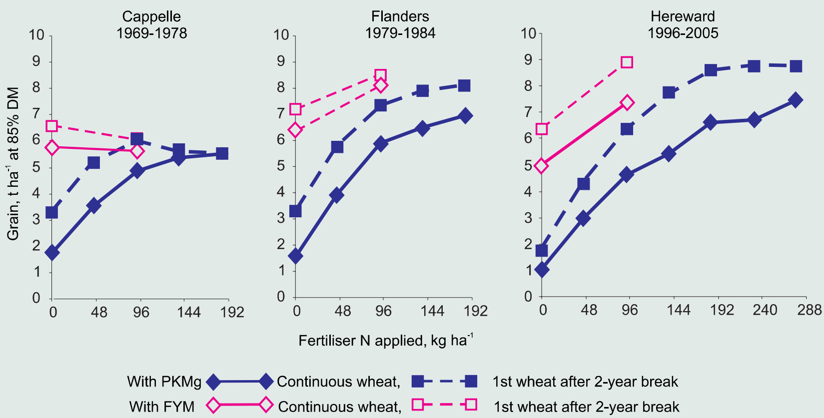
N as ammonium nitrate (Nitram, 34.5% N) since 1986; calcium ammonium nitrate (Nitro-chalk, c.26% N) 1968-85; ammonium sulphate or sodium nitrate (N*) until 1967.

(1) : FYM N3 since 2005
(2) : N1+3+1 (P)KMg since 2006
Note : S has been added, by default, as part of the potassium sulphate, magnesium sulphate, Kieserite, FYM and ammonium sulphate applications. S last applied to strip 14 in 2000.

For detailed information on treatments and management until 1967, see Rothamsted Report for 1968, Part 2, 215pp.

continuously and as the first wheat after a two-year break (Fig.2). In the 10 years in which Cappelle 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. Perhaps as a result, the relative yields of plots given FYM and fertilisers changed (Fig.2) with best yields from fertiliser exceeding those from FYM alone and the combination of FYM+96 kg N ha^{-1} often exceeding both. The increased responses to N fertiliser in 1979-84 suggested that yields might be greater if larger amounts of N were applied. Since 1985, 240 and 288kg N ha^{-1} have been tested, and all cultivars have shown a similar pattern of response to cv. Hereward (Fig.2). On average, only the continuous wheat responded to the larger amounts of N. Yields of wheat grown after a two-year break can be more than 2 t ha^{-1} larger than yields of continuous wheat, almost certainly because the effects of soil borne pests and disease, particularly take-all (*Gaeumannomyces graminis* var. *tritici*), are minimised (see later). Best yields now exceed 11 t ha^{-1}.

Fig.2 Broadbalk. Mean yields of wheat grain



The main purpose of the 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. Currently, oats and maize are the two break crops; yields on selected treatments are shown in Table 1. The oats are not given fertiliser N or FYM. Thus, on plots where P and K is not limiting, any differences in yield between treatments are 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). Maize is a C4 plant. As such, the carbon it contains has a different ^{13}C "signature" than that in the C3 plants that have been grown previously on Broadbalk. Thus, we can distinguish maize-derived organic matter from that of organic matter already in the soil. Over time, we will be able to see where, within the soil structure, the maize carbon is being held and how quickly it is being recycled.

Table 1. Broadbalk; mean yield of oat grain (2002-5) and forage maize (2001-5).

Strip	Treatment 2001-5(1)	Oat grain t ha^{-1} 85% DM	Forage maize t ha^{-1} total DM
3	Nil	1.9	2.2
5	(P)KMg	2.2	2.3
6	N1 (P)KMg	2.7	7.2
7	N2 (P)KMg	3.3	11.0
8	N3 (P)KMg	4.0	12.0
9	N4 (P)KMg	4.7	11.8
15	N5 (P)KMg	4.9	11.1
16	N6 (P)KMg	6.3	11.5
2.2	FYM	7.2	11.7
2.1	FYM N2(2)	7.2	14.3
1	(FYM) N4	6.6	15.2

(1) See plan for details
(2) FYM N3 for maize in 2005
Note; No N fertiliser or FYM was applied for the winter oat crops.

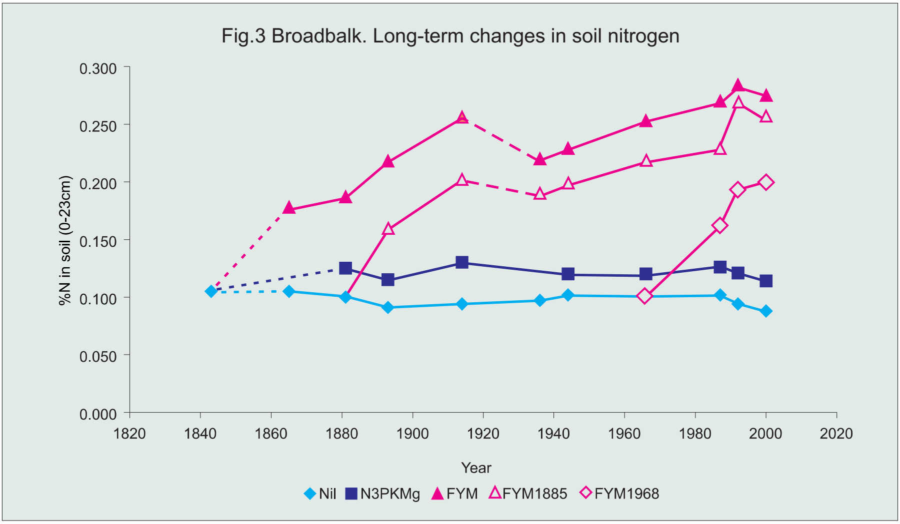
The Broadbalk experiment

Organic matter in the Broadbalk soil

Edwin Grey, soil sampling, 1919

The amounts of soil organic matter (SOM) can be determined indirectly from the % organic carbon (Org C) (% Org C is multiplied by a factor of 1.72 to give % SOM). Most soils have a C:N ratio of about 10:1; so % N can be used as a surrogate for % Org C to calculate SOM. Figure 3 shows the %N in topsoil (0-23cm) on selected treatments. The N 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 N than soil in the nil (and minerals-only plots, not shown) because the better-fertilised crops gave not only more yield but more stubble, and probably roots, to be ploughed-in. Over the last 10-20 years there has been a slight decline in soil N on these plots. Soil N in plots receiving minerals and larger amounts of fertiliser N (192, 240 and 288 kg ha^{-1}) in recent years, and where larger crops have been grown, is still tending to increase. On the FYM treatments, soil N increased, rapidly at first, then more slowly, and now contains more than double the concentration of that in the nil or fertiliser-only soil. The decline in soil N on the FYM plots in the 1920s/1930s was because FYM was not applied in the years when the plots were fallowed to control weeds.

The N balance, *i.e.* N input minus 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, inputs of N in FYM (and from the atmosphere) 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 microbial biomass of the FYM plots is approximately twice that of the plots given either NPK or no fertilisers. Total numbers of microbial cells, estimated directly by microscopy (around 10^9 cells g^{-1} soil), and of culturable bacteria (around 10^8 cells g^{-1} soil), show a similar ratio. Although relative numbers of specific groups of bacteria that can grow on particular selective media differ according to sampling date, the differences are unpredictable at present. The recovery of cells by culture on agar may reflect their physiological status when sampled, resulting in apparently lower numbers at times of stress. 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 cells g^{-1} 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 oxidizers increase 10- to 100-fold after six weeks, then slowly decline over the rest of the year. Currently, there are no similar direct estimates of bacterial populations responsible for either methane oxidation or denitrification. However, measurement of these processes indicates lower activity of methane-oxidizing bacteria and higher activity of denitrifying bacteria in the soils receiving N fertilisers. Both activities were much higher in the Broadbalk Wilderness (see p.19), indicating that soil cultivation may have a major disruptive effect on these microbial populations.

Weeds on Broadbalk

Weeds were controlled initially by hand-hoeing and fallowing but, since 1964, herbicides have been applied to the whole experiment except Section 8. Since 1867, 130 plant species have been recorded on Broadbalk, but many of these occur only sporadically. Detailed weed surveys from 1930 to 1979 provide a unique 50-year record, and were restarted on Section 8 in 1991. Between 1991 and 2002, 50 plant species were recorded in the annual surveys. About 30 of these species were recorded every year, with nine species common on many plots: *viz*. black-grass (*Alopecurus myosuroides*), common chickweed (*Stellaria media*), common poppy (*Papaver rhoeas*), common vetch (*Vicia sativa*), creeping thistle (*Cirsium arvense*), parsley piert (*Aphanes arvensis*), scentless mayweed (*Tripleurospermum inodorum*), shepherd's needle (*Scandix pecten-veneris*) and Venus's-looking-glass (*Legousia hybrida*).

Papaver rhoeas *on Broadbalk*

Analysis of the 1991-2002 survey data showed clearly how the frequencies of individual species are differentially influenced by applications of inorganic N fertiliser. Common chickweed is greatly favoured by increasing amounts of N fertiliser from 0 to 288 kg N ha^{-1} but other species are strongly disadvantaged (e.g. black medick, *Medicago lupulina*, and field horsetail, *Equisetum arvense*). Some species were only slightly disadvantaged (*e.g.* common vetch and parsley-piert) and yet others showed little response to increasing N rates (*e.g.* black-grass and common poppy). These striking differences in species frequency between plots in close proximity show clearly the ecological adaptation of species to N availability. Weed seeds collected from Section 8 have been used in various ecological studies, including research on herbicide resistance.

Broadbalk also provides an invaluable reserve for seven plant species that are rare, uncommon or declining nationally. These are: corn buttercup (*Ranunculus arvensis*), corn cleavers (*Galium tricornutum*), field gromwell (*Lithospermum arvense*), 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 eight plants were seen in 2004 and 11 in 2005.

The revised atlas of British and Irish Flora includes a list of species that have shown the greatest relative decreases 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

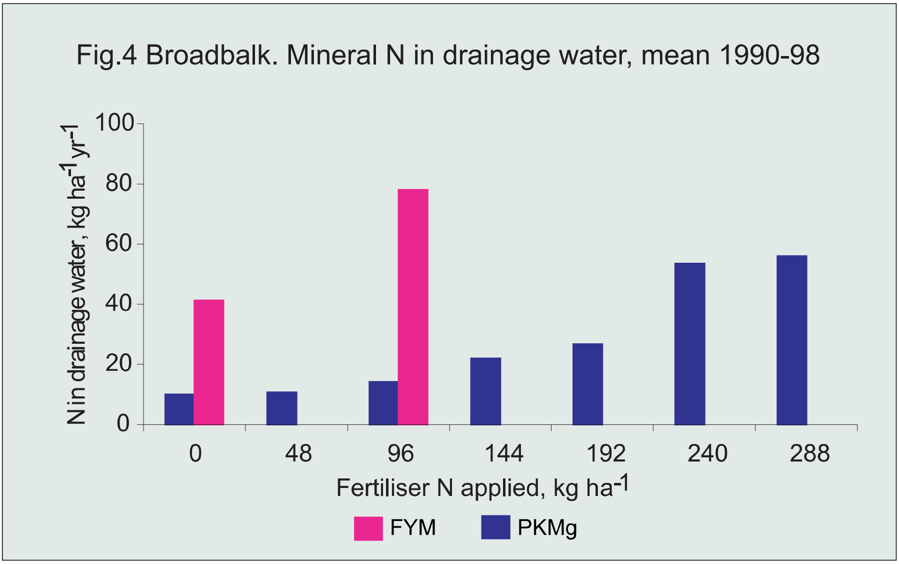
The continuity of cropping and manurial treatments has made Broadbalk a valuable experiment for studying the effects of both plant nutrition and weather on the incidence of wheat pests and diseases.

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.

Both eyespot (*Oculimacula* spp.) and take-all (*Gaeumannomyces graminis* var. *tritici*) are common, and have been assessed on selected plots regularly since the introduction of rotations. It was on this field that, in 1935, eyespot was first identified in the UK. Comparisons of yields and of differences in amounts of take-all between continuous wheat on Broadbalk and wheat in other fields growing shorter sequences of cereals culminated in the development of the hypothesis of 'take-all decline'. This phenomenon, although still inadequately understood, has since been shown to be common when cereals are grown continuously. Since the introduction of rotations, take-all decline can be demonstrated on Broadbalk where severe symptoms are often seen in the short sequences of wheat but less commonly in the continuous wheat.

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 a ditch. The drains were not intended for experimental use, but in 1866 they were opened, and drainage water collected and analysed. 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 in the field 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 drains at 75 cm depth.



The average amounts of NO_3-N lost through the drains each year are shown in Fig 4. Even where no N fertiliser had been applied for more than 150 years, about 10 kg ha^{-1} of NO_3-N is lost each year. Most N is lost where the amount of fertiliser N applied exceeds that needed for "optimum" yield or where FYM has been applied for many years. The EU limit for the maximum concentration of N allowed in potable waters (11.3 mg N l^{-1}) is usually exceeded where the larger amounts of fertiliser N or FYM have been 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.

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 100 mg kg^{-1} of available-P (Olsen P) depending on the treatments. 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.

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 being debated. Both sites had grown arable crops for many years. The Broadbalk surface soil had been heavily chalked and is still calcareous (pH 7.7); Geescroft had not been so heavily chalked and soil 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, this 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, to simulate grazing.

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

Developing woodland, Geescroft, 1933

On both sites, much C has been sequestered in trees and soil since they were abandoned in the 1880s. Geescroft has 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 the covered yards across the road in which bullocks were housed during the winter.

PARK GRASS

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 and organic manure. 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. 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.

Fritillaria meleagris *on Park Grass*

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 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. 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 harvest has been cut and removed immediately. The plots were originally cut by scythe, then by horse-drawn and then tractor-drawn mowers. Yields were originally estimated by weighing the produce from the whole plot, either as hay (1st harvest) or green crop (2nd harvest), and dry matter determined. Since 1960, yields of dry matter have been estimated from strips cut with a forage harvester. However, for the first cut the remainder of each plot is still mown and made into hay, continuing earlier management and ensuring return of seed. For the second cut, the whole of each plot is cut with a forage harvester.

Hay harvest on Park Grass, 1941

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 48, 96 kg N as sodium nitrate
(N2) (N*2) last applied 1989

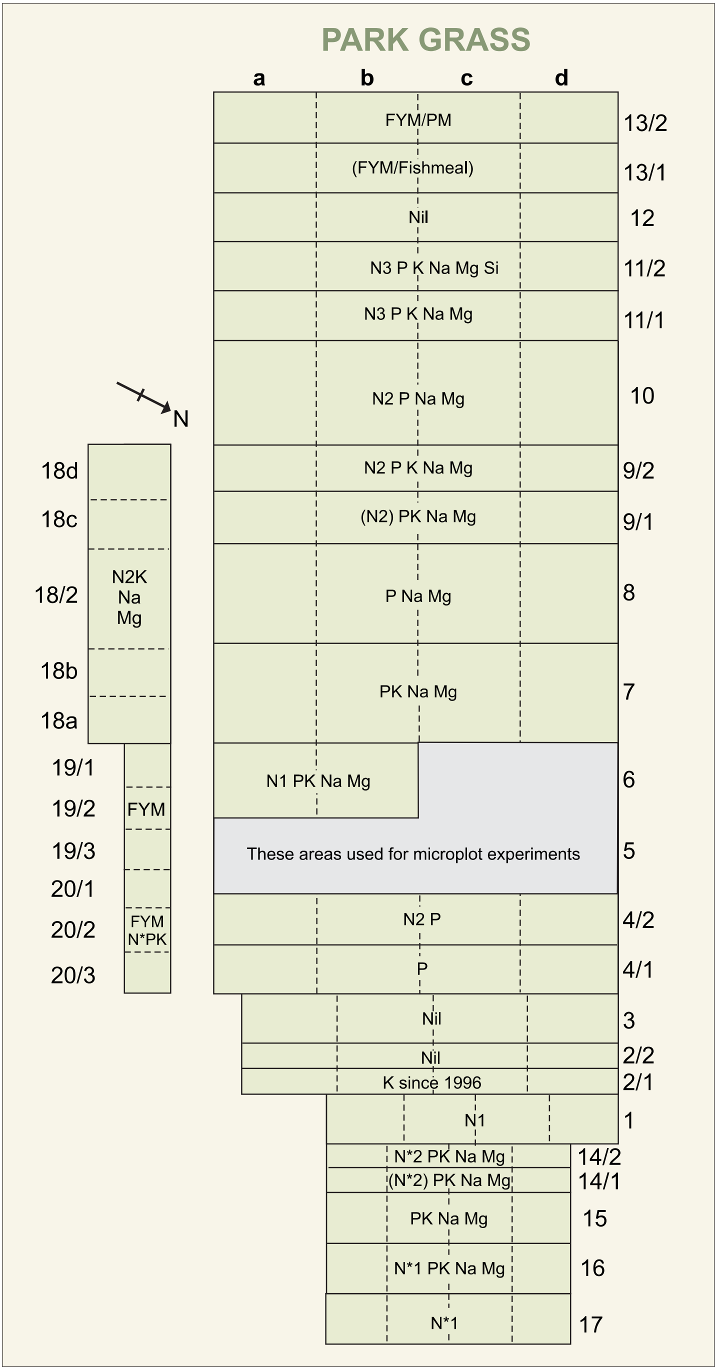
Minerals (applied in winter)
P 35 kg P as triple superphosphate
K 225 kg K as potassium sulphate
Na 15 kg Na as sodium sulphate
Mg 10 kg Mg as magnesium sulphate
Si 450 kg of sodium silicate
Plot 20 30 kg N*, 15 kg P, 45 kg K in years when FYM is not applied

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 kg N

On plot 13/2 FYM and PM (previously fishmeal) are applied in a 4-year cycle *i.e.*:
FYM in 2005, 2001, 1997, 1993 etc.
PM in 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


PARK GRASS
a
b
c
d
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
N
N2 P K Na Mg
9/2
(N2) PK Na Mg
9/1
P Na Mg
8
PK Na Mg
7
N1 PK Na Mg
6
These areas used for microplot experiments
5
N2 P
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
PK Na Mg
15
N*1 PK Na Mg
16
N*1
17
18d
18c
18/2
N2K Na Mg
18b
18a
19/1
19/2
FYM
19/3
20/1
20/2
FYM N*PK
20/3

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 the southern half. On those plots receiving the largest amounts of ammonium sulphate this was enough to stop the soil becoming progressively more acid. However, it remained 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 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 5.1 whilst soils receiving 96 kg N ha^{-1} as ammonium sulphate or sodium nitrate are at pH 3.6 and 6.1, respectively. For the latter two treatments, between 1965 and 2005, 63 and 14 t ha^{-1} $CaCO_3$, respectively, were required to increase and/or maintain the soil at pH 7.

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.

The distributions in the soil of nodule bacteria (*Rhizobium* spp.) for clover, *Lathyrus* and *Lotus* correspond closely to the distributions of their hosts in the different plots; neither medicks nor their nodule bacteria occur. Acid sub-plots contain no nodule bacteria; increasing amounts of lime increase numbers. On limed sub-plots, N fertiliser has neither diminished the numbers nor altered the symbiotic effectiveness of the clover nodule bacteria.

Yields of total dry matter (both harvests) for 2000-4 are shown in Table 2. 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 soils receiving PKNaMg but no N fertiliser (7 and 15), yields are as good as those on plots receiving PKNaMg plus 96 kg N ha^{-1} because of the large proportion of legumes in the sward (Table 3) except that legumes are less common on the 'd' sub-plot where no lime is applied; here soil pH is about 4.9 and yields 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 3.6 - 3.7) dominated by one or two species, mean yields can still be as large as 6-8 t ha^{-1} (“d” sub-plots of 9/2, 11/1 and 11/2).

Table 2. Park Grass; mean annual yield of dry matter, t ha $^{-1}$ (2000-4)

Plot	Treatment[1]	Sub-plot a	b	c	d
No nitrogen group					
3	Nil	3.3	3.6	2.2	2.9
12	Nil	3.5	3.8	3.5	2.8
2/2	Nil	3.5	4.0	2.4	3.0
2/1	K	3.8	4.1	2.4	2.7
4/1	P	4.5	4.9	3.9	3.6
8	P Na Mg	4.4	5.2	4.1	4.3
7	P K Na Mg	7.4	7.4	6.5	4.4
15	P K Na Mg	6.2	6.1	5.0	3.6
Ammonium N group					
1	N1	4.2	3.8	2.9	1.3
18	N2 K Na Mg	3.9	4.4	6.2	2.0
4/2	N2 P	5.5	5.0	6.0	3.0
10	N2 P Na Mg	6.1	6.1	7.1	4.0
6	N1 P K Na Mg	7.0	6.9	-	-
9/1	(N2) P K Na Mg	6.1	6.4	6.5	2.1
9/2	N2 P K Na Mg	7.8	8.3	7.8	6.4
11/1	N3 P K Na Mg	10.2	9.4	8.5	7.3
11/2	N3 P K Na Mg Si	9.7	9.6	8.4	8.3
Nitrate N group					
17	N*1	3.9	4.2	3.6	3.5
16	N*1P K Na Mg	7.4	7.5	6.1	5.3
14/1	(N*2) P K Na Mg	6.1	6.8	6.0	5.9
14/2	N*2 P K Na Mg	7.5	7.3	7.0	6.7
FYM group					
13/1	(FYM/fishmeal)	5.8	6.7	5.7	5.5
13/2	FYM/PM	5.4	7.9	7.9	7.7
		/1	/2	/3	
19[2]	FYM	6.5	7.8	6.5	
20[2]	FYM/N*PK	7.6	9.0	7.5	

(1) See plan for details
(2) Plots 19 and 20 are not part of the liming scheme

Rothamsted Research

CLASSICAL FIELD EXPERIMENTS

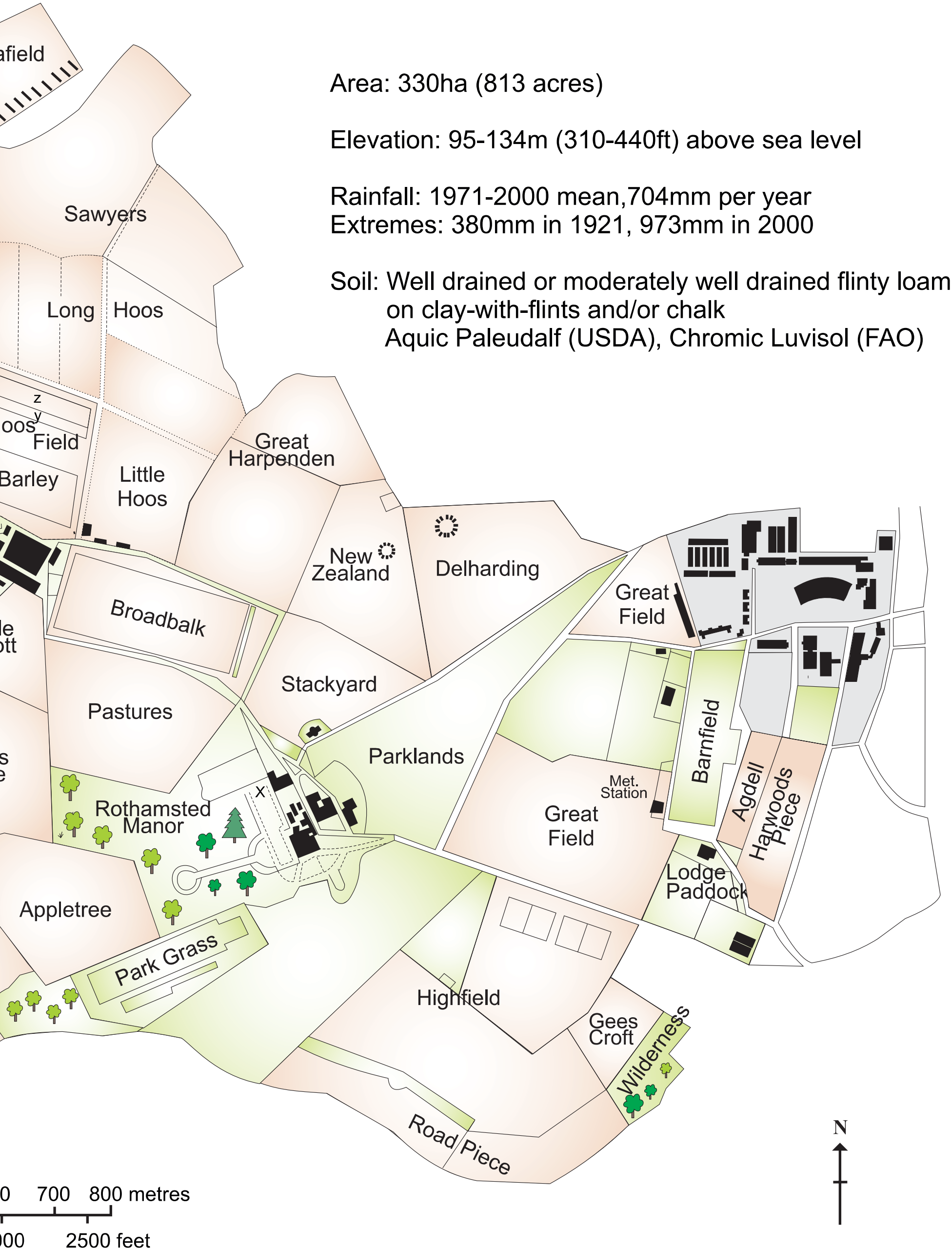
Broadbalk	Wheat since 1844
Hoosfield	Barley since 1852
Park Grass	Hay since 1856
Barnfield	Started 1843
Agdell	1848-1990
x	Garden Clover since 1854
y	Wheat and Fallow since 1851
z	Exhaustion Land, started 1856

Area: 330ha (813 acres)

Elevation: 95-134m (310-440ft) above sea level

Rainfall: 1971-2000 mean,704mm per year
Extremes: 380mm in 1921, 973mm in 2000

Soil: Well drained or moderately well drained flinty loams
on clay-with-flints and/or chalk
Aquic Paleudalf (USDA), Chromic Luvisol (FAO)



Botanical composition

The most recent, comprehensive surveys of botanical composition, made just before the first cut, were done annually between 1991 and 2000. Table 3 shows soil pH and those species comprising 10% or more of the above-ground biomass, and the total number of species identified on each sub-plot (selected treatments, mean 1991-2000). There are many interactions, some clear, some not, between fertiliser and manure treatments and pH. Without exception all the original treatments imposed in 1856 have caused a decline in species number compared to the original sward. In most cases this was due to changes in soil fertility and annual nutrient inputs and, perhaps, also the way the sward was managed.

Sorting herbage samples from Park Grass, 1930s

The most diverse flora, including many broad-leaved species, is on the Nil plots (plots 2/2, 3 and 12), with about 35-45 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 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. Compared to the Nil plots, the dominant species of grasses and forbs are similar, except that at pH 6 and above, common bent is no longer present in large amounts and is replaced by ribwort plantain (*Plantago lanceolata*) and meadow buttercup (*Ranunculus acris*). Applying N with P (N2P, plot 4/2 and N2PNaMg, plot 10) has greatly decreased the total number of species, especially at pH 6 and below. There are fewer forbs and larger proportions of red fescue or sweet vernal grass (*Anthoxanthum odoratum*).

Applying P alone (plot 4/1) had relatively minor effects on species composition, compared to the Nil plots. But giving K with P (plots 7 and 15), increased the amount of legumes, especially red clover (*Trifolium pratense*) and meadow vetchling (*Lathyrus pratensis*), thus greatly increasing yield.

Table 3. Species comprising at least 10% of herbage, and total number of species; mean 1991-2000.

Treatment	Plot	Soil pH 1995-02	*AC*	*AP*	*AO*	*AE*	*DG*	*FR*	*HP*	*HL*	*LoP*	*LaP*	*TP*	*AS*	*CN*	*HS*	*LH*	*PL*	*RaA*	*RuA*	*SM*	Total no. of species
			Percentage of dry matter (Species names are listed below)																			
Nil	3a	7.2	10	+	+	+	+	20	+	+	+	+	+	-	10	+	15	+	+	+	10	39
	b	6.4	10	+	+	+	+	20	+	+	-	+	+	-	10	-	15	10	+	+	+	36
	c	5.3	30	-	+	-	+	30	+	+	-	+	+	-	+	+	15	+	+	+	+	37
	d	5.2	45	+	+	+	+	30	+	+	-	+	+	-	10	-	+	+	+	+	+	36
P	4/1a	6.9	+	+	+	+	+	20	+	+	+	+	10	-	+	+	15	10	+	+	+	34
	b	6.1	+	+	+	+	+	20	+	+	+	+	+	-	+	-	10	15	10	+	+	34
	c	5.2	30	+	+	+	+	25	+	+	+	+	+	-	+	-	10	+	+	+	+	29
	d	5.3	25	+	+	+	+	25	+	+	+	+	+	-	+	-	15	+	+	+	+	32
PKNaMg	15a	6.7	+	+	+	10	+	10	+	+	+	20	10	+	+	+	-	+	+	+	-	28
	b	5.9	+	+	+	15	+	10	+	+	+	+	20	+	+	+	+	10	+	+	-	27
	c	5.0	20	+	+	+	+	10	+	+	+	+	20	-	15	+	-	+	+	+	-	26
	d	4.9	40	+	+	+	+	10	+	+	+	+	10	-	+	+	+	+	+	+	-	27
N*1	17a	7.1	10	+	+	+	+	15	+	+	+	-	+	-	+	+	25	10	+	+	+	32
	b	6.4	15	+	+	+	+	+	+	+	+	+	-	-	+	+	30	15	+	+	+	34
	c	5.8	25	+	+	+	+	10	+	+	+	-	-	-	+	+	25	10	+	+	+	34
	d	5.8	25	+	+	+	+	10	+	+	+	-	+	+	10	+	10	+	+	+	-	34
N*2PKNaMg	14/2a	6.9	+	20	-	50	+	+	+	-	+	+	-	10	-	+	-	+	+	+	-	24
	b	6.4	+	20	+	40	+	+	-	+	+	-	+	10	-	+	-	-	+	+	-	24
	c	6.1	+	20	+	40	+	+	-	+	+	+	-	+	-	+	-	+	+	+	-	21
	d	5.9	+	25	-	30	10	+	+	+	+	+	-	+	-	10	-	+	+	+	-	22
N1	1a	7.1	+	+	+	+	10	25	10	+	-	+	+	-	+	-	10	+	+	+	+	33
	b	6.2	20	+	+	+	10	25	+	+	+	+	+	-	10	-	+	+	+	+	+	31
	c	5.3	35	-	+	+	+	45	+	+	+	+	+	-	+	-	-	-	+	+	-	33
	d	4.1	65	-	30	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	10
N2KNaMg	18a	7.1	15	+	+	+	10	15	+	+	+	-	+	-	10	+	10	+	-	+	-	30
	b	6.3	30	+	+	+	+	15	+	+	+	-	-	-	25	+	+	+	-	+	-	29
	c	5.4	35	+	+	+	15	20	+	+	10	-	-	-	+	+	-	-	-	+	-	21
	d	3.8	80	-	20	+	-	-	-	+	-	-	-	-	-	-	-	-	-	+	-	6
N2P	4/2a	6.9	10	+	+	+	+	55	+	10	+	-	-	-	+	-	-	+	+	+	-	22
	b	6.2	15	10	+	+	+	55	+	10	+	-	-	-	-	-	+	-	-	+	-	14
	c	5.2	30	+	+	+	+	55	+	+	+	-	-	-	-	-	-	+	-	10	-	18
	d	3.7	30	-	70	+	-	+	-	+	-	-	-	-	-	-	-	-	-	+	-	10
N2PKNaMg	9/2a	6.9	+	15	+	25	10	+	-	15	+	+	+	+	-	10	-	+	+	+	-	22
	b	6.3	+	25	+	35	+	+	+	15	-	+	+	+	-	+	-	-	-	+	-	17
	c	5.0	30	10	10	+	+	15	-	+	-	+	+	+	-	+	-	-	-	+	-	18
	d	3.7	15	-	65	-	-	-	-	20	-	-	-	-	-	-	-	-	-	-	-	4
N3PKNaMg	11/1a	6.5	+	20	-	40	10	+	+	10	+	-	-	+	-	+	-	-	+	+	-	14
	b	6.2	+	20	+	35	20	+	+	10	+	-	-	+	-	+	-	-	-	+	-	15
	c	4.9	+	30	+	20	+	-	-	30	-	-	-	+	-	+	-	-	-	+	-	13
	d	3.6	-	-	+	-	-	-	-	100	-	-	-	-	-	-	-	-	-	-	-	3
FYM/PM	13/2a	6.8	30	+	+	+	10	15	+	+	10	-	-	-	+	+	-	-	-	+	-	28
	b	6.1	+	15	+	20	10	+	-	+	+	+	-	+	+	10	-	+	+	+	-	30
	c	5.3	20	+	+	+	+	+	+	10	-	+	+	+	+	+	+	10	+	+	-	32
	d	5.1	35	10	+	+	+	10	+	10	+	+	+	-	+	+	+	+	+	+	-	34

After Crawley *et al.,* 2005, *American Naturalist,* **165**, 179-192.

Data are from surveys immediately before hay harvest; rounded to the nearest 5% of dry matter, mean 1991-2000. (Selected plots only)

+, species present at less than 10%; **-**, species not identified 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
	Arrhenatherum elatius	False Oat Grass
	Dactylis glomerata	Cock's-foot
	Festuca rubra	Red Fescue
	Helictotrichon pubescens	Downy Oat-grass
	Holcus lanatus	Yorkshire Fog
	Lolium perenne	Perennial Ryegrass
Legumes:	*Lathyrus pratensis*	Meadow Vetchling
	Trifolium pratense	Red Clover
Forbs:	*Anthriscus sylvestris*	Cow Parsley
	Centaurea nigra	Common Knapweed
	Heracleum sphondylium	Hogweed
	Leontodon hispidus	Rough Hawkbit
	Plantago lanceolata	Ribwort Plaintain
	Ranunculus acris	Meadow Buttercup
	Rumex acetosa	Common Sorrel
	Sanguisorba minor	Salad Burnet

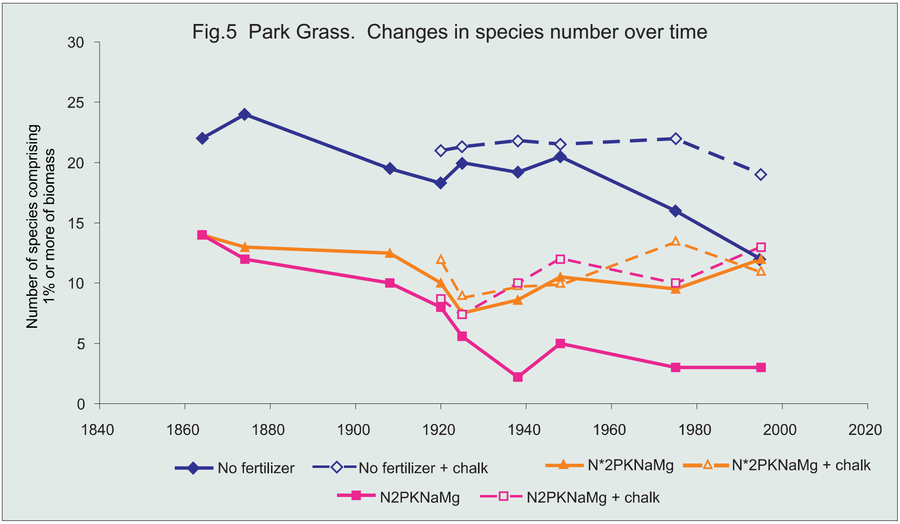
Grasses are dominant on the “d” sub-plots, where the soil pH ranges from 4.1 to 3.6. On these very acid soils, adding P, or P plus K, in the presence of N has had very interesting effects on the proportions of the three dominant grass species (Table 4).

Table 4. The effects on three grass species of applying P and K with N where soil pH is 4.1 - 3.6.

		Percentage of dry matter		
Plot	Treatment(1)	*Agrostis capillaris*	*Anthoxanthum odoratum*	*Holcus lanatus*
1d	N1	67	32	0
4/2d	N2P	28	70	1
9/2d	N2PKNaMg	13	67	20
11/1d	N3PKNaMg	0	0	100

(1) See plan for details

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 5.9 with sodium nitrate. The effect of soil acidification on the total number of species in the sward is dramatic, 4-10 with ammonium sulphate, but 22-34 with sodium nitrate. The effect on species number of adding chalk to these soils is shown in Table 3. Figure 5 summarises, for three contrasting treatments, 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 reduced species number further in the absence of chalk, more so with ammonium sulphate than sodium nitrate. Raising soil pH, by adding chalk, has had more effect on the Nil and ammonium sulphate treatments than on those given sodium nitrate.



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.

The design of the experiment is of a factorial nature with strips 1-4 (see plan), 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.

Hoosfield   Fertiliser and organic manure treatments

Treatments (per hectare per year unless indicated)

Nitrogen (applied in spring)
  N -, 1, 2, 3   0, 48, 96, 144 kg N as calcium ammonium nitrate (Nitro-chalk)

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

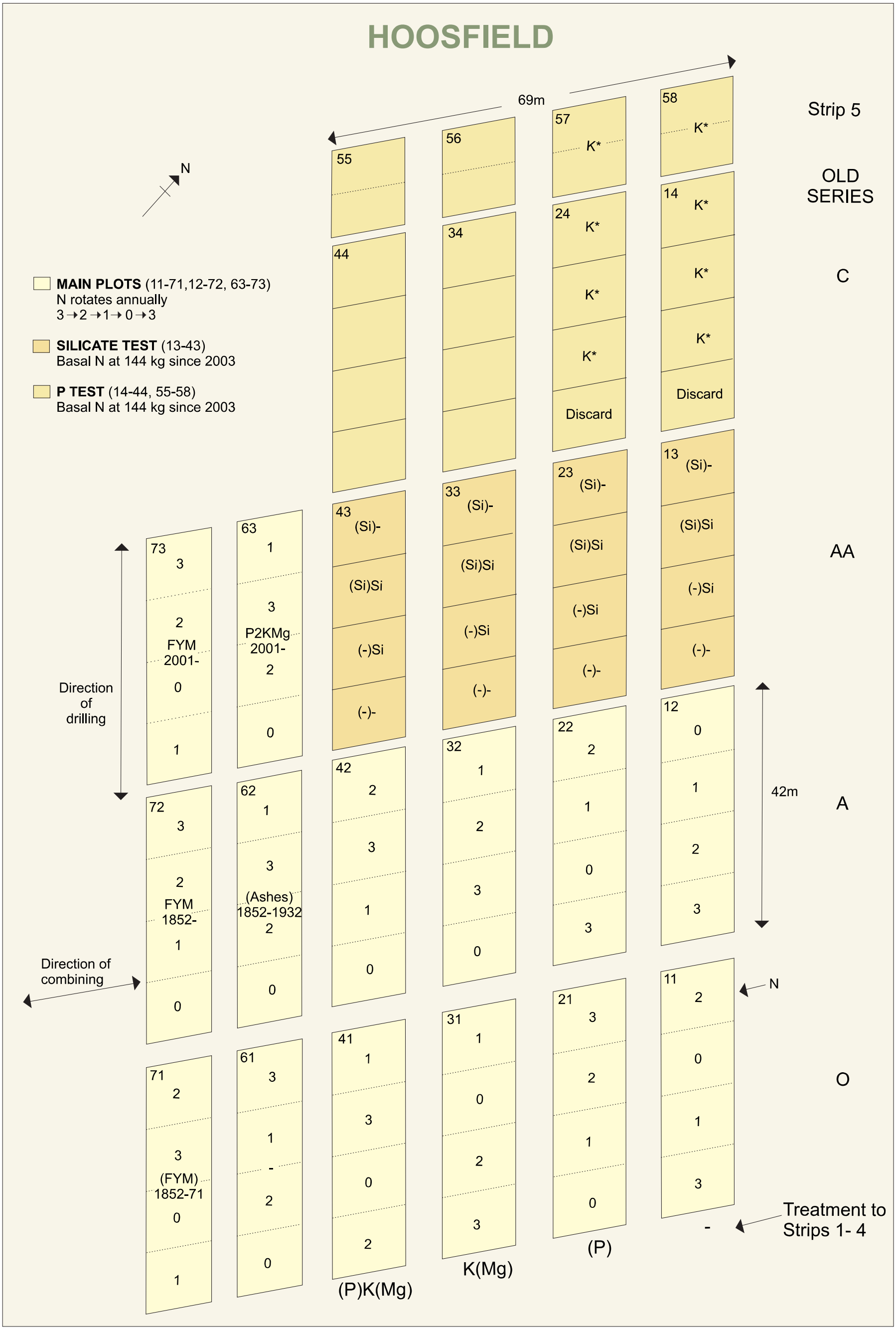
Minerals (applied before ploughing in autumn)
  P2   44 kg P as triple superphosphate since 2001
  (P)   35 kg P until 2002 (to be reviewed for 2008)
  K   90 kg K as potassium sulphate
  K*   180 kg K, 2004-8 (450 kg K in 2003)
  (Mg)   35 kg Mg as Kieserite every 3 years until 2002 (to be reviewed for 2008)
  Mg   35 kg Mg as Kieserite since 2001
  Si   450 kg sodium silicate since 1980
  (Si)   450 kg sodium silicate 1862-1979
  (Ashes) 1852-1932 Ashes, as added to minerals to aid spreading

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

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 continues 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.


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
72
62
71
61
42
32
22
12
41
31
21
11
FYM 2001-
P2KMg 2001-
FYM 1852-
(Ashes) 1852-1932
(FYM) 1852-71
Direction of drilling
Direction of combining
42m
(P)K(Mg)
K(Mg)
(P)
Treatment to Strips 1- 4

Recent yields (Fig. 6) continue to show the great importance of P to spring-sown barley as well as large positive interactions between N, P and K. Until the 1980s, PK with appropriate amounts of N gave yields as large as those from FYM. More recently, yields have increased on the long-term FYM soil such that, on average, they are not now matched by fertilisers alone. However, much of the additional N mineralised from the extra SOM on the FYM soil 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 2002-5 on plots lacking P or K but had no effect on plots receiving these nutrients (Table 5). The mechanism for this is not fully understood but is thought to be a soil rather than a crop effect.

Fig.6 Hoosfield. Mean yield of barley grain, 2002-5

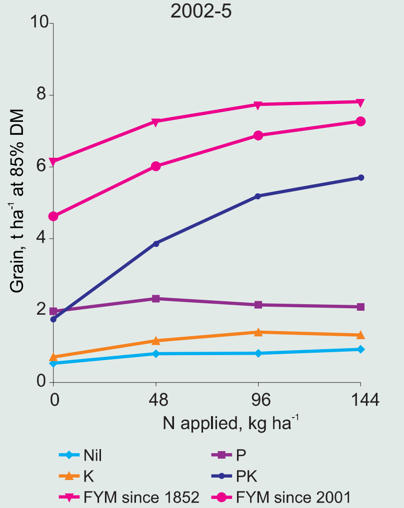


Table 5. Hoosfield; effects of silicate on mean yield of spring barley, 2002-5

Treatment[1]	(-)-	(Si)-	(-)Si	(Si)Si
	Mean yields of grain, t ha^{-1} at 85% dry matter			
N3 -	1.74	2.26	2.58	2.69
N3 K	1.59	3.40	2.98	3.58
N3P	3.11	3.70	4.46	3.79
N3PK	6.14	6.92	6.26	6.39

(1) See plan for details

EXHAUSTION LAND

Unlike some of the other 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. Wheat was grown initially (1856-1875) then 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.

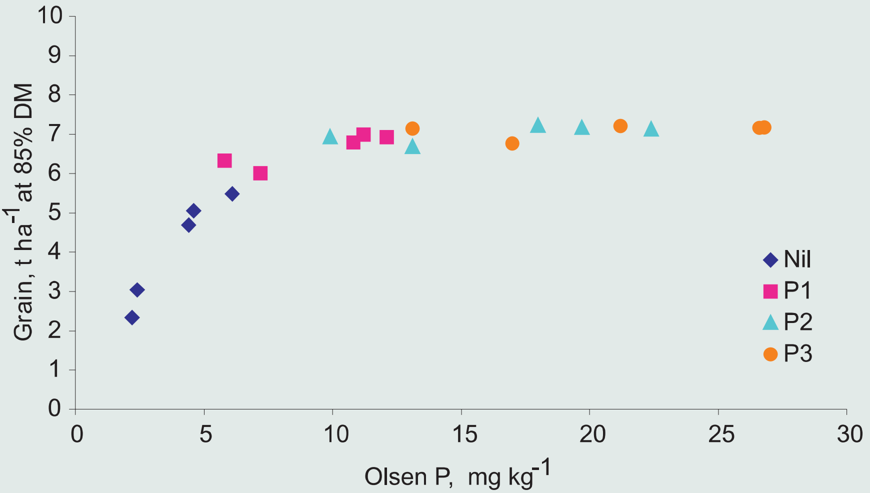
From 1940, fertiliser N was applied to all plots. Nitrogen not only increased yields, but also demonstrated the value of P and K residues remaining in the soil from the first period of the experiment. From 1940 to 1985, spring barley was grown and N fertiliser applied to all plots every year, initially 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 (Table 6).

Table 6. Exhaustion Land; mean yields of barley grain.

Period	N, kg ha^{-1}	Cultivar	Plots 1, 2, 5, 6 no P, no K	Plots 7, 8 residues of PK fertilisers 1856-1901	Plots 3, 4 residues of FYM 1876-1901
			Mean yields of grain, t ha^{-1} at 85% dry matter		
1949-63	63	Plumage Archer	1.8	2.9	3.2
1970-75	88	Julia	1.8	4.2	4.8
1980-83	0	Georgie	0.7	1.5	2.3
	48		1.1	2.2	3.2
	96		1.1	2.7	3.8
	144		1.2	2.8	3.8

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 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 (Fig 7). Although further applications of fresh P increased soil P, they did not increase yield. Applying three fixed rates of P stopped after seven years and, since 2000, maintenance dressings, equivalent to offtakes by the crop, have been applied (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 10-12 mg kg^{-1} there is no further increase in yield. In the first year that wheat was grown take-all was severe (especially in plots deficient in P) despite many decades of continuous spring barley. This raises interesting questions, as yet unanswered, about the nature and causes of take-all decline.

Fig.7 Exhaustion Land. Response of spring barley after 3 years fresh P



On the other half of the experiment, the effects of K residues (in the presence of basal P and N) on yield are investigated.

HOOSFIELD 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, since 1983, the experiment has 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 1.7 t ha^{-1}. When expressed on the basis of the whole area (i.e. wheat plus fallow), the yield of 0.85 t ha^{-1} is slightly less than the 1.0 t ha^{-1} for continuous wheat on Broadbalk. It was in this experiment, in 1935, that symptoms caused by *Gibellina cerealis* were first recorded in the UK.

GARDEN CLOVER

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 resown 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 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 the 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 resown 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 variety S.123. The combination of aldicarb and Hungaropoly gave yields up to 8 t dry matter ha^{-1} but winter survival remained poor.

The plot then grew 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. The cultivar was changed to Merviot in 1996. Between 1979 and 2006 the experiment has been resown seven times. A mean yield of 13t ha^{-1} has been achieved in this period, with up to 20 t ha^{-1} in some years.

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 those of Broadbalk and Hoosfield.

The rich kitchen garden soil on which the experiment was established had received much FYM. In 1857, the 0-23cm soil layer contained 10.8 t N ha^{-1}; by 1983 this had declined to 4.5 t N ha^{-1}.

BARNFIELD

This was the first of the "Classicals", 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}. Before 1968 this was the only Classical in which N was applied with both FYM and FYM + PK fertiliser.

Because yields of continuous roots were declining, perhaps because of increasing numbers 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 superiority of yield on soils given FYM, even where large amounts of N were applied in combination with the minerals. This may have been because the extra organic matter had improved soil structure with considerable effect 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. With optimum N, the yields with minerals 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 taken since 2001

AGDELL

This was the only Classical in which crops were originally 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 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. 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.

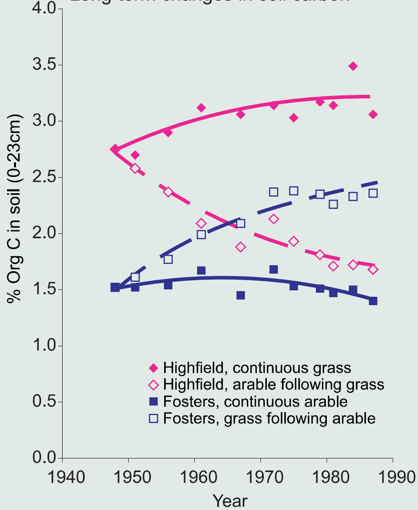
OTHER LONG-TERM EXPERIMENTS

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

AT ROTHAMSTED

The Ley-arable experiments at Rothamsted, on Highfield and Fosters fields, started in 1949. Their purpose was to look at the effects of different cropping systems on soil organic matter and yield. The two sites have the same soil type but the cropping histories of each are very different. Highfield had been in permanent grass for several centuries; 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 8 shows that, even after more than 40 years, soils had still not reached the equilibrium values associated with the revised cropping systems. Thus, in soils ploughed out of permanent grass, SOM is still declining whilst in soils put into permanent grass, SOM is still increasing.

Fig.8 Highfield and Fosters Ley-arable. Long-term changes in soil carbon



Other long-term experiments at Rothamsted have been used to study the effects on yield or soil of plant available P and K, liming, growing continuous maize, incorporating straw or of applying pesticides for many years.

AT WOBURN

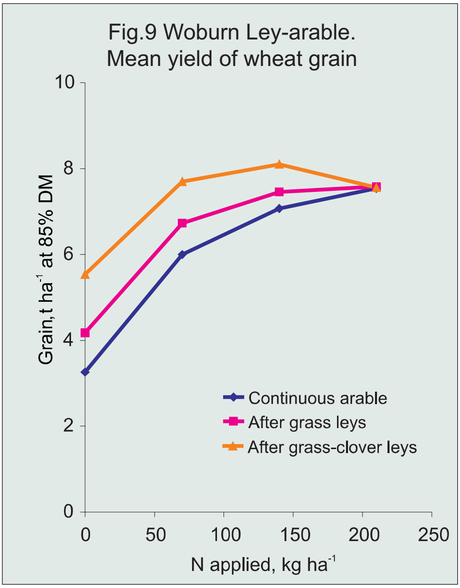
Experiments at Woburn began in 1876 under the auspices of the Royal Agricultural Society of England. The principal aim was to test the residual manurial value to crops of two contrasted feedstuffs fed to animals in covered yards or on the land. Rothamsted took over the management of the farm in the 1920s. 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. 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 of management on SOM and yield.

Ley-arable (foreground) and Organic Manuring (middle) experiments at Woburn

The Intensive Cereals experiment (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 contained little or no free calcium carbonate and the soil pH was probably *c*.6. Consequently, within 20 years the experiment ran into problems with soil acidification where ammonium sulphate was applied, and yields declined markedly. Although the first experiments on liming in the UK were started on these plots in 1897 yields did not recover to their former level. In retrospect, it is possible that yields were also affected by cereal cyst nematodes, which can be a problem with continuous cereals on lighter textured soils. For many years, the yields remained poor, and the site was divided 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.

The Ley-arable experiment started in 1938 to compare the effects of rotations with or without grass or grass-clover leys on SOM and the yield of two arable test crops. Soils at Woburn that have been in continuous arable cropping since 1876 contain about 0.8 % C, and %C is still declining slowly; soils that have alternated between 3-year leys and 2-years arable since 1938 contain about 1.2 % C. Effects on the yield of the first test crop, winter wheat, are shown in Figure 9. Typically, where no fertiliser N is applied, yields are greater following the grass leys than 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. Following the leys, a larger yield is often achieved, with less fertiliser N, compared with continuous arable cropping.

The Market Garden experiment started in 1942, originally to look at the effects on SOM and crop yield of various organic inputs; namely FYM, compost and sewage sludge. The experiment was 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. The value of archiving samples was well demonstrated because soils and samples of sewage sludge from the earlier phase of the experiment had been saved. It was, therefore, possible to compile, for various metals, a budget of the amount applied and the amount remaining in the soil. Total zinc (Zn) and cadmium (Cd) concentrations in the topsoil were much higher in sludge-amended plots than with 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 contents. 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 at N_2 fixation 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. Although the permitted levels of metals in sludges are now much lower than those used in the Market Garden experiment, findings from the experiment are still relevant and were used to help formulate EU legislation regarding loadings for heavy metals in soil. The experiment is now being used to evaluate the effectiveness of hyperaccumulator plants, *i.e.* plants that can naturally accumulate large amounts of metals from soils and which, potentially, could be used to "clean up" soils contaminated with heavy metals.



Other long-term trials at Woburn include the Organic Manuring experiment, which started in 1964, and further experiments on heavy metals, incorporating straw and continuous maize (the latter two experiments duplicating those on the heavier soil at Rothamsted).

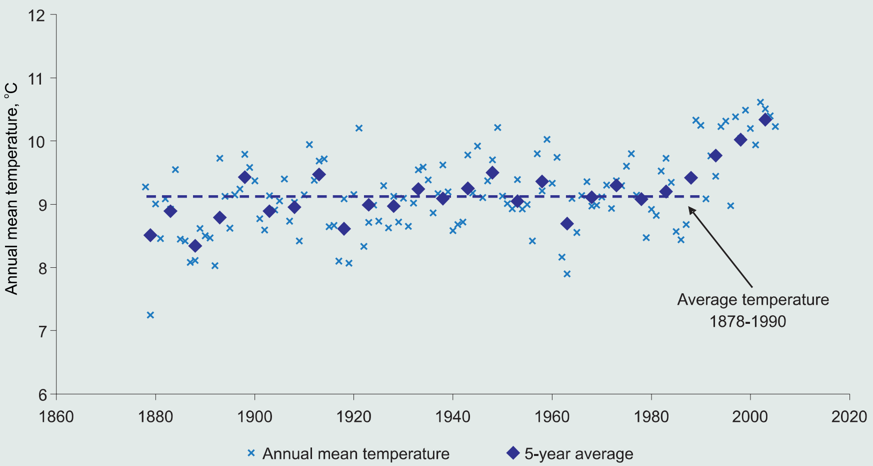
AT SAXMUNDHAM

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 each year. On Rotation I there was a test of combinations of N, P and K plus bone-meal and FYM treatments. 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. The Rotation II experiment has been used to look at the responses by various crops to fresh and residual P. The critical level, above which there is no further response to fresh P, is much higher and more variable on this heavier soil than on the better soil at Rothamsted (see Exhaustion Land above). The Rotation I experiment continues to look at crop responses to both P and K and their interactions with N, particularly where much fertiliser N is being applied to high yielding cultivars of wheat with the aim of achieving bread-making quality.

METEOROLOGICAL DATA

Concerns over the impact of climate change makes it increasingly important that, when interpreting data from long-term experiments, changes in temperature, rainfall, rainfall patterns, chemical inputs in rainfall and as dry deposition *etc*., are all taken into account. Total rainfall has been measured at Rothamsted since 1853, temperature since 1873; other meteorological data have been collected subsequently. Annual rainfall averages 704mm (mean 1971-2000) but ranges widely from 380mm in 1921 to 973mm in 2000. Increases in temperature in many parts of the world are well documented. At Rothamsted, average annual temperature is now more than 1°C higher than the 1878-1990 average (Fig. 10). Much of that rise is accounted for by increases during the autumn and winter months. At Rothamsted, the 10 warmest years on record occurred in the last 17 years. Average soil temperatures have also risen.

Fig. 10 Annual mean temperature at Rothamsted



Since the 1850s, 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}. In contrast, other inputs, such as sulphate, nitrate or ammonium can be much larger. Inputs of sulphate-S were about 5 kg ha^{-1}yr^{-1} in the 1850s, reached a maximum of 65 kg ha^{-1}yr^{-1} by 1980 and, after a dramatic decline, associated with decreasing emissions from power stations and a decline in heavy industry, 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; since then they have declined to 5 and

3 kg $ha^{-1}yr^{-1}$, respectively. Estimates of N in dry deposition are available for the last 20 years. In 1996, it amounted to 34 kg N $ha^{-1}yr^{-1}$; about three times that in rainfall. The total input, for wet and dry deposition, of 43 kg N $ha^{-1}yr^{-1}$ agrees well with other estimates; calculated total inputs ranged from 30-50 kg N $ha^{-1}yr^{-1}$ during the late 20th century. We estimate that, in the mid-1850s, total N inputs were about 10 kg $ha^{-1}yr^{-1}$.

Concentrations of carbon dioxide (CO_2) are not measured at Rothamsted but the rise in atmospheric CO_2 concentrations worldwide has been well documented; increasing from about 280 ppm in 1850 to *c*.380 ppm in 2005.

LONG-TERM EXPERIMENTS AS A RESOURCE

Maintaining soil quality and fertility is of worldwide importance; any changes in the factors influencing soil quality and soil processes can take decades to have any measurable effect. Similarly, the effects of agriculture on the wider environment may take years to become obvious. Long-term experiments with their contrasting treatments and management are an invaluable resource, which we can use to examine these effects in greater detail.

Thus, Broadbalk, Hoosfield and Park Grass have been used for detailed work on N cycling in our temperate climate using the stable isotope, ^{15}N, applied to microplots within each experiment. Results show that, on average *c*.50% of the applied fertiliser N was recovered by the crop, 25% remained, as organic N, in the soil and 25% was not accounted for. Most of the nitrate present in the soil profile in the autumn, and therefore at risk of loss by leaching, was derived from SOM, not from unused fertiliser N. Exceptions are where excessive amounts of N have been applied, in relation to potential crop yield, or where the crop has failed. 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 could be accounted for; 60% in the herbage plus 14% in the soil. 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 was oxidised in the soil where fertiliser N had been applied, compared with soil receiving FYM or the control soil receiving neither fertiliser nor manure. 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.

The progressive acidification of the Geescroft Wilderness and some soils on Park Grass has also resulted in the mobilisation of heavy metals, particularly aluminium.

Broadbalk has been used to investigate the influence of both amount and form of N on gene expression in wheat grain. 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 metabolome profiling to gain insights into processes relating to nitrogen use efficiency in wheat.

SAMPLE ARCHIVE

The unique 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 more finely ground material from many other crops. Soils (air-dried) have been taken from top-soils/plough layer (generally 0-23 cm) and from sub-soils. 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.

Archived soils from Park Grass, 1876

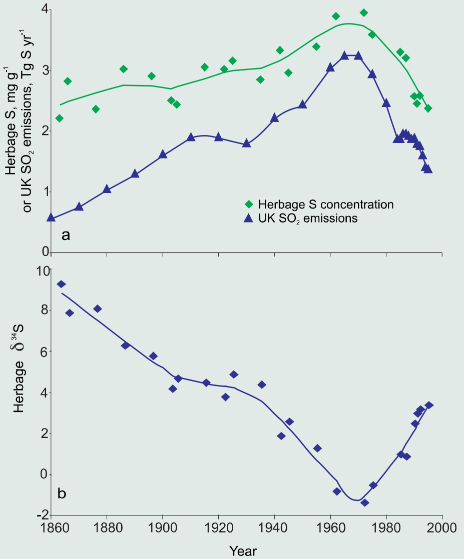
There is a written record of samples that have been archived and, increasingly, information on the samples is being stored electronically in the Electronic Rothamsted Archive (see below).

The Sample Archive has been used extensively by Rothamsted staff and by scientists from other research institutes and universities in the UK and abroad. The retrospective analysis of archived material allows us to look back more than 160 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 needs. Inputs have declined markedly since the 1970s. 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 (Fig. 11), 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. Calculations suggest that up to 50% of the herbage S uptake came from anthropogenic sources at the peak of SO_2 emissions in 1970.

Fig.11 Park Grass. The effect of changes in emissions of SO_2 in the UK on herbage S (a) and herbage $\delta^{34}S$ (b)



DNA of two important wheat pathogens, *Phaeosphaeria nodorum* and *Mycosphaerella graminicola*, has been extracted, and amplified, from archived wheat straw samples from Broadbalk over the period 1844-2003. From 1970-2003, the relative abundance of DNA of these two pathogens in the samples reflected the relative importance of the two diseases they cause in the UK, as assessed by disease surveys. Over the longer period, changes in the dominance of the two species were very strongly correlated with changes in atmospheric pollution, as measured by SO_2 emissions in the UK.

Data from the analyses of soils for their organic carbon and ^{14}C content were used to develop and validate RothC, a computer model that simulates the turnover of soil organic matter, a key component of soil quality. 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. Such measurements have only become possible in recent years with the development of more sophisticated analytical techniques.

THE ROTHAMSTED INSECT SURVEY


Light trap

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 compare 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. Currently, there are about 90 such traps in operation throughout the UK, most of which are run by volunteers, and from which all macro-moths are identified and counted on a daily basis.

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 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. 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.

Suction trap

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. For example, understanding the relationship (Fig. 12) between winter temperatures and the times of the first flights of *Myzus persicae*, 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

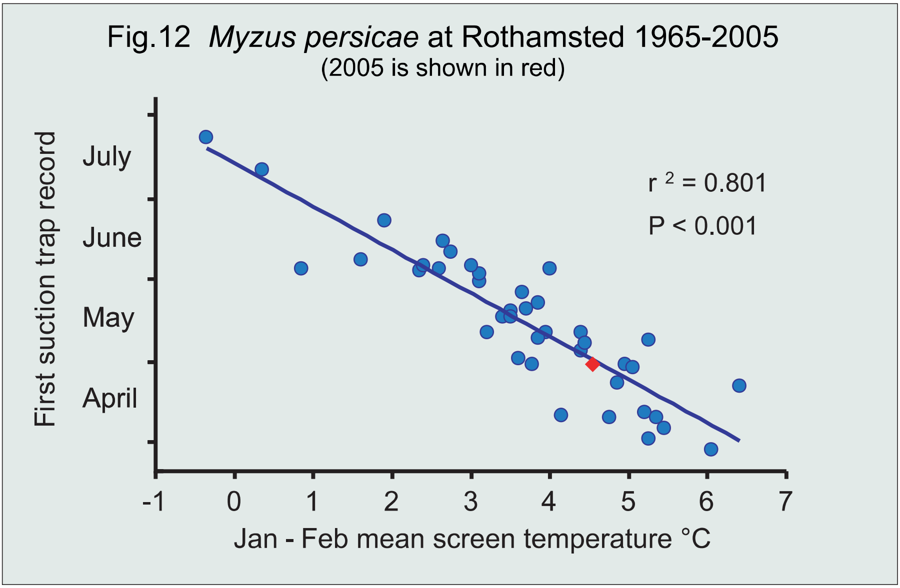
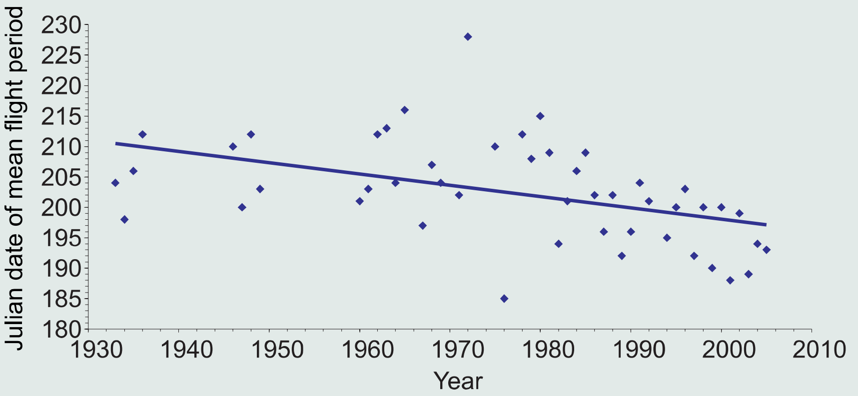


Fig.13 Flight phenology of *Eilema lurideola*, the common footman, Barnfield light-trap 1933-2005



light traps show that there is a long-term trend towards earlier flight times for some moths (Fig. 13). 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, which is of conservation concern.

There are now over 70 12.2m suction traps, operated by various organisations across Europe from which the data are being coordinated for a range of research purposes with particular emphasis on climate change studies (http://www.rothamsted.bbsrc.ac.uk/examine/).

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.

ENVIRONMENTAL CHANGE NETWORK

The UK Environmental Change Network (ECN) was started in 1992 as a multi-agency programme to establish a well-designed national network of sites that could be used to identify, assess and research environmental change nationally, and provide a basis for European and International collaboration. Its specific objectives are:

- To establish and maintain a selected set of terrestrial and freshwater sites within the UK from which comparable long-term datasets could be obtained by means of measurement, at regular intervals, of variables identified as being of major environmental importance.
- To provide for the integration and analysis of these datasets, so as to identify environmental change and improve 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.

The ECN website is at: http://www.ecn.ac.uk/

At Rothamsted the whole of the farm is regarded as the ECN site. An automatic weather station was established near the meteorological enclosure; many weather measurements are logged continuously. Some measurements focus on the Park Grass experiment as this is of most botanical and ecological interest. Soil solution chemistry is measured on Park Grass on a new, unfertilised "Nil" plot. Sets of nitrogen dioxide (NO_2) diffusion tubes are sited on Park Grass and elsewhere on the farm. Concentrations of NO_2 show significant seasonal variations; there are minima in summer and maxima in winter, linked to air chemistry and central heating, with decreases over the Christmas/New Year period when there is less business activity and road transport.

ELECTRONIC ROTHAMSTED ARCHIVE (e-RA)

The long-term experiments, and other measurements at Rothamsted and at other sites managed by Rothamsted, have generated a large amount of data over more than 160 years. The Electronic Rothamsted Archive (e-RA) provides a permanent, managed database to securely hold Rothamsted's important data, and the textual information associated with it. The current focus is to secure the valuable data from the Classical and other long-term experiments, but data from more modern sources is also stored within e-RA. Datasets include yields from Broadbalk, Park Grass and Hoosfield, meteorological data, and data collected for the Environmental Change Network. It also contains a comprehensive bibliography of papers relating to the long-term experiments. In due course it will also be linked to the database detailing what is contained in the Sample Archive.

The e-RA database can be accessed via the Rothamsted website.

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