ROTHAMSTED RESEARCH

Rothamsted Experimental Station Guide

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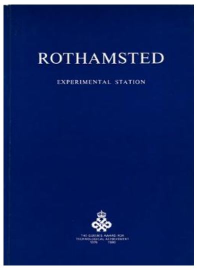

Classical Experiments

Rothamsted Research

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THE CLASSICAL EXPERIMENTS

Between 1843 and 1856 Lawes and Gilbert started nine long-term experiments; some of the plot treatments were changed during the first few years and one experiment was abandoned in 1878, but when Lawes died in 1900 eight experiments were continuing more or less as originally planned. These are now called the 'Rothamsted Classical Experiments'.

Their main object was to measure the effects on crop yields of inorganic compounds containing nitrogen, phosphorus, potassium, sodium and magnesium, elements known to occur in considerable amounts in crops and farmyard manure, but whose separate actions as plant foods had not been systematically studied. The materials used were ammonium salts and nitrate of soda (as alternative sources of nitrogen), superphosphate (at first made by mixing bones and sulphuric acid for each experiment) and the sulphates of potash, soda and magnesia. Farmyard manure was also included in most of the experiments. The inorganic fertilisers were tested alone and in various combinations. Nitrogen was often applied at two or more different rates.

Lawes and Gilbert recorded the weights of all produce harvested from each plot, and samples were kept for chemical analysis. 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, and analysis of soil samples showed whether nutrients accumulated or diminished in soil. The installation of drains (one to each plot) in the Broadbalk wheat experiment in 1849 allowed the losses of nutrients by leaching into the subsoil to be estimated. No other large-scale field experiment in the world is known to have this feature.

The classical experiments gave results of immediate value to farmers planning their use of fertilisers and manures, but their value to farmers diminished as the contrasted processes of depletion and enrichment of nutrients went on, progressively reinforcing the effect of each annual application of the manures. Until about 1939 the best yields obtained on each experiment were roughly equal to the average yields of the same crops as grown on English farms, and the amounts of fertilisers given (especially the nitrogenous ones) were similar to those used by farmers. Since 1939 with better-yielding varieties and increased use of fertilisers English farm yields exceeded those of the Classicals, until the recent modifications.

The Classical experiments have been modified since Lawes's death, mainly in three periods. Sir Daniel Hall, in 1903–06, added a few plots to Broadbalk, Park Grass and Barnfield, mainly to test the combination NKNaMg (that is, all major nutrients except P) which was originally omitted from these experiments. Hall also started the first scheme of regular liming on Park Grass, the only Classical experiment where increasing soil acidity was adversely affecting some plots. (The others were on old arable fields and had received the traditional heavy dressings of locally dug chalk, a practice not followed on grassland.)

From 1957 several of the Classical experiments were modified to evaluate the effects of the annually repeated dressings of different combinations of nutrients. This was done by introducing new crops (often several crops grown side by side on each of the original plots, as on the Exhaustion Land, Barnfield and Agdell) and by subdividing the old plots to test new fertiliser treatments. These modifications, together with detailed analysis of the soil by several

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methods, gave much information on the value of the accumulated residues of the materials applied in the past.

On Broadbalk and Hoos Barley crop rotations were introduced in 1968; substantial areas of each experiment remained in the traditional crops. The rotations were:

Broadbalk: potatoes, spring beans, winter wheat.
Hoos Barley: potatoes, spring beans, spring barley.

Beans became seriously infested with stem eelworm (*Ditylenchus dipsaci*) and they were not sown after 1978. On Broadbalk the rotation is now

fallow, potatoes, wheat

and on Hoos Barley the whole area is in continuous barley. The crop rotations have shown the yields of wheat and barley that can be obtained when soil-borne diseases and pests are lessened by growing non-susceptible crops for 2 years.

Barnfield, formerly a Classical experiment with mangolds and sugar beet, is expected to be used for a new long-term experiment involving leys but the start has been delayed.

The other major change introduced in 1968 except on Park Grass is the replacement of sulphate of ammonia and nitrate of soda by a mixture of ammonium nitrate and calcium carbonate ('Nitro-Chalk'). Castor meal (except on one plot of Broadbalk) has been discontinued, but its residual value is assessed on Hoos Barley and Barnfield, Most of the applications of sodium (as sulphate or chloride) have been discontinued.

On Broadbalk and Barnfield magnesium is now applied as kieserite (rather than Epsom salts) every third year, except for certain plots.

The following accounts of the separate experiments include minor changes made recently, the varieties grown and some of the recent results.

BROADBALK WHEAT (see plan p. 54)

The first experimental crop was wheat sown in autumn 1843 and harvested in 1844. Every year since then wheat has been sown and harvested on all or part of the field. The treatments compared are organic manures (farmyard manure and rape cake, later replaced by castor bean meal) and inorganic fertilisers supplying the elements N, P, K, Na and Mg in various combinations. For the first few seasons the treatments varied somewhat but in 1852 a permanent scheme was established and this continued until 1967. In the early years the field was ploughed in lands by oxen (later by horses) and the crop from each plot was separately cut with sickles. After threshing, the weights of grain and straw were recorded and samples kept for chemical analysis. (Many of these samples are still available and some have been used in recent investigations as 'pre-pollution' standards.)

Now we plough Broadbalk with a tractor-mounted reversible plough (this eliminates gathering ridges and open furrows) and we harvest with a combine harvester taking only the central strip of each plot for yield and samples. The wheat seed is dressed with insecticide and fungicide and the growing crop is sprayed as necessary to control aphids and foliar fungus diseases.

Much hand-hoeing was done in the past. When this became impracticable strips of the field ('Sections') crossing all the plots at right angles were bare

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fallowed, mainly in a 5-year rotation of fallow with four successive crops of wheat. Now most weeds are controlled by chemical sprays but one Section (8) is kept without sprays.

Effective control of weeds by sprays has eliminated the need for bare fallowing and Sections 0, 1 and 9 have been in continuous wheat since 1952, 1967 and 1959 respectively. On Sections 2, 4 and 7 a crop rotation (potatoes, beans, wheat) was followed from 1968; this is now fallow, potatoes, wheat. Sections 3, 5, 6 are now in continuous wheat (fallow, wheat, wheat from 1968–79).

In his first Rothamsted paper, published in 1847, J. B. 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 a five-course rotation would yield about 22 bushels of wheat per acre. In weight this is about 1350 pounds (lb) or 12 hundredweight (cwt); in metric terms this yield is about 1500 kg (=1.5 metric tonnes) per hectare, usually written 1.5 t ha^{-1}. At present the plot that has received neither manure nor fertiliser since 1843 yields about 2.2 t ha^{-1} after continuous wheat, 3.2 t ha^{-1} after potatoes and beans. Where nutrients are plentifully supplied by farmyard

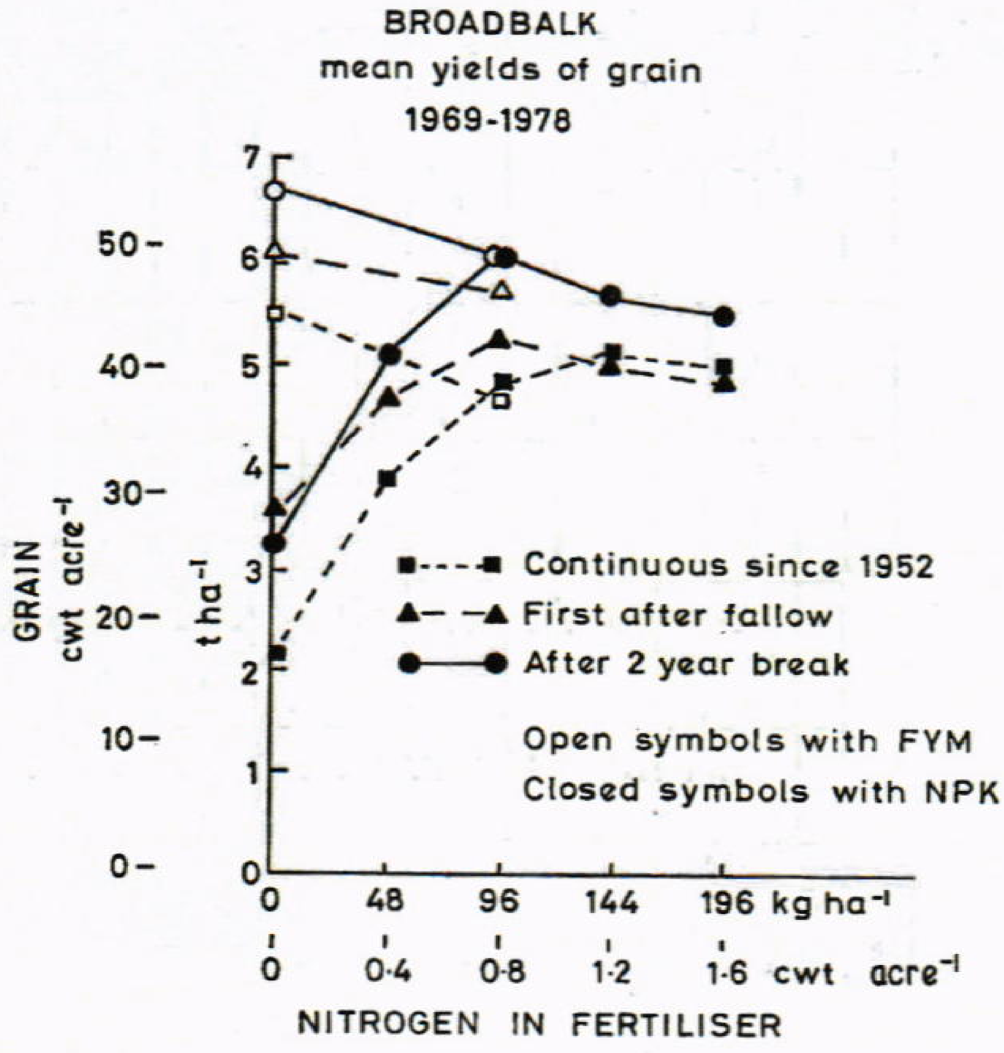

Fig. 1.

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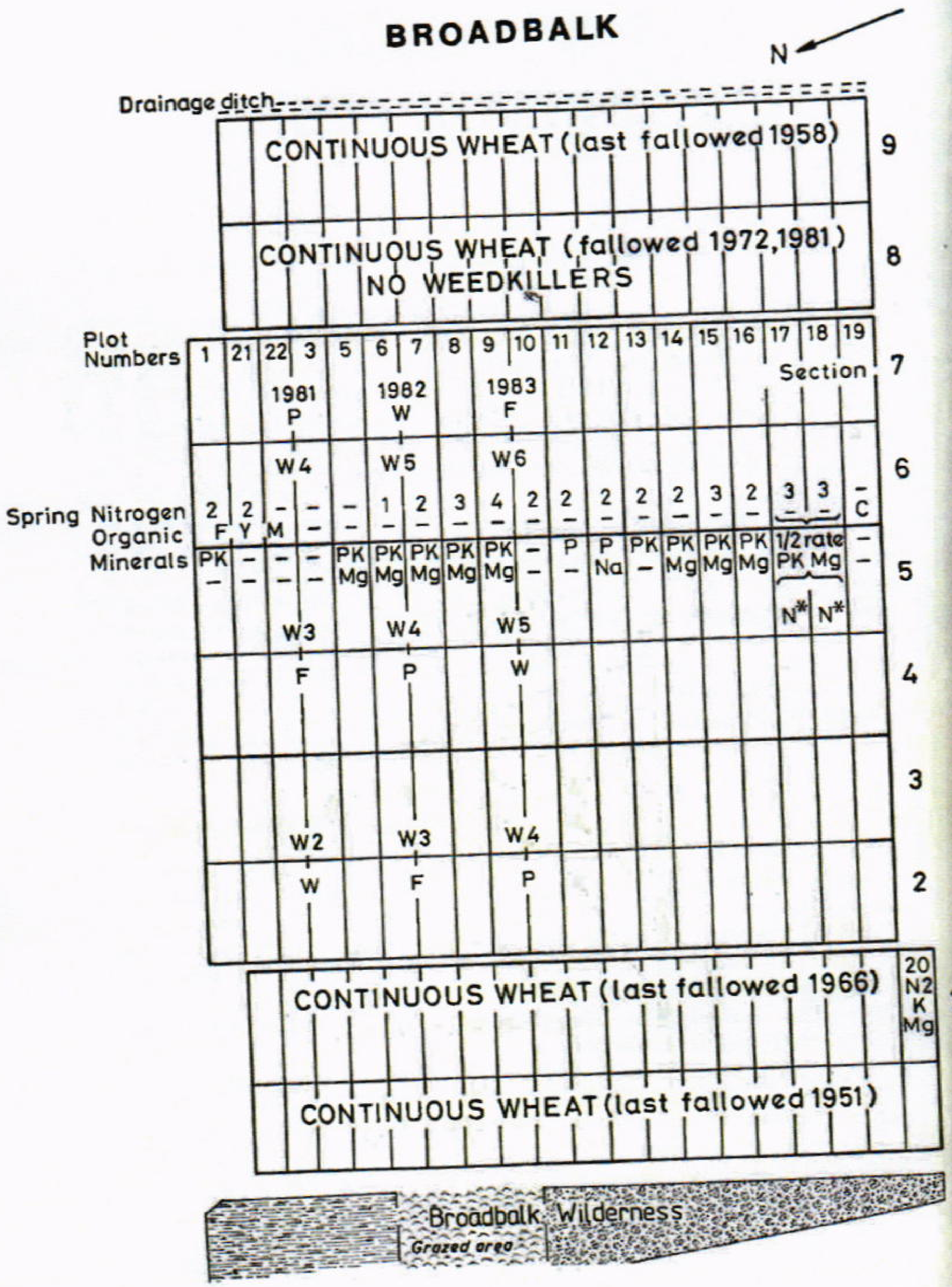

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manure (FYM) or fertilisers yields now average 5–6 t ha^{-1}, more than double the yield of the same treatments in the early years. These differences reflect the improved varieties, cultivations and control of pests, diseases and weeds that have been introduced on Broadbalk (and on English farms generally) in the last 130 years.

For most of the period of the experiment best yields from fertilisers (given by plots receiving PKNaMg and at least 96 kg N ha^{-1}) were equal to those given by FYM, but since the changes made in 1968 FYM has given more grain than fertilisers (see Fig. 1 and Table 2). On Section 0 (continuous wheat since 1952) the difference is 0.5 t ha^{-1}, after 1-year fallow 0.9 t ha^{-1}, and after the 2-year break (potatoes, beans) FYM has given about 0.3 t ha^{-1} more grain. The response curves (Fig. 1) show that more N applied in spring would not eliminate this difference. FYM plus 96 kg N has given consistently less grain than FYM alone; the weight of the extra straw given by the fertiliser N often causes the crop to lodge badly. On plots with fertiliser only, 144 kg N and 192 kg N give less grain than 96 kg N, except on Section 0, although there has been little lodging on these plots.

The 1-year fallow, introduced originally to control weeds, now acts mainly through lessening the inoculum of soil-borne fungi (especially the take-all fungus *Gaeumannomyces graminis*) and by allowing the accumulation of nitrogen available to the following crop. The 2-year break of potatoes, beans leaves very little take-all and, with 96 kg N applied, gives the best yields without FYM. Without applied N the wheat after beans is visibly

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Broadbalk (see plan on opposite page)

Cropping

Sections 0, 1, 3, 5, 6, 8, 9—continuous wheat (each section may be fallowed if necessary to control weeds).
Sections 2, 4, 7—three-course rotation: fallow (F), potatoes (P), wheat (W)

Dressings in autumn

All manures are applied annually to all sections except:

(i) Fallow receives no 'Nitro-Chalk'
(ii) Magnesium—see below.

Organic (applied before ploughing)

FYM	35 t ha^{-1} farmyard manure (from bullocks) (14 tons acre^{-1})
C	Castor meal (about 5% N) to supply 96 kg N ha^{-1} (about 1·9 t meal ha^{-1} or 15 cwt acre^{-1})

Minerals (applied before ploughing)

P	35 kg P ha^{-1} as granular superphosphate (19% P_2O_5) (0·6 cwt P_2O_5 acre^{-1})
K	90 kg K ha^{-1} as sulphate of potash (50% K_2O) (0·9 cwt K_2O acre^{-1})
Na	35 kg Na ha^{-1} as sulphate of soda (14% Na) to plot 12 only
Mg	30 kg Mg ha^{-1} as kieserite (16·8% Mg) to plot 14 only
	35 kg Mg ha^{-1} as kieserite every third year (1980, 1983) to other plots

Residual

Na	15 kg Na ha^{-1} to plots 5, 6, 7, 8, 9, 15, 16, 20 (and at 7·5 kg Na ha^{-1} to plots 17, 18) discontinued 1974

Nitrogen

N1*	48 kg N ha^{-1} as 'Nitro-Chalk' in autumn to plots 17 and 18 in alternate seasons (to plot 18 for 1981 crop; not applied to potatoes)

Dressings in spring

1, 2, 3, 4 'Nitro-Chalk' supplying 48, 96, 144, 192 kg N ha^{-1} (about 0·4, 0·8, 1·2, 1·6 cwt N acre^{-1})

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TABLE 2

Mean yield of wheat grain (10 years, 1969–78) and potatoes (total tubers, 10 years, 1969–78) all in t ha⁻¹

Plot	Treatment	Wheat: After fallow	Wheat: After 2-year break	Wheat: Continuous since 1952	Potatoes
3	None	3·0	2·8	1·8	10·5
5	PK(Na)Mg	3·6	3·3	2·2	15·3
6	N1PK(Na)Mg	4·7	5·1	3·9	24·8
7, 16	N2PK(Na)Mg	5·1	6·0	4·8	31·9
8, 15	N3PK(Na)Mg	5·0	5·8	5·0	36·4
9	N4PK(Na)Mg	4·9	5·5	5·0	40·6
10	N2	3·6	4·9	2·6	9·7
11	N2P	3·6	5·2	3·6	8·1
13	N2PK	4·7	6·0	4·9	23·2
12	N2PNa	4·0	5·5	4·6	11·4
14	N2P(K)Mg[1]	4·9	6·3	4·8	24·3
17, 18	N2+½(PK(Na)Mg)	5·3	6·2	4·6	28·6
22	FYM	6·2	6·6	5·5	37·6
21	FYM N2	5·7	6·1	4·7	42·7
1	FYM N2PK[2]	5·7	6·0	—	33·1
19	C	5·2	5·3	4·1	19·4

[1] K applied since 1968
[2] Since 1968

deficient in N in spring (short and very pale green); comparison with the first crop after fallow shows that fallow leaves more N available than beans, and this is reflected in the yields of grain (Fig. 1). Where N is applied the difference in level of disease is dominant and the order of yields is reversed.

Organic matter in the Broadbalk soil

As the carbon/nitrogen ratios are uniform in different plots, the nitrogen percentages can be taken as indicating the relative amounts of soil organic matter. On plots not receiving farmyard manure the nitrogen contents have remained steady for a century since they were first measured in 1865. By that date plots receiving NPK fertilisers had a little more N than the unmanured and minerals-only plots, where there are less roots and stubble. On the FYM plot nitrogen increased, at first rapidly, then slowly. After a century, annual dressings of FYM had more than doubled the amounts of nitrogen and organic matter (see Table 3).

The introduction in 1926 of regular fallowing, with cultivations to kill weeds and no manures applied, decreased the organic matter, especially on the FYM plot. After the reintroduction of continuous wheat on Section 0 (last fallowed in 1951), the organic matter of the soil increased more than on sections periodically fallowed.

TABLE 3

Nitrogen % of Broadbalk soils 0–23 cm

Plot	Manuring	1865	1944	1966
3	None	0·105	0·106	0·099
5	PKNaMg	0·107	0·105	0·107
7	N2PKNaMg	0·117	0·121	0·115
22	Farmyard manure	0·175	0·236	0·251

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Micro-organisms in the Broadbalk soil

More actinomycetes and bacteria occur in the FYM plot than in the unmanured plot or plot 7 (NPKMg), both of which contain similar numbers. The FYM plot and the fertiliser plot contain similar numbers of fungi, more than in the unmanured plot.

Amoebae are fewer in the unmanured plot than in the FYM plot or plot 7; these last two plots contain about the same number of amoebae, though very different amounts of organic matter.

The nitrogen fixing bacterium *Azotobacter chroococcum* fluctuates in numbers; the average population is greatest in those plots that receive neither N fertiliser nor organic manure. Anaerobic nitrogen-fixing *Clostridium* spp. are more abundant than *Azotobacter*. Nitrogen-fixing root nodule bacteria for field beans (*Vicia*) and clovers are widely distributed but not abundant in Broadbalk soil and those for the medicks and Lotus are sparse; none seems to be much affected by manuring. The continuous wheat crop removes from the soil on plots 3 and 5 about 24 kg N ha^{-1} each year and a further 12 kg N ha^{-1} year^{-1} are lost by leaching but despite this the level of N in the soil has remained almost the same since the beginning of the experiment (Table 3). Nitrogen is added in seed (*c.* 3 kg N ha^{-1} year^{-1}), rain (*c.* 5 kg N ha^{-1} year^{-1}) and by the dry sorption of ammonia (*c.* 13 kg N ha^{-1} year^{-1}) but the largest input appears to come from nitrogen-fixing blue-green algae growing on the surface of the soil between the wheat stems. In a year with average rainfall the algae growing on plot 3 were estimated to fix 19 kg N ha^{-1}. A number of free-living heterotrophic nitrogen-fixing bacteria have been found in Broadbalk soils but their contribution to the nitrogen economy of the arable sections is very small.

Weeds on Broadbalk

Weeds have been surveyed at intervals since 1843 and twice yearly since 1931, and the weed seeds in soil from selected plots have been estimated at intervals since 1925. Weed surveys have been discontinued; the following notes are a slightly modified version of those written in 1976 by Joan Thurston, who has since retired.

About 50 annual and ten perennial weed species occur in the field. Of these, each plot in Section 8 (which has never had herbicides) has its characteristic 10–20 species, determined by its treatment, and the ground is covered with weeds after harvest (except on plot 3). Some species, e.g. blackgrass (*Alopecurus myosuroides*) and corn buttercup (*Ranunculus arvensis*) occur on all plots, but others are associated with individual treatments e.g. legumes where minerals are applied but not nitrogen. In contrast, in the stubble of the cleanest sprayed plots there may be less than five species, represented by only one or two plants of each.

Wild oats (mainly *Avena ludoviciana* with some *A. fatua*) became very numerous on Broadbalk during the 1940s; the 1-year fallow was ineffective against them. Since 1943 they have been pulled by hand as they appear above the wheat; slowly but surely this has decreased the population and pulling is now a relatively short job. On Broadbalk *A. ludoviciana* (which germinates in winter) is much commoner than *A. fatua* (spring germinating), but in the spring-sown barley on the adjacent Hoosfield the wild oats are mainly *A. fatua*. Most annual weeds germinate mainly at specific times of the year, usually autumn and/or spring, and few species germinate throughout the

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year. The preparation of seedbeds at different times of the year for winter wheat and spring barley allows different species to survive.

Several species of perennial grasses spread in Sections 0 and 9 (continuous wheat) while grass-killing herbicides were not used, but did not increase on fallowed sections until 1964 when they too received herbicides that controlled most broad-leaved weeds. More recently aminotriazole has been applied to the wheat stubbles (except on Section 8). It has probably slowed down the multiplication of perennial grasses but has not controlled them because the interval between treatment and ploughing is too short for effective translocation through the whole rhizome system.

Weeds in winter wheat. The use of herbicides to kill broad-leaved weeds has severely decreased susceptible species e.g. common vetch (*Vicia sativa*) and corn buttercup, but no species has been eliminated. Black medick (*Medicago lupulina*) decreased only slowly because the reserve of seeds in the soil was replenished by plants that emerged after spraying and seeded before the stubble was ploughed. Common vetch, corn buttercup and black medick are not well controlled by the fallow because only about half of their seeds germinate during the first year after shedding. Knotgrass (*Polygonum aviculare*) and scentless mayweed (*Tripleurospermum maritimum*) were not controlled by MCPA but are controllable now that mixtures containing dicamba or ioxynil are used.

Terbutryne applied just after sowing has controlled autumn-germinating blackgrass and some broad-leaved autumn-germinating weeds, notably ivy-leaved speedwell (*Veronica hederifolia*) which seeds before the spring spraying and so is not controlled by it but does not persist long enough to control spring-germinating blackgrass which is abundant when very wet or very dry autumns have prevented germination at its usual season.

As nearly all blackgrass seeds germinate during the first year after shedding it is greatly decreased by fallow, except when a very wet season enforces dormancy. A year of fallow decreases scentless mayweed seeds in soil by a quarter. If wheat bulb fly kills many plants in the first wheat crop after fallow, the surviving seeds of blackgrass and mayweed give large plants in the gaps and the numbers of seeds at the end of the year at least equal the number before fallow. The use of seed-dressing against wheat bulb fly thus helps to control these weeds on Broadbalk.

Weeds in potatoes. Although spring planting destroys weeds from autumn- and winter-germinating seeds, the deep cultivations for ridging bring buried weed seeds to the surface where they germinate, giving a mixture of seedlings of autumn, winter and spring-germinating species. These are controlled by pre-emergence herbicide (linuron-paraquat mixture) but field horsetail (*Equisetum arvense*), which emerges at the same time as the potato shoots and is resistant to those herbicides, is not controlled. It proliferates more in potatoes than in winter wheat because potatoes offer very little competition at the early stages of its growth, whereas winter wheat, especially with N, overshadows the young horsetail shoots from the start. Horsetail increased in density on infested plots in the rotation despite hand-pulling in potatoes because beans also offered little competition during early growth. The number of plots infested with horsetail did not increase during the first two cycles of the rotation. Cultivations during the fallow year in the rotation fallow, wheat, wheat (now discontinued) checked but did not eliminate it.

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Pests on Broadbalk

The continuity of cropping and manurial treatments makes Broadbalk a valuable field for studying the effects of weather on the incidence of some wheat diseases and pests.

Insect pests. Wheat bulb fly (*Delia coarctata* Fall.) often caused severe damage to the wheat-after-fallow strip on Broadbalk. 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 are related to the ratio of plants to larvae, to the time of attack and to conditions for plant growth. The plots on Broadbalk deficient in potassium usually suffered most because the plants were less well developed and damage to the primary shoot often killed the whole plant on these plots. The damage may be minimised by sowing wheat early because well developed plants can withstand attack, but the effects on yield vary greatly with season.

Other insect pests cause damage only sporadically; these include cereal aphids, cutworms, wheat-blossom midges and the saddle-gall midge. Now that potatoes have been introduced to the rotations potato aphids occasionally cause concern. The incidence of these insects is monitored and pest outbreaks are recorded.

Broadbalk drains

In 1849 a tile drain was laid down the centre of each of the plots. The tiles, of the 'horseshoe and sole' type, 2 in. (5 cm) internal diameter, were laid 60 cm below the surface, and led to a 10 cm cross main, which conveyed the water to a ditch. The drains were not intended for experimental use, but in 1866 they were opened at their junctions with the main, and at each of these points a small pit was dug to catch the runnings from each plot. The classical analyses by Dr. A. Voelcker were on samples drawn in this way in 1866–68. The main was enlarged and set deeper in 1879, and in 1896 a bricked trench was made to give easier access to the outfalls. Analyses of the drainage provided important information on the losses of plant nutrients by leaching. The biggest loss from this calcareous soil was calcium carbonate, and it increased with increasing amounts of ammonium salts given to the plot. The loss of nitrate was considerable, and this also increased with the amount of ammonium salts added. Phosphate, although applied in water-soluble form, was almost completely retained, and the loss of potash, though appreciable, was small.

Some of the free-living nematodes of the Broadbalk soils are carried down in the water reaching the drains and can be caught on fine-mesh sieves at the outfalls. This has added to the knowledge gained more laboriously by taking soil samples and extracting the nematodes.

Other uses of Broadbalk

Broadbalk has for many years attracted the interest of scientists working in subjects that were not in the minds of Lawes and Gilbert when they planned the experiment. Because the soil of each plot is now in a virtually stable condition and cultivations and husbandry are changed as little as practicable the crops on Broadbalk offer especially good facilities for studying fluctuations of yield or of pests, diseases, etc., in relation to seasonal differences. For example, eyespot (*Pseudocercosporella herpotrichoides*) and take-all

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HOOSFIELD
Classical Barley Experiment, started 1852

Continuous Barley

N rotation (–,3,2,1,) every year from 1981 (see text)

Revised arrangements for Silicate of Soda (S) Started Autumn 1979 (see text)

N

OLD SERIES

	N2	–	1	–	–	2	1	3	
	3	1	3	2	1	3	–	2	
	1	2	1	3	3	–	1	–	
	–	3	–	2	1	2	3	2	C
	–	2	2	3	2	–	1	2	
	3	1	1	–	3	1	–	3	
	1	–	2	3	3	1	2	1	
	2	3	–	1	–	2	–	3	
(S) –	–	2	–	1	1	2	3	2	
	1	3	3	2	3	–	–	1	AAS
(S)S	–	1	2	–	3	–	1	2	
	2	3	3	1	1	2	–	3	
(–)S	1	2	–	3	–	1	1	3	
	3	–	2	1	3	2	2	–	AA
(–)–	2	–	1	2	3	2	–	2	
	1	3	–	3	–	1	1	3	

N –	2	3	2	3	1	
3 – FYM –	–	–	3	2	2	A
2	3	2	–	1	3	
1	1	1	1	–	–	
3	–	2	2	–	3	
– FYM 1852-71	2	–	1	3	1	O
1	3	1	3	2	2	
2	1	3	–	1	–	
Strip manures None	None	P K Mg	– K Mg	P –	– –	

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(*Gaeumannomyces graminis*), both soil-borne diseases of wheat, were studied by Mary Glynne for many years. H. F. Barnes studied the fluctuations in numbers of wheat blossom midges (*Contarinia tritici* and *Sitodiplosis mosellana*) for nearly 40 years. The statistical analysis of the relation between rainfall and yields of the Broadbalk plots was one of the first tasks of R.A. (later Sir Ronald) Fisher.

Current projects that use Broadbalk material include:

(1) growth analysis in relation to yield of wheat from season to season in standard soil conditions
(2) investigation of the uptake and losses of N fertiliser using ^{15}N as a tracer.

Material from the field is occasionally provided for workers outside Rothamsted.

BROADBALK WILDERNESS

In 1882 about 0·2 ha of the wheat crop on land unmanured for many years was enclosed by a fence at the end of the Broadbalk Field nearest the farm buildings, left unharvested and the land not cultivated. The wheat was left to compete with the weeds, and after only 4 years the few plants surviving were stunted and barely recognisable as cultivated wheat. One half of the area has been untouched; it is now woodland of mature trees about 20 m high, and leading species are ash, sycamore and oak. Hawthorn, now the understorey, is dying out. The ground is covered with ivy in the densest shade, and with dog's mercury, violet and blackberry in the lighter places. A recent winter gale blew down a tree of moderate size, creating the first appreciable gap in the canopy.

The other half has been cleared of bushes annually to allow the open-

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Hoosfield (see plan on opposite page)

Cropping
Continuous barley

Annual dressings
N1, 2, 3 — 'Nitro-Chalk' supplying 48, 96, 144 kg N ha^{-1} to barley (about 0·4, 0·8, 1·2 cwt N $acre^{-1}$).

The rates of N shown on the diagram are those applied to barley in 1981; they change cyclically, every year in order N3 following N⁻ following N1 following N2.

Minerals (applied before ploughing in autumn)
P — 35 kg P ha^{-1} as granular superphosphate (19% P_2O_5) (0·6 cwt P_2O_5 $acre^{-1}$)
K — 90 kg K ha^{-1} as sulphate of potash (50% K_2O) (0·9 cwt K_2O $acre^{-1}$)
S — 450 kg ha^{-1} silicate of soda

Applied every 3rd year (1980, 1983 etc.)
Mg — 35 kg Mg ha^{-1} as kieserite (15% Mg)

Organic
FYM — 35 t ha^{-1} farmyard manure (14 tons $acre^{-1}$)

Residuals
Na — 15 kg Na ha^{-1} as sodium sulphate discontinued in 1974 (applied with K and Mg)

Series treatments (discontinued 1968)
O — None
A — 48 kg N ha^{-1} as sulphate of ammonia (0·4 cwt N $acre^{-1}$)
AA & AAS — 48 kg N ha^{-1} as nitrate of soda
C — 48 kg N ha^{-1} as castor bean meal

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ground vegetation to develop. This consists of coarse grasses, hogweed, agrimony, willow-herb, nettles, knapweed and cow parsley, but many other species are present in smaller numbers. The bushes that appear are mostly hawthorn, dog-rose, wild plum, blackberry, with a few maple and oak.

In 1957 this grubbed section was divided into two parts. The part farther from the woodland area was left unchanged, and the nearer part was mown several times during each growing season and the produce removed to encourage grasses. This management was continued for 3 years as a preparation for grazing; although the hogweed and cow parsley gave place to ground ivy, the grasses did not substantially increase. Starting in March 1960 sheep were put in to graze whenever the growth was sufficient. 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 the miscellaneous plants is much restricted.

The soil has gained much organic matter since the Wilderness was fenced off in 1882. Over the period 1883–1964, the net gain of nitrogen by the top 69 cm of soil from the grubbed part was 4·5 t ha^{-1}, and the corresponding gain of organic carbon 51 t ha^{-1}. The wooded and grubbed parts of the Wilderness accumulated carbon and nitrogen at almost exactly the same rates. By 1964, the Wilderness had gained more organic matter than the plot on Broadbalk receiving 35 t ha^{-1} of farmyard manure annually since 1843.

Legumes have been absent from the grubbed section of the Wilderness since 1915 and the nitrogen gains (equivalent to 49 kg N ha^{-1} $year^{-1}$) appear to come from rain, bird droppings, dry sorption of ammonia (15 kg N ha^{-1} $year^{-1}$) and from nitrogen fixation by bacteria in the rhizosphere of the perennial weeds. Acetylene reduction assays show that hogweed, hedge woundwort, ivy and ground ivy all support a nitrogen fixing flora which can, under wet conditions, fix as much as 0·5 kg N ha^{-1} day^{-1}.

Nitrogen gains in the wooded section are as yet unexplained.

HOOSFIELD BARLEY

This experiment, just north of the farm buildings, offers an interesting contrast with Broadbalk. On the Hoos experiment barley has always been sown in spring and there has been no regular fallowing. Indeed, in the 116 seasons 1852–1967, the area has been fallowed only four times.

A three-course rotation of crops (potatoes, beans, barley) was followed on small areas of certain plots from 1968 to 1978. The whole area is now cropped with barley each year.

The design of the experiment is of a factorial nature with strips running approximately east–west with the four combinations of

(1) None, superphosphate (P) and
(2) None, K Mg

and, on 'series' running north–south

(3) No nitrogen, N as sulphate of ammonia, N as nitrate of soda, N as rape cake (later castor meal) all at the same rate of N.

The nitrogen treatments to series are now discontinued, each of the original plots now being split into four sub-plots to test four rates of N (as 'Nitro-Chalk') in a rotating scheme.

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There are a few additional plots at the south and west, one of which has received FYM throughout the period of the experiment.

The edges of the plots are not at right angles, but at approximately 80°; this unusual arrangement conforms to the boundaries of the field and uses the available space effectively.

The barley on plots with incomplete manuring usually shows symptoms of deficiencies when about 10 cm high. As with all cereals, shortage of N causes the whole plant to be pale; the oldest leaves may turn yellow and die at the tips. K deficiency, especially obvious during dry springs, causes the early leaves to turn yellow and die at the tips; P deficiency sometimes produces a steely-blue tinge. Such symptoms, which soon disappear, are seldom shown by winter wheat on Broadbalk where differences of colour reflect mainly differences in supply of N.

The test of silicate of soda has now been modified so that the four combinations of

(1) None, silicate from 1980 and
(2) None, silicate 1862–1979

are all present each year. See *Rothamsted Report for 1979*, Part 1, 103, for more details.

PARK GRASS

The Park Grass Plots, laid down in 1856, are much the oldest surviving grassland experiment in Great Britain. They demonstrate in a unique way how continued manuring with different fertilisers affects the botanical composition and yield of a mixed population of grasses, clovers and weeds. The Park had already been in grass for several centuries when the experiment began; nevertheless, there are faint traces of plough furrows marking lands about seven paces wide. After more than 100 years, the boundaries of the plots are still sharp; the transition between adjacent treatments occupies 30 cm or less, showing that there is little sideways movement of nutrients in undisturbed soil.

The plots have been cut each year for hay all at the same time, although no single date can be suitable for all plots. For a few years the aftermath was grazed by sheep, penned on each plot and duly weighed. Since 1873 a second cut has been taken and carted green. Since 1960 yields have been calculated from the weights of produce from sample strips cut with a forage harvester (two per plot). Sub-samples are taken to estimate dry matter. At the first cutting the produce of the remainder of each plot is made into hay; this allows the return of seeds to the soil as in the past. At the second cutting the whole produce is carted green. The position of the sample strips differs from year to year.

The soil of Park Grass, in contrast to that of the nearby arable fields, contained little or no calcium carbonate when the experiment began; on plots treated with sulphate of ammonia, increasing acidity of the soil soon caused the sward to deteriorate. Lawes recognised this and made tentative applications of lime in 1883 and 1887, but regular liming was not begun until 1903. Then, and every fourth year until 1964, lime (originally burnt lime, recently calcium carbonate) was applied to the southern halves of most of the plots (see plan, p. 64). Except for plots 18, 19 and 20, a fixed amount was applied without regard to the different requirements of the several plots. From 1965

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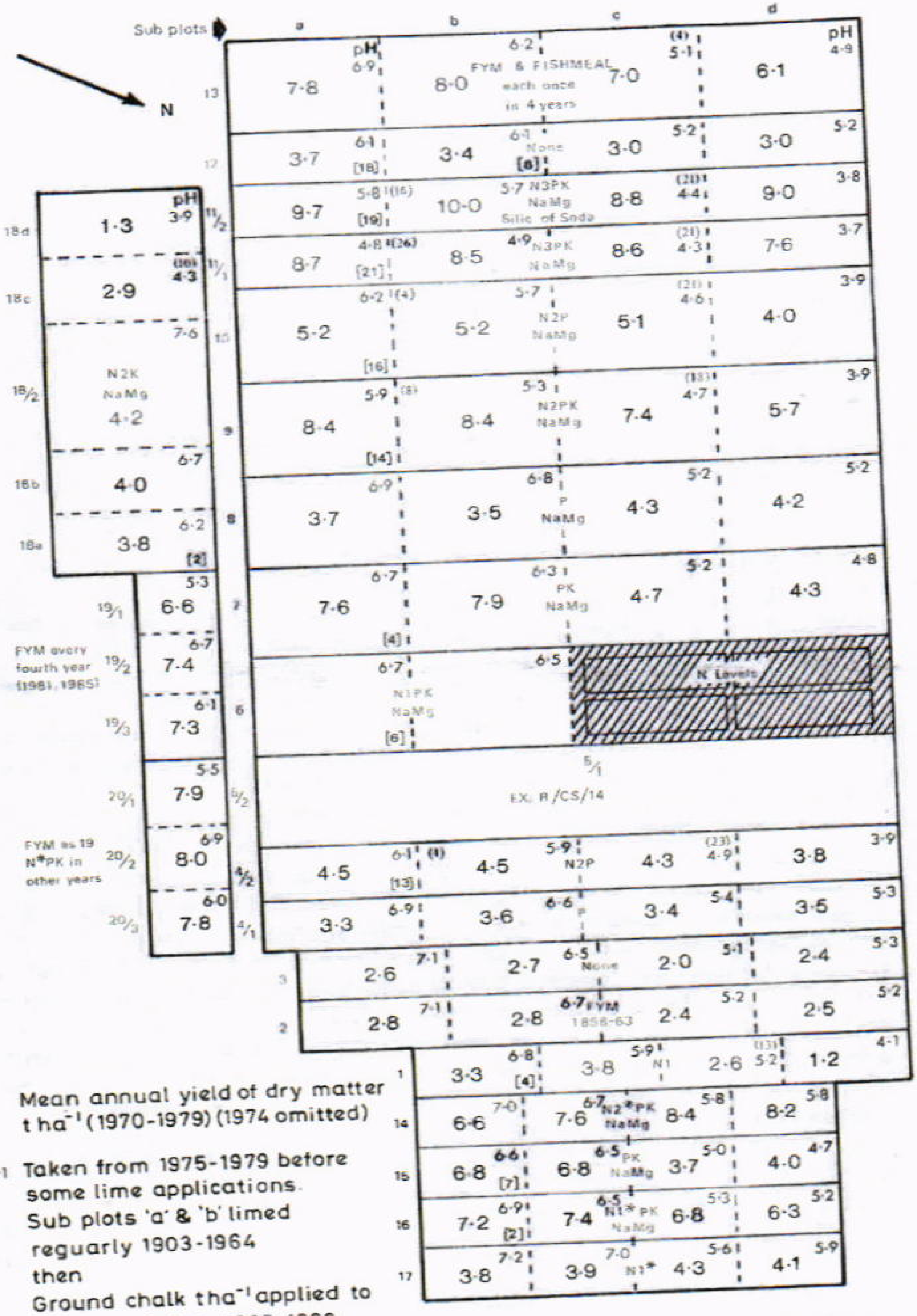
PARK GRASS

Hay each year since 1856



3·3 Mean annual yield of dry matter t ha^{-1} (1970-1979) (1974 omitted)

pH 5·1 Taken from 1975-1979 before some lime applications. Sub plots 'a' & 'b' limed reguarly 1903-1964 then

(21) Ground chalk t ha^{-1} applied to 'b' & 'c' subplots 1965-1968

[18] Ground chalk t ha^{-1} applied to 'a' subplots and '12b' since 1968

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each half-plot on plots 1 to 18 was further subdivided. (At this stage the old plots 5–1, 5–2 and 6, whose treatments had not been constant throughout were given over to new experiments.) From 1965 only sub-plots 'd' remain unlimed. On the more acid plots, sub-plots 'c' (previously unlimed) now receive chalk calculated to give pH 5. Sub-plots 'b' (already limed) are chalked to give pH 6 and (from 1976) sub-plots 'a' to give pH 7.

The unmanured plots (3, 12) have the richest flora, with many red clover plants and broad-leaved weeds, but none grows vigorously, and yields are small. These swards are the nearest approximation to the state of the whole field in 1856. Lime alone or P alone (plot 4–1) has little effect. Plot 7 (PKNaMg) has a much stronger growth of legumes, including red clover (*Trifolium pratense*) and white clover (*Trifolium repens*), and meadow vetchling (*Lathyrus pratensis*); on this plot lime greatly increases the vigour and yield of the legumes. Plot 8 (PNaMg) is much poorer in meadow vetchling, and on this plot alone lime depresses yields.

With nitrogen, either as sulphate of ammonia or as nitrate of soda, yields are reasonable except on some of the unlimed ends. Plots 11–1 and 11–2 show the extreme effects of sulphate of ammonia. The unlimed end is dominated by Yorkshire fog (*Holcus lanatus*) and the mineral soil is covered by a layer of peat; earthworms are absent. The limed end has tall coarse species, false oat (*Arrhenatherum avenaceum*) and meadow foxtail (*Alopecurus pratensis*), and makes a poor hay, but the yield of dry matter compares well with much sown grassland. Nitrate of soda (14, 16, 17) supplies nitrogen without acidifying the soil; lime has little effect on these plots. Organic manures applied in alternate years (13) produce a well-mixed herbage, but yield is much less than from the best fertiliser treatments.

The most interesting feature of the experient since 1965 has been the change in the botanical composition of the swards of the sub-plots where lime has been applied to very acid soils. Red clover has occurred on most of these plots and is now well established on plots 1c and 9c. Fescues (*Festuca* spp.) have increased on plots given N1 and N2 with incomplete minerals (1c, 4–2c, 10c and 18c); tall oat grass (*Arrhenatherum elatius*) and cocksfoot (*Dactylis glomerata*) are now common on plots receiving N2 and N3 and

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Park Grass (see plan on opposite page)

Treatments (every year except as indicated)

Nitrogen (applied in spring)

N1, N2, N3	sulphate of ammonia supplying 48, 96, 144 kg N ha^{-1} (about 0·4, 0·8, 1·2 cwt N $acre^{-1}$)
N1*, N2*	nitrate of soda supplying 48, 96 kg N ha^{-1} (about 0·4, 0·8 cwt N $acre^{-1}$)

Minerals (applied in winter)

P	35 kg P ha^{-1} as granular superphosphate (19% P_2O_5) (0·6 cwt P_2O_5 $acre^{-1}$)
K	225 kg K ha^{-1} as sulphate of potash (50% K_2O) (2·2 cwt K_2O $acre^{-1}$)
Na	15 kg Na ha^{-1} as sulphate of soda (14% Na)
Mg	10 kg Mg ha^{-1} as sulphate of magnesia (10% Mg)
	Silicate of soda at 450 kg ha^{-1} of water soluble powder (plot 11/2)

Plot 20. Rates of manuring in years when FYM not applied:
30 kg N, 15 kg P, 45 kg K ha^{-1}

Organic (each applied every fourth year)

FYM 35t ha^{-1} farmyard manure (bullocks) (1981, 1985) (14 tons $acre^{-1}$)

Fish meal (about 6·5% N) to supply 63 kg N ha^{-1} (1979, 1983) (about 950 kg ha^{-1} meal or 850 lb $acre^{-1}$)

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complete minerals (9c, 11–1c and 11–2c) and also meadow foxtail and rough-stalked meadow grass (*Poa trivialis*) on N3 plots (11–1c and 11–2c). Smooth-stalked meadow grass (*Poa pratensis*) is now plentiful on all these sub-plots. Much mouse-ear chickweed (*Cerastium holosteoides*) and pignut (*Conopodium majus*) occur on sub-plots 1c and 18c and cow parsley (*Anthriscus sylvestris*) and hogweed (*Heracleum sphondylium*) on sub-plots 9c and 11–2c. Dandelions (*Taraxacum officinale*) are now present on all the recently-limed previously acid plots and occasional plants of many other broad-leaved weeds also occur. Increasing the pH to 6 on plots 9b, 11–1b and 11–2b has halved the amount of meadow foxtail but increased tall oat grass, expecially on 11–1b.

(The botanical notes above were written in 1976 by Joan Thurston who has since retired.)

The distributions in the soil of nodule bacteria 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 plots contain no nodule bacteria and liming increases numbers. On limed plots, N fertiliser has neither diminished the numbers nor altered the symbiotic effectiveness of the clover nodule bacteria.

ROTHAMSTED GARDEN CLOVER

The Garden Clover, pleasantly situated in the formal garden of the Manor House, has some claim to be the first micro-plot experiment. It is the simplest of the Classical Experiments, with (until 1956) only one plot, and that unmanured. Lawes, interested in the repeated growing of the same crop on the same land, found that red clover, however often resown on farmland, soon failed to give a useful yield. In 1854 he laid down this small plot in his garden. Yields were very large for the first 10 years averaging about 10 t dry matter ha^{-1}, probably because the soil was very rich in nutrients and because the soil-borne pests and diseases of clover were absent. Average crops 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 potassium, molybdenum, formalin, nitrogen and magnesium. N, K and Mg all increased yields, molybdenum and formalin did not. With N, P, K and Mg yields of about 6 t dry matter ha^{-1} were obtained in the year of sowing. The crop was usually severely damaged during the winter by clover-rot (*Sclerotinia trifoliorum*) and was re-sown each spring. From 1973 basal N, P, K and Mg were applied (corrective dressings were given to sub-plots which did not receive K and Mg in years of tests) and by 1975 the plot had returned to reasonable uniformity.

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

The plot now grows Hungaropoly only, with basal aldicarb, and tests benomyl applied during autumn and winter. This treatment gave almost complete winter survival and a yield in 1980 of 14·6 t dry matter ha^{-1}, the largest recorded this century.

Clover nodule bacteria and their bacteriophages are abundant. Nodule bacteria for *Vicia* are sparse and those for *Lotus* and medicks absent.

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EXHAUSTION LAND (HOOSFIELD)

This area was cropped with wheat without manure from 1850 to 1855 when it was divided into five strips for a fertiliser test with continuous wheat given treatments similar to some of those on Broadbalk. This continued till 1875; potatoes were then grown from 1876 to 1901 with the strips halved to test ten manurial treatments repeated on the plots each year. Three of these treatments were the same as applied to the same plots under wheat.

TABLE 4

Number of annual dressings applied 1856–1901 and estimated amounts of P and K applied in FYM and fertiliser

	Plot number									
	1	2	3	4	5	6	7	8	9	10
	Number of dressings									
FYM	—	6	26	26	—	—	—	—	—	—
PK	—	—	—	—	—	—	42	42	17	42
P only	—	—	7	7	—	—	—	—	25	—
N	—	—	—	6	43	43	43	43	—	—
	Nutrients applied (kg ha^{-1})									
P	0	235	1260	1260	0	0	1410	1410	1410	1410
K	0	900	3920	3920	0	0	5040	5040	1570	5040

Table 4 shows the number of annual dressings given to these plots between 1856 and 1901 and estimates of the total amounts of P and K applied in FYM and fertilisers.

The potato experiment ended in 1901, and from 1902 to 1922 the plots were cropped with cereals without any manure; the yields of grain and straw were recorded in some years to measure the residual values of the manures applied to the potatoes. After 1922 cereal yields were not taken for many years, although differences between the plots were still visible. From 1940

TABLE 5

Mean yields of barley 1949–75 and recent soil analyses

Period	N kg ha^{-1}	Variety	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}		
1949–53	63	Plumage Archer	1·6	2·9	3·0
1954–59	63	Plumage Archer	1·8	3·1	3·3
1960–63	63	Plumage Archer	2·0	2·6	3·1
1964–69	88	Maris Badger	1·7	3·6	4·3
1970–75	88	Julia	1·8	4·2	4·8
1976–79	None	Julia	0·9	1·6	2·1
	48		1·3	2·9	3·5
	96		1·4	3·0	4·0
	144		1·6	3·1	3·8
			Nutrients in air-dry soil and year of sampling		
N %		1974	0·102	0·100	0·124
P soluble in 0·5M-$NaHCO_3$, mg kg^{-1}		1951	7	21	27
		1965	6	12	18
		1974	2	8	12
K soluble in M-ammonium acetate, mg kg^{-1}		1951	74	121	106
		1965	88	122	114
		1974	69	89	87

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onwards a basal dressing of 63 kg N ha^{-1} as sulphate of ammonia was given to every barley crop. This increased the yield and accentuated the visual effects of the former manuring. From 1949 yields of barley have again been recorded. From 1964 to 1969 the variety Maris Badger was grown and given 88 kg N. Julia was introduced in 1970, also with 88 kg N and from 1976 fertiliser N has been tested at four rates (none, 48, 96, 144 kg N ha^{-1}) on sub-plots.

Table 5 shows yields and soil analysis for various periods from 1949 to 1975. Yields on plots without residues have fluctuated and new varieties there yielded no better than Plumage Archer. On plots with residues, Maris Badger and Julia, given 88 kg N or more, have yielded more than Plumage Archer, given 63 kg N. It is interesting that the difference in yield between plots with FYM residues and those with residues of PK fertilisers has been greater with the new varieties than with Plumage Archer. Plot 9, which received much less K than plots 7, 8 and 10, nevertheless gave for many years the same yield of barley, suggesting that the important effects were from P residues. During the last few years, however, yields have been about 0·5 t grain ha^{-1} less than on plots 7, 8, 10; possibly K reserves on this plot are now critically small. The plots with residues of FYM and 96 kg N ha^{-1} now yield about as much grain per hectare as the average of all barley crops in England and Wales.

Although this experiment shows the prolonged residual value of phosphate, the extra amount taken up in the crops is only a very small fraction (0·5% per annum) of the total amounts applied last century.

The above effects were measured in barley. Effects on five other crops were studied in a series of micro-plots in 1957 and 1958, when the residual effects were measured against direct additions of P and K.

MODERN EXPERIMENTS

Most of the experiments on the Farm (about 170 in all) last only one season and cannot be described in this Guide. Modern long-term experiments include:

(a) the two Ley-Arable experiments started 1949, now modified to continue studies of changes in soil organic matter due to different cropping systems, and to study the soil-borne diseases of wheat in relation to past cropping

(b) the Cultivation Weedkiller experiment started 1961, now modified to compare methods of cultivation and sowing (including direct drilling) for continuous winter barley

(c) the Reference Plots of the Soils and Plant Nutrition Department which show the responses of a range of crops grown in rotation to fertilisers and farmyard manure and provide material for chemical analysis and calculation of the nutrients removed in the crop. Additional plots have tested applications of trace elements, which usually produce no increase of yield

(d) several experiments which explore the effects of loosening the subsoil with or without the addition of P and K fertilisers below plough depth.

In addition there are several complex multidisciplinary experiments (on a fresh site each year) designed to assess the maximum yields of winter wheat and winter barley when every known limitation to yield (pests, diseases,

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drought, nutrient deficiencies) is eliminated. The factorial nature of these experiments gives measures of the loss of yield caused by omitting one or more of the inputs, some of which are admittedly uneconomic.

WOBURN

Experiments began on the farm at Woburn in Bedfordshire in 1876, under the auspices of the Royal Agricultural Society of England, and Rothamsted assumed responsibility in 1926. The farm is not owned by the Lawes Trust but is rented from the Bedford Estates. Over most of the farm the soil is a sandy loam, derived from the Lower Greensand, differing greatly from the Clay-with-flints at Rothamsted, and many of the problems in arable agriculture differ at least in degree from those on the heavier soil. Woburn still fulfils an original purpose, to duplicate experiments done at Rothamsted on a different soil type, but for many years work has also been done on problems especially important in light-land farming, such as acidity, nitrogen deficiency, poor soil structure, and small water-holding capacity. Experiments on green manuring, ley farming and organic manuring have for long been major parts of Woburn's programme; work with irrigation began there in 1951. Since 1974 substantial increases in yield of wheat, barley and sugar beet have been obtained from subsoiling alone and of potatoes, barley and sugar beet from incorporating PK fertilisers in the subsoil. Reasons for these increases are being sought.

The light soil of most of the Woburn farm is favourable to nematodes, both the free-living and cyst-forming types. Experiments, mostly long-term, are being done on potato cyst-nematode, both species of which (*Globodera* (formerly *Heterodera*) *rostochiensis* and *G. pallida*) occur at Woburn. The complex relations between the species, and how this is affected by nematicides and different varieties of potatoes, some with a degree of resistance, are being studied in long-term experiments. Other experiments deal with population dynamics and seek economic means of control by chemicals. There is evidence that potatoes at Woburn occasionally suffer appreciably from other nematodes that do not form cysts. Growth and yield experiments on winter wheat at Woburn provide a useful comparison with similar, more detailed work at Rothamsted.

Cereal cyst nematode (*H. avenae*) is also studied. Other pathogens which are more prevalent in the Woburn soil than at Rothamsted are the fungi *Verticillium* (which attacks potatoes in conjunction with cyst nematode) and *Streptomyces scabies* (common scab of potatoes) and experiments test methods of control of both.

Some fields have a heavier soil derived partly from Oxford Clay, and about half is devoted to a long-term rotation experiment on cultivation and the effect of deeply incorporated PK.

Cropping and organisation

The farm totals 76 ha, the main arable crops being barley (18 ha), wheat (20 ha) and potatoes (8 ha). It is not easy to grow suitable break crops; beans and leys suffer from drought and sugar beet clashes with potato harvest. Some beans are grown on the heavy land and more recently winter oats have been introduced. Because of potato cyst-nematode part of the area of potatoes is planted with Maris Piper or more recently Cara which is

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