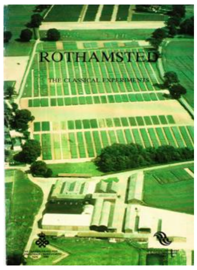
ROTHAMSTED RESEARCH

Rothamsted- the Classical Experiments



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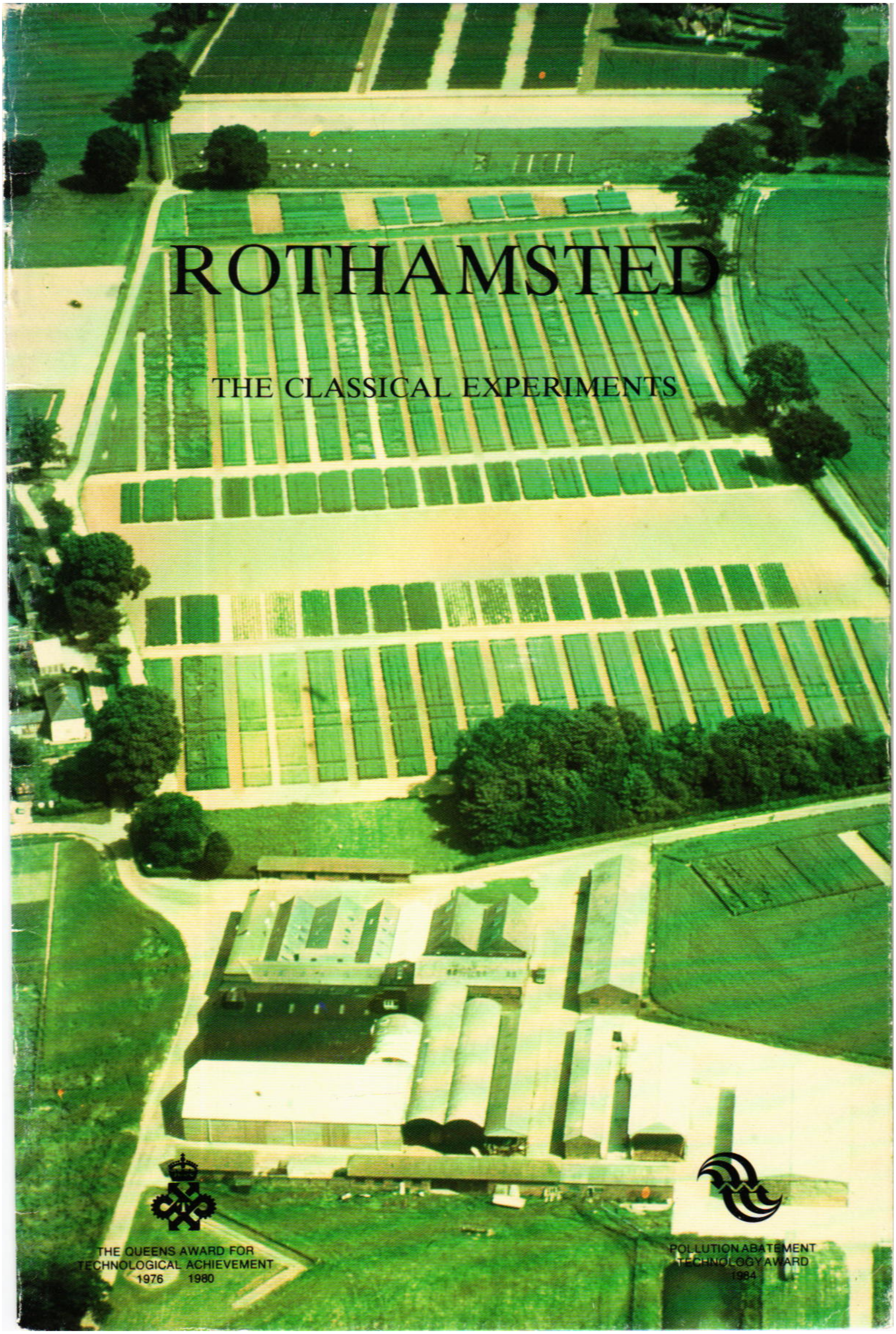
ROTHAMSTED

THE CLASSICAL EXPERIMENTS



ROTHAMSTED

EXPERIMENTAL STATION

Guide to the Classical Field Experiments

1984

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LAWES
AGRICULTURAL
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INTRODUCTION

Between 1843 and 1856 Lawes and Gilbert started nine long-term experiments, only one of which has been abandoned, in 1878. Some of the plot treatments were changed during the first few years and later further changes were made to a few plots 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 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 studied systematically. The materials used were superphosphate (at first made by mixing bones and sulphuric acid for each experiment) and the sulphates of potash, soda and magnesia (often referred to then, and in this Guide, as minerals) and ammonium salts and nitrate of soda (as alternative sources of nitrogen). Farmyard manure was also compared with inorganic fertilizers in most of the experiments. The inorganic fertilizers were tested alone and in various combinations. Nitrogen was often applied at two or more different rates.

A feature of many of the experiments was the growing of the same crop each year on the same land. This practice, considered bad farming in the nineteenth century, is now common in cereal growing and has given added interest to the experiments.

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 fertilizer applied, enabled a balance sheet for the major nutrients to be compiled for each plot. Analysis of soil samples showed how nitrogen, phosphate and potash accumulated or diminished in soil depending on fertilizer applications, offtakes in crops and losses from leaching in drainage water.

The results were of immediate importance to farmers, showing which nutrients had the largest effects on different crops. However, 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. Since 1939 with better-yielding varieties and increased use of fertilizers English farm yields exceeded those of the Classicals, until the recent modifications.

The Classical experiments have been modified occasionally since Lawes's death. 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 had been omitted from these experiments. Hall also started the first scheme of regular liming on Park Grass, the only Classical experiment not on a neutral or slightly calcareous soil. (The others were on old arable fields and had received the traditional heavy dressings of locally dug chalk,

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a practice not followed on grassland.) A new, differential, liming scheme started in 1965.

From 1957 several of the Classical experiments were modified to evaluate the residual effects of the annually repeated dressings of different combinations of nutrients. This was done for a range of crops (often several crops grown side by side on each of the original plots, as on the Exhaustion Land, Barnfield and Agdell) by subdividing the old plots to test new fertilizer treatments. These modifications, together with detailed analysis of the soil by several methods, gave much information on the value of the accumulated residues of materials applied in the past.

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

Broadbalk: Potatoes, spring beans, winter wheat.
Hoosfield 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, winter wheat

and on Hoosfield Barley the whole area has returned to continuous spring barley. The crop rotations have shown the extent to which the yields of wheat and barley can be increased when soil-borne diseases and pests are lessened by growing non-susceptible crops for two years.

Barnfield, formerly a Classical experiment with mangolds and sugar beet, has been progressively modified since 1960 and is at present in ley.

Another major change introduced in 1968 except on Park Grass was 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 Hoosfield Barley and Barnfield. Most of the applications of sodium (as sulphate or chloride) have been discontinued. On Broadbalk, Hoosfield Barley and Barnfield magnesium is now applied as kieserite (rather than Epsom salts) every third year, except for certain plots.

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BROADBALK WINTER WHEAT

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 manurial treatments compared are organic manures (farmyard manure and rape cake, later replaced by castor bean meal) and inorganic fertilizers supplying the elements N, P, K, Na and Mg in various combinations. For the first few seasons these treatments varied somewhat but in 1852 a permanent scheme was established and this has remained largely unaltered. In the early years the field was ploughed in lands by oxen (later by horses) and all the crop from each plot was separately cut with sickles and bound into sheaves to await threshing. 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 Broadbalk is 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. The wheat seed is treated with insecticide and fungicide and the growing crop is sprayed to control aphids and foliar fungus diseases.

Weeds were controlled by hand-hoeing in the past. When this became impracticable five strips ('Sections') crossing all the plots at right angles were made and bare fallowed, mainly in a 5-year rotation of fallow with four successive crops of wheat. Now chemical weedkillers are used on all Sections but one (Section 8) which has never received any.

Effective control of weeds by sprays eliminated the need for bare fallowing and the five Sections were halved. Sections 0, 1 and 9 were returned to continuous wheat in 1952, 1967 and 1959 respectively. On Sections 2, 4 and 7 the crop rotation fallow, potatoes, wheat is practised and Sections 3, 5 and 6 are again in continuous wheat after following the rotation fallow, wheat, wheat from 1968 to 1979.

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 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, sometimes written as 1·5 t ha^{-1}. At present the plot that has received neither manure nor fertilizer since 1843 yields about 1·6 t ha^{-1} after continuous wheat, 2·8 t ha^{-1} in rotation. Where nutrients are plentifully supplied by farmyard manure (FYM) or fertilizers yields now average 7 to 8 t ha^{-1}, about three times 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 140 years.

Until 1968 the best yields from fertilizers (given by plots receiving PKNaMg and at least 96 kg N ha^{-1}) were equal to those given by FYM. After the change to the shorter-strawed variety Cappelle in 1968, together with the introduction of the rotation, FYM gave about 0·5 t ha^{-1} more grain than fertilizers (see Fig. 1). In the period of 10 years in which Cappelle was grown foliar fungicides

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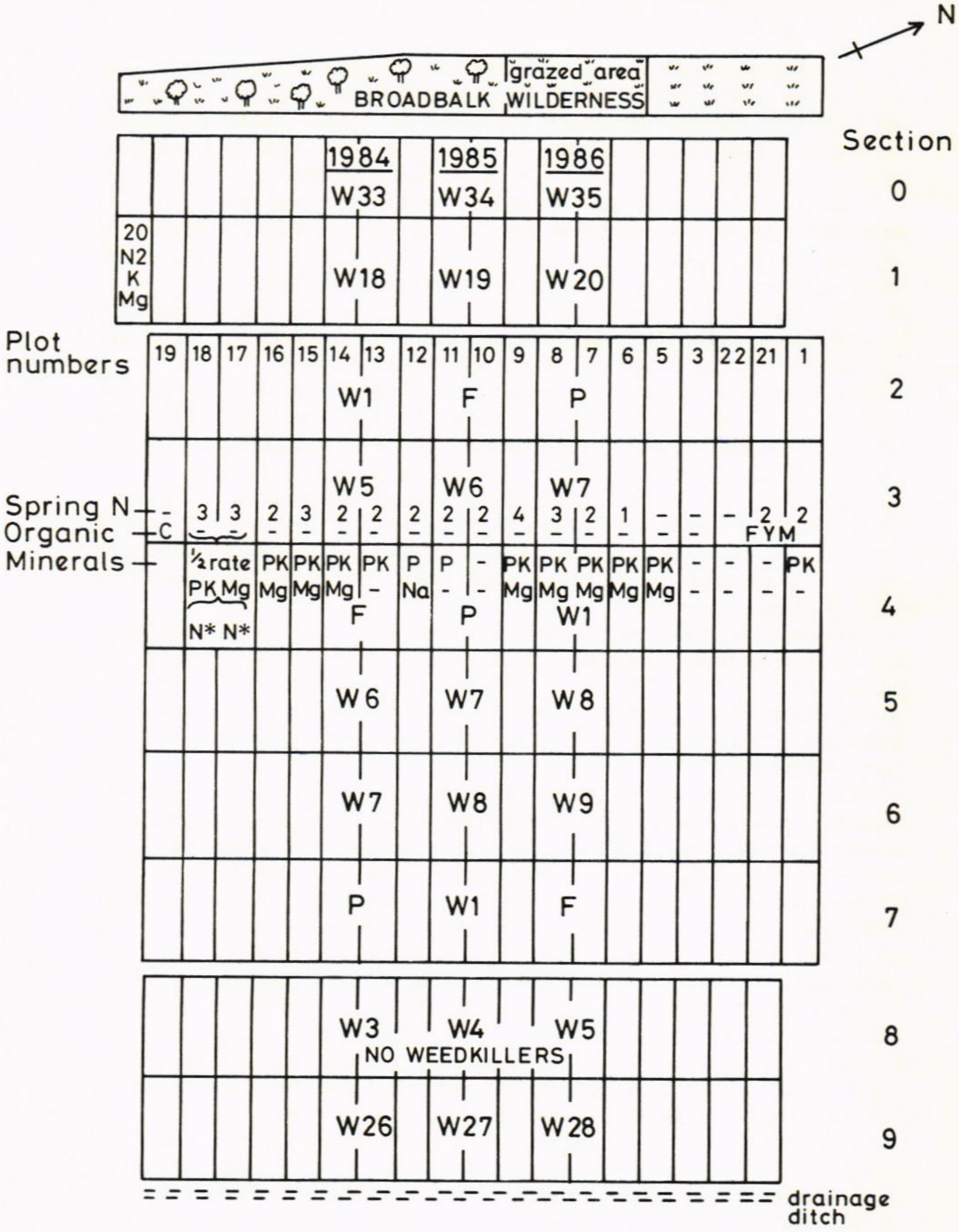
BROADBALK



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were not applied and foliar diseases, particularly mildew, were common and most severe on plots given most nitrogen. Since the introduction of Flanders in 1979 summer fungicides have been used and perhaps as a result the relative yields of FYM and fertilizers have again changed (see Fig. 1 and Table 1). Best yields from fertilizers (given by plots with minerals plus 192 kg N ha^{-1}) have exceeded those from FYM alone by 0·7 t in continuous wheat and 1·1 t in rotation. However, the plot with FYM plus fertilizer nitrogen (96 kg N ha^{-1}) now gives the greatest yield.

The increased responses to nitrogen fertilizer in this period suggest that yields might be greater on both FYM and fertilizer plots if larger rates of nitrogen were used and a proposal for this change is being considered for the period starting in 1985.

Organic matter in the Broadbalk soil

The amounts of soil organic matter can be determined only indirectly from the % carbon or % nitrogen. Percentage carbon may be multiplied by an arbitrary factor of 1·72 to give % organic matter. Most soils have a carbon to nitrogen ratio of about 10 : 1 so that % N can be converted to % C and hence to % organic matter. Accordingly % N alone can be used to show relative amounts of organic matter. On plots not receiving farmyard manure the nitrogen contents have

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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). W33: 33rd crop since last fallow.
Sections 2, 4, 7 – three-course rotation: fallow (F), potatoes (P), wheat (W1).

Dressings in autumn

All manures are applied annually to all sections except:

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

Organics (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 (1983, 1986) 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

N*	48 kg N ha^{-1} as 'Nitro-Chalk' in autumn to plots 17 and 18 in alternate seasons (to plot 17 for 1984 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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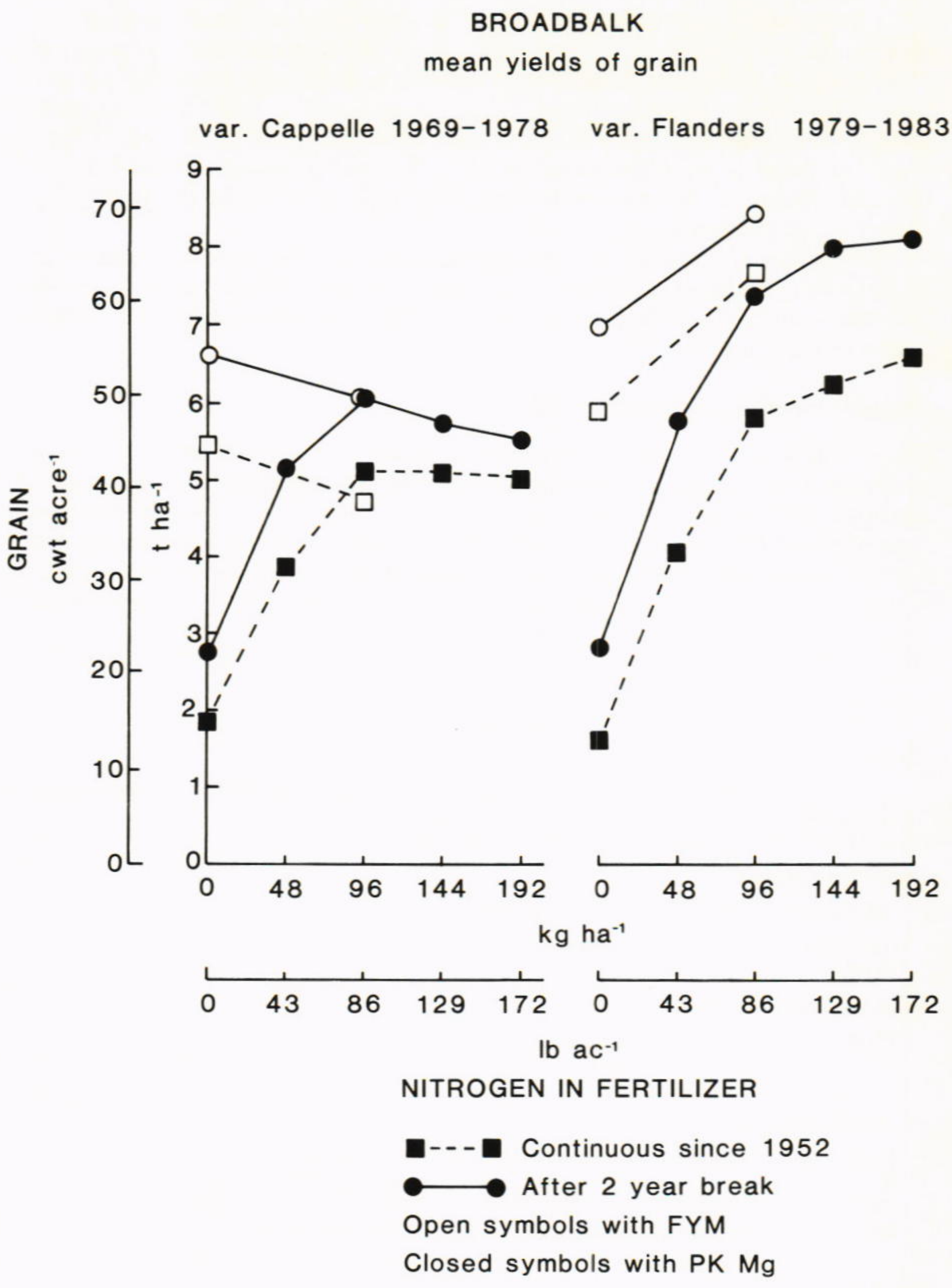

FIG. 1

remained steady for a century since they were first measured in 1865. By that date plots receiving NPK fertilizers had a little more N than the unmanured and minerals-only plots, because the better-fertilized crop gave not only more yields but more stubble, and probably roots, to be ploughed in. On the FYM plot nitrogen increased, at first rapidly, then more slowly. After a century, annual

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TABLE 1

Mean yield (5 years, 1979–83) of wheat grain and potatoes (total tubers) all in t ha^{-1}

Plot	Treatment	Wheat: After 2-year break	Wheat: Continuous since 1952	Potatoes
3	None	2·8	1·6	7·2
5	PK(Na)Mg	3·2	1·8	13·6
6	N1PK(Na)Mg	5·8	4·0	23·3
7, 16	N2PK(Na)Mg	7·1	5·7	28·6
8, 15	N3PK(Na)Mg	7·7	6·3	33·8
9	N4PK(Na)Mg	8·0	6·6	33·0
10	N2	4·9	3·3	7·4
11	N2P	6·0	4·2	11·0
13	N2PK	6·9	5·5	21·5
12	N2PNa	6·3	5·0	12·7
14	N2P(K)Mg[1]	7·2	5·8	27·0
22	FYM	6·9	5·9	30·8
21	FYM N2	8·4	7·6	37·8
1	FYM N2PK[2]	8·3	–	32·8
19	C	5·3	3·3	14·8

[1] K applied since 1968.
[2] Since 1968.
Plots 17/18 omitted, autumn N since 1980 only.

TABLE 2

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	FYM	0·175	0·236	0·251

dressings of FYM had more than doubled the amounts of nitrogen and hence organic matter (see Table 2) but only about 15% of the total N in these FYM dressings now remains in the soil.

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.

Microorganisms in the Broadbalk soil

More actinomycetes and bacteria occur in the FYM plot than in the unmanured plot or that given N2PKMg, both of which contain similar numbers. The FYM plot and the fertilizer plot, although differing greatly in organic matter, contain similar numbers of fungi and amoebae both of which are more than in the unmanured plot.

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The nitrogen-fixing bacterium *Azotobacter chroococcum* fluctuates in numbers; the average population is greatest in those plots that receive neither N fertilizer 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 annually removes from the soil on the unmanured and minerals-only plots about 30 kg N ha^{-1} but despite this the level of N in the soil has remained almost the same since the beginning of the experiment (Table 2). Each year nitrogen is added in seed (*c*. 3 kg N ha^{-1}), rain (*c*. 5 kg N ha^{-1}) and by the dry sorption of ammonia (*c*. 13 kg N ha^{-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 the unmanured plot 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

For many years weeds and weed seeds in soil were surveyed regularly until the retirement of Joan Thurston in 1980. The notes below are a modified extract of those written by her in 1976.

About 50 annual and ten perennial weed species occur in the field. Where weedkillers have never been applied each plot has its characteristic 10–20 species, and the ground is covered with weeds after harvest, except on the unmanured plot. Some species, e.g. blackgrass (*Alopecurus myosuroides*) and corn buttercup (*Ranunculus arvensis*) occur on all plots, but others are associated with manurial 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 one-year fallow having been ineffective against them. Since 1943 they have been pulled by hand which has decreased the population greatly. On Broadbalk *A. ludoviciana* (winter germinating) 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 year. The preparation of seedbeds at different times of the year for winter wheat and spring barley allows different species to survive.

Weeds in winter wheat. The use of weedkillers to kill broad-leaved weeds greatly decreased susceptible species, e.g. common vetch (*Vicia sativa*) and corn buttercup, but no species was eliminated. Black medick (*Medicago lupulina*) has decreased only slowly because the reserve of seeds in the soil is replenished by plants emerging after spraying and seeding before the stubble is ploughed. Knotgrass (*Polygonum aviculare*) and scentless mayweed (*Tripleurospermum maritimum*) were not controlled by the MCPA initially used but mixtures containing dicamba, bromoxynil or ioxynil have since been effective.

Terbutryne and later chlortoluron have been applied just after sowing and have controlled autumn-germinating blackgrass and some broad-leaved autumn-

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germinating weeds, notably ivy-leaved speedwell (*Veronica hederifolia*) which seeds before the spring spraying and so is not controlled by it but they do 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.

Weeds in potatoes. Although spring cultivation destroys weeds from autumn and winter-germinating seeds, the deep cultivations before planting potatoes 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 weedkiller (linuron-paraquat mixture) but field horsetail (*Equisetum arvense*), which emerges at the same time as the potato shoots and is resistant to these weedkillers, is not controlled. It proliferates more in potatoes than in winter wheat, except where no nitrogen is given, 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.

Pests on Broadbalk

The continuity of cropping and manurial treatments has made Broadbalk a valuable field for studying the effects of weather on the incidence of some wheat diseases and pests although this value is much less since the use of foliar fungicide and insecticide sprays became common and since regular fallowing ceased.

Insect pests. Wheat bulb fly (*Delia coarctata* Fall.) often caused severe damage to wheat after fallow 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 on Broadbalk varied greatly with season and were related to the ratio of plants to larvae, to the time of attack and to conditions for plant growth. Plants on plots deficient in potassium usually suffered most because they were less well tillered and damage to the primary shoot often killed the whole plant. The damage was minimized by sowing wheat early.

Other insect pests, cereal aphids, cutworms, wheat-blossom midges and the saddle-gall midge caused damage only sporadically. Since the introduction of potatoes to the rotation, potato aphids occasionally cause concern.

Broadbalk drains

In 1849 a tile drain was laid down the centre of each of the plots. The tiles, of the 'horsehoe 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 took 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 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 data provided important information on the losses of plant nutrients by leaching. Although ammonium, potassium, magnesium and sodium salts were all added to the soil the biggest loss was of calcium and its loss increased with increasing amounts of ammonium salts given. 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.

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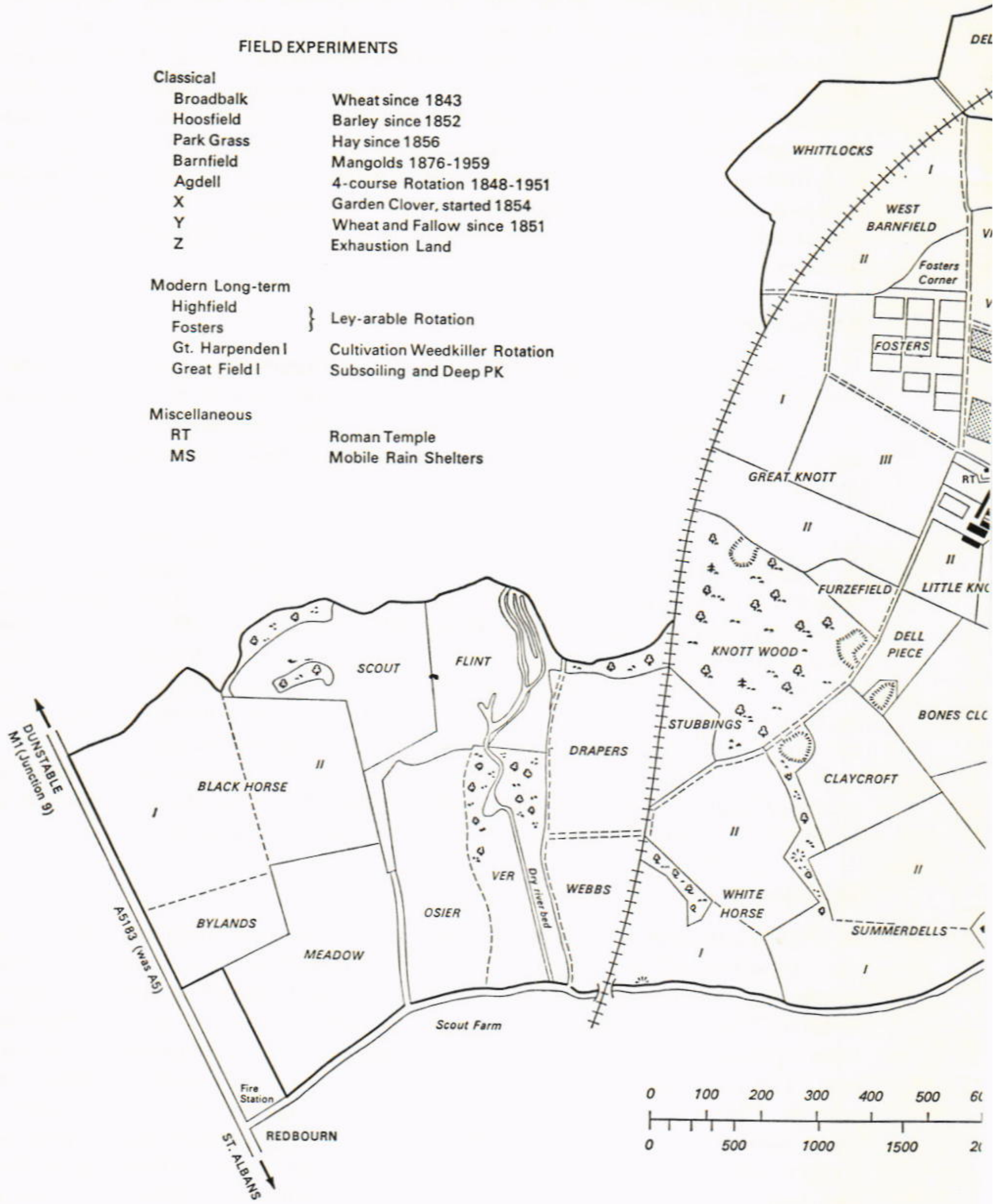
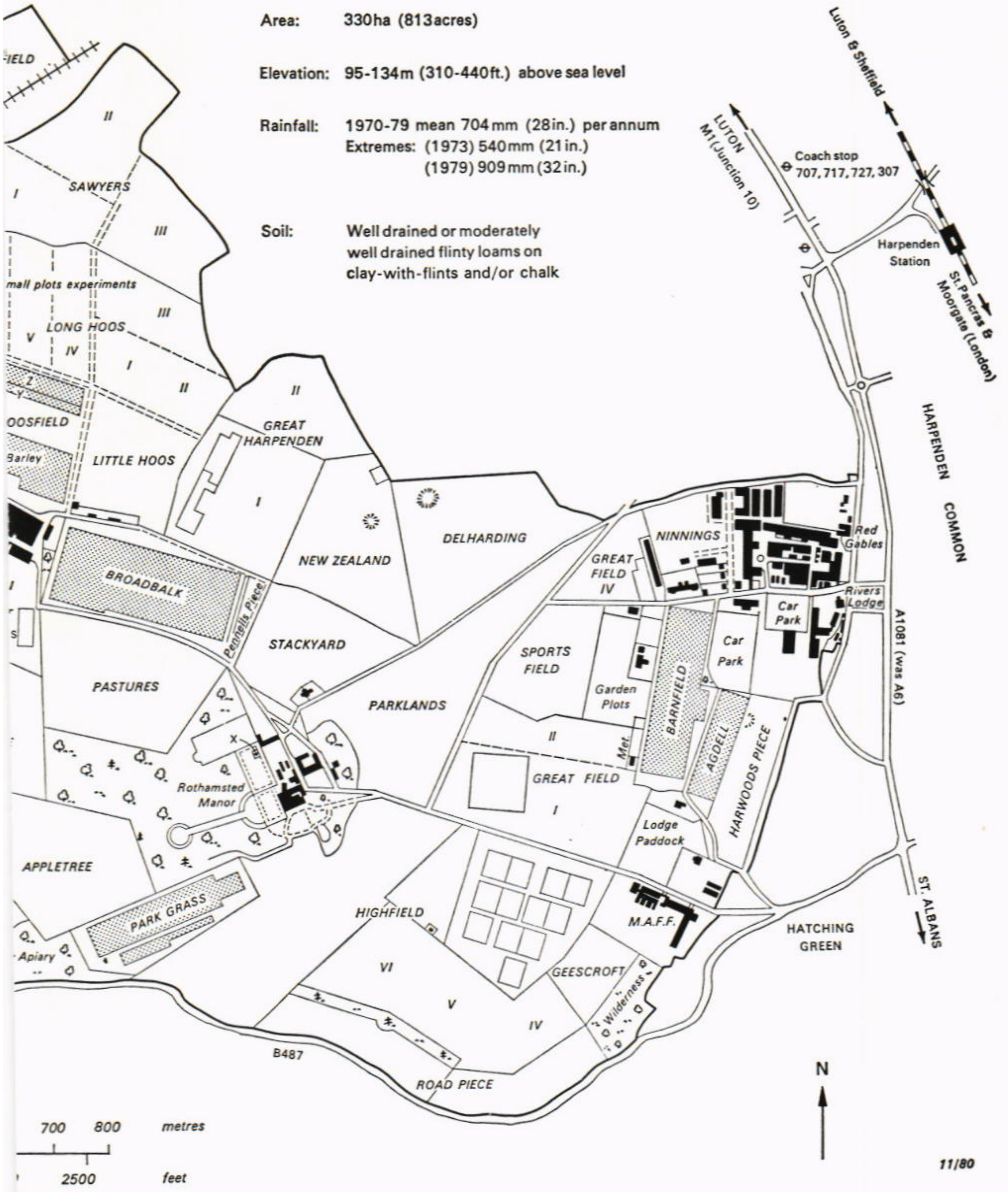
ROTHAMSTED EXPERIMENTAL STATION




Area: 330ha (813acres)
Elevation: 95-134m (310-440ft.) above sea level
Rainfall: 1970-79 mean 704mm (28in.) per annum
Extremes: (1973) 540mm (21in.)
(1979) 909mm (32in.)
Soil: Well drained or moderately well drained flinty loams on clay-with-flints and/or chalk
Luton & Sheffield
LUTON
M1 (Junction 10)
Coach stop
707, 717, 727, 307
Harpenden Station
St. Pancras & Moorgate (London)
HARPENDEN COMMON
A1081 (was A6)
ST. ALBANS
HATCHING GREEN
SAWYERS
mall plots experiments
LONG HOOS
OOSFIELD
Barley
LITTLE HOOS
GREAT HARPENDEN
NEW ZEALAND
DELHARDING
BROADBALK
Pennells Piece
STACKYARD
PASTURES
PARKLANDS
NINNINGS
GREAT FIELD IV
Red Gables
Rivers Lodge
Car Park
SPORTS FIELD
Garden Plots
BARNFIELD
AGDELL
HARWOODS PIECE
Met.
GREAT FIELD
Rothamsted Manor
Lodge Paddock
APPLETREE
PARK GRASS
HIGHFIELD
M.A.F.F.
GEESCROFT
Wilderness
Apiary
B487
ROAD PIECE
700 800 metres
2500 feet
N
11/80

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. It was on this field that, in 1935, eyespot (*Pseudocercosporella herpotrichoides*) was first identified in this country. Comparisons of yields and of differences in amounts of take-all (*Gaeumannomyces graminis* var. *tritici*) between continuous wheat on Broadbalk and other fields in shorter sequences of cereals over a period of years culminated in D. B. Slope and Judith Cox developing the hypothesis of 'take-all decline'. Severe symptoms of take-all are often seen in short sequences but seldom in the continuous wheat and the latter generally gives only about 1 t ha^{-1} less yield than wheat in rotation. This decline of take-all, although still inadequately understood, has since been shown to be common when cereals are grown continuously. 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.

Recent projects that used Broadbalk material included:

(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 fertilizer 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 present farm buildings, left unharvested and the land not cultivated. The wheat was left to compete with the weeds, and after only four years the few plants surviving were stunted and barely recognizable as cultivated wheat. One half of the area has remained 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.

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

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In 1957 this 'grubbed' section was divided into two parts, that farther from the woodland area has continued to be grubbed each year. The other part was mown several times during each of the next three growing seasons 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 sheep were put in to graze. 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 were absent from the grubbed section of the Wilderness until recently and the nitrogen gains (equivalent to 49 kg N ha^{-1} year^{-1}) appear to have come from rain, bird droppings, dry sorption of ammonia (13 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 ALTERNATE WINTER WHEAT AND FALLOW

From 1856 to 1932 this area, which has been completely without manures since 1851, was divided into two strips which alternated wheat and fallow in successive years. From 1932 to 1982 a modification allowed a yearly comparison of a one-year and a three-year fallow but the effects were fairly small (Table 3) and since 1983 the experiment has reverted to the original design.

TABLE 3

Hoosfield Wheat after fallow (mean yields of grain, t ha^{-1})

	Hoosfield wheat Years of fallow		Broadbalk wheat Unmanured continuous
	1	3	
1856–65	1·8	–	1·2
1973–82	1·5	2·0	1·6

The variety of wheat has always 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 (Table 3). In the first 10 years of the experiment the one-year fallow gave an extra 0·6 t ha^{-1}. Unlike Broadbalk the yield on Hoosfield has declined during the experiment and from 1973 to 1982 the yield after one-year fallow equalled that of the continuous wheat.

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HOOSFIELD SPRING BARLEY

Spring barley has been grown continuously here since 1852. The experiment offers interesting contrasts to that on Broadbalk, being spring-sown, having been fallowed only four times to control weeds and testing not only nitrogen, minerals and FYM but also silicate of soda.

In 1968 a crop rotation of potatoes, beans and barley on small areas of some plots and a four-level N test on all plots were introduced. The effects of the two-year break on the yield of barley were small and the whole experiment has again grown continuous barley since 1979.

The design of the experiment is of a factorial nature with east-west strips (see plan) having the four combinations of:

(1) 0 *vs* P and
(2) 0 *vs* KMg

and north-south strips, which cross these, originally testing forms of nitrogen, all applied at the same rate of N:

(3) 0 *vs* sulphate of ammonia *vs* nitrate of soda *vs* rape cake (later castor meal)

The nitrate of soda strip is divided for a test of 0 *vs* silicate of soda.

Additional plots at the south side test FYM, since the experiment started, and residues of FYM applied 1852–71.

Hoosfield (see plan on opposite page)

Cropping

Continuous barley

Nitrogen dressing in spring

N1, 2, 3	'Nitro-Chalk' supplying 48, 96, 144 kg N ha^{-1} (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 1984; they change cyclically, every year in order N3 following N– following N1 following N2.

Organic (applied before ploughing in autumn)

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

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 $acre^{-1}$) discontinued to Series C since 1980
K	90 kg K ha^{-1} as sulphate of potash (50% K_2O) (0·9 cwt K_20 $acre^{-1}$) discontinued to Series C since 1980
S	450 kg ha^{-1} silicate of soda since 1980, (S) each year until 1979

Applied every 3rd year (1983, 1986 etc.)

Mg	35 kg Mg ha^{-1} as kieserite (15% Mg)

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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HOOSFIELD

Spring Barley since 1852

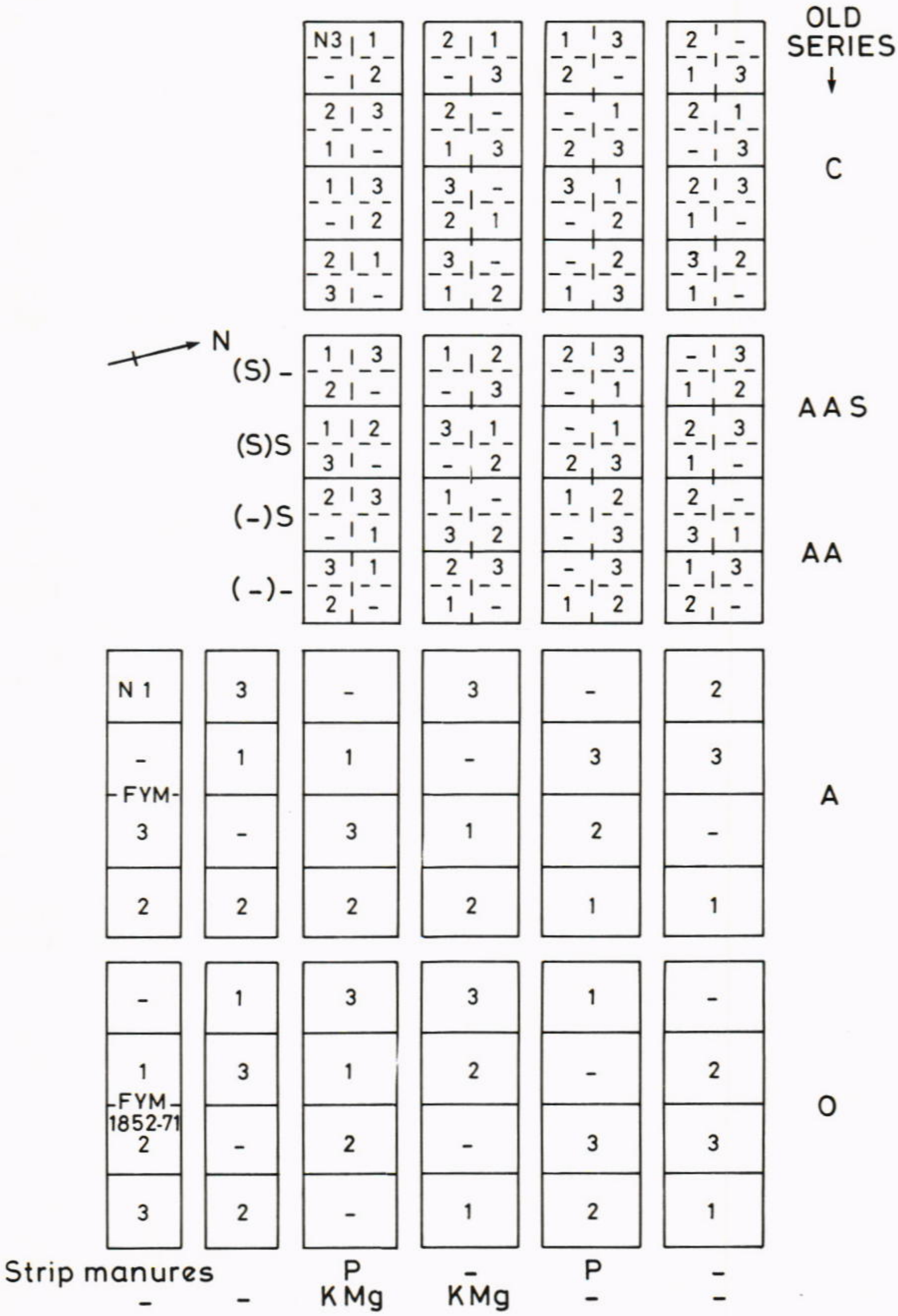

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TABLE 4

Mean yield (4 years, 1980–83) of Georgie spring barley grain t ha^{-1}

	Continuous barley since fallow in 1967			
	N0	N1	N2	N3
–	0·8	1·2	1·5	1·6
P	1·9	3·0	3·0	2·5
K	1·0	1·6	2·0	2·1
PK	1·7	3·6	4·5	5·1
FYM	5·0	5·6	5·3	5·8

	After continuous barley 1968–79		After barley in rotation 1968–79	
	–	(S)–	(–)S	(S)S
N3–	1·5	3·2	3·3	3·8
N3P	3·6	4·5	5·2	5·3
N3K	2·3	4·3	4·0	4·6
N3PK	5·3	6·0	5·6	5·6

Forms of nitrogen have not been tested since 1967, PKMg applications on the old rape cake series were discontinued after 1979 and the silicate of soda test was modified in 1980 to include the four combinations of:

(1) 0 *vs* silicate from 1980
(2) 0 *vs* silicate 1862–1979

Recent yields (Table 4) continue to show the great importance of P to spring-sown barley as well as large positive interactions between N, P and K. Although the yields from complete fertilizers match the yields from FYM alone, the largest yields, as on Broadbalk, come from the combination of FYM and nitrogen fertilizer. The residual effect of silicate of soda applied until 1979 more than doubled the yield of plots given nitrogen alone and even when P is supplied the effect is considerable. Fresh or continued dressings of silicate since 1979 appear also to be beneficial but at present these effects are uncertain because of differences in the continuity of barley cropping.

EXHAUSTION LAND SPRING BARLEY

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

Table 5 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 fertilizers.

The potato experiment ended in 1901 and with few exceptions cereals have been grown each year since then. From 1902 to 1939 no manures were given; yields of grain and straw recorded in some of the earlier years measured the residual values of the manures applied to the potatoes. From 1940 fertilizer

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TABLE 5

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

	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 6

Mean yields of barley 1949–83 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 fertilizers 1856–1901	Plots 3, 4 residues of FYM 1876–1901
			Mean yields of grain, t ha^{-1}		
1949–63	63	Plumage Archer	1·8	2·9	3·2
1964–69	88	Maris Badger	1·7	3·6	4·3
1970–75	88	Julia	1·8	4·2	4·8
1976–79	0	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
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
			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
		1981	2	6	10
K soluble in M-ammonium acetate, mg kg^{-1}		1951	74	121	106
		1965	88	122	114
		1974	69	89	87
		1981	66	85	81

nitrogen has been given each year; this increased yields, which have been recorded since 1949, and accentuated the visual effects of the former manuring. From 1976 fertilizer N has been tested at four rates (0, 48, 96, 144 kg N ha^{-1}) on sub-plots.

Table 6 shows N rates, varieties and yields from 1949–83 and some soil analyses during this period. The introduction of new varieties from 1964 to

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1975, together with an increase in nitrogen rate considerably increased yields on plots with residues but gave no improvement on plots without. Since then, despite the inclusion of larger nitrogen rates and probably as a result of continued depletion of P and K, yields have generally declined on all plots. The decline has been less on plots with FYM residues, supporting the view that the prolonged residual effects in this experiment are primarily those of P.

During the 40 years, 1901–40, when no N was applied, crops made little use of the P and K residues in the soil. However, these residues must have remained in available forms because for the next 40 years they increased yields to twice those on unmanured plots and these larger yields equalled the national average for spring barley.

PARK GRASS

The Park Grass experiment, laid down in 1856, is much the oldest on grassland in Great Britain. The field had been in grass for at least a century when the experiment began. It demonstrates in a unique way how continued manuring with different fertilizers affects both the botanical composition and the yield of a mixed population of grasses, clovers and weeds. After more than 100 years, the boundaries of the plots are still clearly defined; 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 their weight increases recorded but from 1873 the second cut has been weighed and carted green. Since 1960 yields, corrected to dry matter, have been calculated from the weights of produce from sample strips cut with a forage harvester (two per plot). At the first cutting the produce of the remainder of each plot is made into hay; this allows the return of

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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}

Organics (each applied every fourth year)

FYM 35 t ha^{-1} farmyard manure (bullocks) (1985, 1989) (14 tons acre^{-1})

Fish meal (about 6·5% N) to supply 63 kg N ha^{-1} (1983, 1987) (about 950 kg ha^{-1} meal or 850 lb acre^{-1})

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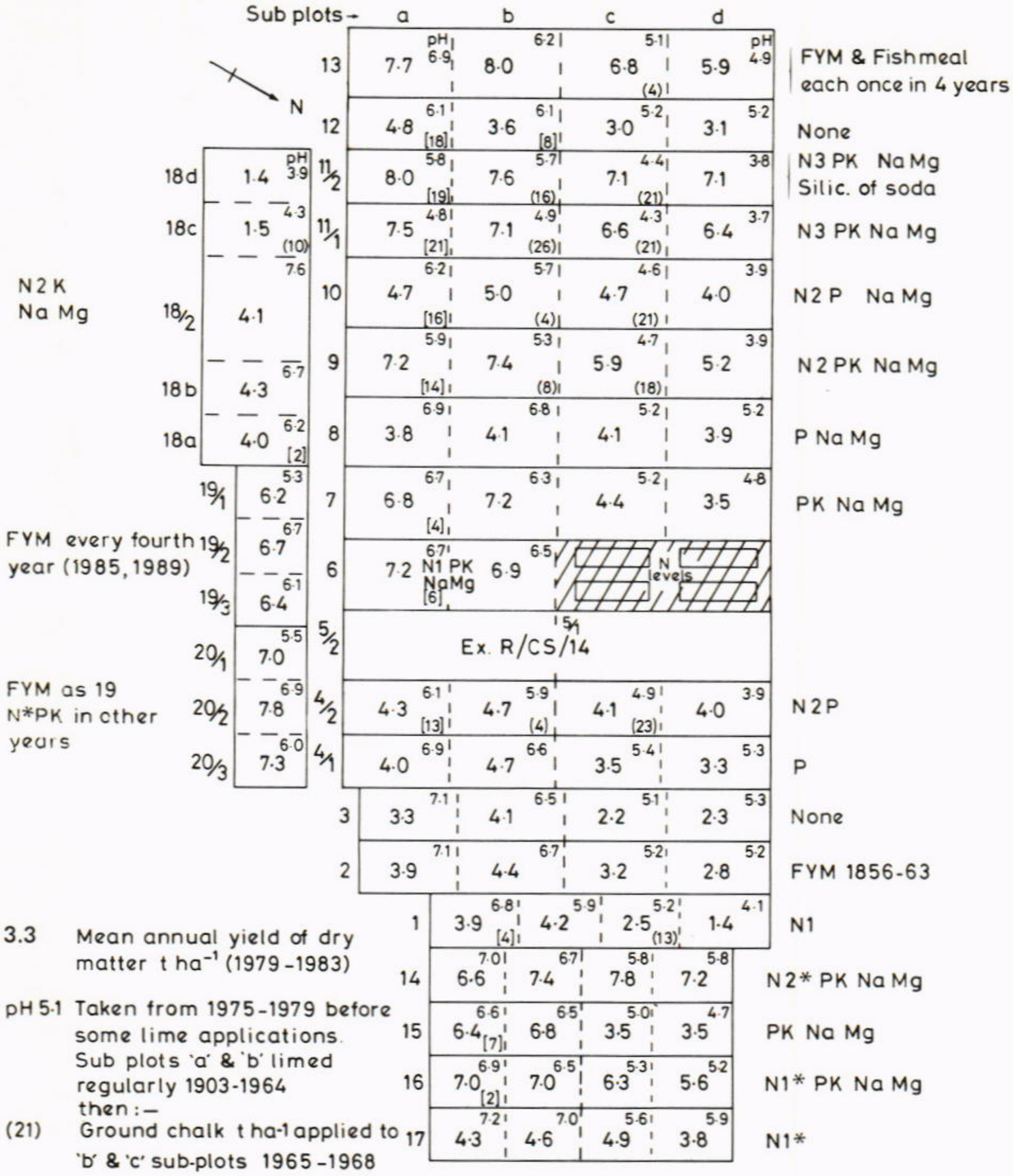
PARK GRASS

Hay since 1856



3.3 Mean annual yield of dry matter t ha^{-1} (1979 – 1983)

pH 5.1 Taken from 1975-1979 before some lime applications. Sub plots 'a' & 'b' limed regularly 1903-1964 then :–

(21) Ground chalk t ha-1 applied to 'b' & 'c' sub-plots 1965 – 1968

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

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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 caused a gradual deterioration in the species composition, although not the yield, of the sward. Lawes recognized this and made two tests of lime in 1883 and 1887, but these were without immediate effect. Regular liming was not begun until 1903. Then, and every fourth year until 1964, lime (originally burnt lime, more recently calcium carbonate) was applied to the southern halves of most of the plots (see plan). Except for plots 18, 19 and 20, a fixed amount was applied on each occasion. From 1965 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 used for 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, about 60 species, with many red clover plants and broad-leaved weeds, but none grows vigorously, and yields are small. These swards are probably the nearest approximation to the state of the whole field in 1856. Lime alone or P alone (Plot 4/1) has little effect. Giving PKNaMg (Plot 7) produces 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. Omitting K and giving PNaMg (Plot 8) results in much less meadow vetchling, and on this plot lime depresses yields.

With nitrogen, either as sulphate of ammonia or as nitrate of soda, yields are above average except on some of the unlimed ends. Plots 11/1 and 11/2 show the extreme effects of sulphate of ammonia. The unlimed ends are dominated by Yorkshire fog (*Holcus lanatus*) and the mineral soil is covered by a peaty layer of only partly decomposed plant residues; earthworms are absent. The limed ends have tall coarse species, false oat (*Arrhenatherum avenaceum*) and meadow foxtail (*Alopecurus pratensis*), which makes a poor hay, although yielding well. Nitrate of soda (Plots 14, 16, 17) supplies nitrogen without acidifying the soil; lime has little effect on these plots. The organic manures are applied on a four-year cycle of farmyard manure, none, fish meal, none to Plot 13 which has a well-mixed herbage, but yield is much less than from the best fertilizer treatments.

The most interesting feature of the experiment 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 and is now well established on sub-plots 1c and 9c. Fescues (*Festuca* spp.) have increased on plots given 48 and 96 kg N ha^{-1} with incomplete minerals (sub-plots 1c, 4/2c, 10c and 18c); tall oat grass (*Arrhenatherum elatius*) and cocksfoot (*Dactylis glomerata*) are now common on plots receiving 96 and 144 kg N ha^{-1} and complete minerals (sub-plots 9c, 11/1c and 11/2c) and also meadow foxtail and rough-stalked meadow grass (*Poa trivialis*) on 144 kg N plots (sub-plots 11/1c and 11/2c). Smooth-stalked meadow grass (*Poa pratensis*) is now plentiful on all these. 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

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previously acid plots and occasional plants of many other broad-leaved weeds also occur. Increasing the pH to 6 on sub-plots 9b, 11/1b and 11/2b has halved the amount of meadow foxtail but increased tall oat grass, especially 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 (*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 and liming increases numbers. On limed sub-plots, N fertilizer has neither diminished the numbers nor altered the symbiotic effectiveness of the clover nodule bacteria.

BARNFIELD

Although less well-known than the other Classicals this was the first, having treatments applied in spring 1843 for a crop of turnips several months before the start of Broadbalk. However, the treatments and the cropping, although mainly roots, varied until 1876 when a period of continuous cropping with mangolds was started which lasted until 1959 (sugar beet were also grown from 1946).

As on Hoosfield Barley the treatments were applied in strips crossing at right angles. North–south strips tested minerals and FYM, including a test of FYM + PK, and these were crossed by strips comparing no nitrogen fertilizer with forms of nitrogen supplying 96 kg N ha^{-1}. Before 1968 this was the only Classical in which N was applied with both FYM and FYM + PK fertilizer.

Because yields of the continuous roots were declining, perhaps because of increasing amounts of cyst nematodes (*Heterodera schachtii*), the cropping has been progressively modified since 1959 and has included a range of arable crops with an increased range of N dressings and grass. Since 1977 the strip which had never received nitrogen fertilizer has been kept in fallow and since 1975 the remainder has been in grass.

A feature of the continuous roots and of recent arable crops has been the superiority of yields from plots given FYM even when a wide range of N dressings has been tested with the minerals. This may be because the extra organic matter has improved soil structure with greater effect on this field which is one of the most difficult to cultivate well. Yields of grass have also been larger on FYM-treated soils although FYM has not been applied since sowing the grass. This may be because more of the N applied to grass on fertilizer-treated soils is being used to increase soil organic matter. Accordingly a range of nitrogen dressings (75, 100, 125, 150 kg N per cut) has been tested on the grass since 1983.

AGDELL

This was the only Classical in which crops were grown in rotation. From 1848 to 1951 three different manurial combinations (none, PKNaMg and NPKNaMg plus rape cake/castor meal) were applied to the root crops of two four-course rotations. The rotations differed only in their third course – roots, barley, fallow or legume, wheat. There were only six plots and only one course of the rotation was present each year. The roots were turnips or swedes, the legume

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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 acidity. By 1948 the produce was too small to weigh and the four-course rotation ceased in 1951. The soil acidity was subsequently corrected.

The six plots have since been divided, initially on one half grass was grown, on the other a range of arable crops. Both tested the value of the P and K residues accumulated during the rotations. For the arable crop the residues were evaluated in terms of fresh dressings which were applied to sub-plots.

Later, wide ranges of soil P and K were established, on both the grass and arable half plots, by further fresh dressings. The grass plots were then ploughed so that all amounts of soil P and K were present on soils with two amounts of organic matter. Arable crops have subsequently been grown to establish the relationship between yields, soil P and K and the response to fresh P and K for each amount in the soil. These tests are continuing, in winter wheat in 1984.

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 resown 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 mean yield in 1980–82 of 16·6 t dry matter ha^{-1}, the largest yields in the history of the experiment.

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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PUBLICATIONS

The following are available from the Librarian:

Report, Rothamsted Experimental Station From 1909 (annual, some are out of print). Prices upon application.

Yields of the Field Experiments Formerly called 'Numerical Results' ... or 'Results' ... published annually 1948 onwards. Prices upon application.

Details of the Classical and Long-term Experiments up to 1973 Two books '... up to 1967' and supplementary volume '... up to 1973'. Price £1 each, sold separately.

Botanical Composition of the Park Grass Plots at Rothamsted 1856–1976 Price £1.

The Broadbalk Wheat Experiment Up to 1968. Price £1.

The Manor of Rothamsted Price £1.

The following are available from the Field Experiments Section:

SLIDE SETS

Rothamsted

A general slide set showing Broadbalk, Park Grass, the Main Building and the Manor House. 4 slides (2 × 2) with notes. Colour. £1 per set.

The Park Grass Experiment

The effects of fertilizers, organic manures and lime on the botanical composition of permanent grassland and on the yield of hay. (Miss J. M. Thurston, E. D. Williams and G. V. Dyke.) 34 slides (2 × 2) with notes. Colour. £10 per set.

CONVERSION FACTORS

Conversion Factors

1 metric ton or tonne (t)	= 1000 kilograms (kg) = 0·984 ton
1 hectare (ha)	= 10 000 square metres = 2·47 acres
1 tonne hectare^{-1} (t ha^{-1})	= 0·398 tons acre^{-1}
	= 7·97 cwt acre^{-1}
	= 892 lb acre^{-1}

Nutrients

To convert	Multiply by
P_2O_5 to P	0·436
K_2O to K	0·830

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