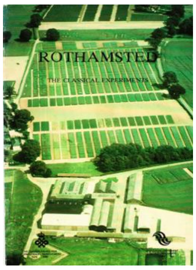
Rothamsted- the Classical Experiments



Full Table of Content

Broadbalk Winter Wheat

Rothamsted Research

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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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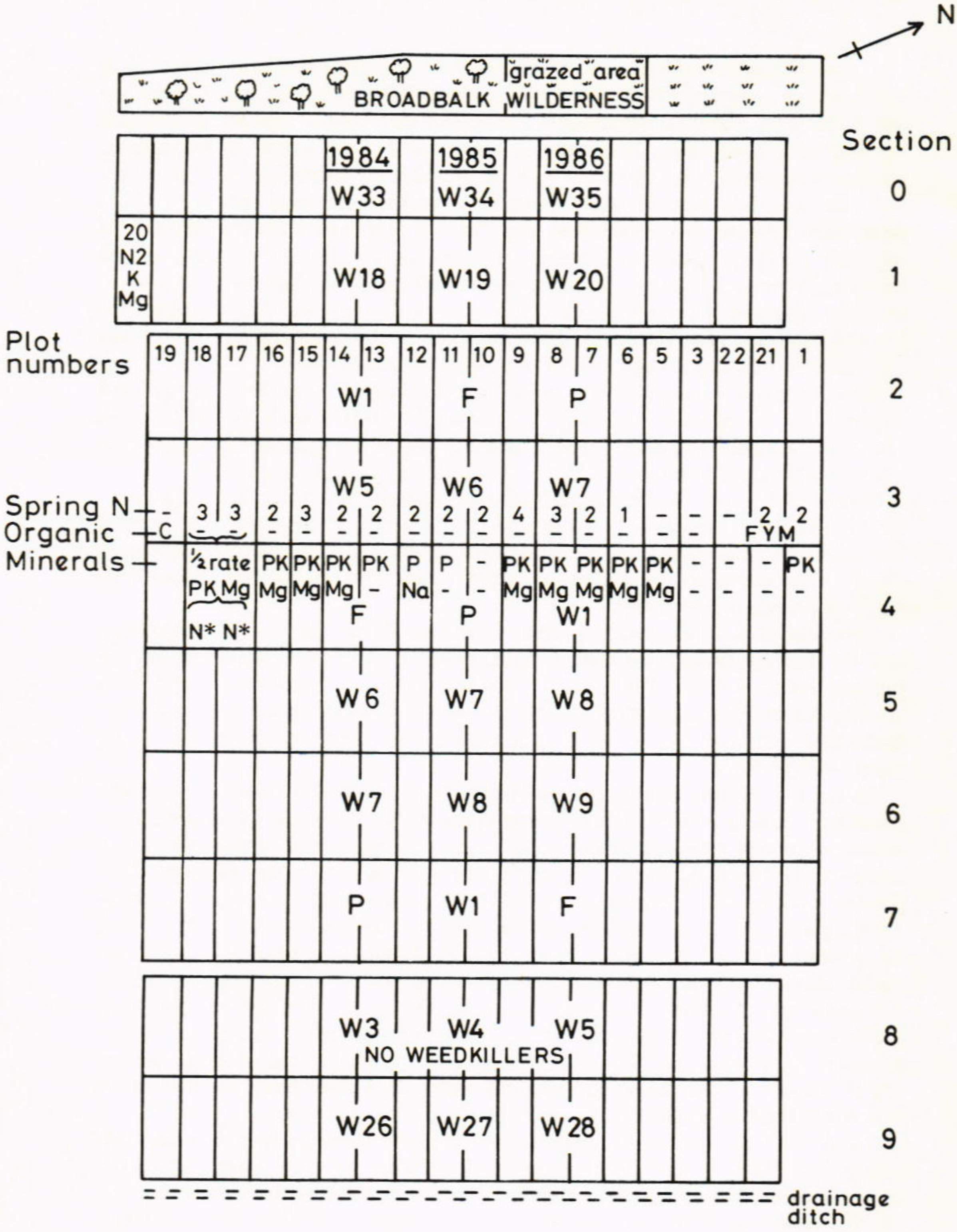
BROADBALK


N
grazed area
BROADBALK WILDERNESS
Section
0
1
2
3
4
5
6
7
8
9
1984
W33
1985
W34
1986
W35
20 N2 K Mg
W18
W19
W20
Plot numbers
19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 3 22 21 1
W1
F
P
W5
W6
W7
Spring N
Organic
Minerals
C
FYM
½ rate PK Mg
N* N*
PK Mg
PK
P Na
P
W1
W6
W7
W8
W9
W3
W4
W5
NO WEEDKILLERS
W26
W27
W28
drainage ditch

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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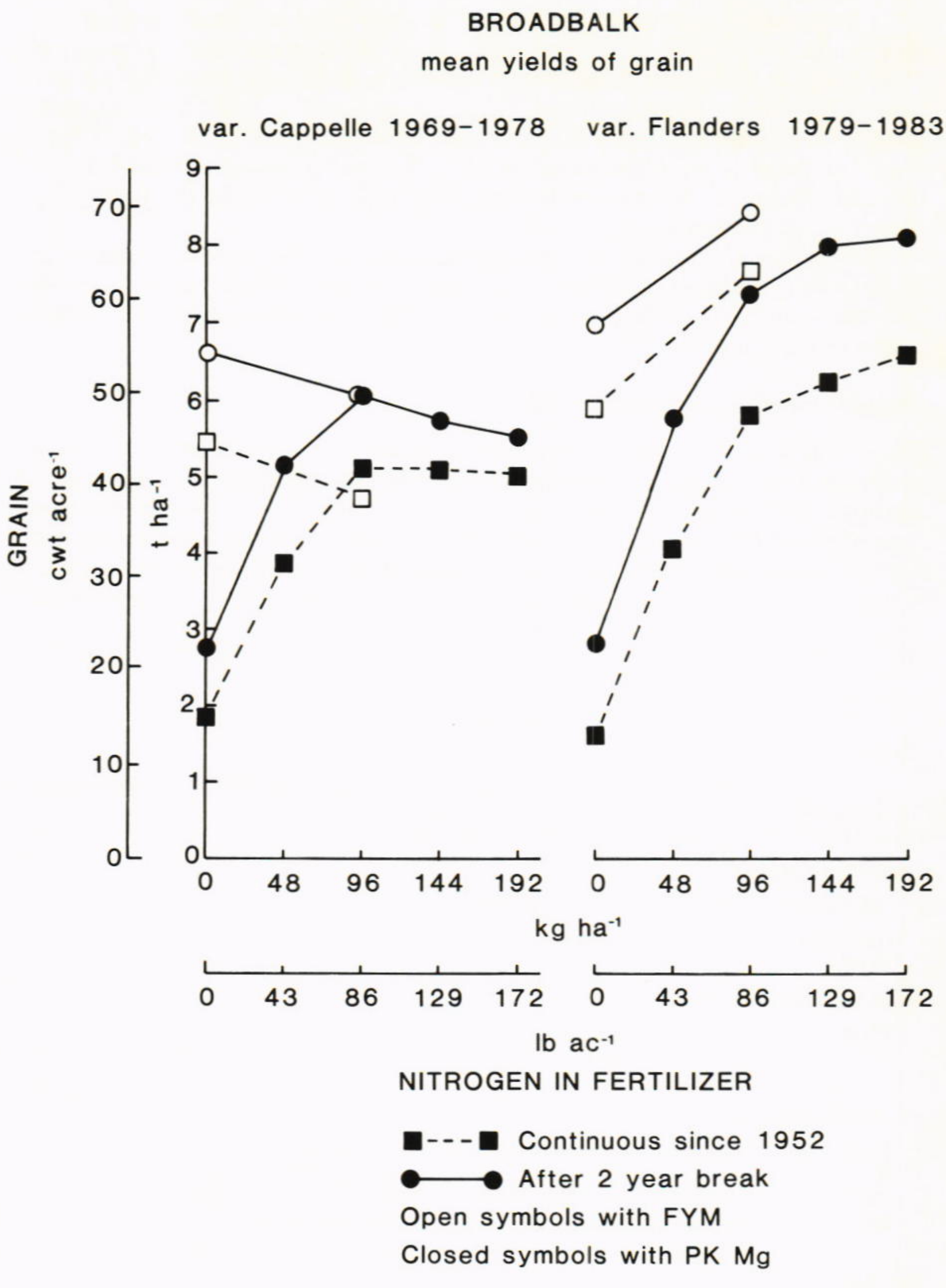

FIG. 1

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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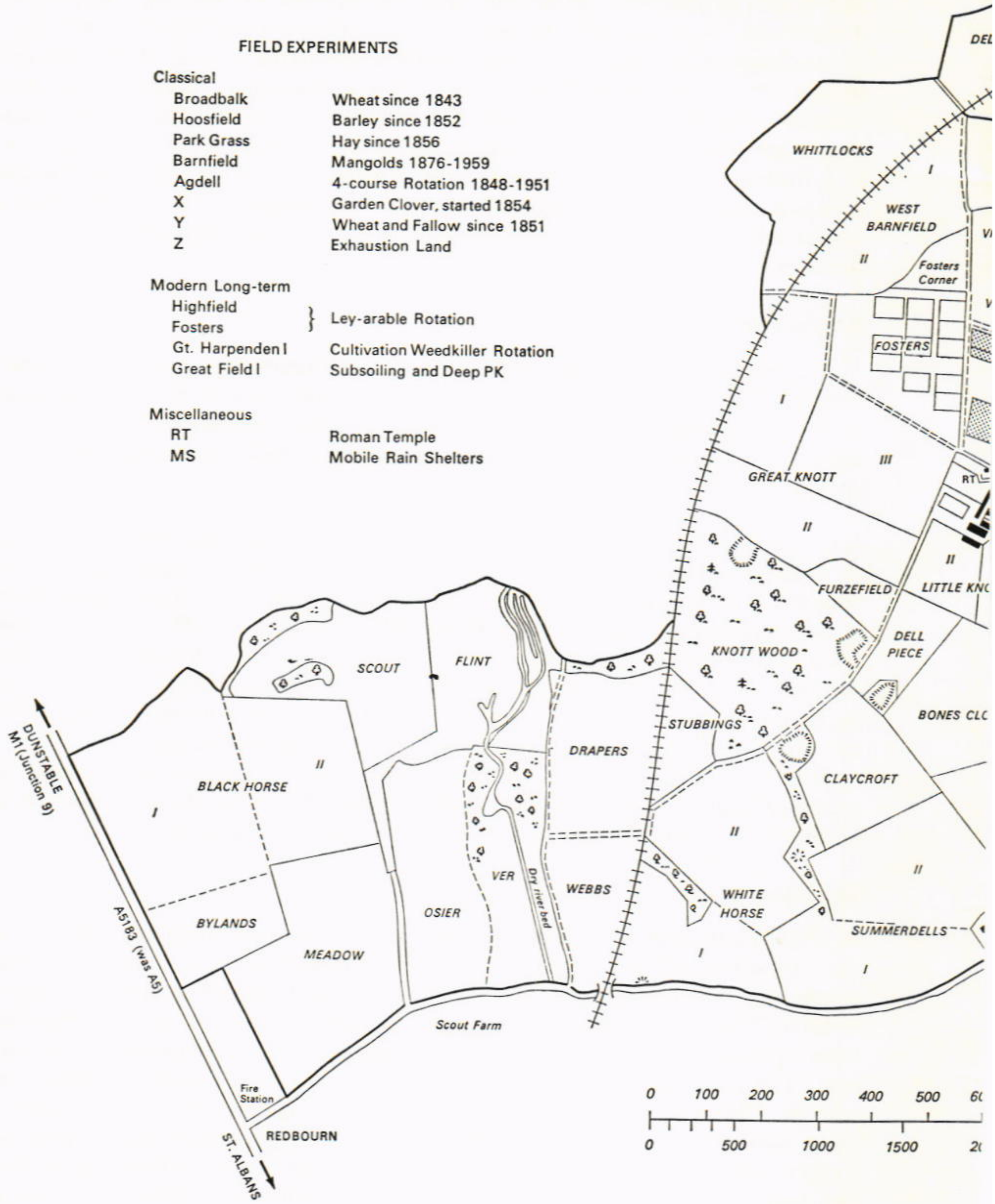
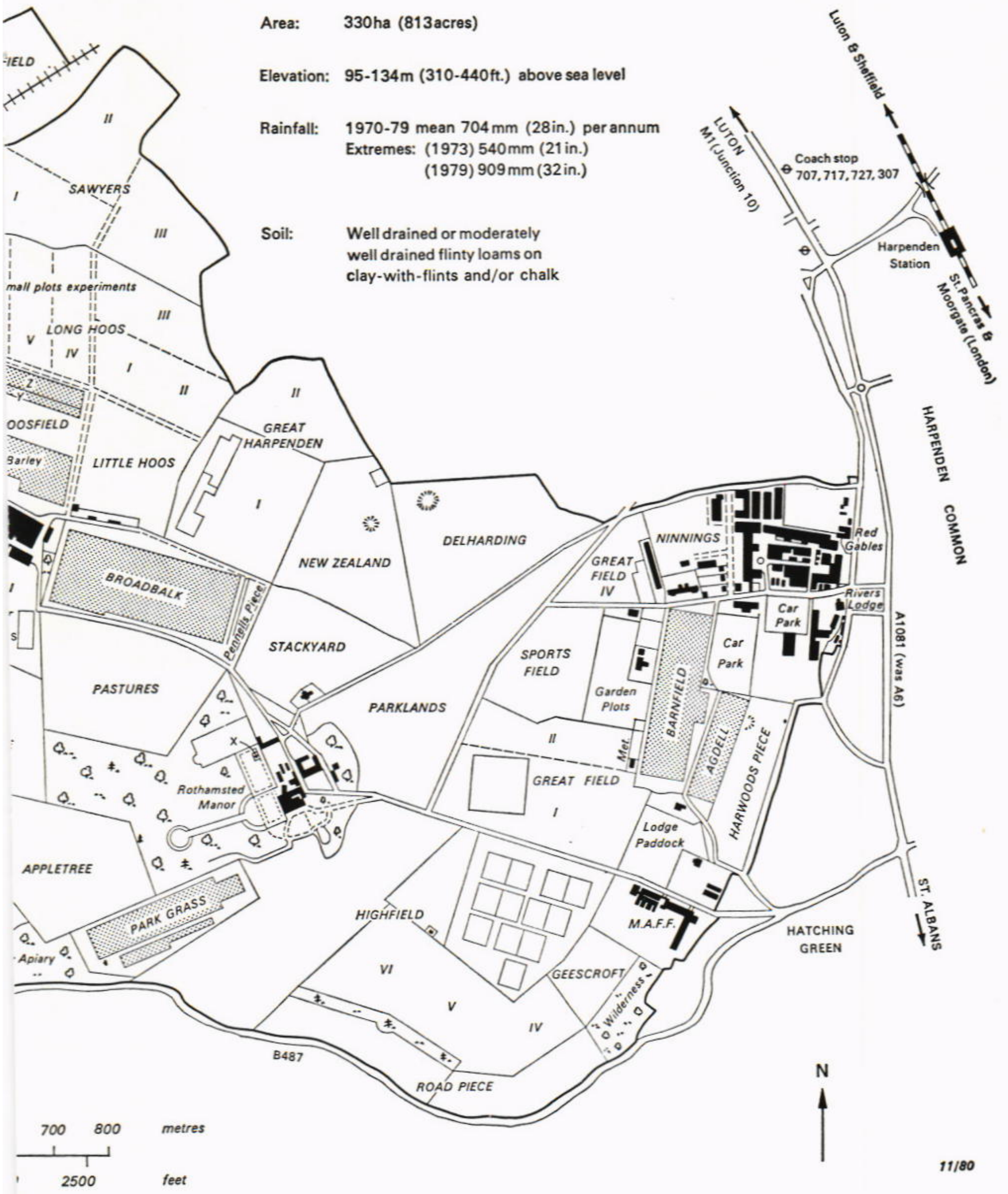
ROTHAMSTED EXPERIMENTAL STATION




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
Small plots experiments
LONG HOOS
HOOSFIELD
Barley
LITTLE HOOS
GREAT HARPENDEN
BROADBALK
NEW ZEALAND
DELHARDING
NINNINGS
GREAT FIELD IV
Red Gables
Rivers Lodge
Car Park
Car Park
Pennells Piece
STACKYARD
PASTURES
PARKLANDS
SPORTS FIELD
Garden Plots
BARNFIELD
AGDELL
HARWOODS PIECE
Met.
GREAT FIELD
Rothamsted Manor
Lodge Paddock
APPLETREE
PARK GRASS
HIGHFIELD
M.A.F.F.
Apiary
GEESCROFT
Wilderness
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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