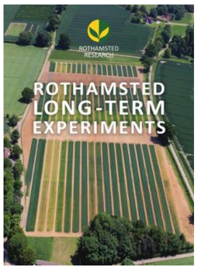
ROTHAMSTED RESEARCH

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



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The Classical Experiments

Rothamsted Research

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THE CLASSICAL EXPERIMENTS

Broadbalk Winter Wheat

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

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

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

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

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

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

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Broadbalk

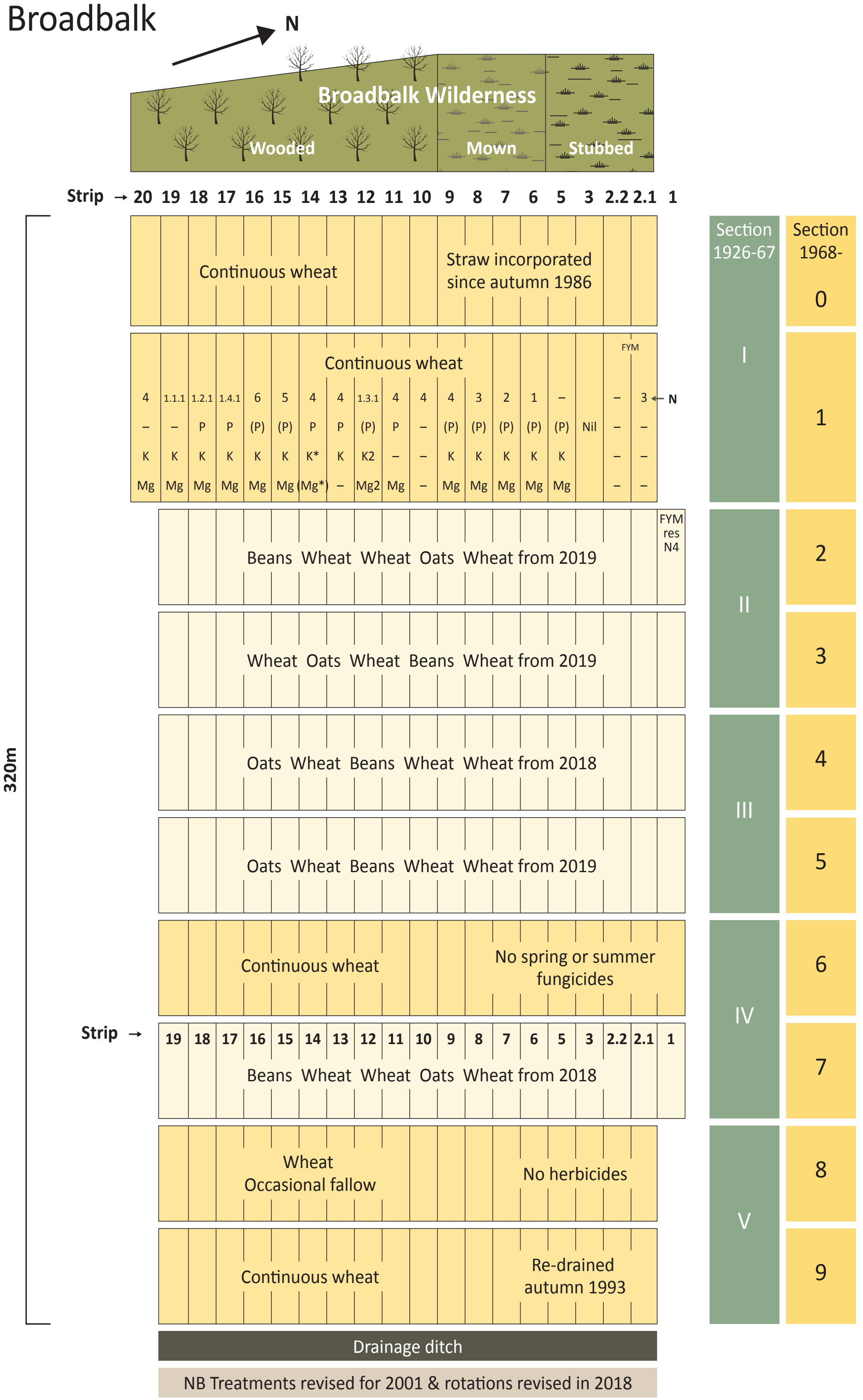

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Table 1. Broadbalk fertiliser and organic manure treatments

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

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

Annual treatment per hectare

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

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

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

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

No N or FYM to beans from 2018

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

(1) : FYM N2 from 1968-2004

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

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

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

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

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

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

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

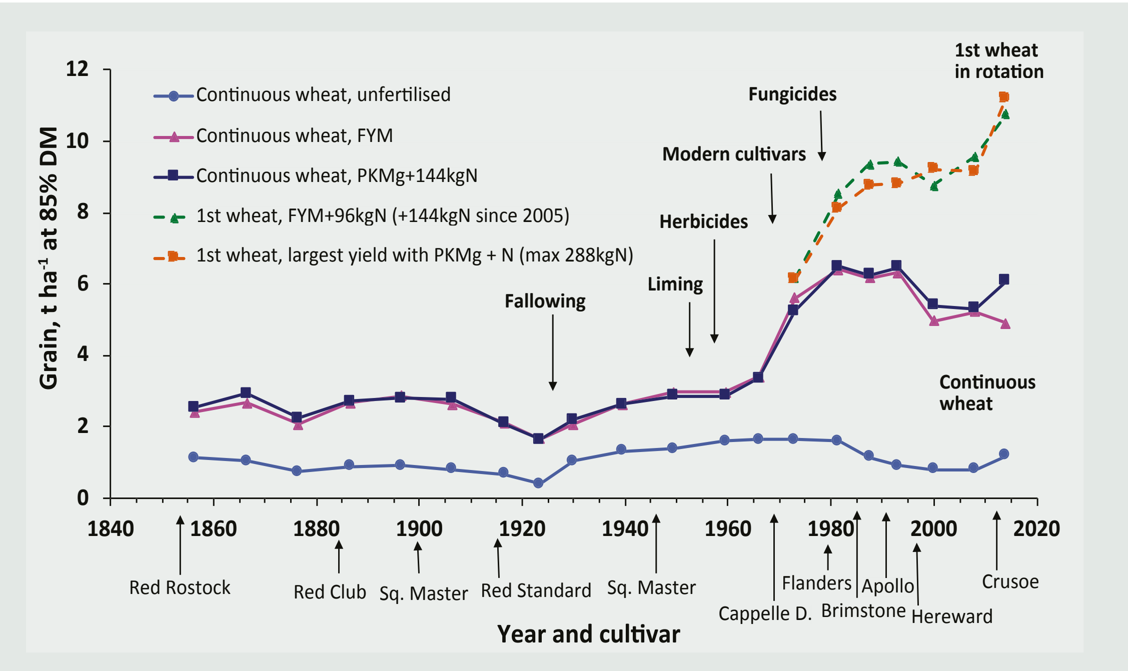

Fig. 1 Broadbalk: Mean yields of wheat grain and changes in husbandry (1852-2016)

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

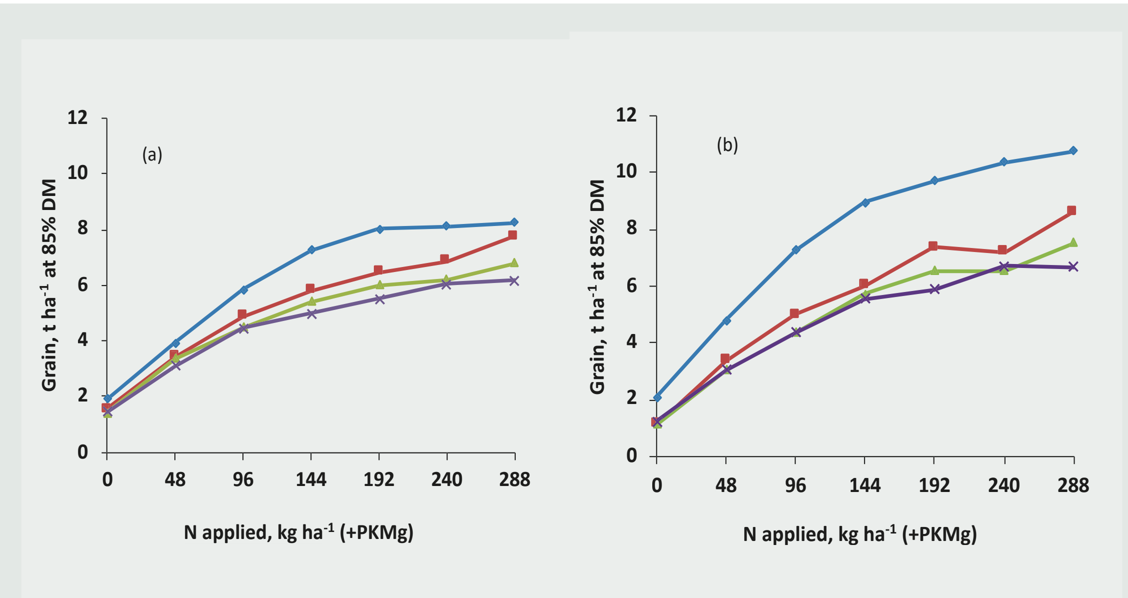

Fig. 2 Broadbalk; mean yields of wheat grain for (a) cv. Hereward, 2009-2012, and (b) cv. Crusoe, 2013-2017 (excluding 2015). Data are for: (x) continuous wheat; (♦) 1st wheat after a two-year break; (■) 2nd wheat; (▲) 3rd wheat.

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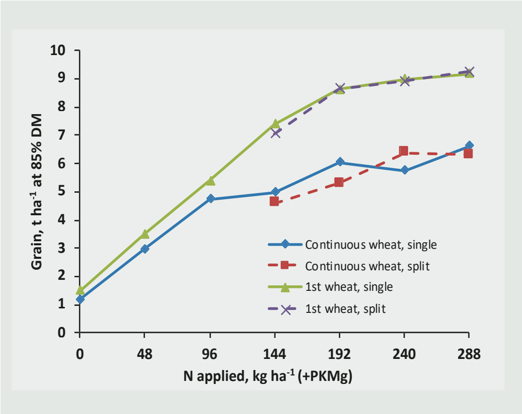

Fig. 3 Broadbalk; mean yields of wheat grain, 2002-11; where N fertiliser was given as single or split applications.

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

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

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

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

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

Organic matter in the Broadbalk soil

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

Broadbalk, soil sampling, 1944

The Broadbalk experiment

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

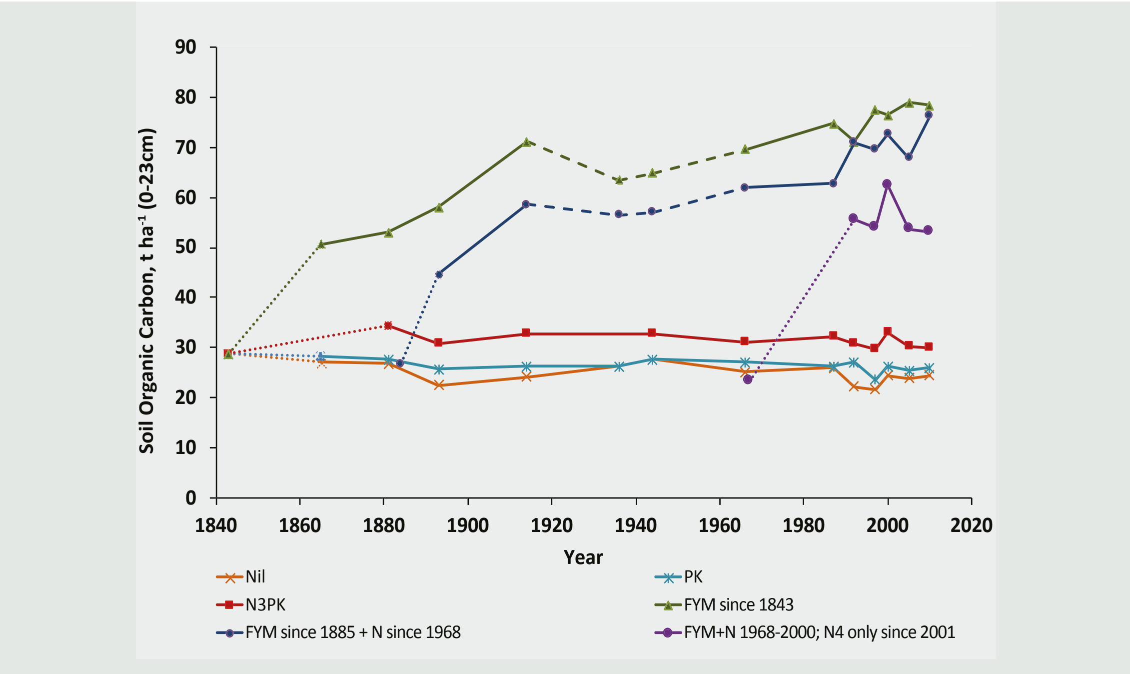

Fig. 4 Broadbalk; long-term changes in soil organic carbon, 1843-2010. Data is from soils where wheat is grown continuously, except that between 1926 and 1967 one or more sections were bare fallowed each year to control weeds; FYM was not applied to the fallow sections. Data has been adjusted for changes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

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

The microbiology of Broadbalk

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

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

Measurement of bacterial genes involved in denitrification in Broadbalk soil indicated that, in general, the genes responsible increased in abundance with increasing N fertiliser, consistent with the increased N_2O emissions from soils receiving large

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

Weeds on Broadbalk

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

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

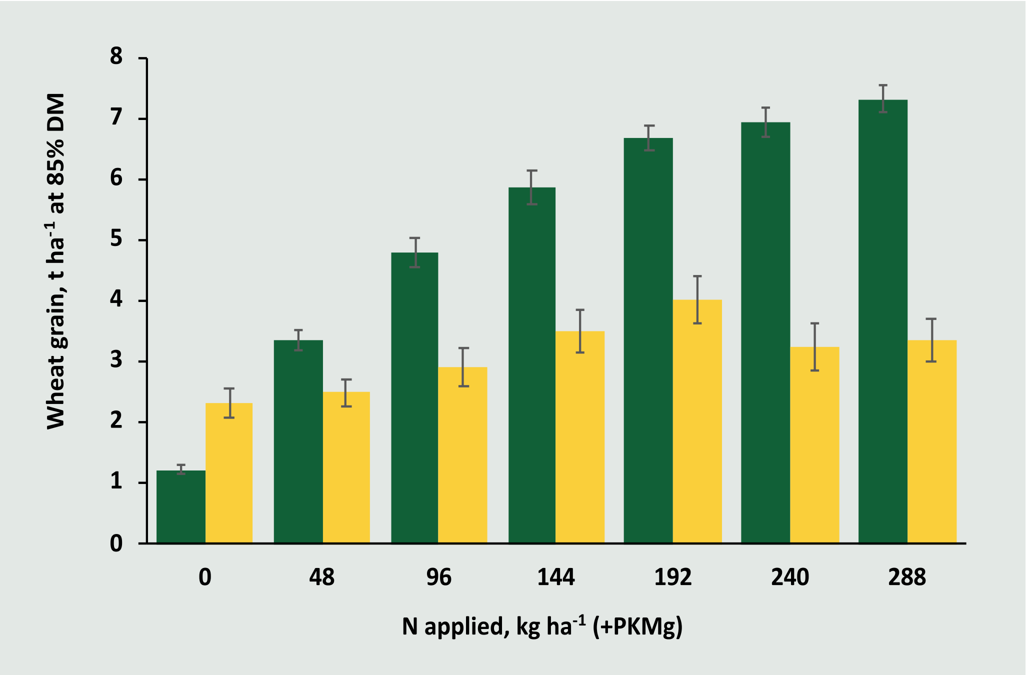

Fig. 5 Broadbalk; mean yields of grain, 1985-2014; where wheat was grown continuously or with occasional fallows, without herbicides (section 8; yellow histograms) or with herbicides (section 9; green histograms).

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

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

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

Broadbalk, weeds on Section 8, July 2017

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

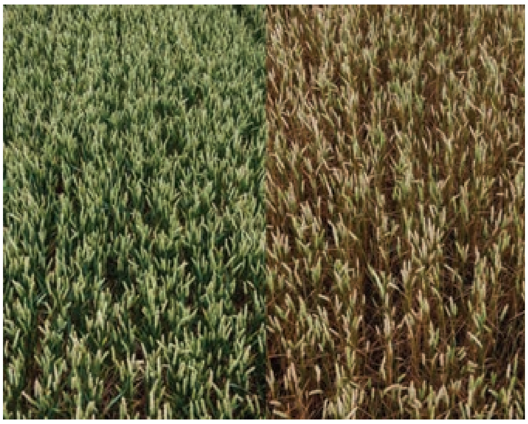
The revised atlas of British and Irish Flora includes a list of species which have shown the greatest relative decrease nationally between the 1930-69 and 1987-99 national recording periods. Seven weeds on Broadbalk are among the 50 species that have shown the greatest decline, and three of them are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

Pests and diseases on Broadbalk

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

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

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



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

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

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Broadbalk drains

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

Measurements of N leached to groundwater plus losses via the drains indicated that even where no N fertiliser had been applied for more than 150 years on average about 10 kg ha^{-1} of NO_3-N was lost each year (1990-1998). Most N was lost where the amount of fertiliser N applied exceeded that needed for "optimum" yield or where FYM was applied for many years. The EU limit for the maximum concentration of N allowed in potable waters (11.3 mg N l^{-1}) was often exceeded where the larger amounts of fertiliser N or FYM were applied. However, in years when through drainage was less than average, the EU limit was sometimes exceeded even where little or no N had been applied (Goulding *et al*., 2000).

Drain outlets at eastern end of Broadbalk, 2010

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

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Broadbalk and Geescroft Wildernesses

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

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

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

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

Broadbalk Wilderness, July 2017

Geescroft Wilderness, 1933

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

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

Park Grass

Park Grass, 1941

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

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

The experiment was established on *c*. 2.8 ha of parkland that had been in permanent pasture for at least 100 years. The uniformity of the site was assessed in the five years prior to 1856. Treatments imposed in 1856 and subsequently included controls (Nil - no fertiliser or manure),

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and various combinations of P, K, Mg, Na, with N applied as either sodium nitrate or ammonium salts (Table 3). FYM was applied to two plots but was discontinued after eight years because, when applied annually to the surface in large amounts, it had adverse effects on the sward. FYM, applied every four years, was re-introduced on three plots in 1905.

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

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

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Park Grass

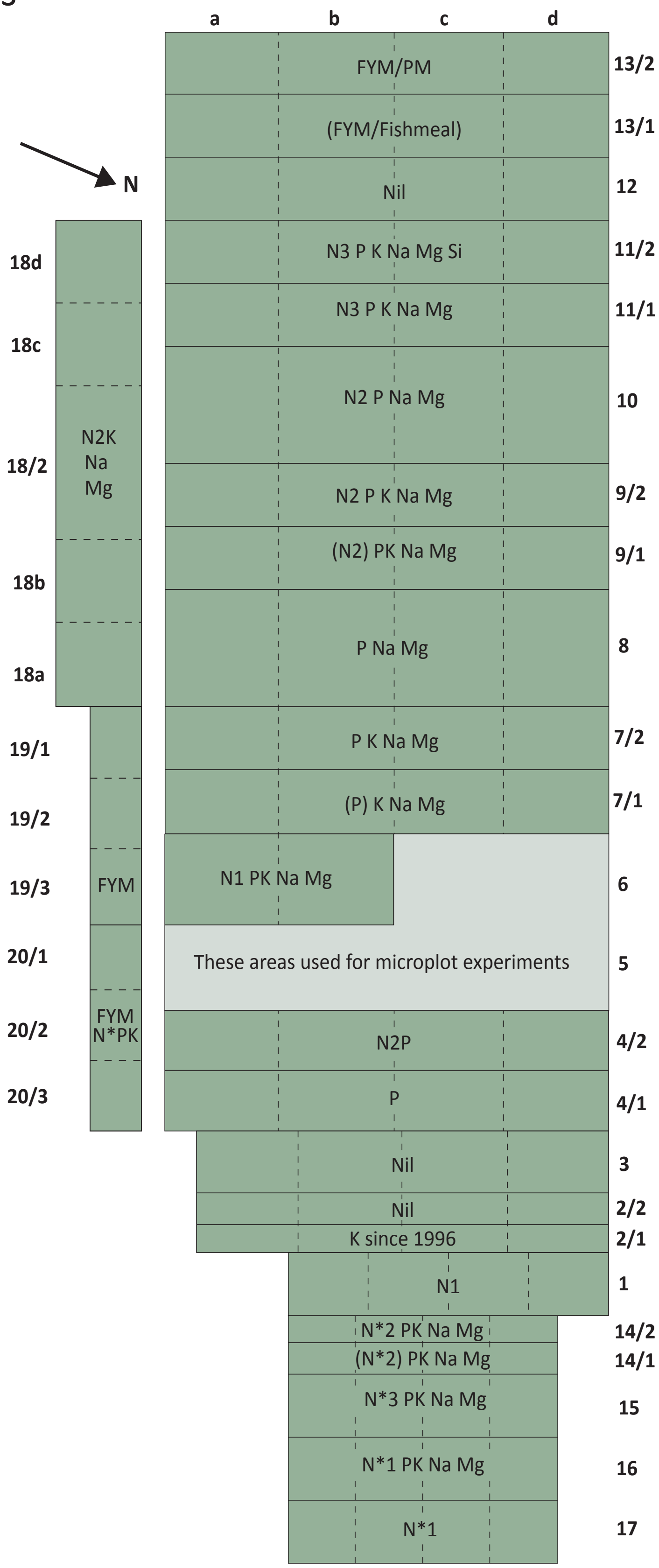
a
b
c
d
N
FYM/PM
13/2
(FYM/Fishmeal)
13/1
Nil
12
N3 P K Na Mg Si
11/2
N3 P K Na Mg
11/1
N2 P Na Mg
10
N2 P K Na Mg
9/2
(N2) PK Na Mg
9/1
P Na Mg
8
P K Na Mg
7/2
(P) K Na Mg
7/1
N1 PK Na Mg
6
These areas used for microplot experiments
5
N2P
4/2
P
4/1
Nil
3
Nil
2/2
K since 1996
2/1
N1
1
N*2 PK Na Mg
14/2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

Table 3 Park Grass fertiliser and organic manure treatments.

Treatments (per hectare per year unless indicated)

Nitrogen (applied in spring)

N1, N2, N3	48, 96, 144 kg N as ammonium sulphate
N*1, N*2, N*3	48, 96, 144 kg N as sodium nitrate
(N2) (N*2)	last applied 1989

Minerals (applied in winter)

P	17 kg P as triple superphosphate since 2017, previously 35 kg P
K	225 kg K as potassium sulphate
Na	15 kg Na as sodium sulphate
Mg	10 kg Mg as magnesium sulphate
Si	450 kg of sodium silicate
Plot 20	30 kg N*, 15 kg P, 45 kg K in years when FYM is not applied

In 2013, plot 7 was divided into 7/1 and 7/2; P applications on 7/1 stopped
Since 2013, plot 15 has also received N*3 (previously PKNaMg but no N)

Organics (applied every fourth year)

FYM	35 t ha^{-1} farmyard manure supplying c.240 kg N, 45 kg P, 350 kg K, 25 kg Na, 25 kg Mg, 40 kg S, 135 kg Ca
PM	Pelleted poultry manure (replaced fishmeal in 2003) supplying c.65 kgN

On plot 13/2 FYM and PM (previously fishmeal) are applied in a 4-year cycle i.e.:
FYM in 2017, 2013, 2009, 2005 etc.
PM in 2015, 2011, 2007, 2003, fishmeal in 1999, 1995 1991 etc.

(FYM/Fishmeal) FYM and fishmeal last applied in 1993 and 1995 respectively

Lime (applied every third year)
Ground chalk applied as necessary to maintain soil (0-23 cm) at pH 7, 6 and 5 on sub-plots “a”, “b” and “c”.
Sub-plot “d” does not receive any chalk

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

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

available (Olsen)P kg^{-1}. Consequently, in 2016, the P application to these plots was decreased from 35 to 17 kg P ha^{-1}, so that it more closely matches P offtakes. Since 2013, plot 15 has received sodium nitrate at 144 kg N ha^{-1}, in

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addition to PKNaMg, to provide a comparison with plot 11, which receives the same rate of N as ammonium sulphate.

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

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

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

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

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

Botanical composition

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

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

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

Sorting herbage samples from Park Grass, 2010

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

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

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

26

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

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

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

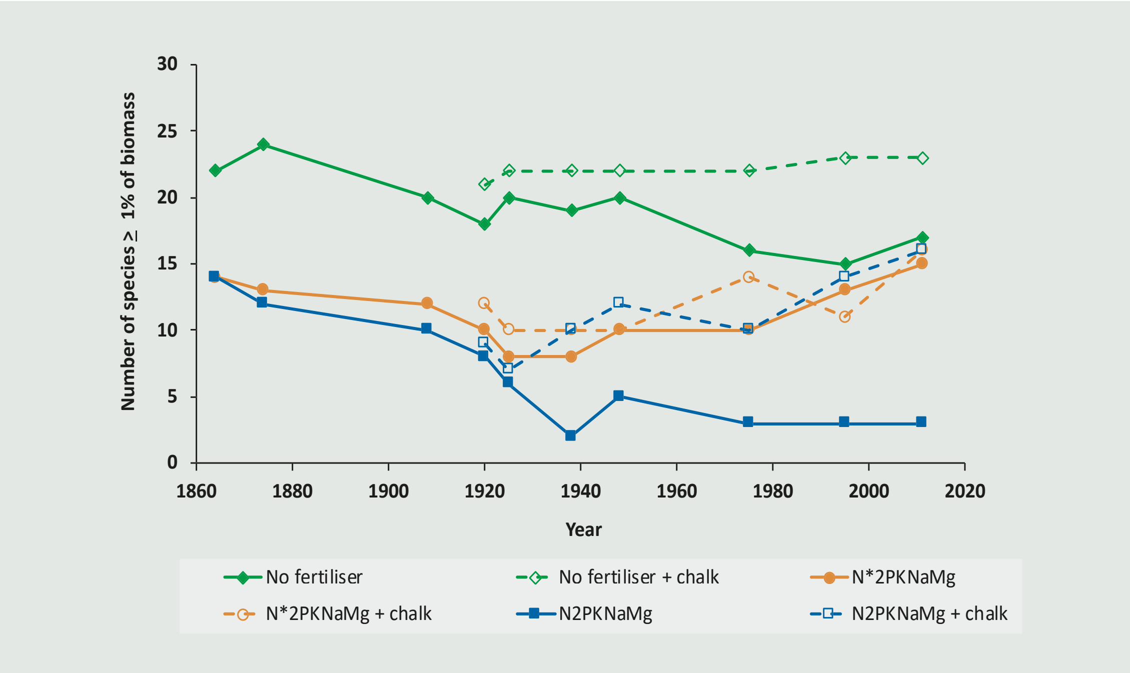

Fig. 6 Park Grass; changes in the number of species comprising 1% or more of the above-ground biomass over time, 1864-2011.

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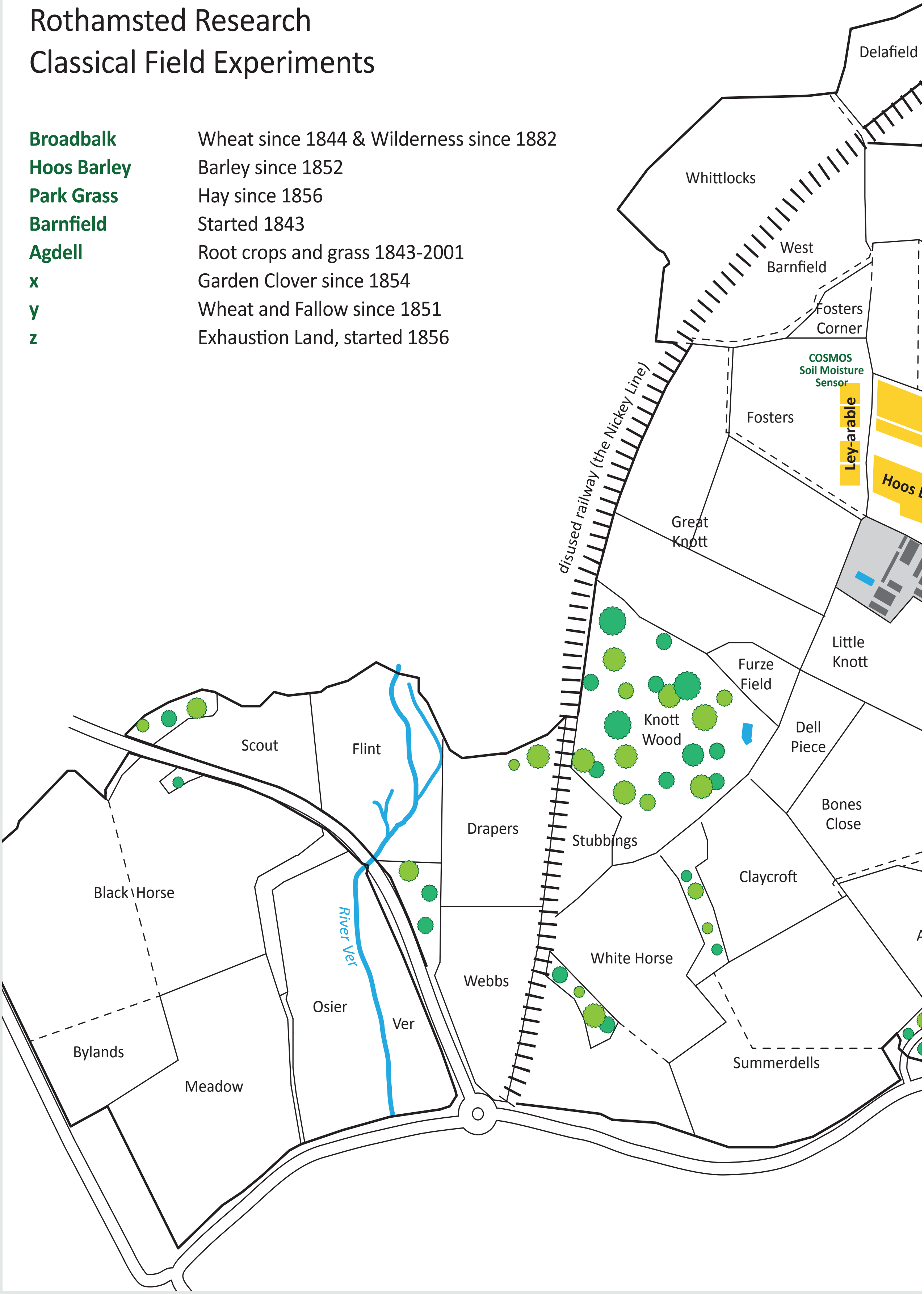
Rothamsted Research Classical Field Experiments

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



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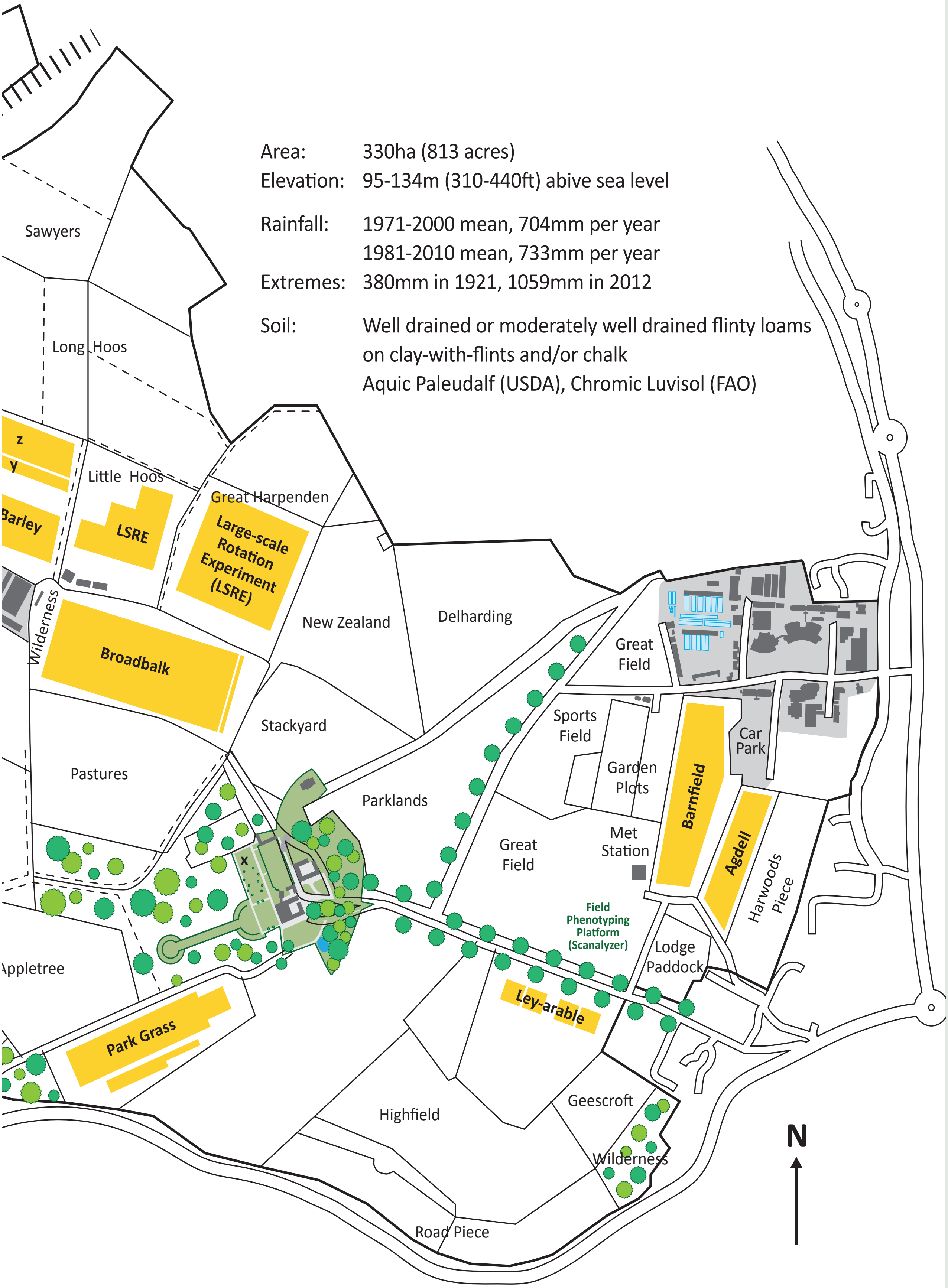
Area:	330ha (813 acres)
Elevation:	95-134m (310-440ft) abive sea level
Rainfall:	1971-2000 mean, 704mm per year
	1981-2010 mean, 733mm per year
Extremes:	380mm in 1921, 1059mm in 2012
Soil:	Well drained or moderately well drained flinty loams on clay-with-flints and/or chalk Aquic Paleudalf (USDA), Chromic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



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

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

The microbiology of Park Grass

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

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

Hoosfield Spring Barley

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

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

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

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

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

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

Hoosfield

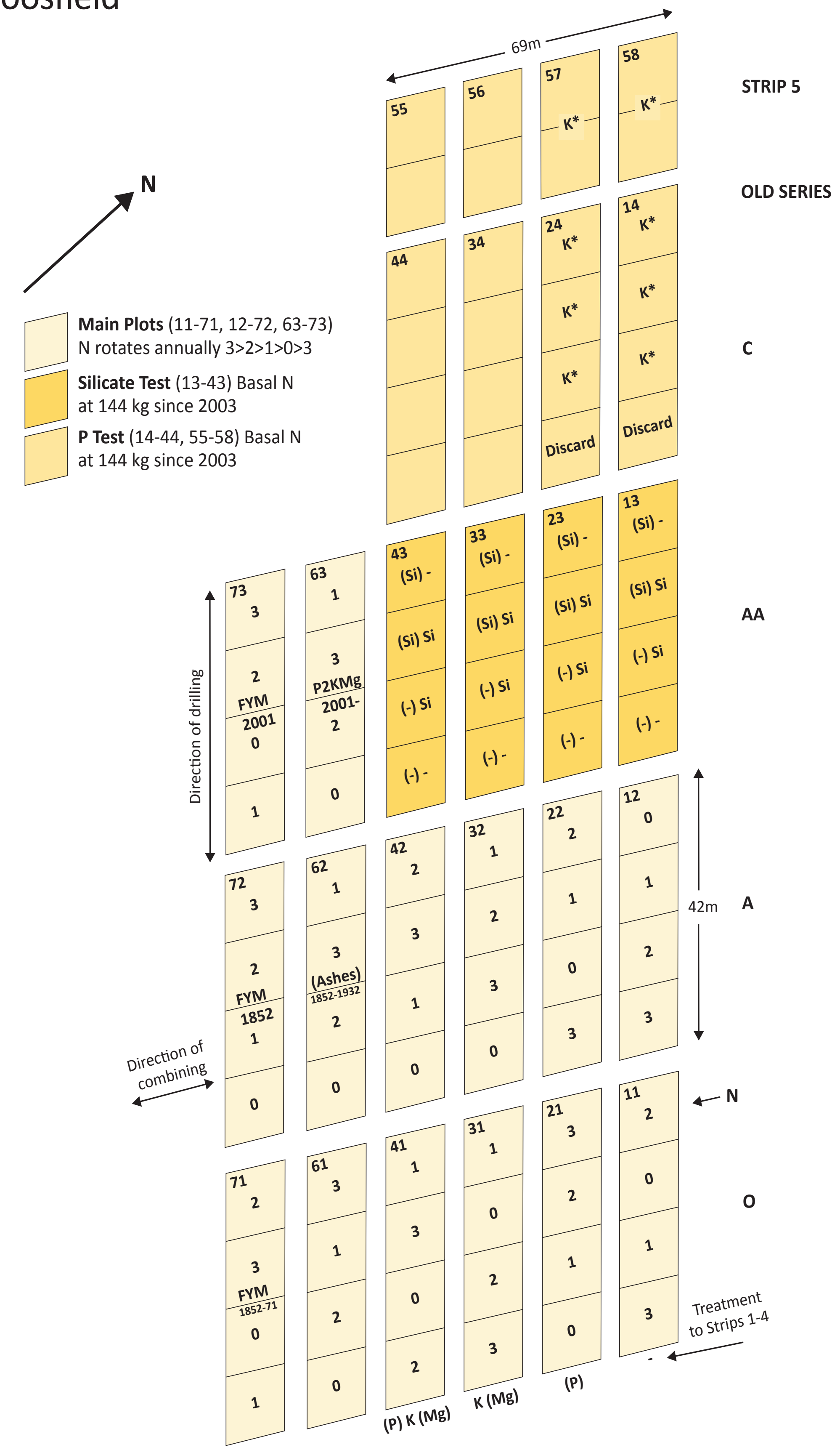


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Table 6. Hoosfield fertiliser and organic manure treatments.

Annual treatment per hectare

Nitrogen (applied in spring)

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

Organics (applied before ploughing in autumn)

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

Minerals (applied before ploughing in autumn)

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

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

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

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

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

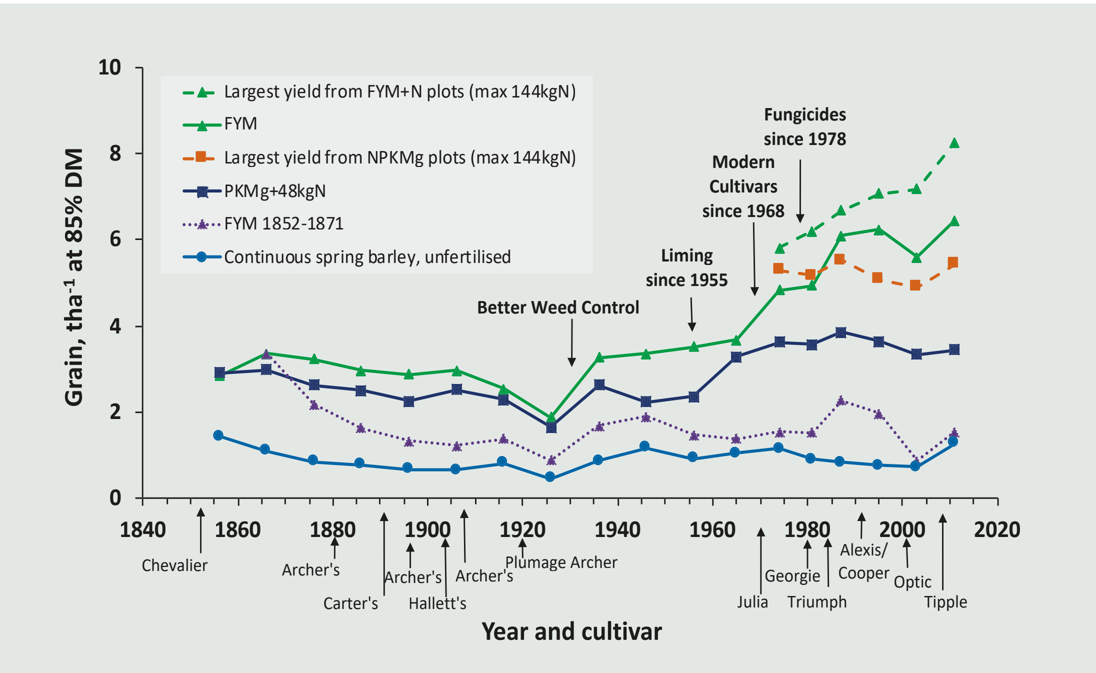

Fig. 7 Hoosfield; mean yields of spring barley grain and changes in husbandry, 1852-2015.

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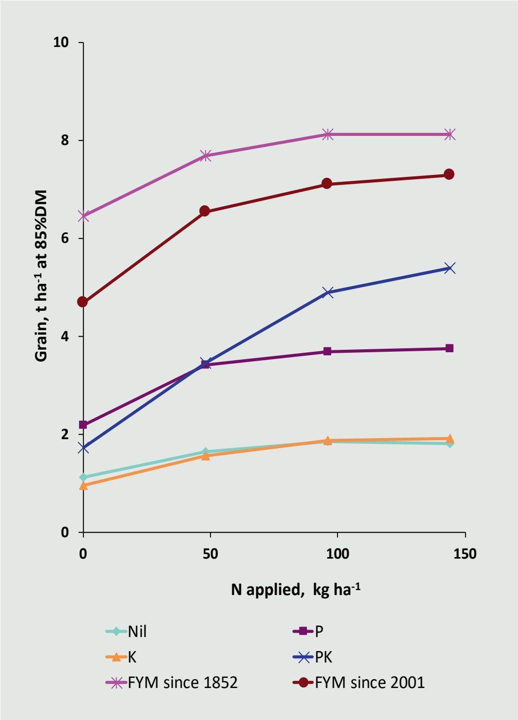

Fig. 8 Hoosfield; mean yields of spring barley grain (cv. Tipple), 2008-2015.

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

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

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

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

[1] See Table 6 for details

Exhaustion Land

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

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

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

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

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

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

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

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

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

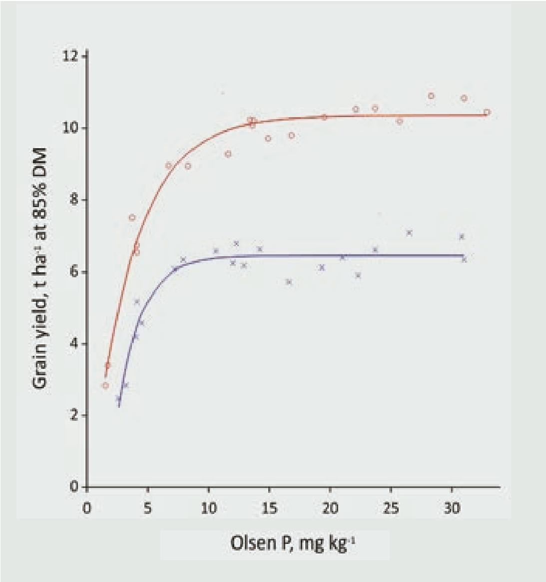

Fig. 9 Exhaustion Land; responses in the yield of wheat grain to concentrations of plant-available P (Olsen P) in the soil in contrasting years: 2003 (x) and 2008 (o).

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

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Garden Clover

Garden Clover experiment, 2008

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

Between 1956 and 1972 the plot was sub-divided and a sequence of tests made of K, molybdenum (Mo), formalin, N and Mg. N, K and Mg all increased yields, Mo and formalin did not. With N, P, K and Mg yields of about 6 t dry matter ha^{-1} were obtained in the year of sowing. The crop was usually severely damaged during the winter by clover rot

(*Sclerotinia trifoliorum*) and was re-sown each spring. Since 1973 basal N, P, K, Mg and chalk have been applied.

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

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

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

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