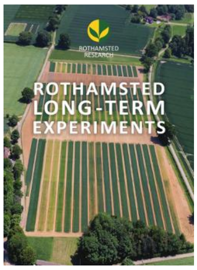
ROTHAMSTED RESEARCH

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



Broadbalk Winter Wheat

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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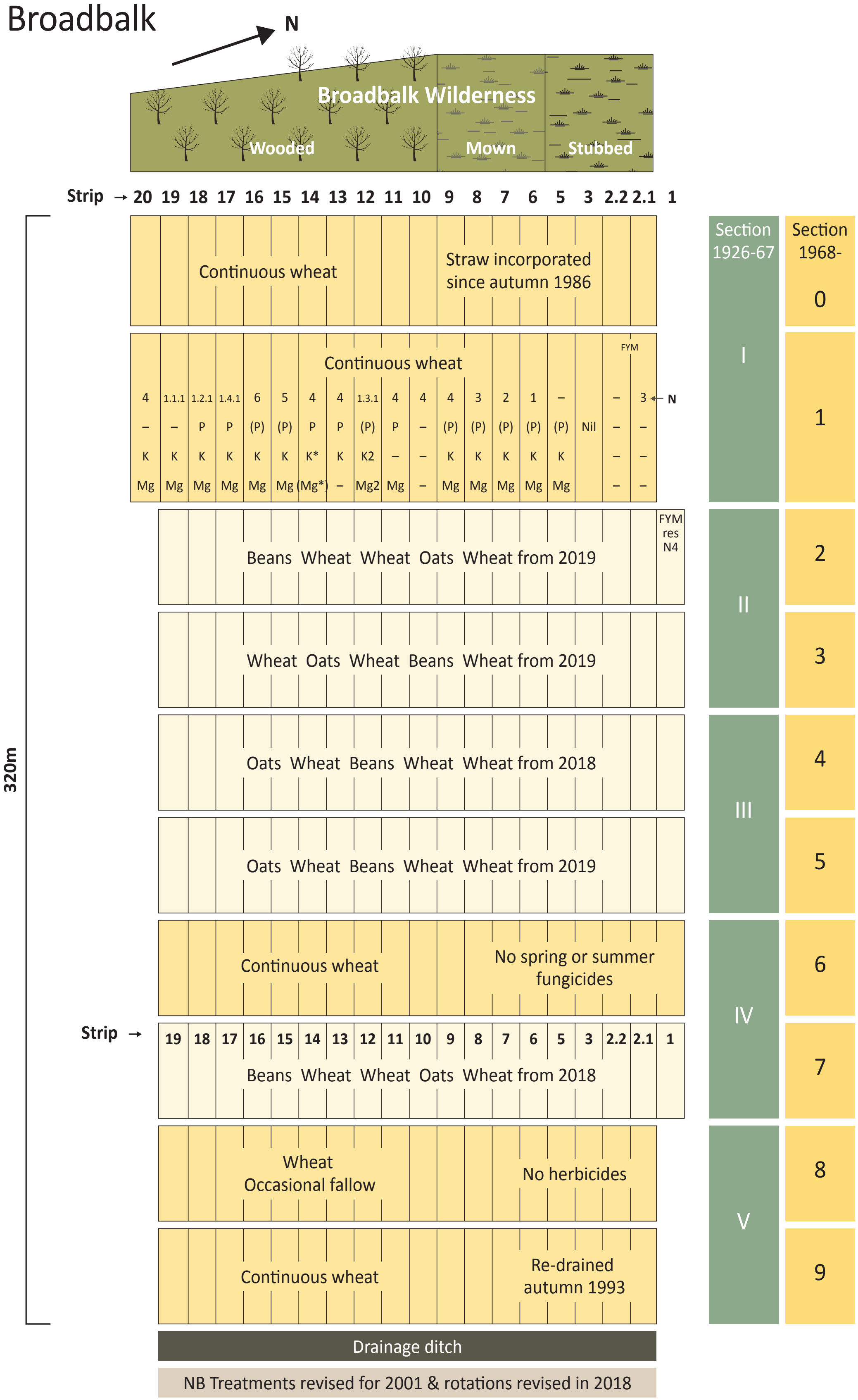
Broadbalk


N
Broadbalk Wilderness
Wooded
Mown
Stubbed
Strip → 20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 3 2.2 2.1 1
Continuous wheat
Straw incorporated since autumn 1986
Continuous wheat
FYM
4 1.1.1 1.2.1 1.4.1 6 5 4 4 1.3.1 4 4 4 3 2 1 – – 3 ← N
– – P P (P) (P) P P (P) P – (P) (P) (P) (P) (P) Nil – –
K K K K K K K* K K2 – – K K K K K – –
Mg Mg Mg Mg Mg Mg (Mg*) – Mg2 Mg – Mg Mg Mg Mg Mg – –
FYM res N4
Beans Wheat Wheat Oats Wheat from 2019
Wheat Oats Wheat Beans Wheat from 2019
Oats Wheat Beans Wheat Wheat from 2018
Oats Wheat Beans Wheat Wheat from 2019
Continuous wheat
No spring or summer fungicides
Strip → 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 3 2.2 2.1 1
Beans Wheat Wheat Oats Wheat from 2018
Wheat Occasional fallow
No herbicides
Continuous wheat
Re-drained autumn 1993
Drainage ditch
NB Treatments revised for 2001 & rotations revised in 2018
320m
Section 1926-67
I
II
III
IV
V
Section 1968-
0
1
2
3
4
5
6
7
8
9

8

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

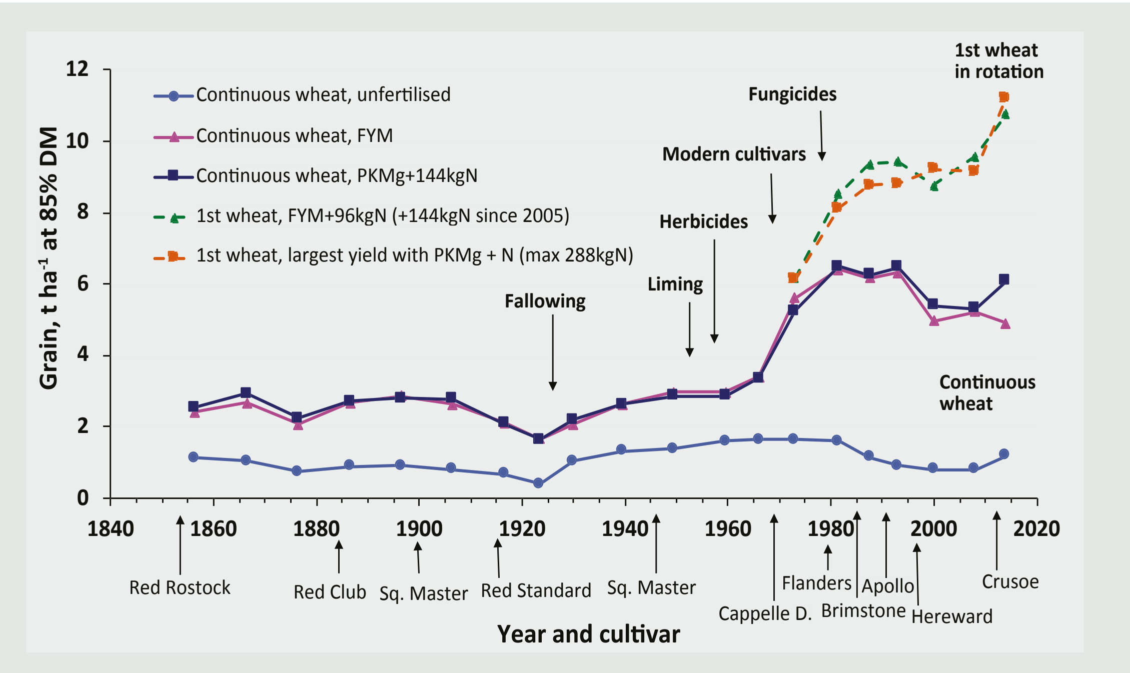

Fig. 1 Broadbalk: Mean yields of wheat grain and changes in husbandry (1852-2016)

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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

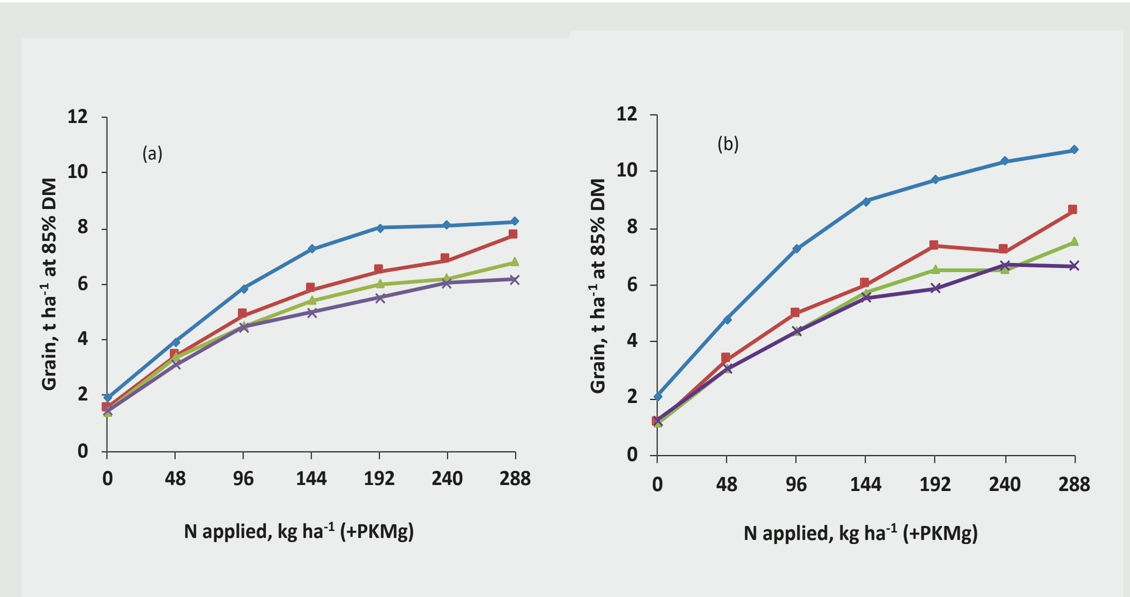

Fig. 2 Broadbalk; mean yields of wheat grain for (a) cv. Hereward, 2009-2012, and (b) cv. Crusoe, 2013-2017 (excluding 2015). Data are for: (x) continuous wheat; (♦) 1st wheat after a two-year break; (■) 2nd wheat; (▲) 3rd wheat.

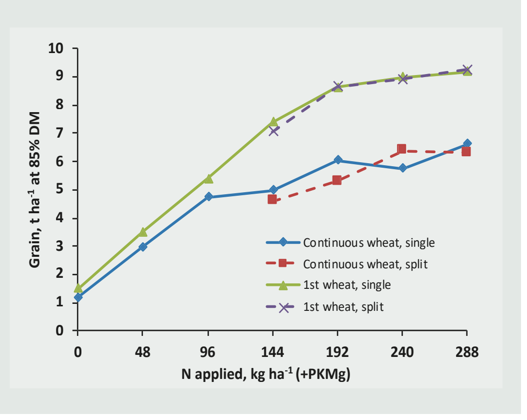

Fig. 3 Broadbalk; mean yields of wheat grain, 2002-11; where N fertiliser was given as single or split applications.

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.

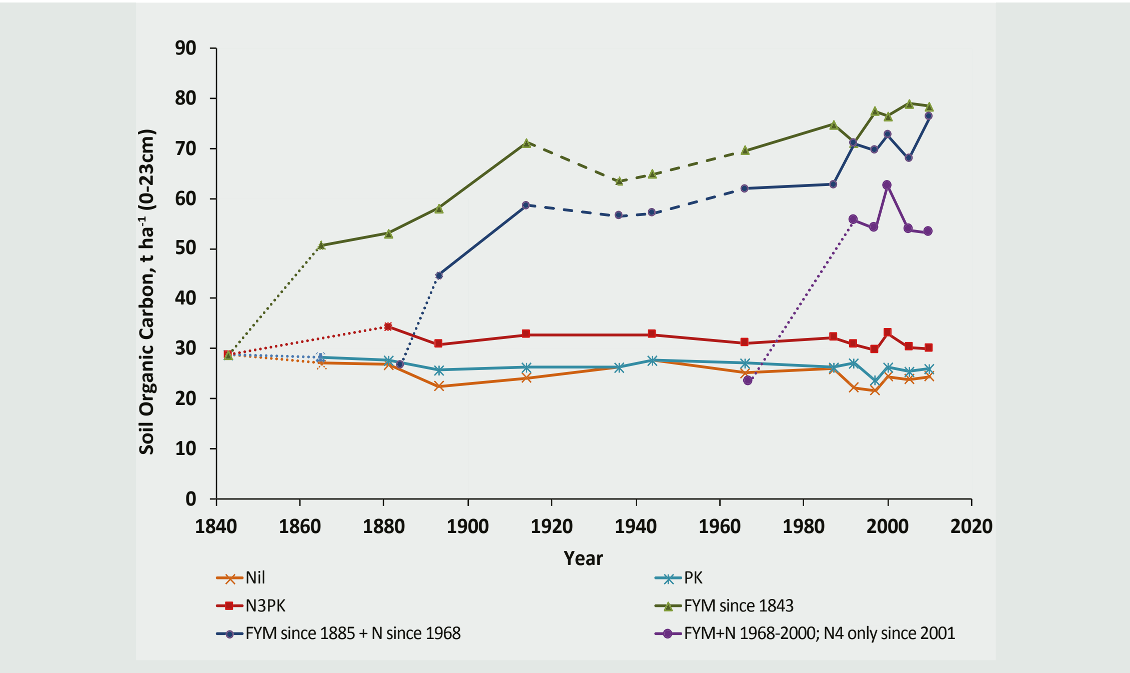

Fig. 4 Broadbalk; long-term changes in soil organic carbon, 1843-2010. Data is from soils where wheat is grown continuously, except that between 1926 and 1967 one or more sections were bare fallowed each year to control weeds; FYM was not applied to the fallow sections. Data has been adjusted for changes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

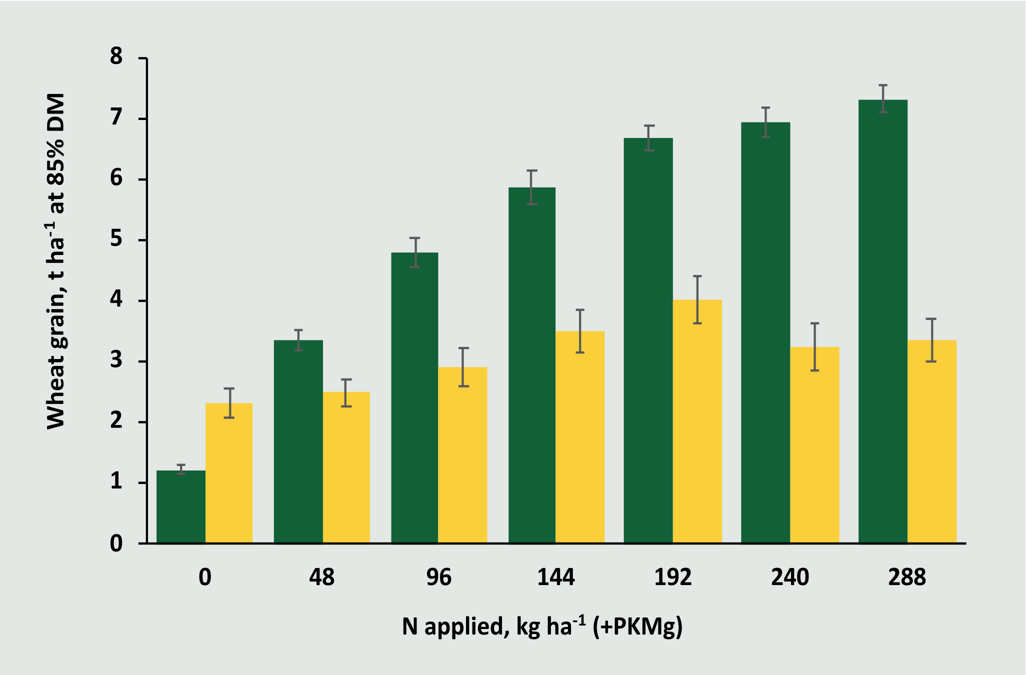

Fig. 5 Broadbalk; mean yields of grain, 1985-2014; where wheat was grown continuously or with occasional fallows, without herbicides (section 8; yellow histograms) or with herbicides (section 9; green histograms).

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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).

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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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