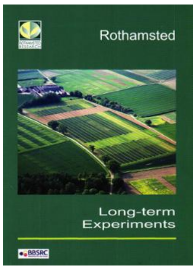
ROTHAMSTED RESEARCH

The Long Term Experiments



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 year of harvest). 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. 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 analyses. Broadbalk is now ploughed by a tractor-mounted reversible plough and harvested by a combine harvester; only the central strip of each plot is taken for yield and samples.

Weeds were initially controlled by hand-hoeing. When this became impracticable, five 'Sections' (I - V on plan), crossing all the treatment strips at right angles, were made and bare fallowed sequentially. 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.

Following the correction of soil acidity on parts of the experiment in the 1950s a review of the treatments and management led to a number of 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) 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 more appropriate agronomic levels. 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 detailed in the legend that accompanies the plan of the experiment.

After the 1968, changes Sections 0, 1, 8 and 9 continued to grow wheat only, whilst Sections 2, 4, 7 and Sections 3, 5, 6 went into two different 3-course rotations. In 1978,

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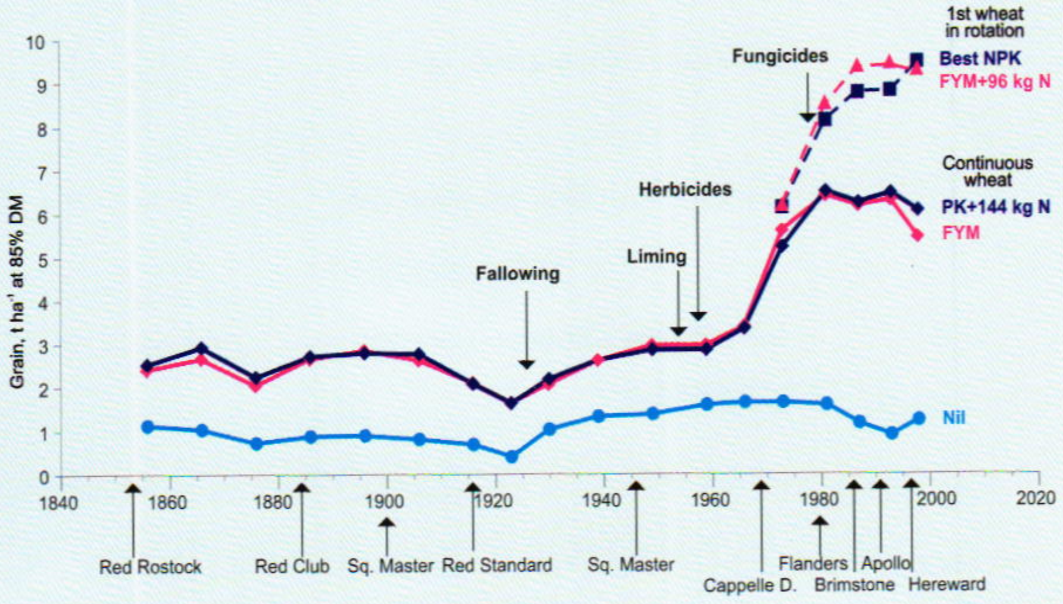
Section 6 reverted to continuous wheat and the other five Sections went into a 5-course rotation; currently, oats, forage maize, wheat, wheat, wheat. Pesticides are applied when necessary, except on Section 6, which does not receive spring or summer fungicides, and Section 8, which has never received 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. Similar land in the neighbourhood, farmed in rotation, typically yielded *c*.1.2 t ha^{-1}. Figure 1 shows yields from selected treatments. 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.

Fig.1 Broadbalk. Mean yields of wheat grain, and changes in husbandry



Until the First World War, the experiment had been hand-weeded but the subsequent shortage of labour allowed weed competition 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 continuous wheat given no fertiliser or manure (but with pesticides) are now *c*.1 t ha^{-1}, similar to yields earlier in the experiment. Mean yields of wheat given PKNaMg+144 kg N ha^{-1} are 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 on these two treatments doubled to about 5 t ha^{-1}. Since 1968 we have been able to compare the yields of wheat grown

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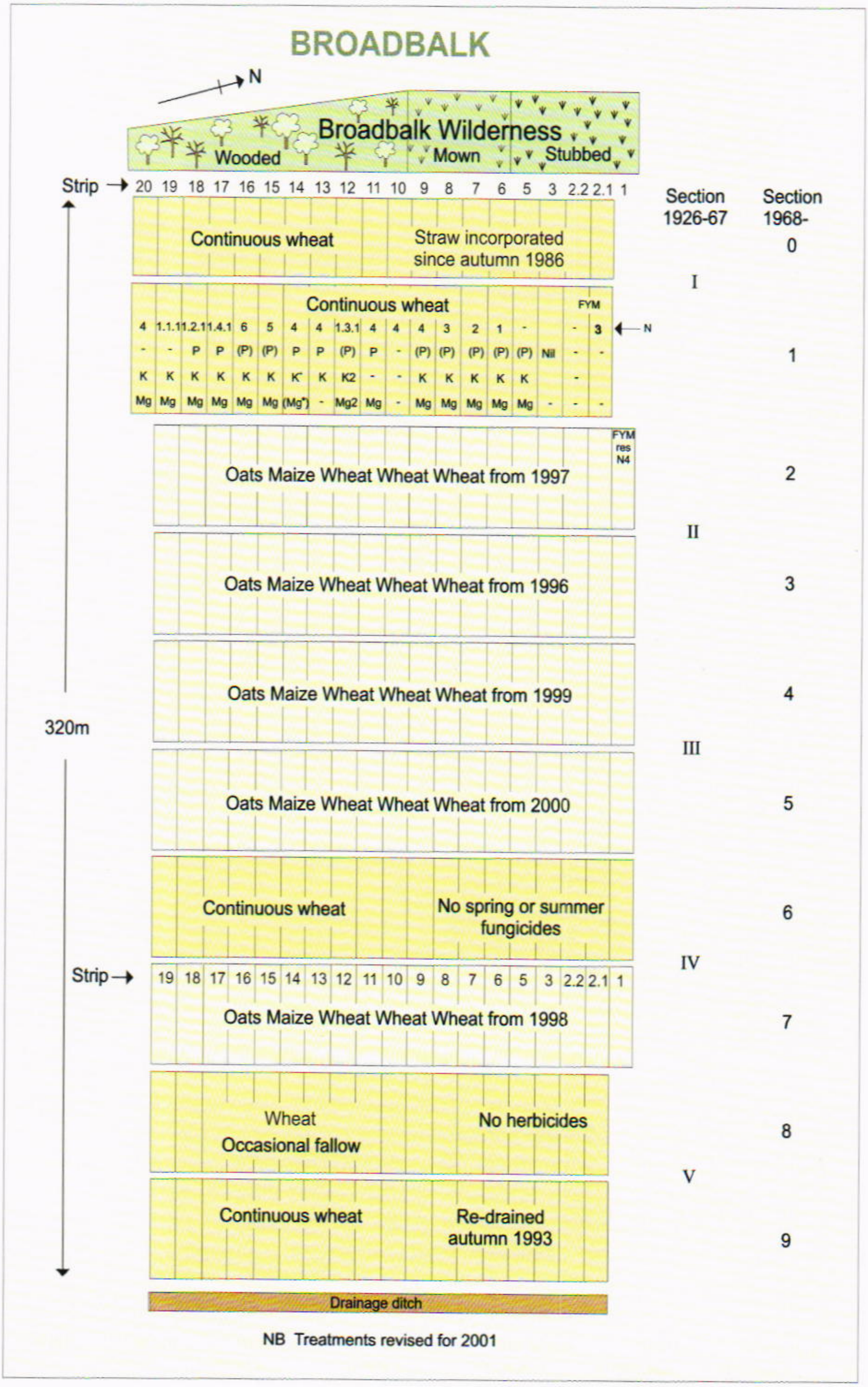

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Broadbalk Fertiliser and organic manure treatments

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 N2[(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)K2Mg2[(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 1/2[PK(Na)Mg]	N0+3 1/2[PKMg](A)	N1+4+1 PKMg
18	PKNaMg(A)	N2 1/2[PK(Na)Mg]	N1+3 1/2[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 1/2-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. Maize did not receive autumn N.

<u>Annual treatment per hectare</u>

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 2011
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 until1988

N 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)

Split N to forage maize (seedbed and post-emergence)
N2+1 : 96+48 kgN (strip 19)
N2+2 : 96+96 kgN (strip 18)
N2+3 : 96+144 kgN (strip 12)
N2+4 : 96+192 kgN (strip 17)

No N or FYM to oats

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 N3 since 2005
(2) : N1+3+1 (P)KMg since 2006

Note : S has been added, by default, as part of the potassium sulphate, magnesium sulphate, Kieserite, FYM and ammonium sulphate applications. S last applied to strip 14 in 2000.

For detailed information on treatments and management until 1967, see Rothamsted Report for 1968, Part 2, 215pp.

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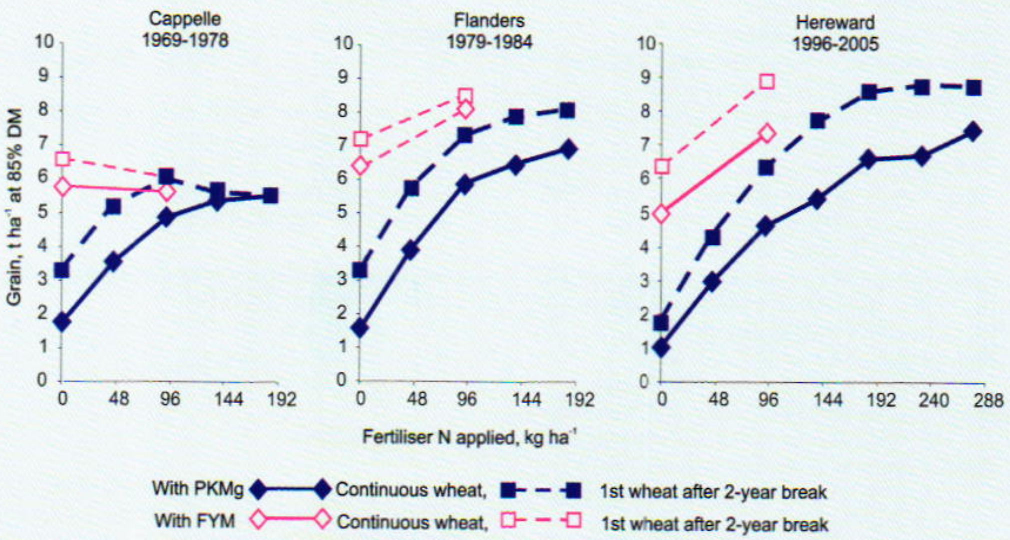
continuously and as the first wheat after a two-year break (Fig.2). In the 10 years in which Cappelle was grown, foliar fungicides were not applied and foliar diseases, particularly powdery mildew, were common, and most severe on plots given most nitrogen. Since 1979, summer fungicides have been used, when necessary (except on Section 6), and this has allowed us to exploit the greater grain yield potential of modern cultivars. Perhaps as a result, the relative yields of plots given FYM and fertilisers changed (Fig.2) with best yields from fertiliser exceeding those from FYM alone and the combination of FYM+96 kg N ha^{-1} often exceeding both. The increased responses to N fertiliser in 1979-84 suggested that yields might be greater if larger amounts of N were applied. Since 1985, 240 and 288kg N ha^{-1} have been tested, and all cultivars have shown a similar pattern of response to cv. Hereward (Fig.2). On average, only the continuous wheat responded to the larger amounts of N. Yields of wheat grown after a two-year break can be more than 2 t ha^{-1} larger than yields of continuous wheat, almost certainly because the effects of soil borne pests and disease, particularly take-all (*Gaeumannomyces graminis* var. *tritici*), are minimised (see later). Best yields now exceed 11 t ha^{-1}.

Fig.2 Broadbalk. Mean yields of wheat grain



The main purpose of the 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. Currently, oats and maize are the two break crops; yields on selected treatments are shown in Table 1. The oats are not given fertiliser N or FYM. Thus, on plots where P and K is not limiting, any differences in yield between treatments are 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). Maize is a C4 plant. As such, the carbon it

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contains has a different ^{13}C "signature" than that in the C3 plants that have been grown previously on Broadbalk. Thus, we can distinguish maize-derived organic matter from that of organic matter already in the soil. Over time, we will be able to see where, within the soil structure, the maize carbon is being held and how quickly it is being recycled.

Table 1. Broadbalk; mean yield of oat grain (2002-5) and forage maize (2001-5).

Strip	Treatment 2001-5[(1)]	Oat grain $t\ ha^{-1}$ 85% DM	Forage maize $t\ ha^{-1}$ total DM
3	Nil	1.9	2.2
5	(P)KMg	2.2	2.3
6	N1 (P)KMg	2.7	7.2
7	N2 (P)KMg	3.3	11.0
8	N3 (P)KMg	4.0	12.0
9	N4 (P)KMg	4.7	11.8
15	N5 (P)KMg	4.9	11.1
16	N6 (P)KMg	6.3	11.5
2.2	FYM	7.2	11.7
2.1	FYM N2[(2)]	7.2	14.3
1	(FYM) N4	6.6	15.2

(1) See plan for details
(2) FYM N3 for maize in 2005
Note; No N fertiliser or FYM was applied for the winter oat crops.

The Broadbalk experiment

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Organic matter in the Broadbalk soil

The amounts of soil organic matter (SOM) can be determined indirectly from the % organic carbon (Org C) (% Org C is multiplied by a factor of 1.72 to give % SOM). Most soils have a C:N ratio of about 10:1; so % N can be used as a surrogate for % Org C to calculate SOM. Figure 3 shows the %N in topsoil (0-23cm) on selected treatments. The N 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 N than soil in the nil (and minerals-only plots, not shown) because the better-fertilised crops gave not only more yield but more stubble, and probably roots, to be ploughed-in. Over the last 10-20 years there has been a slight decline in soil N on these plots. Soil N in plots receiving minerals and larger amounts of fertiliser N (192, 240 and 288 kg ha^{-1}) in recent years, and where larger crops have been grown, is still tending to increase. On the FYM treatments, soil N increased, rapidly at first, then more slowly, and now contains more than double the concentration of that in the nil or fertiliser-only soil. The decline in soil N on the FYM plots in the 1920s/1930s was because FYM was not applied in the years when the plots were fallowed to control weeds.

Edwin Grey, soil sampling, 1919

The N balance, *i.e.* N input minus 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, inputs of N in FYM (and from the atmosphere) 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).

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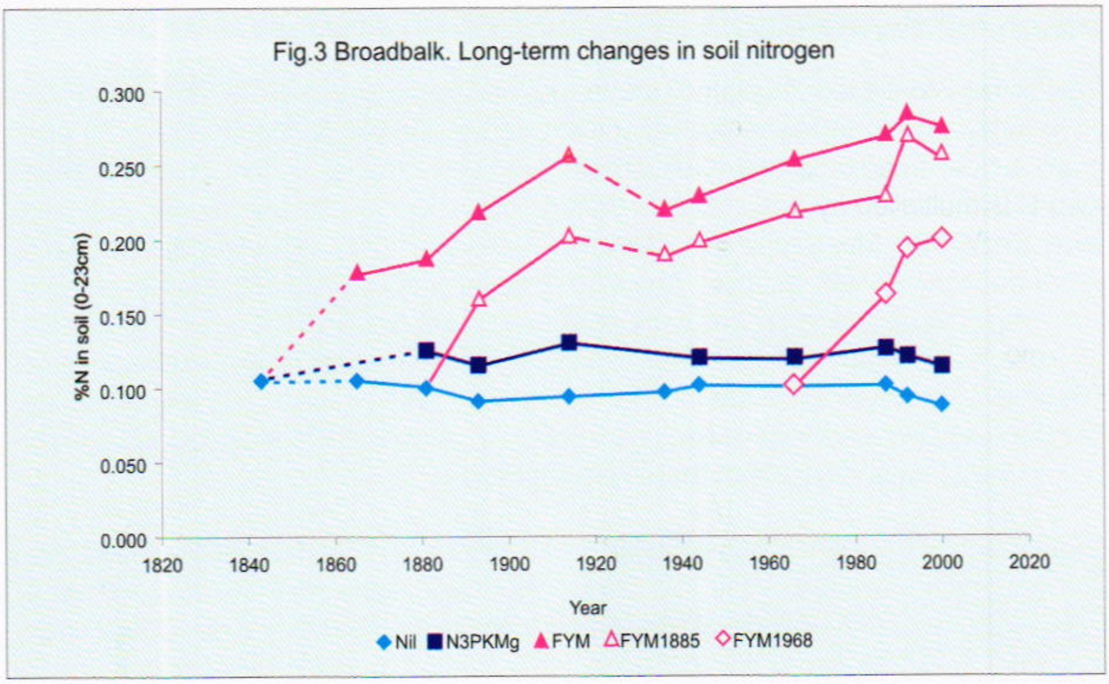

The microbiology of Broadbalk

The microbial biomass of the FYM plots is approximately twice that of the plots given either NPK or no fertilisers. Total numbers of microbial cells, estimated directly by microscopy (around 10^9 cells g^{-1} soil), and of culturable bacteria (around 10^8 cells g^{-1} soil), show a similar ratio. Although relative numbers of specific groups of bacteria that can grow on particular selective media differ according to sampling date, the differences are unpredictable at present. The recovery of cells by culture on agar may reflect their physiological status when sampled, resulting in apparently lower numbers at times of stress. 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 cells g^{-1} 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 oxidizers increase 10- to 100-fold after six weeks, then slowly decline over the rest of the year. Currently, there are no similar direct estimates of bacterial populations responsible for either methane oxidation or denitrification. However, measurement of these processes indicates lower activity of methane-oxidizing bacteria and higher activity of denitrifying bacteria in the soils receiving N fertilisers. Both activities were much higher in the Broadbalk Wilderness (see p.19), indicating that soil cultivation may have a major disruptive effect on these microbial populations.

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Weeds on Broadbalk

Weeds were controlled initially by hand-hoeing and fallowing but, since 1964, herbicides have been applied to the whole experiment except Section 8. Since 1867, 130 plant species have been recorded on Broadbalk, but many of these occur only sporadically. Detailed weed surveys from 1930 to 1979 provide a unique 50-year record, and were restarted on Section 8 in 1991. Between 1991 and 2002, 50 plant species were recorded in the annual surveys. About 30 of these species were recorded every year, with nine species common on many plots: *viz*. black-grass (*Alopecurus myosuroides*), common chickweed (*Stellaria media*), common poppy (*Papaver rhoeas*), common vetch (*Vicia sativa*), creeping thistle (*Cirsium arvense*), parsley piert (*Aphanes arvensis*), scentless mayweed (*Tripleurospermum inodorum*), shepherd's needle (*Scandix pecten-veneris*) and Venus's-looking-glass (*Legousia hybrida*).

Papaver rhoeas on Broadbalk

Analysis of the 1991-2002 survey data showed clearly how the frequencies of individual species are differentially influenced by applications of inorganic N fertiliser. Common chickweed is greatly favoured by increasing amounts of N fertiliser from 0 to 288 kg N ha^{-1} but other species are strongly disadvantaged (e.g. black medick, *Medicago lupulina*, and field horsetail, *Equisetum arvense*). Some species were only slightly disadvantaged (*e.g.* common vetch and parsley-piert) and yet others showed little response to increasing N rates (*e.g.* black-grass and common poppy). These striking differences in species frequency between plots in close proximity show clearly the ecological adaptation of species to N availability. Weed seeds collected from Section 8 have been used in various ecological studies, including research on herbicide resistance.

Broadbalk also provides an invaluable reserve for seven plant species that are rare, uncommon or declining nationally. These are: corn buttercup (*Ranunculus arvensis*), corn cleavers (*Galium tricornutum*), field gromwell (*Lithospermum arvense*), 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 eight plants were seen in 2004 and 11 in 2005.

The revised atlas of British and Irish Flora includes a list of species that have shown the greatest relative decreases 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.

Both eyespot (*Oculimacula* spp.) and take-all (*Gaeumannomyces graminis* var. *tritici*) are common, and have been assessed on selected plots regularly since the introduction of rotations. It was on this field that, in 1935, eyespot was first identified in the UK. Comparisons of yields and of differences in amounts of take-all between continuous wheat on Broadbalk and wheat in other fields growing shorter sequences of cereals culminated in the development of the hypothesis of 'take-all decline'. This phenomenon, although still inadequately understood, has since been shown to be common when cereals are grown continuously. Since the introduction of rotations, take-all decline can be demonstrated on Broadbalk where severe symptoms are often seen in the short sequences of wheat but less commonly in the continuous wheat.

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 a ditch. The drains were not intended for experimental use, but in 1866 they were opened, and drainage water collected and analysed. 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 in the field 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

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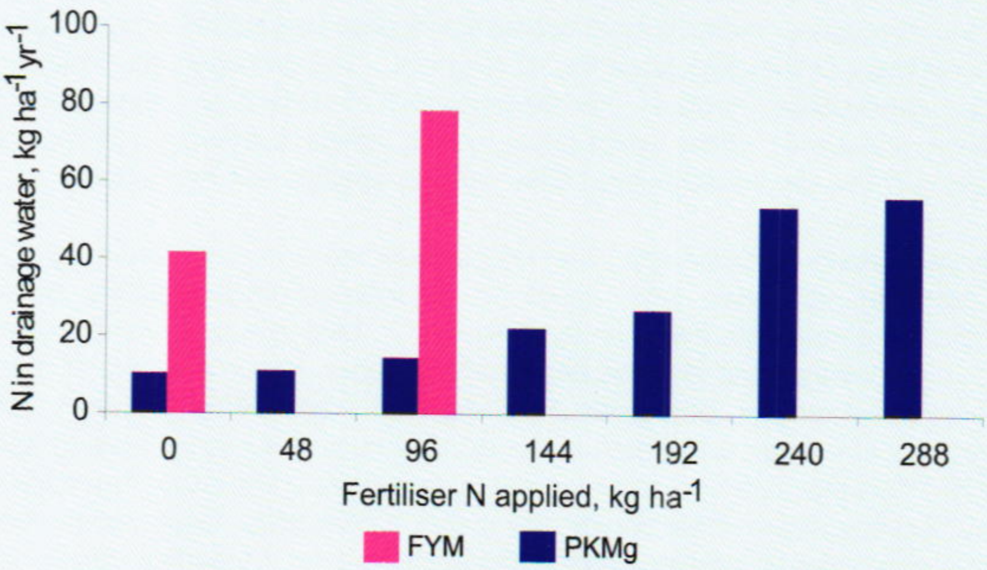
sections, and because some drains ran intermittently it was no longer possible to know where the drainage water was coming from. The drains on Section 9 (nearest the drainage ditch) were, therefore, replaced in autumn 1993. The old drains, draining Sections 0-8, were intercepted and taken to waste. The 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 drains at 75 cm depth.

Fig.4 Broadbalk. Mineral N in drainage water, mean 1990-98



The average amounts of NO_3-N lost through the drains each year are shown in Fig 4. Even where no N fertiliser had been applied for more than 150 years, about 10 kg ha^{-1} of NO_3-N is lost each year. Most N is lost where the amount of fertiliser N applied exceeds that needed for "optimum" yield or where FYM has been applied for many years. The EU limit for the maximum concentration of N allowed in potable waters (11.3 mg N l^{-1}) is usually exceeded where the larger amounts of fertiliser N or FYM have been 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.

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 100 mg kg^{-1} of available-P (Olsen P) depending on the treatments. 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.

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