The Broadbalk Wheat Experiment, Rothamsted, UK: Crop yields and soil changes during the last 50 years

Paul R. Poulton[a,*], A. Edward Johnston[a], Margaret J. Glendining[b], Rodger P. White[b], Andrew S. Gregory[c], Suzanne J. Clark[b], Wendy S. Wilmer[a], Andy J. Macdonald[d], and David S. Powlson[a]
[a]Sustainable Soils and Crops, Rothamsted Research, Harpenden, Herts, United Kingdom
[b]Intelligent Data Ecosystems, Rothamsted Research, Harpenden, Herts, United Kingdom
[c]Protecting Crops and the Environment, Rothamsted Research, Harpenden, Herts, United Kingdom
[d]Sustainable Agriculture Sciences, Rothamsted Research, Harpenden, Herts, United Kingdom
[*]Corresponding author: e-mail address: paul.poulton@rothamsted.ac.uk

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Abstract

Long-term experiments (LTEs) are a vital source of information contributing to understanding and assessing the sustainability of agricultural systems. The Broadbalk Wheat Experiment at Rothamsted Research, UK, started in 1843, is the oldest continuing LTE in the world. In 1968, and later, major modifications were made to the experiment. These included the introduction of short-straw winter wheat varieties, growing wheat in rotation with other crops, for comparison with continuous (monoculture) wheat and testing higher rates of N fertilizer (up to 288 kg N ha^{-1}). Other changes included the use of herbicides and other agrochemicals, except on selected sections. Regular liming continued to maintain soil pH. This paper reports crop yields and soil changes since 1968 and summarizes other studies including the incidence of weeds, pests and crop diseases, effects of treatments on nitrate and phosphate movement to drainage water, greenhouse gas fluxes, measurements of N and S inputs from the atmosphere, and many other factors.

The change to short-straw varieties led to a doubling of grain yields. In recent years with *cv.* Crusoe yields of first wheat after a 2-year break in a rotation were >3 t ha^{-1} greater than continuous wheat, mainly because of decreased incidence of soil-borne pests and diseases. On average, yields of continuous wheat tended to increase at N rates up to 240 or 288 kg N ha^{-1} while the 1st wheat after a 2-year break often needed less N to reach maximum yield. Best yields now exceed 12 t ha^{-1} in some years.

1. Introduction

Long-term experiments (LTEs) are one vital tool for studying the impacts of agricultural management practices on crop production, soil properties and the interactions between agriculture and the wider environment. Consequently, LTEs can contribute to an understanding of the sustainability of different farming systems. The Broadbalk Wheat Experiment, which began in autumn 1843, is the longest running LTE globally and a prime example of a long-term agricultural experiment that combines continuity with adaptation to address emerging practical or scientific issues. That the experiment is still relevant to agricultural science 180 years later is because changes in its management have only been made after careful consideration, and only when needed to ensure its continuation or to address new scientific questions. As the effects of global climate change become ever more apparent (IPCC, 2023), LTEs become increasingly important. With the global population predicted to reach almost 10 billion by 2050 (www.un.org/en/global-issues/population), we need LTEs to help assess the sustainability of different agricultural systems if we are to maintain, or increase, food production. Importantly, we need to know what effect those systems might have on the wider environment and how the environment affects them. The value of these experiments has been discussed in numerous papers including Brown (1991), Leigh and Johnston (1994), Johnston and Powlson (1994), Powlson and Johnston (1994), Powlson et al. (2013), Körschens (2021), Ostler et al. (2023). Despite their many unique benefits, LTEs have limitations that must be acknowledged; several of these are discussed here in the context of the Broadbalk Wheat Experiment. They include:

(a) Plot size. This can lead to "edge effects" as discussed later. Additionally, in plot-based experiments with different treatments it is not possible take account of processes that occur at the landscape scale such as soil erosion or the lateral spread of pests and diseases or of beneficial insects.

(b) The sustainability of agricultural systems is highly dependent on economics and on the behavior of farmers as influenced by local, social or infrastructure factors. These are generally not amenable to study within an LTE, although data on inputs and yields can be fed into economic analyses (Barnett et al., 1995).

Broadbalk was first sown with an experimental crop of winter wheat (*Triticum aestivum*) in autumn 1843 and wheat has been grown on all, or part, of the experiment every year since. It was the second large scale field experiment established by John Bennet Lawes at Rothamsted. The first, Barnfield, on root crops, was begun a few months earlier (Lawes, 1847) but has been in grass since the 1970s. Broadbalk is therefore the oldest continuing field experiment in the world which, although modified over the years, has continued in much the same form. In the following years, Lawes, together with Joseph Henry Gilbert, a trained chemist, who joined Lawes in June 1843, established other experiments on cereals, legumes and permanent pasture, which eventually became long-term. Several still continue and are known collectively as the Rothamsted Classical

Experiments (Macdonald et al., 2018). They form part of what is now the Rothamsted Long-term Experiments National Bioscience Research Infrastructure (RLTE-NBRI) at Rothamsted Research.

Other LTEs were started at Woburn, Bedfordshire, in 1876 (Voelcker, 1897) with advice from Lawes and Gilbert, and at Saxmundham, Suffolk, in 1899 (Cooke, 1975), both in the United Kingdom. Others, around the world, include Sanborn in the United States in 1888 (Miles and Brown, 2011), Bad Lauchstaedt in Germany in 1902 (Körschens, 2021), and Askov in Denmark in 1894 (Christensen et al. (2006). These, and many others are an extraordinarily valuable resource which can and should be utilized as much as possible. Collaborating with scientists managing other LTEs in networks such as SOMNET (Smith et al., 1997) or the Global Long-term Agricultural Experiments Network, GLTEN, (https://glten.org/) helps to enhance the value of participating LTEs.

Lawes and Gilbert described the Broadbalk field as "fair average wheat land." and the soil as "a somewhat heavy loam, with a subsoil of raw yellowish red clay, but resting in its turn upon chalk, which provides good natural drainage" (Lawes and Gilbert, 1864). Their purpose in setting up the experiment was to answer several important questions, including:

(a) What was the grain yielding potential of such land.
(b) How long might that potential last.
(c) What constituents of the soil would soonest show signs of exhaustion.
(d) To what extent would the findings be applicable to other arable land in the United Kingdom.

The questions they set indicate that Lawes and Gilbert were attuned to the concept of sustainability long before it became a dominant theme in agriculture and environmental science. To address these questions, they tested various combinations of the major nutrients found in wheat grain and straw, including nitrogen (N) potassium (K), phosphorus (P), magnesium (Mg), sodium (Na) and silica (Si). N was applied in various inorganic forms and in farmyard manure (FYM) or in rape cake (Rothamsted Research, 2018). They also decided to grow the wheat on Broadbalk as a monoculture, even though this was unusual at the time, as they thought this would simplify data interpretation and help them better understand what the main nutrient requirements of wheat were.

Winter wheat was a major crop in the England in the 19th century and is the most widely grown cereal in the 21st century with >50% of the arable acreage in England sown to winter wheat (www.gov.uk). World-wide, wheat represents *c.* 28% of total cereal production (www.fao.org).

The fact that Broadbalk is still relevant to modern agricultural practice, to environmental studies, to scientists wishing to model the effects of long-term management on, e.g., soil organic matter (SOM) and those seeking to assess the potential effects of global change on the sustainability of agricultural systems, bears witness to the astonishing foresight of Lawes and Gilbert who established and maintained Broadbalk and other long-term experiments in the mid-19th century. Indeed, the conference held in 1993 to mark the 150th anniversary of the start of the Broadbalk Experiment was entitled *Insight from Foresight* (Leigh and Johnston, 1994). Credit must also go to the successive generations of scientists at Rothamsted, who, with the support of the Lawes Agricultural Trust (LAT) and the UK Biotechnology and Biological Sciences Research Council (BBSRC), have continued the experiments long after the original questions they were set up to address have been answered. The experiments are a valuable scientific asset, but, equally remarkable is the Rothamsted Sample Archive of crop and soil samples which dates to the 1840s. It also includes samples of inorganic and organic inputs. This unique resource gives us a window back in time, providing a record of environmental and management change and allowing us to analyze samples retrospectively for different aspects of plant nutrition and pathology, soil fertility and pollution; many of which could not have been imagined 180 years ago. Equally important has been the effort involved over the last 30+ years to put the information and data accumulated since 1843 into an electronic database (www.era.rothamsted.ac.uk) and to make this accessible to scientists world-wide as the Electronic Rothamsted Archive (e-RA) (Perryman et al., 2018).

We do not regard the experiment as a “museum piece” which should never be changed; indeed, its great strength lies in the fact that it has been modified over the years. Some changes have been needed to ensure its continuation, e.g., fallowing and/or the use of herbicides to control weeds or liming to prevent the soil of some treatments becoming too acid for winter wheat. Others have been made to ensure its relevance, e.g., modern cultivars, larger N rates, the use of pesticides and the introduction of crop rotations for comparison with wheat in monoculture. Broadbalk has evolved over the years to address emerging problems or to answer new scientific questions; the challenge has always been to make changes without compromising the long-term integrity of the experiment and the data generated by it.

A comprehensive review of the experiment was published in 1969 (Rothamsted Experimental Station, 1969); some details and many links to that review (all available electronically) are given here. In this paper, we describe the major changes that were introduced in the late 1960s and modifications that have been made since. The effect of these changes on crop yields, nutrient uptakes and various soil parameters are discussed and related to earlier years of the experiment. We also give examples of how crop and soil samples and data from the experiment have been used over the last 50+ years to investigate specific points of interest. Our purpose is to highlight the extent and value of the data and its availability to other scientists, particularly to modelers and those looking at the long-term sustainability of cropping systems and the potential effects of global change. These data are available through the e-RA database (www.era.rothamsted.ac.uk).

2. Historical background

The historical context in which Lawes and Gilbert established their pioneering experiments was considered by Johnston and Garner (1969). In the first half of the 19th century the use of inorganic fertilizers was not common, and the fertilizer industry was in its infancy. Lawes had conducted pot and small-scale field trials in the 1830s/early-1840s on the value of different inorganic fertilizers (e.g., Lawes, 1842) and in 1842 he successfully patented an industrial process for the manufacture of superphosphate (Johnston and Poulton, 2019). He established two factories in London making superphosphate and importing other fertilizers, e.g., Chilean nitrate and guano, and used part of the profits to fund the experiments at Rothamsted. Lawes sold his factories in 1872 and, with part of the proceeds (equivalent to *c.* $20 million now), established the Lawes Agricultural Trust (LAT) in 1889 to oversee research at Rothamsted. No government funding was forthcoming until 1910/11. In 1934, when the Lawes family decided to sell the Rothamsted estate, the LAT were able to raise money by public subscription to purchase the estate and secure the land upon which the LTEs were sited.

In relation to SOM, which is discussed later, it is worth noting that the Broadbalk field has been in arable cropping for very many years. The estate is known to have existed since the 12th century and there is a map of Rothamsted, dated 1623, in which Broadbalk (then called Lower Shepcote

Fielde) is shown as being arable at that time (Boalch, 1953). Indeed, it is possible that parts of the estate have been farmed since Roman times. Rothamsted is <10 km from St. Albans, Hertfordshire (Verulamium; a major Roman city) and the remains of a Romano-British cemetery or mausoleum, only *c.* 100 m from Broadbalk, were excavated in 1937; the site is now a scheduled monument (Historic England, 1998).

3. Layout of the experiment, treatments and management

Unless stated otherwise the year given is the year of harvest; i.e., the year following planting of autumn-sown wheat.

Details of the initial layout of the experiment are given by Johnston and Garner (1969). In the 1840s, arable fields at Rothamsted were cultivated in a "ridge and furrow" system. Each year on Broadbalk, and always in the same position, long narrow strips running the length of the field were plowed to create a ridge in the center and leave a furrow at the outer edge. Lawes realized that these well-defined strips were ideal for applying the different treatments he wished to test (Fig. 1). Since the experiment was divided into 5 sections in 1926 (Fig. 2), then 10 sections in 1968 (Fig. 3), we have tended to regard the area of each treatment strip within a section as a "plot"; with an additional suffix descriptor (0–9) to identify the section (e.g., plot 07 in section 5 would be 075).

The experiment initially comprised single or double strips which were 3.76 or 7.52 m wide and *c.* 300 m long (Glendining and Poulton, 2021). In the first 8 years, the double strips were divided length-ways and the two halves often received different treatments. From 1852 to 1967 most halves received the same treatment but were harvested separately until 1893. In 1894, the two single strips, 03 and 04, were merged and harvested as one (designated strip 03).

One major change was made within 1 year of the experiment starting. Lawes and/or Gilbert realized that it was a mistake to have a Nil strip (control with no inputs, strip 03) butted up to a treatment receiving $35\,\mathrm{t\,ha}^{-1}$- of FYM (strip 02). The FYM treatment was reduced in width and a wide path introduced between the FYM and Nil strip. In 1885, a second FYM treatment was created. Various other treatments were also tested on strips which did not run the full length of the field; these are not discussed here.

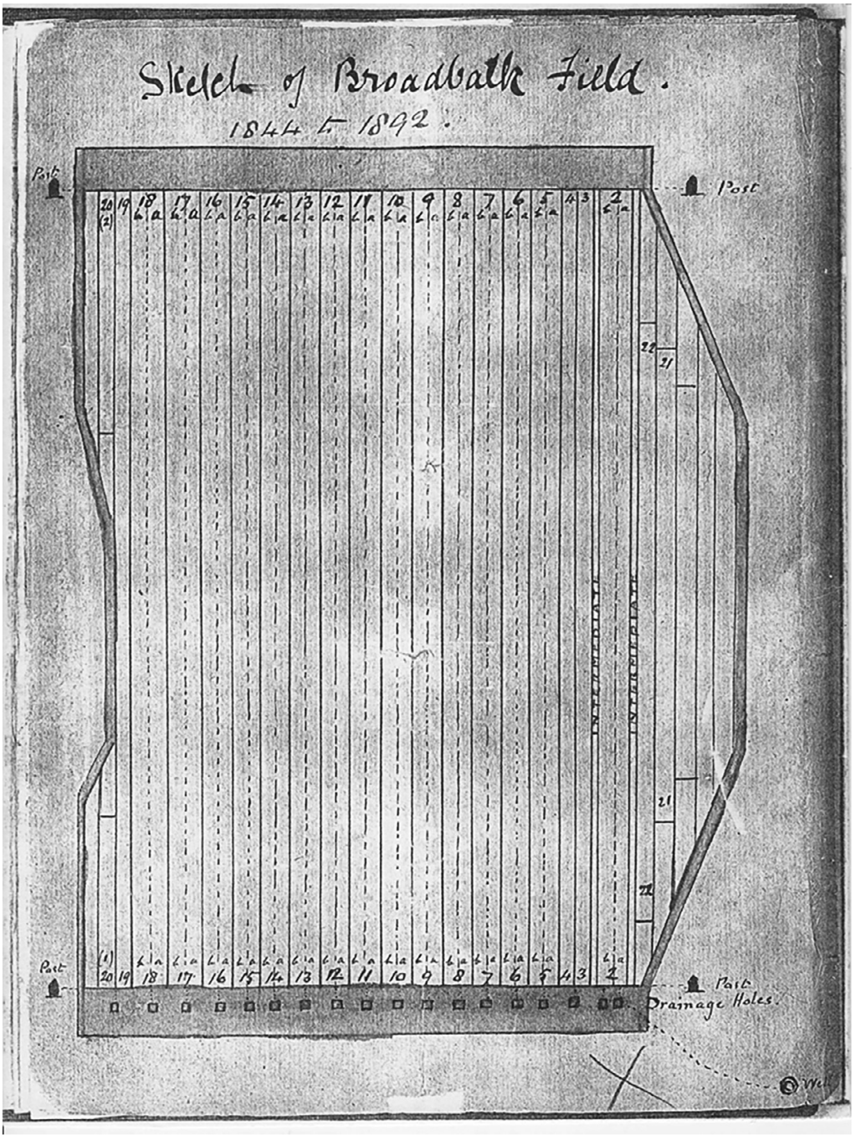

Fig. 1 Sketch plan showing layout of the experiment prior to 1894. Broadbalk Wheat Experiment.

Like many other long-term experiments at Rothamsted and elsewhere, treatments were not randomized or replicated as modern field experiments would be. Statistical evaluation of the data is therefore limited. However, the strips were large as it was always intended that

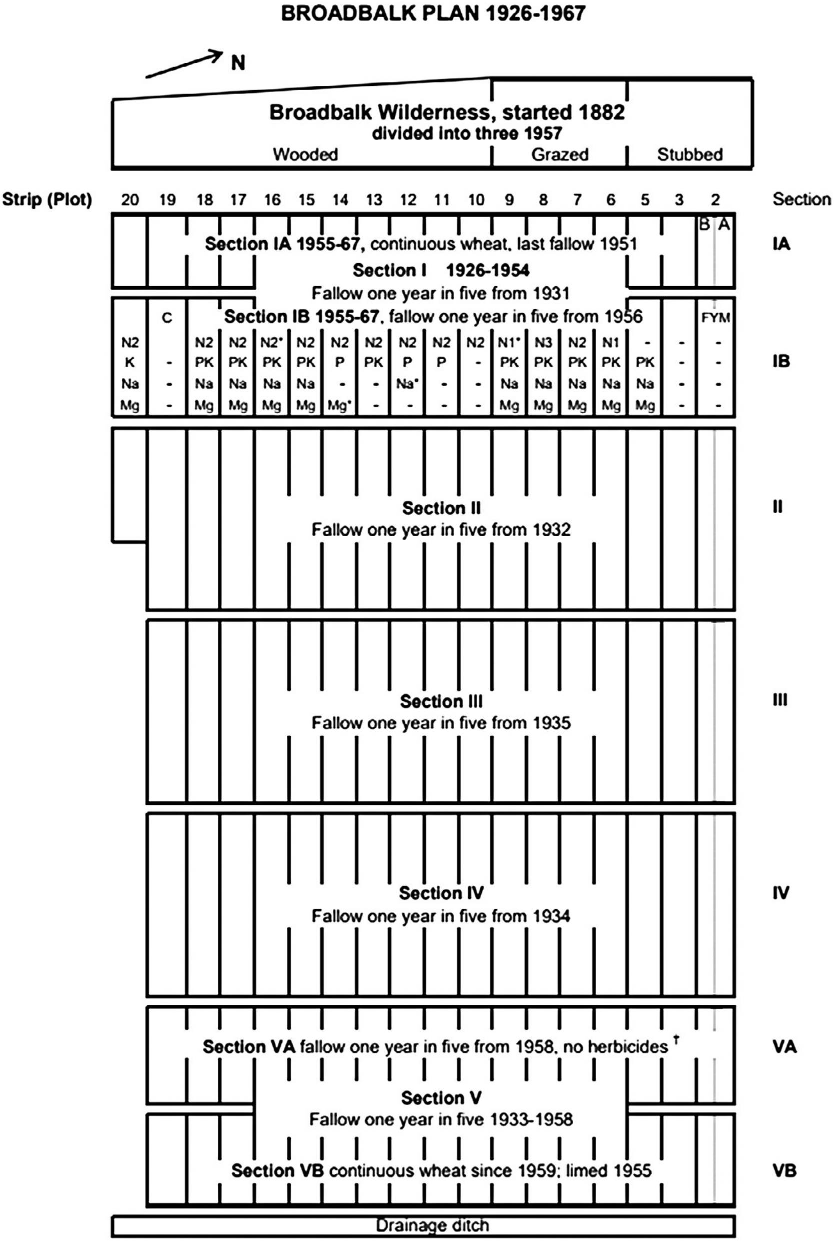

Fig. 2 Generic plan of the experiment, 1923–67, after its division into five sections in 1926. Broadbalk Wheat Experiment.

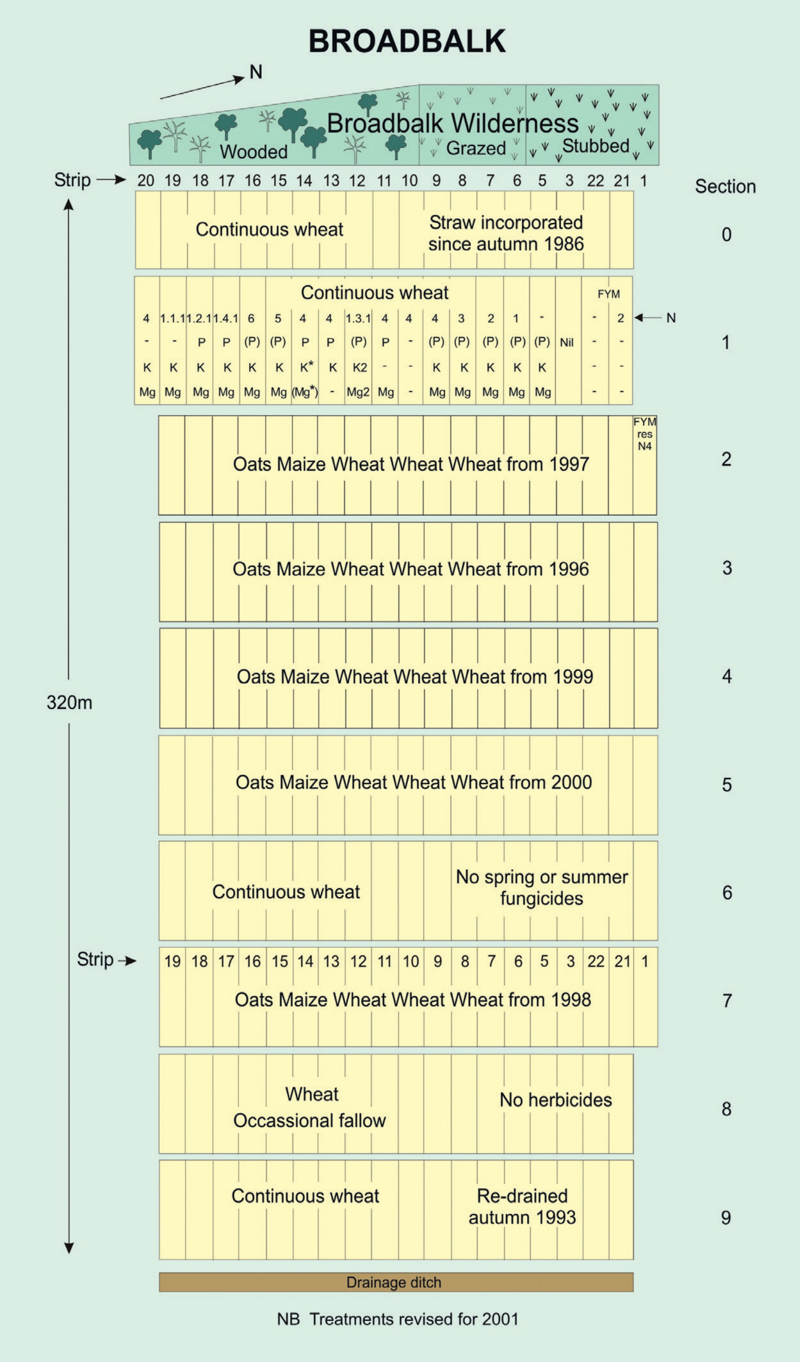

Fig. 3 Generic plan of the experiment after its division into 10 sections in 1968. Broadbalk Wheat Experiment.

they would be demonstrated to the farming community. Their size gives us confidence that the findings are real and that the trends we see are as a result of particular treatments rather than an artifact of their position in the field. It has also proved invaluable as it allowed later division into smaller units to test different management practices.

Before considering the changes made since the 1960s, it is helpful to look at treatments during the first 125 years of the experiments. These were given by Johnston and Garner (1969) and can be found in e-RA with metric units (Rothamsted Research, 2018). In the first 8 years treatments on many strips changed to answer specific points of interest. Of particular note was the increase in the amount of N tested from only *c.* 15 kg ha^{-1} in 1844 to 12, 24, 36 and 48 kg N ha^{-1} in 1845. Progressively larger amounts were tested in the next few years (Lawes and Gilbert, 1864). This helped to refute the assertion made by Liebig in the third edition of his book published in 1843 that crops could get sufficient N from the air; this was in direct contrast to his comments in the first edition (Liebig, 1840) which stated that additional N applied to soil was required to increase the yield of crops. This resulted in a long-running and very acrimonious argument between Lawes and Gilbert at Rothamsted and Liebig in Giessen, Germany. Much of this argument was conducted in the scientific journals of the time (Lawes and Gilbert, 1851, 1855). This dispute with Liebig is often regarded as one of the reasons why Lawes and Gilbert continued Broadbalk and the other LTEs.

After 8 years, Lawes and Gilbert decided that, with some exceptions, the treatments on each strip should be fixed (Lawes and Gilbert, 1864). As before, various combinations of P, K, Mg, Na without N or with different rates of N as either ammonium sulfate or sodium nitrate were compared with strips which received either no inputs (Nil) or organic manures (Rothamsted Research, 2018).

Weeds, which were initially controlled by hand-hoeing by large groups of men, had become a problem by the 1890s and parts of the experiment were fallowed to help control them. The problem was exacerbated when many of the farm workers who left to fight in the First World War did not return (Thurston, 1969) and by the agricultural labor force drifting from rural areas into the larger towns in search of higher wages. The shortage of labor allowed weed competition to become so severe that yields on all treatments declined markedly by the 1920s. To help control weeds the experiment was divided into five sections (I–V) in 1926.

Sections I–III were fallowed in 1926 and 1927, followed by Sections III (again), IV and V in 1928 and 1929. From 1931 one section was fallowed each year and four cropped in a 5-year cycle (Appendix Table A1a). In autumn 1954, Sections I and V were divided for a test of liming and the use of herbicides. Fig. 2 shows the experiment after it was divided into five sections (Rothamsted Research, 2021a). From 1926 to 1967, fertilizers and organic manures were not applied to the sections being fallowed.

3.1 Changes in 1967 and later

In the 1960s, the continuation of the long-term experiments at Rothamsted, including Broadbalk, was being questioned. If they were to remain relevant to modern agriculture (and retain government funding) they had to be changed. After much discussion, involving scientists from a range of disciplines, major modifications were introduced in autumn 1967 in advance of the crops to be harvested in 1968. Each of the existing 5 sections (I–V) were divided to create 10 sections (0–9; Fig. 3). Two 3-course rotations began on six of the sections and the remaining four sections reverted to, or remained in, continuous wheat (Rothamsted Research, 2021b). The rotations were fallow, wheat, wheat on Sections 3, 5 and 6; potatoes (*Solanum tuberosum*), beans (*Vicia faba*), wheat on Sections 2, 4 and 7 (Appendix Table A1b). This allowed, for the first time, a comparison of wheat grown continuously with wheat grown in rotation with other crops. A key aspect of this comparison was more detailed research on the effects of take-all (*Gaeumannomyces tritici*, formerly *Gaeumannomyces graminis* var. *tritici)* on yield. Herbicides began to be used on the whole experiment except Section 8.

Another major change in 1968 was replacing the long-strawed cultivar, Squarehead's Master, with a modern shorter-strawed cultivar, Cappelle Desprez, which was less prone to lodging and had a greater grain yield potential. This allowed the maximum amount of N tested to be increased to 192 kg ha^{-1} (N4). The two different forms of N (ammonium sulfate and sodium nitrate) were replaced by calcium ammonium nitrate (ammonium nitrate since 1986). The strip receiving FYM since 1885 now also started to receive 96 kg N ha^{-1} in spring and an additional treatment was started which received FYM plus PK and 192 kg N ha^{-1} (strip 01; this did not run the full length of the experiment) (Fig. 3). Table 1 shows the treatments up until 1967.

Other modifications have been made since 1967 (Table 1); always after much discussion as it sometimes involved stopping some existing treatments which were deemed to be less important. Major changes have needed agreement from the LAT.

Cultivars have changed as newer varieties have appeared on the UK recommended lists; all have been bread-making wheats, except for *cv*. Apollo (1991–95) which was a feed wheat. New varieties are chosen on the basis of disease resistance, a potentially larger yield and the hope that they will remain on the recommended list for at least 5 years. Although it became increasingly outclassed *cv*. Hereward was grown for 17 years as it was popular with millers.

The two 3-course rotations were stopped in 1978 and, after a brief hiatus, a 5-course rotation was started on five sections (Appendix Table A1b) which allowed a comparison of wheat grown continuously or as the 1st, 2nd or 3rd wheat crop after a 2-year break. The rotation of fallow, potatoes, wheat, wheat, wheat on Sections 2, 3, 4, 5 and 7 was phased-in from 1982 and was, in turn, replaced by oats (*Avena sativa*), maize (*Zea mays*), wheat, wheat, wheat in 1996. Two higher N rates, 240 and 288 kg N ha^{-1} (N5 and N6), were introduced in 1985. FYM and fertilizers (except N) have been applied to fallows in the rotations (1968–95) and to the occasional fallows on Section 8. No FYM or fertilizer N was applied to the oats from 1996 to 2018. Fertilizer N was applied to the beans (1968–78). Section 6 reverted to continuous wheat.

Straw is baled and removed from the plots except on Section 0 where it has been incorporated since autumn 1986. In 1987–90, the older long-strawed cultivar, Squarehead's Master, was grown side-by-side with the then current short-strawed cultivar, Brimstone, on selected treatments within sections growing either continuous wheat, with or without fungicides, or wheat as the first crop after a 2-year break (Appendix Table A1b).

In 2000, another major review of the experiment led to changes for 2001 (Table 1). On four strips (12, 17, 18 and 19), split applications of N were introduced to compare with the largest four N rates where N was applied as a single application. In one of these new split N treatments (N1 + 3 + 1, strip 12; see Table 1) large inputs of K and Mg were applied to ensure that

Table 1 Fertilizer and organic manure treatments, 1852–2018. Broadbalk Wheat Experiment.
Treatments

Strip	Until 1967	1968–1984	1985–2000	2001–2018
2.2	FYM	FYM	FYM	FYM
2.1	FYM since 1885	FYM N2	FYM N2	FYM N3[a]
01	–	FYM N2 PK	FYM N4 PK	(FYM) N4
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
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
19	C	C	(C)	N1 + 1 + 1KMg
18	PKNaMg(A)	N2 ½[PK(Na)Mg]	N1+3 ½[PKMg](A)[b]	N1 + 2 + 1 PKMg
12	N2 P Na	N2 P Na	N2 P Na	N1 + 3 + 1 (P)KMg2[c]
17	N2 (A)	N2 ½[PK(Na)Mg]	N0 + 3 ½[PKMg](A)[b]	N1 + 4 + 1 PKMg
10	N2	N2	N2	N4
11	N2 P	N2 P	N2 P	N4 P Mg
13	N2 PK	N2 PK	N2 PK	N4 PK
14	N2 P Mg*	N2 PKMg*	N2 PKMg*	N4 PK*(Mg*)
20	N2 KNaMg	N2 K(Na)Mg	N2 KMg	N4 KMg

Annual treatment per hectare		
FYM:	Farmyard manure at 35 t	N to wheat as single applications (mid-April)
(FYM):	Farmyard manure at 35 t 1968–2000 only	N1, N2, N3, N4, N5, N6:48, 96, 144, 192, 240, 288 kg N
P:	35 kg P as triple superphosphate	
(P):	35 kg P as triple superphosphate until 2000;	Split N to wheat (mid-March, mid-April, mid-May)
	to be reviewed in 2025	N1 + 1 + 1:48 + 48 + 48 kg N (strip 19)
K:	90 kg K as potassium sulfate	N1 + 2 + 1:48 + 96 + 48 kg N (strip 18)
K2:	180 kg K as potassium sulfate, 2001–2005.	N1 +3 + 1:48 + 144 + 48 kg N (strip 12)
	(plus 450 kg K in autumn 2000 only)	N1 +4 + 1:48 + 192 + 48 kg N (strip 17)
K*:	90 kg K as potassium chloride	
Mg:	12 kg Mg as Kieserite. Was 35 kg Mg every	Beans, 1968–1978, received FYM and N (and PK, etc.)
	3rd year 1974–2000. Previously 11 kg Mg	Potatoes, 1968–1996, did not receive autumn N
	as magnesium sulfate until 1973	Fallows, 1968–1995, in rotation and on Section 8 since
Mg2:	24 kg Mg as Kieserite, 2001–2005	1968, did receive FYM, PK, etc. but no N
	(plus 60 kg Mg in autumn 2000 only)	Fallows, 1926–1967, did not receive manures or fertilizers
(Mg*):	30 kg Mg as Kieserite 1974–2000. Previously	Oats, 1996–2017 did not receive FYM or N
	31 kg Mg as magnesium sulfate until 1973	
(Na):	16 kg Na as sodium sulfate until 1973;	N applied as:
	55 kg Na on strip 12 only until 2000 (57 kgNa until 1973)	ammonium sulfate[d] or sodium nitrate (N*) until 1967
		calcium ammonium nitrate (Nitro-chalk, *c.*26% N) 1968-85;
(C):	Castor meal to supply 96 kgN until 1988	ammonium nitrate (Nitram, 34.5% N) since 1986;

[a] FYM N2 2001–2004.

[b] (A) Treatment to strips 17 and 18 alternated each year. From 1968 both strips received N2 and ½-rate PK(Na)Mg; from 1980 to 2000 wheat on strips 17 and 18 received N1 + 3, i.e., autumn N1 in alternate years plus N3 in spring.

[c] N1 + 3 + 1 (P)K2Mg2 from 2001 to 2005.

[d] For detailed information on treatments and management until 1967, see Johnston and Garner, 1969 and Appendix Tables A1, A2 and A3.

Between 1968 and 2016 the 35 t ha^{-1} application of "fresh" FYM had, on average, 24% dry matter and contained 249 kg N (range 158–322 kg), 47 kg P, 333 kg K, 146 kg Ca, 30 kg Mg, 28 kg Na, 42 kg S (1999–2016 only).

Note: Sulfur has been added (except on strip 14 since 2001) as the sulfate anion with K, Mg and Na, as calcium sulfate in single superphosphate, in FYM and ammonium sulfate applications. S last applied to strip 14 in 2000.

these nutrients did not limit yield. On "unbalanced" treatments (strips 10, 11, 13, 14 and 20) the amount of N applied was increased to 192 kg ha^{-1} and on strip 2.1 the amount of N applied to the FYM treatment was increased from 96 to 144 kg ha^{-1} in 2005. On strip 01 applications of FYM + PK, that had started in autumn 1967 were stopped, but applications of 192 kg N ha^{-1} continued.

Although P had been applied for more than 150 years, it was decided that, from 2001, P dressings would be withheld on some strips until concentrations of plant-available P had fallen to an agronomically appropriate level.

By default, most of the experiment receives sufficient sulfur (S) from the FYM or fertilizers that are applied as potassium sulfate or kieserite (containing S). However, since 2001, K on strip 14 has been applied as potassium chloride and kieserite has been withheld (concentrations of exchangeable Mg in the soil were sufficient for maximum yield); S is now the limiting nutrient on this strip.

In the 1990s, the perennial weed, *Equisetum arvense* (field horsetail), became a problem on plots receiving little or no N. After harvest 2002, Section 0 was left uncultivated; no crop was grown in 2003 and 2004. Seven different herbicides were applied to 3 m × 6 m sub-plots within plots 030, 050 and 190 to identify the best means of controlling this deep-rooted weed.

From 2018, a new 5-course rotation (wheat, wheat, oats, wheat, beans) was phased-in. This will allow a comparison of continuous wheat with a first wheat after a legume and a non-legume. The beans do not receive FYM or fertilizer N. The oats receive FYM and fertilizer N at half of the rate applied to the wheat. Results from this latest phase of the experiment are not discussed.

3.2 Cultivations, liming, pesticide use, fertilizer and organic manure applications, drilling, harvesting and chemical analysis

Details of cultivations were given by Johnston and Garner (1969). Plowing, originally by oxen or horses, would only have been to 10–15 cm (4–6 in.). Until 1892, each strip, was plowed separately and no soil would have been moved from one strip to the next. Tractors were first used for plowing in 1925. With more powerful tractors plow depth gradually increased but is restricted to about 20–23 cm (8–9 in.). To minimize soil movement when plowing, the soil is turned one way in 1 year and in the opposite direction the following year.

Although large amounts of chalk were applied to the field *before* the experiment started, by the 1940s soil pH on some treatments, particularly those receiving higher rates of N as ammonium sulfate, had declined to a level where the growth of wheat might be compromised. Differential amounts of chalk were applied between 1955 and 68 and regular basal dressings between 1976 and 92. No chalk was needed between 1993 and 2007 but differential dressings, based on soil pH measurements re-started in 2008 (Glendining et al., 2022).

Seed dressings were first tested in 1912, again in 1923/4 and have been used regularly since 1932. Herbicides have been used since 1957, initially on half of one existing section (Ia) and, since 1964, on the whole experiment except for half of Section V (Va; now Section 8; see Fig. 3). Summer fungicides have been used, when necessary, on the whole experiment since 1979, except on Section 6 where they have not been used since 1985. Growth regulators have been used since the mid-1980s. Insecticides and molluscicides are rarely used.

Organic manures and most inorganic fertilizers are applied in autumn and plowed in. The dates of FYM applications, plowing, drilling, N application and harvest and the cultivars grown from 1968 to 2018 are given by Poulton and Glendining (2023). All fertilizer N is now applied to the growing crop in spring but previously some was applied in autumn. Winter wheat is usually drilled in October or November and has, occasionally, been very late sown in December–March. Spring wheat was grown in 2015 due to a very wet previous autumn. The wheat is usually harvested in August, occasionally in early September if the weather is wet, or in late July if the summer has been very dry and hot. Initially, crops were cut by scythe and a reaper binder was first used in 1902; sheaves were stooked in the field before being taken to a barn for storage before threshing. A combine harvester has been used since 1957, typically taking a strip 2.0–2.3 m wide down the center of each plot. Wheat grain and straw samples are taken to calculate yield and, for some sections, sub-samples are ground for chemical analysis and archiving. Oats and beans are harvested in the same way as wheat. For potatoes, eight rows were planted; the central four were lifted for yield. The tops were usually desiccated and yields of the tops not taken. Eight rows of maize were sown on 60 or 70 cm rows; three quadrats, each 3 rows × 3 m, per plot were cut by hand. They were harvested for forage when dry matter reached *c*. 26–30%.

Sub-samples of oat grain and straw, bean grain and straw, potato tubers and forage maize were all oven-dried, ground and retained for chemical analysis and archiving. Un-ground sub-samples of grain and straw from the continuous wheat on Section 1, from the first wheat in the rotation and from the other crops in the rotation have been archived. Since 1968 crop samples have usually been analyzed for N, P, K, Ca, Mg, Na and S (since 2000) and occasionally for trace elements. Not all sections in wheat have been analyzed every year and, in 1979–85 they were only analyzed for N. Details of the various analytical techniques are given in Appendix.

3.3 Soil type, sampling, drainage and chemical analysis

Since Lawes and Gilbert described the soil on Broadbalk in 1864 (Lawes and Gilbert, 1864), it has been classified into three related soil series within the Soil Survey of England and Wales Classification system; these are Batcombe, Hook and Charity-Notley (Avery and Catt, 1995). Internationally, the soil is classified as a Chromic Luvisol (IUSS, 2015) or as an Aquic Paleudalf (Soil Survey Staff, 1999). The morphology and classification of the soils, their mineralogy and their origin and development are described by Avery and Bullock (1969), Weir et al. (1969) and Catt (1969).

Soil samples have been taken for chemical analysis and archiving at irregular intervals. Typically, samples are air-dried. Major samplings were done in 1865, 1881, 1893 (detailed in Dyer, 1902), 1904, 1914, 1936, 1944, 1966 (Johnston, 1969a,b) and 1987/88; not all plots were sampled on each occasion (Appendix Table A2). Since 1992 soils have been sampled more regularly with all plots being sampled over a 5-year period, except 2000 when all plots were sampled prior to treatment changes. Samples were usually taken after harvest and before plowing. Except where noted samples have been taken by 22.9 cm (9 in.) layers but, for ease of reference, this is "rounded" to the nearest centimeter in the text, tables and figures. Since the 1960s soils have mostly been sampled with semi-cylindrical gouge augers and usually only the top 23 cm layer is sampled. Typically, 15–20 cores are taken from each plot in each section with a 2 cm diameter auger; cores are bulked to give one sample per plot. Samples are not taken within 1 m of the plot edges. As major changes to some of treatments were to be made for 2001, the topsoil, 0–23 cm, of all plots was sampled in autumn 2000. In addition, on more than half of the plots, subsoils (23–46, 46–69 and 69–91 cm) were sampled. To prevent carry over of soil from the top layers to deeper layers the topsoil was first removed with a 3 cm diameter auger, and discarded, before sampling the lower depths with a pneumatic sampler fitted with a 2 cm diameter auger; 10 cores were taken per plot and bulked to give one sample for each of the three subsoil layers.

Also, in 2000, topsoil (0–23 cm) was sampled with a 4.8 cm diameter tube (two cores per plot, bulked) on more than half of the plots; the gravimetric water content, weight and bulk density of the soil was determined.

Soil samples have been taken, analyzed and archived from the "Wilderness" areas of Broadbalk, notably in 1904, 1964 and 1999. Soils have also been taken from selected plots/sub-plots/microplots on many other occasions for particular studies, but not all of these have been archived.

It is not clear why Lawes and Gilbert initially chose to sample by 23 cm (9 in.) depths. Plowing would only have been to about 10–15 cm at that time; presumably, they wanted to ensure that they included all of the cultivated layer. They did say "It is perhaps to be regretted that the depth originally fixed upon did not more nearly represent that to which the soil is more directly affected by the mechanical operations, and by the application of manure, say 6 inches. But having originally adopted 9 inches, it has been necessary to adhere to this depth subsequently, in order, as far as possible, to obtain comparable results at different dates" (Lawes and Gilbert, 1883). This decision has proved very helpful as plowing has not usually exceeded 23 cm and we have been able to compare directly results from soils taken in more recent years with those taken many years ago. In autumn 2004, the experiment was inadvertently plowed 2 or 3 cm deeper than 23 cm in a few limited areas (probably <5% of the field). The 0–23 cm layer of all plots, and the 23–46 cm layer of those plots previously sampled in 2000, were re-sampled in 2005–7 to assess the effect of the deeper plowing and to establish a new baseline (if necessary) with which future samplings could be compared.

Since 1966, soils have typically been analyzed for pH, Olsen P, exchangeable cations and organic C by the wet oxidation Tinsley method, total N by Kjeldahl, or total C and N by combustion (using a LECO or similar combustion instrument) plus inorganic C using a calcimeter. In 1876, Lawes said of the archive of soil samples "looking forward to the great questions which are being raised in regard to exhaustion of soil and restoration of fertility, I certainly think that our soil samples, and their history, takes the first place in importance" (Lawes Agricultural Trust, 1896). This has certainly proved to be the case. Many archived soils from 1865, 1881, 1893, 1914, 1936 and 1944 were sub-sampled in 2000 and re-analyzed using current analytical techniques. Some samples from 1966, 1987/88 and 1992–96 had also been previously re-analyzed for, e.g., total C and N by combustion (LECO). Unless stated otherwise, the chemical data given is from these later re-analyses. Some soils taken in the 1840s and 1850s were initially stored moist and were not suitable for re-analysis (see Section 5.1). Analytical details are given in Appendix.

The soil on Broadbalk was regarded as having good natural drainage, but to increase the number of days when manure and fertilizer applications and autumn cultivations could be carried out, field drains were installed under each treatment strip in autumn 1849 (Johnston and Garner, 1969). In the 1860s, Lawes and Gilbert realized that if they dug pits to access the drain outlets, they could measure losses of plant nutrients in the drainage. A ditch was eventually constructed in 1898 into which each drain emptied. These "horseshoe and tile" drains were still operational in the 1990s but, as the experiment had been divided into 10 sections by then, some growing crops other than wheat, it was unclear where the drainage was coming from. It was therefore decided that modern perforated plastic drains would be installed under each plot on Section 9, in autumn 1993, i.e., after Rothamsted's 150th Anniversary Conference earlier that year. The old drains were intercepted and drainage from them taken off to one side. The new drains were installed *c.* 50 cm to one side of the existing drains and at a depth of *c.* 75 cm using commercial drain-laying machinery cutting a narrow slot into which the pipe was laid. The channel above the drain was filled with coarse shingle to just below plow depth. The following year it was not possible to see any signs of disturbance.

3.4 Meteorological data and atmospheric inputs

The Broadbalk experiment has been conducted against a background of local and global change. A meteorological station located about 750 m from Broadbalk was established in the 1850s. A 1/1000th acre (*c.* 2 m^2) lead-lined rain gauge was constructed to measure daily rainfall and collect it for analysis. This was complemented by a Meteorological Office Standard MK2 cylindrical 5-in. rain gauge (an automated tipping bucket rain gauge is now used). Mean annual rainfall, 1870–2018 was 704 mm. Between 1967 and 2018, it was slightly higher, 727 mm, but varied greatly from 516 to 1059 mm. Monthly totals averaged 52–72 mm (range, 2–169 mm). Air temperature has been recorded since 1878. The increasing concentration of CO_2 in the atmosphere has been measured at Mauna Loa since 1958 (Keeling et al., 2005) and has now reached 420 ppm CO_2 (SCRIPPS Institution of Oceanography, 2023). The resulting rise in global temperature has been widely reported and at Rothamsted the increase in the average annual temperature over the last 35 years is clear (Perryman et al., 2023). The long-term average annual temperature from 1878 to 1988 was 9.0 °C and showed a very slight upward trend over that time. Since the late-1980s, the temperature at Rothamsted has increased markedly (Fig. 4), mainly because of warmer winters.

Industrialization and the use of coal-fired power stations in the United Kingdom during the 19th century and much of the 20th century led to significant increases in atmospheric pollution. The subsequent decline in heavy industry and phasing out of coal-fired power stations toward the end of the 20th century resulted in a decrease in pollution. At Rothamsted, inputs of N from the atmosphere, as wet and dry deposition, are estimated to have increased from *c.* 10 kg ha^{-1} in the 1880s to *c.* 45 kg ha^{-1} by the 1980s (Goulding et al., 1998) and are now *c.* 10 kg N ha^{-1} (Storkey et al., 2015). The amount of atmospheric N, some of which will be available to the growing plants, is ironic given the long-standing dispute between Lawes and Gilbert and Liebig. Inputs of S peaked at *c.* 65 kg ha^{-1} in the 1970s but declined dramatically to *c.* 5 kg ha^{-1} by the early 21st century (McGrath et al., 2002). For many years, rain had a pH of <5.0 but over the last 20–25 years it has become less acid and is now about pH 5.8 (Tony Scott, pers. comm).

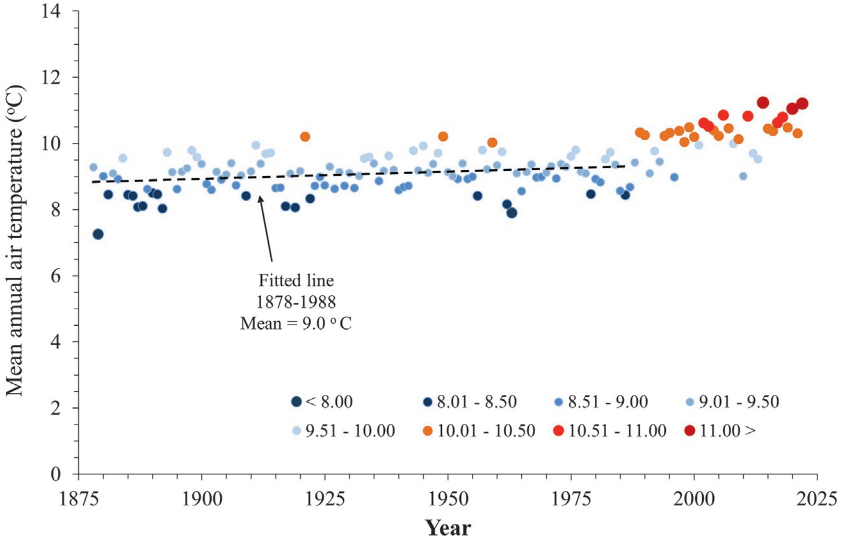

Fig. 4 Mean annual air temperature, °C, 1878–2022. Darker blues shows colder years, darker reds show hotter years. Fitted line, 1878–1988, shows a slight upward trend (mean 9.0 °C). Rothamsted. *Adapted from Perryman, S.A.M., Scott, T., Hall, C., 2023. Dataset: Annual Mean Air Temperature at Rothamsted 1878–2022. Electronic Rothamsted Archive, Rothamsted Research. https://doi.org/10.23637/rms-RMAAtemp-03.*

3.5 Statistical analysis

Like many older long-term experiments, treatments on Broadbalk were not randomized or replicated. Statistical analysis is therefore limited. We have not attempted to estimate errors on the measured soil parameters. In many instances, we think that long-term trends or changes in, e.g., total N in soil or Olsen P following treatment changes are sufficiently convincing. Statistical analysis was done through REML (Residual Maximum Likelihood) using individual years and strips within years as the random model and cultivars or groups of years by strips as the fixed model or treatments. Given the neighboring arrangement of the strips, a spatial component was added in the form of an autoregressive term across the plots for the residuals. This accounts for the lack of independence between residuals and inflates the variance between means. However, note that while the variances for means are inflated, the estimation of the autocorrelation allows the residual variance to be reduced. Note that for 1st, 2nd and 3rd wheats and other crops in the rotation, years essentially includes sections relating to the rotation sequence. Sections for continuous wheat have occasional fallow years and these are ignored. Results from this analysis are presented as tables of means for the cultivar or year group by treatment, together with the relevant standard error for each column and the F-statistic with its associated degrees of freedom for the interaction. Residual diagnostic plots were examined to determine if there was any evidence for a transformation of any of the data and in only one instance, that for potatoes (yield and nutrient uptake data) was it found necessary (errors for the log transformed data are not shown). The autocorrelation (φ) for each measure is presented at the base of each table and they are seen to be similar in every case. The effect of the autocorrelation is seen when evaluating standard errors of differences between means (not presented as this is a very large matrix).

3.5.1 Response curves

An "exponential plus linear" model (George, 1984) has previously been used to fit response curves to grain yield vs applied fertilizer N data from the Broadbalk experiment (Addy et al., 2020; Dyke et al., 1983; Johnston et al., 1994). Here, we have modeled data from selected treatments for the 17 years of cv. Hereward grown either continuously (Section 1) or as the 1st, 2nd or 3rd wheat after a 2-year break. The treatments were those receiving (P)KMg plus the seven rates of fertilizer N (0–288 kg ha^{-1}). The model is described in terms of four parameters: the linear trend, the asymptotic yield ignoring the trend, the rate of curvature of the exponential curve and the range (the difference between the asymptotic yield and that for zero N):

$$Y = A + B^{*}R^{N} + C^{*}N \tag{1}$$

where Y is the grain yield in $\mathrm{t\,ha^{-1}}$ and N is the applied N fertilizer in $\mathrm{kg\,ha^{-1}}$. Including a linear term in the model allows us to determine a maximum asymptotic yield (Y_{max}) and its associated N application (N_{max}). Parameter A is the asymptotic maximum yield, B is the range (the difference between the asymptotic maximum yield and that for zero N), R relates to the rate of curvature of the exponential component and C is the slope of the linear trend (a decline if negative). The values of R and C were constrained to be common for continuous wheat and the 1st, 2nd and 3rd wheats. Constraining C to be common allows for the subsequent "curve shifting" described below. Where there is evidence for the R parameter to be common across a series of independent responses the values of A, B and C can be estimated by least square fitting as a multiple linear regression in response to N and R raised to the power of N, rather than using an iterative least-squares fitting approach for the non-linear function. This approach further allows the exploration of how the A, B and C parameters vary between years and management, or for combinations of data, e.g., for all years for a particular rotation.

3.5.2 Superimposing yield vs N response curves

A "curve shifting" technique has previously been used to compare and attribute the benefits to cereal grain yields when they are grown either continuously or in rotation, and where a range of amounts of N fertilizer are tested (Dyke et al., 1983). When the same model is used for each of the yield vs N response relationships the curves have the same shape and the Y_{max} for each response curve can be shifted diagonally to bring it into coincidence with the other Y_{max} and produce a unified N response curve.

4. Results

4.1 Crop yields, nutrient concentrations, grain quality and nutrient uptakes

4.1.1 Wheat yields

Lawes (1847) described the Broadbalk soil as "rather a heavy loam resting upon chalk, capable of producing good wheat when well manured." On similar land in the neighborhood, wheat grown in a crop rotation,

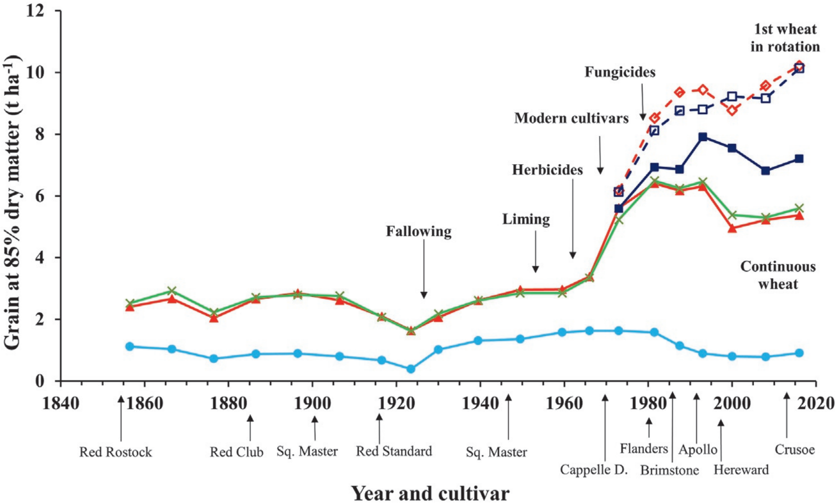

Fig. 5 Mean yields of wheat grain, t ha^{-1}, on selected treatments for different periods, showing changes in cultivar and management. Continuous wheat (mean of Sections 1 and 9 after division into 10 sections): ●, Nil; ×, (P)KMg + 144 kg N ha^{-1}; ■, largest yield with (P)KMg + N (max. 288 kg N ha^{-1}); ▲, FYM. 1st wheat in rotation: □, largest yield with (P)KMg + N (max. 288 kg N ha^{-1}; ◊, FYM + 96 kg N ha^{-1} (+144 kg N ha^{-1} since 2005) 1852–2018. Current treatments given; see Table 1 for earlier treatments. Broadbalk Wheat Experiment. Updated from Rothamsted Research (2017).

typically yielded *c.* 1.2 t ha^{-1}. Fig. 5 shows yields from selected treatments for 1852–2018. The changes reflect the improved cultivars, management and control of pests, diseases and weeds that have been introduced on Broadbalk over the years as on English farms generally.

An aerial view taken during harvest in August 1925 (Fig. 6) shows the experiment immediately before it was divided into five sections and regular fallowing was introduced to help control weeds (Appendix Table A1a). The yields shown in Fig. 5 during this fallowing period are the means of the 1st, 2nd, 3rd and 4th wheat crops after a break. Yields of wheat given no fertilizer or manure were *c.* 1 t ha^{-1} year^{-1}, similar to yields in earlier years. Perhaps more importantly, yields of wheat given PKNaMg + 44 kg N ha^{-1} were the same as those of wheat given FYM every year. Although the FYM contained much more N in total (on average *c.* 220 kg ha^{-1} at that time) most of this was not in a readily available form and the crop relied on the mineralization of organic N for its supply of N, partly from the current seasons application and partly from accumulated residues. Most of the cultivars grown then had a limited response compared with later cultivars. Yields of grain and straw for 1852–1967 (Rothamsted Research, 2023) are discussed in detail by Garner and Dyke (1969).

Fig. 6 Aerial view of the experiment, 17th August 1925. Broadbalk Wheat Experiment.

Fig. 7 Aerial view of the experiment, 2015. Broadbalk Wheat Experiment.

Fig. 5 shows the dramatic effect on grain yield of the changes made since 1968 (Fig. 5); particularly, the introduction of short-strawed cultivars, of rotations on some sections, higher N rates and the use of summer fungicides. After the change from Squarehead's Master to Cappelle Desprez, with its greater grain yield potential, mean yields of continuous wheat on the PKNaMg + 44 kg N ha^{-1} and the FYM treatments doubled to about 5.5–5.8 t ha^{-1} (Fig. 5) Grain yields of most plots receiving N were similarly increased by about 100%; those not receiving N by somewhat less. Yields of Cappelle Desprez were discussed by Dyke et al. (1983). Fig. 7 is an aerial view of the experiment taken in 2015, following its division into 10 sections in 1968.

The yields of grain grown either continuously on Section 1 or as the 1st wheat after a 2-year break are in Tables 2 and 3, respectively. Mean annual yields are given for the different cultivars except for Hereward where the

Table 2 Mean yields of winter wheat grain, $\mathrm{t\,ha^{-1}\,year^{-1}}$ at 85% dry matter, when grown continuously (Section 1). Broadbalk Wheat Experiment.

Cultivars, years grown and mean yield of grain ($\mathrm{t\ ha^{-1}\ yr^{-1}}$)

Strip	Treatments[a] from 1968	C. Desprez 1970-78[b]	Flanders 1979-84	Treatments from 1985	Brimstone 1985-90	Apollo 1991-95	Hereward 1996-2000	Treatments from 2001	Hereward 2001-04	Hereward 2005-12	Crusoe 2013-18[c]
2.2	FYM	5.85	6.27	FYM	5.76	6.42	5.99	FYM	4.18	4.89	4.89
2.1	FYM N2	5.75	8.06	FYM N2	7.68	8.43	8.19	FYM N3[e]	6.43	7.06	6.95
01	FYM N2 PK	-	-	FYM N4 PK	-	-	-	(FYM) N4	-	-	-
03	Nil	1.72	1.60	Nil	1.18	1.06	1.26	Nil	0.65	0.97	1.01
05	PK(Na)Mg	1.67	1.45	PKMg	1.30	1.26	1.28	(P)KMg	0.86	1.26	1.24
06	N1 PK(Na)Mg	3.48	3.74	N1 PKMg	3.16	3.42	3.18	N1 (P)KMg	2.73	3.07	2.80
07	N2 PK(Na)Mg	4.81	5.87	N2 PKMg	5.26	5.43	5.28	N2 (P)KMg	4.08	4.89	4.38
08	N3 PK(Na)Mg	5.13	6.37	N3 PKMg	5.95	6.54	6.10	N3 (P)KMg	4.53	5.22	5.14
09	N4 PK(Na)Mg	5.49	6.85	N4 PKMg	6.10	6.56	7.16	N4 (P)KMg	5.78	6.07	5.86
15	N3 PK(Na)Mg	5.42	6.59	N5 PKMg	6.77	7.52	7.62	N5 (P)KMg	5.03	6.20	6.53
16	N2 PK(Na)Mg	4.78	5.60	N6 PKMg	6.50	7.52	8.00	N6 (P)KMg	6.42	6.61	6.48
19	C	4.05	3.76	(C)	2.69	1.86	1.91	N1+1+1 KMg	4.13	4.96	4.61
18	N2 ½[PK(Na)Mg]	4.67	6.08	N1+3 ½[PKMg](A)[d]	6.43	6.91	6.85	N1+2+1 PKMg	4.96	5.58	5.81
12	N2 P Na	4.57	4.81	N2 P Na	4.62	3.14	3.82	N1+3+1 (P)KMg2	5.81	6.56	6.71
17	N2 ½[PK(Na)Mg]	4.57	6.23	N0+3 ½[PKMg](A)[d]	6.10	6.45	6.64	N1+4+1 PKMg	6.05	6.38	6.76
10	N2	3.53	3.18	N2	2.79	2.68	2.69	N4	1.78	1.97	1.84
11	N2 P	3.51	3.87	N2 P	4.10	3.66	3.61	N4 P Mg	3.81	4.09	4.88
13	N2 PK	5.01	5.69	N2 PK	5.54	4.84	4.77	N4 PK	5.33	5.74	5.97
14	N2 PKMg*	5.18	5.95	N2 PKMg*	5.74	5.35	5.30	N4 PK*(Mg*)	5.64	6.04	5.25
20	N2 K(Na)Mg	3.58	3.07	N2 KMg	2.16	2.84	2.44	N4 KMg	1.54	0.79	0.76
	s.e.	**0.320**	**0.392**		**0.392**	**0.429**	**0.429**		**0.480**	**0.339**	**0.429**

$F(126,641) = 8.22,\ p < 0.001 \quad \varphi = 0.4185\ (0.0382)$

[a] See Table 1 for detailed description of treatments

[b] Although Cappelle Desprez was grown from 1968, the mean yields from 1970 - 1978 shown here, and in other tables, are to compare with the yields of the 1st wheat grown after a 2-year break which was not "in phase" until 1970 (see Appendix Table 1b).

[c] Excludes spring wheat in 2015

[d] Between 1985 - 2000 the treatment on strips 17 and 18 alternated *i.e.* in one year the treatment included the application of autumn N, the following year it did not. Data shown for this period are NOT the mean yields on strips 17 or 18; rather they are the means of the years either without or with autumn N.

[e] FYM N2 until 2004

Table 3 Mean yields of winter wheat grain, t ha^{-1} year^{-1} at 85% dry matter, when grown as the 1st wheat after a 2-year break. Broadbalk Wheat Experiment.

	Cultivars, years grown and mean yield of grain (t ha^{-1} yr^{-1})										
Strip	Treatments[a] from 1968	C. Desprez 1970-78[b]	Flanders 1979-84	Treatments from 1985	Brimstone 1985-90	Apollo 1991-95	Hereward 1996-2000	Treatments from 2001	Hereward 2001-04	Hereward 2005-12	Crusoe 2013-18[c]
2.2	FYM	6.47	7.20	FYM	7.89	7.95	7.45	FYM	4.91	6.20	7.00
2.1	FYM N2	5.99	8.52	FYM N2	9.36	9.44	9.28	FYM N3[e]	8.12	9.58	10.35
01	FYM N2 PK	6.00	8.38	FYM N4 PK	9.00	9.43	9.31	(FYM) N4	8.82	9.39	10.01
03	Nil	2.68	2.94	Nil	2.57	1.70	2.40	Nil	1.22	1.73	1.89
05	PK(Na)Mg	3.13	3.29	PKMg	2.59	1.62	2.07	(P)KMg	1.38	1.77	1.72
06	N1 PK(Na)Mg	5.08	5.74	N1 PKMg	5.46	4.96	4.81	N1 (P)KMg	3.67	3.99	4.35
07	N2 PK(Na)Mg	6.02	7.34	N2 PKMg	7.48	7.15	7.11	N2 (P)KMg	5.57	6.02	6.69
08	N3 PK(Na)Mg	5.66	7.92	N3 PKMg	8.41	8.48	8.53	N3 (P)KMg	7.05	7.33	8.61
09	N4 PK(Na)Mg	5.51	8.09	N4 PKMg	8.53	8.52	9.25	N4 (P)KMg	7.95	8.49	9.40
15	N3 PK(Na)Mg	5.92	7.59	N5 PKMg	8.35	8.31	9.27	N5 (P)KMg	8.40	8.77	9.92
16	N2 PK(Na)Mg	5.97	6.99	N6 PKMg	8.61	8.30	9.11	N6 (P)KMg	8.49	8.86	10.25
19	C	5.41	5.32	(C)	5.00	2.75	2.83	N1+1+1 KMg	6.31	7.19	8.08
18	N2 ½[PK(Na)Mg]	6.15	7.61	N1+3 ½[PKMg](A)[d]	8.88	8.31	8.69	N1+2+1 PKMg	7.99	8.54	9.44
12	N2 P Na	5.60	6.35	N2 P Na	6.53	5.18	6.46	N1+3+1 (P)KMg2	8.02	8.79	10.01
17	N2 ½[PK(Na)Mg]	6.20	7.58	N0+3 ½[PKMg](A)[d]	8.49	8.16	8.32	N1+4+1 PKMg	8.87	8.83	10.54
10	N2	4.94	4.99	N2	4.70	5.91	6.15	N4	6.16	6.00	6.23
11	N2 P	5.22	6.08	N2 P	6.03	4.72	6.39	N4 P Mg	5.92	5.26	6.68
13	N2 PK	6.07	6.96	N2 PK	6.93	6.73	6.65	N4 PK	7.10	7.99	9.24
14	N2 PKMg*	6.33	7.22	N2 PKMg*	7.36	6.49	6.76	N4 PK*(Mg*)	7.22	7.93	8.35
20	N2 K(Na)Mg	-	-	N2 KMg	-	-	-	N4 KMg	-	-	-
	s.e.	**0.374**	**0.458**		**0.458**	**0.501**	**0.501**		**0.560**	**0.396**	**0.501**

F(126,640) = 8.27, $p < 0.001$ $\varphi = 0.4255$ (0.0389)

[a] See Table 1 for detailed description of treatments

[b] Although Cappelle Desprez was grown from 1968, the mean yields from 1970 - 1978 shown here, and in other tables, are to compare with the yields of the 1st wheat grown after a 2-year break which was not "in phase" until 1970 (see Appendix Table 1b).

[c] Excludes spring wheat in 2015

[d] Between 1985 - 2000 the treatment on strips 17 and 18 alternated *i.e.* in one year the treatment included the application of autumn N, the following year it did not. Data shown for this period are NOT the mean yields on strips 17 or 18; rather they are the means of the years either without or with autumn N.

[e] FYM N2 until 2004

mean yields for three different periods are given which reflect treatment changes over the 17 years in which Hereward was grown. The treatments for each cultivar/period are shown in (what is now) a logical order, *not* in strip order as they have usually been shown. Tables 4–8 give the yields for wheat grown as the 2nd or 3rd wheat after a 2-year break or continuously on Section 9, without summer fungicides (Section 6), with straw incorporated since autumn 1986 (Section 0).

In the 11 years in which Cappelle Desprez was grown, foliar fungicides were not applied and diseases, particularly powdery mildew, were common, and most severe on plots given most N. However, since 1979, summer

Table 4 Mean yields of winter wheat grain, $t\,ha^{-1}\,year^{-1}$ at 85% dry matter, when grown as the 2nd wheat after a 2-year break. Broadbalk Wheat Experiment.

	Cultivars, years grown and mean yield of grain ($t\ ha^{-1}\ yr^{-1}$)							
Strip	Treatments[a] from 1985	Brimstone 1985-90[b]	Apollo 1991-95	Hereward 1996-2000	Treatments from 2001	Hereward 2001-04	Hereward 2005-12	Crusoe 2013-18[c]
2.2	FYM	5.86	5.44	5.22	FYM	4.05	5.02	5.63
2.1	FYM N2	8.64	8.47	8.50	FYM N3[e]	7.44	8.90	10.03
01	FYM N4 PK	8.61	9.01	9.50	(FYM) N4	8.00	8.16	8.70
03	Nil	1.28	0.63	1.03	Nil	0.94	1.22	0.90
05	PKMg	1.47	0.65	1.01	(P)KMg	1.06	1.45	1.02
06	N1 PKMg	4.05	3.10	3.04	N1 (P)KMg	2.69	3.62	3.12
07	N2 PKMg	5.90	5.01	4.95	N2 (P)KMg	4.16	5.03	4.85
08	N3 PKMg	6.77	6.80	6.23	N3 (P)KMg	4.73	5.79	5.96
09	N4 PKMg	7.26	7.57	7.52	N4 (P)KMg	6.32	6.92	7.16
15	N5 PKMg	7.60	7.95	8.10	N5 (P)KMg	5.75	6.95	7.09
16	N6 PKMg	7.85	7.88	8.43	N6 (P)KMg	7.02	8.03	8.40
19	(C)	2.61	0.96	1.25	N1+1+1 KMg	5.29	5.79	5.15
18	N1+3 ½[PKMg](A)[d]	7.60	7.27	7.49	N1+2+1 PKMg	6.97	7.59	8.11
12	N2 P Na	5.63	4.63	4.85	N1+3+1 (P)KMg2	6.19	7.65	8.57
17	N0+3 ½[PKMg](A)[d]	6.99	6.77	7.11	N1+4+1 PKMg	7.31	8.18	9.32
10	N2	4.70	3.51	2.90	N4	3.20	3.83	3.28
11	N2 P	5.51	4.76	4.70	N4 P Mg	4.82	4.79	6.60
13	N2 PK	5.47	4.58	4.72	N4 PK	5.16	6.71	6.99
14	N2 PKMg*	5.83	4.62	4.73	N4 PK*(Mg*)	4.90	6.49	5.98
20	N2 KMg	-	-	-	N4 KMg	-	-	-
	s.e.	**0.471**	**0.516**	**0.516**		**0.576**	**0.408**	**0.516**

$F(90,429) = 6.38$, $p < 0.001$ $\varphi = 0.4227\ (0.0438)$

[a] See Table 1 for detailed description of treatments

[b] No 2nd wheat in rotation until 1985 (see Appendix Table 1b)

[c] Excludes spring wheat in 2015

[d] Between 1985 - 2000 the treatment on strips 17 and 18 alternated *i.e.* in one year the treatment included the application of autumn N, the following year it did not. Data shown for this period are NOT the mean yields on strips 17 or 18; rather they are the means of the years either without or with autumn N.

[e] FYM N2 until 2004

Table 5 Mean yields of winter wheat grain, t ha^{-1} year^{-1} at 85% dry matter, when grown as the 3rd wheat after a 2-year break. Broadbalk Wheat Experiment

Cultivars, years grown and mean yield of grain (t ha^{-1} yr^{-1})

Strip	Treatments[a] from 1985	Brimstone 1986-90[b]	Apollo 1991-95	Hereward 1996-2000	Treatments from 2001	Hereward 2001-04	Hereward 2005-12	Crusoe 2013-18[c]
2.2	FYM	5.37	5.58	5.24	FYM	3.78	5.16	5.28
2.1	FYM N2	7.59	7.88	7.53	FYM N3[e]	6.71	8.49	8.65
01	FYM N4 PK	7.40	8.49	8.60	(FYM) N4	7.14	7.57	7.30
03	Nil	1.16	0.59	1.02	Nil	0.76	1.18	1.01
05	PKMg	1.37	0.69	0.99	(P)KMg	0.69	1.27	1.15
06	N1 PKMg	3.42	2.82	2.67	N1 (P)KMg	2.21	3.24	3.05
07	N2 PKMg	4.99	4.17	4.50	N2 (P)KMg	3.12	4.53	4.37
08	N3 PKMg	6.12	5.16	5.84	N3 (P)KMg	3.74	5.46	5.72
09	N4 PKMg	6.33	6.36	6.53	N4 (P)KMg	5.09	6.46	6.55
15	N5 PKMg	5.98	6.98	7.13	N5 (P)KMg	5.05	6.21	6.56
16	N6 PKMg	6.47	7.52	7.58	N6 (P)KMg	5.80	7.06	7.53
19	(C)	2.49	1.19	1.44	N1+1+1 KMg	4.46	5.33	5.38
18	N1+3 ½[PKMg](A)[d]	6.31	6.49	6.52	N1+2+1 PKMg	5.76	6.98	7.44
12	N2 P Na	5.07	3.37	3.72	N1+3+1 (P)KMg2	5.18	7.11	7.50
17	N0+3 ½[PKMg](A)[d]	5.56	5.82	6.08	N1+4+1 PKMg	6.37	7.43	8.41
10	N2	3.91	2.73	3.23	N4	2.55	3.06	3.13
11	N2 P	4.79	3.43	3.67	N4 P Mg	3.20	4.54	5.19
13	N2 PK	4.87	3.79	4.19	N4 PK	4.16	6.11	6.23
14	N2 PKMg*	5.01	4.00	4.29	N4 PK*(Mg*)	3.98	5.93	5.36
20	N2 KMg	-	-	-	N4 KMg	-	-	-
	s.e.	**0.496**	**0.496**	**0.496**		**0.554**	**0.392**	**0.554**

F(90,391) = 4.22, p < 0.001 φ = 0.4675 (0.0493)

[a] See Table 1 for detailed description of treatments

[b] No 3rd wheat in rotation until 1986 (see Appendix Table 1b)

[c] Excludes spring wheat in 2015

[d] Between 1985 - 2000 the treatment on strips 17 and 18 alternated *i.e.* in one year the treatment included the application of autumn N, the following year it did not. Data shown for this period are NOT the mean yields on strips 17 or 18; rather they are the means of the years either without or with autumn N.

[e] FYM N2 until 2004

fungicides have been used (except on Section 6; Table 7), and the greater grain yield potential of modern cultivars can be assessed. Overall, however, the effect of fungicides has been variable, with little or no benefit where lack of N or P limited yield but a greater benefit where larger rates of N or FYM has been applied (Table 2 cf. Table 7). As a result of the use of fungicides, the relative yields of plots given FYM and fertilizers changed (e.g., Tables 2 and 3) with best yields from fertilizer exceeding those from FYM alone but with the combination of FYM

Table 6 Mean yields of winter wheat grain, t ha^{-1} year^{-1} at 85% dry matter, when grown continuously (Section 9). Broadbalk Wheat Experiment

	Cultivars, years grown and mean yield of grain (t ha^{-1} yr^{-1})										
Strip	Treatments[a] from 1968	C. Desprez 1970-78[b]	Flanders 1979-84	Treatments from 1985	Brimstone 1985-90	Apollo 1991-95	Hereward 1996-2000	Treatments from 2001	Hereward 2001-04	Hereward 2005-12	Crusoe 2013-18[c]
2.2	FYM	5.82	6.53	FYM	6.58	6.20	4.93	FYM	4.45	5.57	5.84
2.1	FYM N2	5.34	8.20	FYM N2	8.17	8.18	7.82	FYM N3[e]	6.76	7.23	7.74
01	FYM N2 PK	-	-	FYM N4 PK	-	-	-	(FYM) N4	-	-	-
03	Nil	1.58	1.56	Nil	1.11	0.73	0.93	Nil	0.25	0.60	0.80
05	PK(Na)Mg	1.88	1.63	PKMg	1.42	0.98	1.17	(P)KMg	0.76	1.14	1.03
06	N1 PK(Na)Mg	3.56	4.17	N1 PKMg	3.96	3.78	3.07	N1 (P)KMg	2.73	3.18	3.00
07	N2 PK(Na)Mg	4.86	5.92	N2 PKMg	5.30	5.30	4.92	N2 (P)KMg	3.85	4.33	4.51
08	N3 PK(Na)Mg	5.51	6.60	N3 PKMg	6.54	6.38	6.01	N3 (P)KMg	4.56	5.37	6.06
09	N4 PK(Na)Mg	5.49	7.01	N4 PKMg	6.22	7.14	7.20	N4 (P)KMg	5.78	6.22	6.13
15	N3 PK(Na)Mg	5.24	6.52	N5 PKMg	6.30	7.59	7.86	N5 (P)KMg	5.85	6.31	6.79
16	N2 PK(Na)Mg	4.71	5.88	N6 PKMg	6.88	7.93	8.22	N6 (P)KMg	6.98	6.71	6.99
19	C	3.63	3.79	(C)	2.18	1.73	1.84	N1+1+1 KMg	4.28	4.21	6.05
18	N2 ½[PK(Na)Mg]	4.91	6.37	N1+3 ½[PKMg](A)[d]	6.54	7.05	7.35	N1+2+1 PKMg	5.75	5.17	6.88
12	N2 P Na	3.83	4.21	N2 P Na	4.06	3.01	3.63	N1+3+1 (P)KMg2	5.86	6.90	7.38
17	N2 ½[PK(Na)Mg]	4.52	6.40	N0+3 ½[PKMg](A)[d]	6.46	6.94	7.13	N1+4+1 PKMg	6.79	6.12	7.20
10	N2	2.61	2.73	N2	2.62	2.73	2.46	N4	1.49	1.34	1.82
11	N2 P	2.67	2.96	N2 P	3.30	2.37	2.89	N4 P Mg	3.84	4.28	5.19
13	N2 PK	4.65	5.91	N2 PK	5.57	5.26	5.40	N4 PK	5.12	6.15	6.78
14	N2 PKMg*	4.83	5.54	N2 PKMg*	5.46	5.34	5.27	N4 PK*(Mg*)	5.49	6.11	6.78
20	N2 K(Na)Mg	-	-	N2 KMg	-	-	-	N4 KMg	-	-	-
	s.e.	**0.345**	**0.422**		**0.422**	**0.462**	**0.462**		**0.517**	**0.366**	**0.462**

F(119,605) = 7.12, $p < 0.001$ $\varphi = 0.4516$ (0.0390)

[a] See Table 1 for detailed description of treatments

[b] Although Cappelle Desprez was grown from 1968, the mean yields from 1970 - 1978 shown here, and in other tables, are to compare with the yields of the 1st wheat grown after a 2-yr break which was not "in phase" until 1970 (see Appendix Table 1b).

[c] Excludes spring wheat in 2015

[d] Between 1985 - 2000 the treatment on strips 17 and 18 alternated *i.e.* in one year the treatment included the application of autumn N, the following year it did not. Data shown for this period are NOT the mean yields on strips 17 or 18; rather they are the means of the years either without or with autumn N.

[e] FYM N2 until 2004

Table 7 Mean yields of winter wheat grain, t ha^{-1} year^{-1} at 85% dry matter, when grown continuously with no summer fungicides since 1985 (Section 6). Broadbalk Wheat Experiment.

Cultivars, years grown and mean yield of grain (t ha^{-1} yr^{-1})

Strip	Treatments[a] from 1968	Flanders 1979-84	Treatments from 1985	Brimstone 1985-90	Apollo 1991-95	Hereward 1996-2000	Treatments from 2001	Hereward 2001-04	Hereward 2005-12	Crusoe 2013-18[b]
2.2	FYM	5.46	FYM	5.72	5.42	5.42	FYM	4.01	5.33	5.04
2.1	FYM N2	8.12	FYM N2	7.85	6.90	7.81	FYM N3[d]	6.64	7.20	5.92
01	FYM N2 PK	7.90	FYM N4 PK	7.38	6.71	8.14	(FYM) N4	7.09	6.53	5.15
03	Nil	1.12	Nil	1.21	1.23	1.12	Nil	1.01	1.26	1.08
05	PK(Na)Mg	1.24	PKMg	1.49	1.30	1.13	(P)KMg	0.95	1.38	1.20
06	N1 PK(Na)Mg	3.45	N1 PKMg	3.71	3.50	3.00	N1 (P)KMg	2.69	2.99	2.99
07	N2 PK(Na)Mg	5.58	N2 PKMg	5.29	4.92	4.73	N2 (P)KMg	4.01	4.34	4.04
08	N3 PK(Na)Mg	6.55	N3 PKMg	6.26	5.77	5.77	N3 (P)KMg	4.37	5.19	4.63
09	N4 PK(Na)Mg	6.97	N4 PKMg	6.05	6.13	6.77	N4 (P)KMg	5.93	6.33	5.40
15	N3 PK(Na)Mg	6.42	N5 PKMg	5.93	6.09	6.93	N5 (P)KMg	5.43	6.06	5.15
16	N2 PK(Na)Mg	5.31	N6 PKMg	6.25	6.09	7.34	N6 (P)KMg	6.74	6.94	5.54
19	C	2.86	(C)	1.93	1.80	1.25	N1+1+1 KMg	4.41	4.46	4.26
18	N2 ½[PK(Na)Mg]	6.36	N1+3 ½[PKMg](A)[c]	6.72	6.25	6.93	N1+2+1 PKMg	6.52	5.88	5.33
12	N2 P Na	4.82	N2 P Na	4.62	3.75	3.95	N1+3+1 (P)KMg2	6.22	6.61	5.56
17	N2 ½[PK(Na)Mg]	6.27	N0+3 ½[PKMg](A)[c]	6.39	6.06	6.83	N1+4+1 PKMg	7.14	6.91	5.73
10	N2	4.04	N2	3.30	2.83	2.44	N4	2.00	2.45	2.13
11	N2 P	4.48	N2 P	3.84	2.85	3.03	N4 P Mg	3.75	4.53	3.88
13	N2 PK	5.22	N2 PK	4.42	4.63	4.58	N4 PK	5.40	5.90	5.32
14	N2 PKMg*	5.29	N2 PKMg*	5.01	4.78	4.80	N4 PK*(Mg*)	5.57	5.92	5.35
20	N2 K(Na)Mg	-	N2 KMg	-	-	-	N4 KMg	-	-	-
	s.e.	**0.441**		**0.441**	**0.483**	**0.483**		**0.540**	**0.382**	**0.483**

F(126,586) = 6.60, p < 0.001 φ = 0.5017 (0.0397)

[a] See Table 1 for detailed description of treatments

[b] Excludes spring wheat in 2015

[c] Between 1985 - 2000 the treatment on strips 17 and 18 alternated *i.e.* in one year the treatment included the application of autumn N, the following year it did not. Data shown for this period are NOT the mean yields on strips 17 or 18; rather they are the means of the years either without or with autumn N.

[d] FYM N2 until 2004

Table 8 Mean yields of winter wheat grain, t ha^{-1} year^{-1} at 85% dry matter, when grown continuously with straw incorporated since autumn 1986 (Section 0). Broadbalk Wheat Experiment.

		Cultivars, years grown and mean yield of grain (t ha^{-1} yr^{-1})									
Strip	Treatments[a] from 1968	C. Desprez 1970-78[b]	Flanders 1979-84	Treatments from 1985	Brimstone 1985-90	Apollo 1991-95	Hereward 1996-2000	Treatments from 2001	Hereward 2001-02[c]	Hereward 2005-12	Crusoe 2013-18[d]
2.2	FYM	5.56	6.09	FYM	5.55	5.54	4.62	FYM	2.78	4.65	4.49
2.1	FYM N2	4.59	7.85	FYM N2	7.05	7.63	6.85	FYM N3[f]	5.05	6.83	6.71
01	FYM N2 PK	-	-	FYM N4 PK	-	-	-	(FYM) N4	-	-	-
03	Nil	1.81	1.74	Nil	1.43	1.07	1.17	Nil	0.57	1.13	0.98
05	PK(Na)Mg	2.21	1.86	PKMg	1.32	1.20	1.03	(P)KMg	0.47	1.28	1.11
06	N1 PK(Na)Mg	3.82	4.11	N1 PKMg	4.03	3.61	3.08	N1 (P)KMg	1.85	3.18	2.74
07	N2 PK(Na)Mg	5.06	5.77	N2 PKMg	5.31	5.10	4.92	N2 (P)KMg	2.76	4.55	4.18
08	N3 PK(Na)Mg	4.99	6.32	N3 PKMg	5.97	6.13	5.83	N3 (P)KMg	3.27	5.21	5.43
09	N4 PK(Na)Mg	4.96	6.58	N4 PKMg	5.83	6.61	7.26	N4 (P)KMg	5.36	6.27	5.71
15	N3 PK(Na)Mg	5.00	6.45	N5 PKMg	6.20	7.27	7.42	N5 (P)KMg	4.18	6.35	5.89
16	N2 PK(Na)Mg	4.51	5.56	N6 PKMg	4.88	7.29	7.87	N6 (P)KMg	6.01	6.83	6.42
19	C	4.21	3.43	(C)	2.19	1.69	1.70	N1+1+1 KMg	3.13	5.22	5.46
18	N2 ½[PK(Na)Mg]	4.48	6.20	N1+3 ½[PKMg](A)[e]	6.12	6.71	6.95	N1+2+1 PKMg	4.78	6.36	6.34
12	N2 P Na	4.57	5.04	N2P Na	4.86	4.14	4.57	N1+3+1 (P)KMg2	4.88	6.81	6.41
17	N2 ½[PK(Na)Mg]	4.68	6.07	N0+3 ½[PKMg](A)[e]	5.78	6.21	6.57	N1+4+1 PKMg	5.84	6.76	6.89
10	N2	2.68	3.39	N2	2.69	2.44	2.71	N4	1.14	1.98	1.49
11	N2 P	3.48	4.13	N2 P	4.02	3.44	3.99	N4 P Mg	3.48	5.24	5.31
13	N2 PK	4.81	5.44	N2 PK	5.02	4.93	4.93	N4 PK	3.74	5.88	5.89
14	N2 PKMg*	4.79	5.73	N2 PKMg*	5.45	5.40	5.11	N4 PK*(Mg*)	4.14	6.28	5.05
20	N2 K(Na)Mg	3.51	3.39	N2 KMg	2.40	3.09	2.69	N4 KMg	0.92	1.88	1.56
	s.e.	**0.340**	**0.417**		**0.417**	**0.457**	**0.457**		**0.722**	**0.361**	**0.457**

F(126,603) = 8.97, $p < 0.001$ φ = 0.3829 (0.0411)

[a] See Table 1 for detailed description of treatments

[b] Although Cappelle Desprez was grown from 1968, the mean yields from 1970 - 1978 shown here, and in other tables, are to compare with the yields of the 1st wheat grown after a 2-year break which was not "in phase" until 1970 (see Appendix Table 1b).

[c] Fallow in 2003 & 2004 to test various combinations of herbicides to control *Equisetum arvense* (see Appendix Table 1b)

[d] Excludes spring wheat in 2015

[e] Between 1985 - 2000 the treatment on strips 17 and 18 alternated *i.e.* in one year the treatment included the application of autumn N, the following year it did not. Data shown for this period are NOT the mean yields on strips 17 or 18; rather they are the means of the years either without or with autumn N.

[f] FYM N2 until 2004

+96 (or 144) kg N ha^{-1} often exceeding both. The increased response to N fertilizer in 1979–84 suggested that yields might be greater if larger rates of N were applied, and since 1985, 240 and 288 kg N ha^{-1} have been tested.

Since 1970, when the new rotations were fully "phased-in," we can compare the yields of wheat grown continuously and as the first wheat after a 2-year break (Tables 2 and 3). Fig. 8A–H shows these responses to N and FYM. Mean yields of Hereward in 2001–04 were lower than previous or later yields because wet weather in autumn 2000 prevented the crop from being drilled until 17th January 2001 and after early drilling in autumn 2001 the wheat was severely affected by Gout Fly (*Chlorops pumilionis*). Yields in both 2001 and 2002 were poor.

On average, continuous wheat tended to respond up to 240 or 288 kg N ha^{-1} while the 1st wheat after a 2-year break often needed less N to reach maximum yield. Mean yields of wheat grown after a 2-year break were often >1 t ha^{-1} larger than yields of continuous wheat, almost certainly because the effects of soil borne pests and disease, particularly take-all are minimized (see below). For *cv*. Crusoe (Fig. 8H; Table 3) the differences were even greater with mean yields of the 1st wheat >3 t ha^{-1} larger than those of continuous wheat. The reasons for this large difference are not clear although yields of the continuous wheat are slightly lower than previous cultivars and those of the 1st wheat are larger than for previous cultivars. Best yields now exceed 12 t ha^{-1} in some years. Since 1985/6 we have also been able to compare the yields of continuous wheat and the 1st wheat after a 2-year break with those of the 2nd and 3rd wheat crops after a 2-year break (Appendix Table A1b, Tables 2–5). Yields of the 2nd wheat after a 2-year break are smaller than those of the 1st wheats but are mostly larger than those of continuous wheat particularly on plots with FYM or larger amounts of fertilizer N. Yields of the 3rd wheat after a 2-year break are more similar to those of continuous wheat.

As noted above, yields of continuous wheat on soil given FYM are very similar to those on soils given PKMg +144 kg N ha^{-1}. With the introduction of larger rates of N in 1968 and 1985 and fungicides in 1979, the best yields on soils given PKMg plus one of these larger rates now exceed those of FYM alone (Fig. 5). Yields of the 1st wheat after a 2-year break are about 1 t ha^{-1} larger with PKMg + 144 kg N ha^{-1} than yields with FYM (Tables 2 and 3). However, where additional fertilizer N was applied to one of the FYM treatments (strip 2.1), yields exceed those of the "best" NPKMg plots in some years. When *cv*. Hereward was introduced in 1996

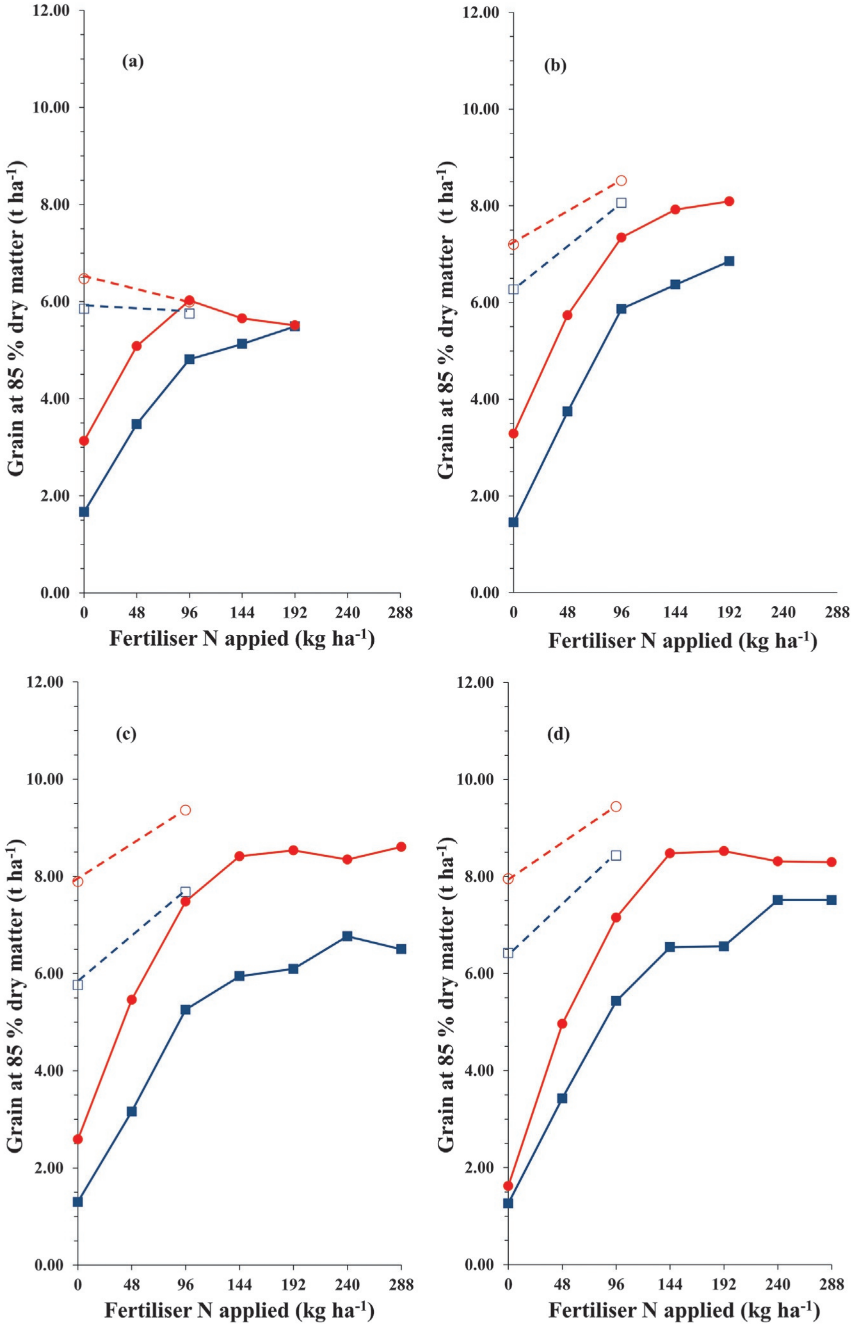

Fig. 8 Mean yields of wheat grain, t ha^{-1}, grown continuously (Section 1), ■, PKMg+N; □, FYM + N; or as the 1st wheat after a 2-year break, ●, PKMg+N; ○, FYM + N. (A) Cappelle Desprez, 1970–78; (B) Flanders, 1979–84; (C) Brimstone, 1985–90; (D) Apollo, 1991–95; (E) Hereward, 1996–2000; (F) Hereward, 2001–04; (G) Hereward, 2005–12; (H) Crusoe, 2013–18 (excluding 2015). Broadbalk Wheat Experiment.

(Continued)

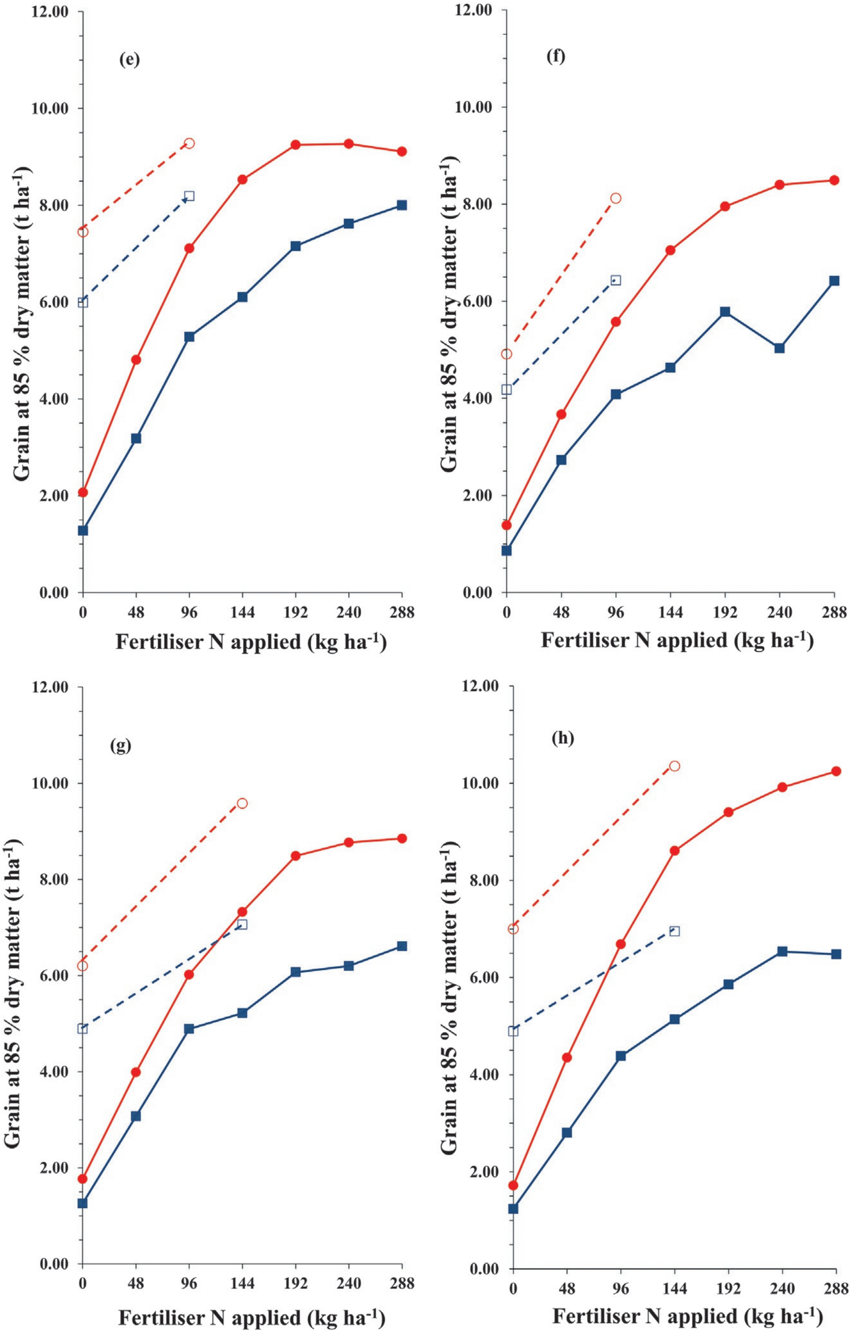
(e)
(f)
(g)
(h)
Grain at 85 % dry matter (t ha-1)
12.00
10.00
8.00
6.00
4.00
2.00
0.00
0
48
96
144
192
240
288
Fertiliser N applied (kg ha-1)

Fig. 8—Cont'd

it appeared that FYM + 96 kg N ha^{-1} was not sufficient to achieve maximum yield. The benefit of applying 144 kg N ha^{-1} was tested on microplots on plots 2.11 and 2.19 in 2003 and 2004. Mean grain yields and standard errors were 6.95 ± 0.26 and 7.88 ± 0.19 t ha^{-1} on microplots with FYM + 96 and FYM + 144 kg N ha^{-1}, respectively. Consequently, the larger rate of additional N was applied on the whole strip in 2005. However, the effect on yield of the FYM + N treatment remains variable. On the adjacent Hoosfield Spring Barley experiment yields on soils with long-term applications of FYM consistently exceed those with NPKMg fertilizers (Macdonald et al., 2018). A spring sown crop has a much shorter growing season, so is presumably more sensitive than an autumn sown crop to improved establishment resulting from the improved soil structure and water holding capacity resulting from increased SOM. In addition, the greater supply of N throughout the growing season from mineralization may be more beneficial for a spring-sown crop. On Broadbalk, winter wheat is usually drilled in mid-October and has many months to establish before more rapid growth starts with stem elongation in March or April. Although establishment is invariably better on the FYM treatments this does not necessarily result in a larger grain yield. This difference between the response of spring- and autumn-sown crops to additional soil organic matter derived from manure application is consistent with the results from other European LTEs (Hijbeek et al., 2017).

To test for any residue of N or PKNaMg, Lawes alternated the fertilizer applied to strips 17 and 18; in even numbered years strip 17 received N and strip 18 received PKNaMg, in odd numbered years strip 17 received PKNaMg and strip 18 received N. This continued until 1967. The mean yield of grain on strips receiving N or PKNaMg was 2.11 and 1.03 t ha^{-1}, respectively. There was little or no residual benefit of the applied N in the following year when PKNaMg, but no N, was applied (Garner and Dyke, 1969; Rothamsted Research, 2023). Lawes and Gilbert (1864) used the results from these two treatments as further evidence in their argument with Liebig that crops needed additional N to increase yield and that they could not receive all the N they need from the air. From 1968 to 1984 both strips received N2 and PK(*Na*)Mg at half the normal rate; there was no difference in yield between the two strips. From 1985 to 2000 both strips continued to receive PKMg at half-rate and both received N3 in spring. However, they alternated each year as to whether they received autumn-applied N (48 kg ha^{-1}) at drilling or not. For the three cultivars grown during this period, yields were about 0.3 t ha^{-1} greater where autumn N had been applied to continuous wheat or the 1st wheat in rotation, but this difference was not statistically significant in most cases (Tables 2, 3, 6–8). For the 2nd and 3rd wheats in rotation the benefits of applying autumn N tended to be larger (Tables 4 and 5). However, by the 1990s, concerns about over-winter losses of NO_3-N into watercourses meant that farmers were no longer recommended to apply autumn N to winter wheat, except for some direct-drilled crops (RB 209, 1988). Later studies with ^{15}N-labeled fertilizers on Broadbalk and other sites in eastern England clearly showed inefficient uptake of autumn-applied N by winter wheat and large losses (Powlson et al., 1986b).

In 2001, the treatment on these two strips changed again when they became part of a group of four treatments testing split applications of fertilizer N. Until 2000, even the larger rates of N were applied as single dressings at stem extension, usually mid-April. However, advice in the United Kingdom at that time was that, in most situations, amounts of N exceeding 100 kg ha^{-1} should be applied as two or three dressings (RB 209, 1988). When demonstrating the experiment to visitors it was difficult to explain why we did not follow this advice. It was therefore decided that a comparison between single vs split applications should be introduced for the four largest rates of N, i.e., 144, 192, 240 and 288 kg ha^{-1}. Four existing treatments were identified which, it was felt, were of less agronomic interest and could be changed. These were the two strips testing autumn N (see above) and the strips to which castor meal (strip 19) or N2PNa (strip 12) had been applied. Strip 12 had not received K or Mg and to ensure that lack of these nutrients did not limit yield, large dressings of both were applied in autumn 2000 plus double the usual rate for the next five 5 years (Table 1). Strip 19 had previously received P fertilizer and rape cake or castor meal containing P and in 2000 plots in this strip contained 16–30 mg kg^{-1} Olsen P (plant-available P) and will, in time, become deficient in P. On this soil type, there was, very surprisingly, little or no difference in yield between wheat given single large applications of fertilizer N and wheat given split dressings (Tables 2 and 3). However, for the 2nd and 3rd wheats after a 2-year break there were benefits from applying fertilizer N in split rather than single large applications, although these were not always significant (Tables 4 and 5). It is likely that, on these crops which have significant levels of take-all, the poorer root system can make better use of the applied N when it is divided into three applications.

As the amount of atmospheric SO_4-S being deposited to agricultural land declined in the 1980s/1990s it became apparent that, on some soils, farmers needed to apply fertilizer S to maintain yield and, more importantly, maintain the appropriate protein content in bread-making wheats (Zhao et al., 2003). To test this on Broadbalk the form of K fertilizer applied to strip 14 was changed from K_2SO_4 to KCl and applications of Kieserite (containing Mg and S) were stopped. Thus, no S has been applied to this strip since 2000. Over the next 18 years the effect on yield of withholding S was modest. Compared with the yield on strip 9 which receives the same amount of N but still receives K_2SO_4, yields of continuous wheat and of the 1st wheat after a 2-year break are now less by 0.23 and 0.74 $t\,ha^{-1}$, respectively (Tables 2 and 3). The effect on % S in the grain and S uptake is discussed below.

Yields on all other treatments are also given in Tables 2–8. On strip 03 (Nil), where no fertilizer or manure has been applied since 1852, mean yields of continuous wheat on Sections 1, 9 and 0 (Tables 2, 6 and 8) ranged from 0.2 to 1.8 $t\,ha^{-1}$ and have declined since 1979–84; possibly because of the decline in atmospheric N deposition. By the 1980s, annual inputs of N from the atmosphere, as wet plus dry deposition, totaled 40–45 $kg\,ha^{-1}$. Of this, modeling suggested that *c.* 50% was taken up by the crop (Goulding et al., 1998). Since then, atmospheric inputs of N at Rothamsted have declined by about 75% (Storkey et al., 2015) and it seems likely that this has led to a decrease in yield where no fertilizer N is applied. Mean yields of the 1st wheat after a 2-year break on the Nil plots (Table 3) were greater than those of continuous wheat, ranging from 1.2 to 2.9 $t\,ha^{-1}$ but have also declined over the last 50 years. On the nearby Park Grass Experiment (started in 1856 on permanent pasture) this decrease in atmospheric N resulted in an *increase* in the proportion of legumes in the sward, species richness and diversity (Storkey et al., 2015).

Yields on soils receiving PKMg but no fertilizer N (strip 05) were similar to those on the Nil treatment but where N but no PKMg was applied (strip 10, where the soil contains little Olsen P), yields were larger than those on the Nil plots. Yields of the 1st wheat were larger than those of continuous wheat, mainly because of a decline in disease, but possibly also because the soils contained slightly more plant-available P (see below).

Yields on soils receiving N and P but no K or Mg, were less than those receiving PKMg and the same amount of N (strip 11 cf. strip 07; strip 09 from 2001). Adding K (strip 13) or K plus the higher rate of Mg (strip 14) increased yield compared with N2P. Castor meal, which applied 96 $kg\,N\,ha^{-1}$ plus PK, increased yield compared with the control but after applications stopped in 1988 the residual effect was small. Strip 20, which only extends over Sections 0 and 1, received N2KMg (N4KMg from 2001); yields were less than those on the corresponding treatment which also received P (strip 07; strip 09 from 2001). A third FYM treatment, on a short strip of previously cropped land next to the two existing FYM strips started in 1968 (Fig. 3). It had received various applications of N, P and K prior to 1883 but nothing since. In addition to 35 t FYM ha^{-1} it also received PK and 96 kg N ha^{-1} (increased to 192 kg N ha^{-1} in 1985). This treatment continued until 2000, when it was replaced by 192 kg N ha^{-1} only. Yields of the 1st wheat were no better than those on the FYM + 96 kg N ha^{-1} treatment but yields of the 2nd and 3rd wheats were better following an increase in the amount of N (Tables 3–5). Since the application of FYM and PK fertilizer stopped in 2000, the residual value of the accumulated SOM on strip 01 has been measured. Compared with strip 09, which also receives 192 kg N ha^{-1} (+ (P)KMg), yields of 1st, 2nd and 3rd wheats are better with residues of the previously applied FYM.

On Section 8, herbicides have never been applied and the section is often fallowed in an attempt to control weeds. During a fallow year, the section will be plowed or cultivated several times to kill germinating weed seedlings. This has had little effect on the seed bank in the soil and the mass of weeds which appear every year severely reduces wheat yields. The different weeds present in this section and their effect on yield is discussed below.

On Section 0, with straw incorporated since autumn 1986 there has been little or no effect on yield compared with the adjacent Section 1 (Table 8 cf. Table 2).

4.1.2 Fitted nitrogen response curves and curve shifting

Dyke et al. (1983) fitted grain yield vs N applied response curves to continuous and rotational wheat crops for *cv.* Cappelle Desprez. By bringing the fitted response curves into coincidence by diagonal shifts it was possible to assess the benefit, if any, in terms of yield (the vertical component of the shift) or the amount of fertilizer N required to achieve that yield (the horizontal component of the shift), for wheat grown continuously or in rotation. Here, we have fitted response curves to one of the later varieties, *cv.* Hereward, grown either continuously or as the 1st, 2nd or 3rd wheat after a 2-year break. Compared with Cappelle Desprez, Hereward is a higher yielding cultivar, it receives fungicides to protect that yield potential and seven, rather than five, amounts of fertilizer N are tested. The individual N response curves were fitted to all available data (Fig. 9A); in the figure each symbol is the mean of 17 years. Table 9 gives, for each curve,

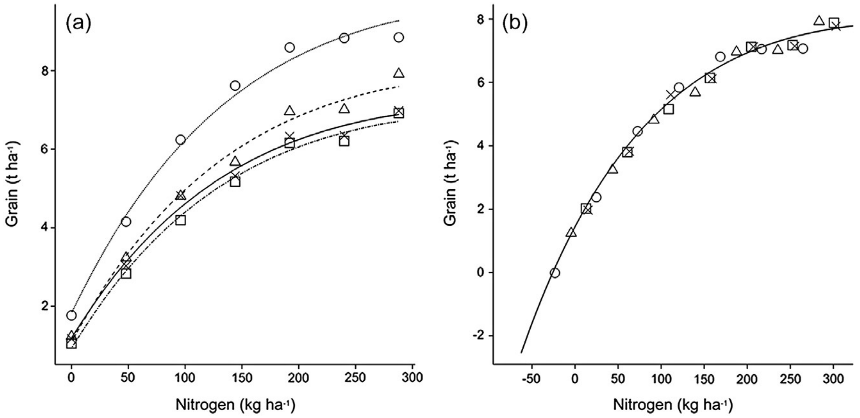

Fig. 9 (A) Fitted response curves for continuous wheat, x; and the 1st, o; 2nd, △; and 3rd, □; wheat after a 2-year break. (B) response curves bought into coincidence with that for continuous wheat (same symbols). 1996–2012, *c.v.* Hereward, Broadbalk Wheat Experiment.

Table 9 Estimated mean maximum yield, Y_{max}, in the fitted model for winter wheat given P, K, Mg and seven rates of N, and the vertical and horizontal shifts needed to bring the rotational curves into coincidence with that for continuous wheat. Broadbalk Wheat Experiment.

	Wheat grain		
Management	**Y_{max} (t ha^{-1})**	**s.e.**[a]	**Range (t ha^{-1})**
Continuous wheat (Section 1)	7.12	0.380	4.47–9.08
1st wheat after a 2-year break	9.70	0.303	7.01–11.99
2nd wheat after a 2-year break	7.91	0.291	5.77–9.69
3rd wheat after a 2-year break	6.96	0.421	4.12–9.62

	Vertical shift[b] **(t ha^{-1})**	**s.e.**	**Horizontal shift**[c] **(kg N ha^{-1})**	**s.e.**
1st wheat after a 2-year break	2.58	0.128	38.4	4.92
2nd wheat after a 2-year break	0.79	0.124	19.6	4.97
3rd wheat after a 2-year break	−0.17	0.122	2.4	5.17

[a] Standard errors derived from the estimated values for Y_{max} for each year.

[b] Vertical shift is the estimated shift in maximum yield, t ha^{-1}, compared with the yield for continuous wheat. A negative value indicates that the fitted yield is lower than that for continuous wheat.

[c] Horizontal shift is the equivalent of spring applied N fertilizer, kg ha^{-1}, compared with the continuous wheat.

the fitted asymptotic yield (Y_{max}). However, the fitted curves continue to increase gradually and do not turnover and decline until a rate of N is reached which is much larger than would be recommended to farmers; it would be uneconomic and could lead to excessive leaching of NO_3-N. The N needed to achieve that asymptotic maximum yield is therefore not shown. The three curves fitted to the rotational wheat crops can be bought into coincidence with the continuous wheat curve by a series of diagonal shifts, each of which comprises a vertical and a horizontal component; in the resulting composite curve (Fig. 9B) the model accounted for 95.5% of the variance. The vertical component of the diagonal shift represents the difference in yield between the crops while the horizontal component is equivalent to the amount of fertilizer N required (Table 9). Thus, for the 17 years of Hereward, the fitted curves suggest that the maximum yield for the 1st wheat after a 2-year break was 2.6 t ha^{-1} more than for continuous wheat and that 38 kg ha^{-1} less N was needed to achieve that yield. The 2nd wheat after the break gave 0.8 t ha^{-1} more yield than continuous wheat and required 20 kg ha^{-1} less N. Maximum yield and N required for the 3rd wheat after a 2-year break were the same as for continuous wheat.

4.1.3 Old vs modern cultivars

Between 1987 and 1990 selected plots on several sections were split lengthways and the older long-strawed cultivar, Squarehead's Master, which had been grown intermittently between 1900 and 1967 (Poulton and Glendining, 2023) and the then current short-strawed cultivar, Brimstone, were grown side-by-side. The aim was to see if the total grain plus straw yield of the two cultivars was the same because, in some situations, straw is as valuable as grain and the older cultivars with a wide grain:straw ratio could be recommended. At one end of each split plot the crops were supported by a wide mesh net to prevent lodging. The netted areas (2 m × 2 m) were harvested by hand and the results discussed by Austin et al. (1993). The rest of each plot was harvested with a small plot combine. Fig. 10A shows the mean yields of grain of Brimstone, with its greater grain yield potential, and of Squarehead's Master. Grown continuously or as the 1st wheat in rotation the average maximum yield of grain was *c.* 1.5 t ha^{-1} and *c.* 3.5 t ha^{-1} greater, respectively, for Brimstone compared with Squareheads' Master. Despite the difference in grain yield the total yields of grain plus straw were the same (Fig. 10B), thus confirming that the effect of breeding short-straw wheat varieties was to increase harvest index but not total above-ground dry matter accumulation (Austin et al., 1993).

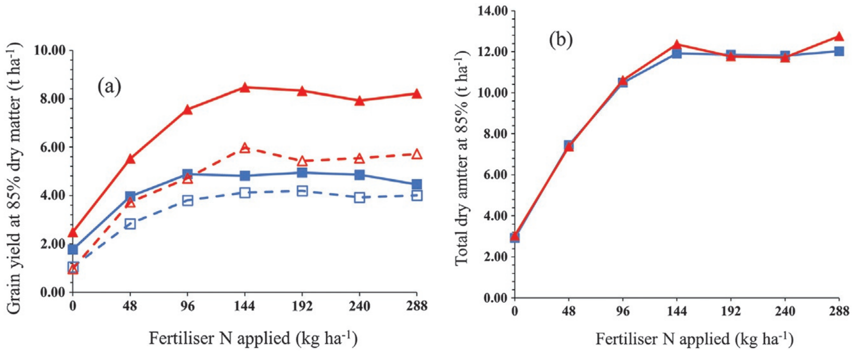

Fig. 10 Broadbalk Wheat Experiment, 1988–90. (A) Mean grain yields (t ha^{-1}) for *c.v.* Brimstone, ▲, 1st wheat after a 2-year break; △, continuous wheat: *c.v.* Squarehead's Master, ■, 1st wheat after a 2-year break; □, continuous wheat. (B) Total dry matter yield (t ha^{-1}) for the 1st wheat after a 2-year break; ▲, *c.v.* Brimstone; ■, *c.v.* Squarehead's Master.

4.2 Nutrient concentrations in wheat grain and straw, nutrient uptakes, grain quality, and nutrients in other crops grown in rotation

Grain and straw samples from the continuous wheat on Section 1 and the 1st wheat in rotation have been analyzed each year since 1968, usually for N, P, K, Mg, Na, Ca and S (since 2001). Samples from other sections in wheat are not analyzed routinely. Before 1968, crop samples were analyzed irregularly and samples from the same treatments were often bulked (according to yield) over several years before analysis (Johnston, 1969a,b). Earlier grain and straw samples are available in the Sample Archive for any retrospective analyses.

4.2.1 Nitrogen

Mean grain % N in the continuous wheat on Section 1 ranged from *c.* 1.4% to 2.6% N; and was slightly lower for the 1st wheat in rotation as is common for higher yielding crops (full data not shown but is available through e-RA). Average concentrations in straw ranged from *c.* 0.3% to 0.8% N (data not shown). The total uptake of N by grain plus straw is given in Tables 10 and 11; on average, the grain contained about 90% of the total N uptake.

The % recovery of fertilizer N (often termed apparent recovery) is usually calculated as:

$$\frac{\text{N uptake by crop with fertilizer N} - \text{N uptake by crop without fertilizer N} \times 100}{\text{Amount of fertilizer N applied}}$$

Table 10 Mean N uptake by wheat grain plus straw, kg ha^{-1} year^{-1}, continuous wheat, Section 1. Broadbalk Wheat Experiment.

Cultivars, years grown and mean N uptake by grain + straw (kg ha^{-1} yr^{-1})

Strip	Treatments[a] from 1968	C. Desprez 1970-78[b]	Flanders 1979-84	Treatments from 1985	Brimstone 1985-90	Apollo 1991-95	Hereward 1996-2000	Treatments from 2001	Hereward 2001-04	Hereward 2005-12	Crusoe 2013-18[c]
2.2	FYM	125	113	FYM	95	105	100	FYM	72	80	81
2.1	FYM N2	152	174	FYM N2	155	168	162	FYM N3[e]	117	155	153
01	FYM N2 PK	-	-	FYM N4 PK	-	-	-	(FYM) N4	-	-	-
03	Nil	30	25	Nil	17	15	18	Nil	9	15	16
05	PK(Na)Mg	30	23	PKMg	19	18	18	(P)KMg	12	18	18
06	N1 PK(Na)Mg	57	57	N1 PKMg	50	50	45	N1 (P)KMg	42	47	43
07	N2 PK(Na)Mg	90	104	N2 PKMg	90	89	85	N2 (P)KMg	71	84	71
08	N3 PK(Na)Mg	115	133	N3 PKMg	111	124	109	N3 (P)KMg	89	100	93
09	N4 PK(Na)Mg	130	156	N4 PKMg	128	139	148	N4 (P)KMg	129	131	120
15	N3 PK(Na)Mg	115	137	N5 PKMg	155	172	176	N5 (P)KMg	122	150	147
16	N2 PK(Na)Mg	90	100	N6 PKMg	156	176	195	N6 (P)KMg	154	165	156
19	C	72	64	(C)	44	28	28	N1+1+1 KMg	86	100	95
18	N2 ½[PK(Na)Mg]	86	124	N1+3 ½[PKMg](A)[d]	122	131	137	N1+2+1 PKMg	111	122	120
12	N2 P Na	85	91	N2 P Na	77	61	67	N1+3+1 (P)KMg2	133	152	149
17	N2 ½[PK(Na)Mg]	83	126	N0+3 ½[PKMg](A)[d]	115	123	122	N1+4+1 PKMg	143	158	160
10	N2	70	66	N2	53	57	50	N4	39	41	41
11	N2 P	69	78	N2 P	73	70	65	N4 P Mg	74	84	102
13	N2 PK	92	101	N2 PK	94	85	75	N4 PK	118	124	122
14	N2 PKMg*	92	101	N2 PKMg*	92	86	81	N4 PK*(Mg*)	121	128	111
20	N2 K(Na)Mg	73	65	N2 KMg	40	53	48	N4 KMg	34	17	17
	s.e.		**7.9**		**7.9**	**8.7**	**8.7**		**9.7**	**6.9**	**8.7**

$F(108,507) = 11.31$, $p < 0.001$ $\varphi = 0.4689$ (0.0421)

[a] See Table 1 for detailed description of treatments

[b] Although Cappelle Desprez was grown from 1968, the mean yields from 1970 - 1978 shown here, and in other tables, are to compare with the yields of the 1st wheat grown after a 2-year break which was not "in phase" until 1970 (see Appendix Table 1b). See Dyke et al. (1983) for s.e. of N uptake.

[c] Excludes spring wheat in 2015

[d] Between 1985 - 2000 the treatment on strips 17 and 18 alternated *i.e.* in one year the treatment included the application of autumn N, the following year it did not. Data shown for this period are NOT the mean yields on strips 17 or 18; rather they are the means of the years either without or with autumn N.

[e] FYM N2 until 2004

Table 11 Mean N uptake by wheat grain plus straw, kg ha^{-1} year^{-1}, 1st wheat after a 2-year break. Broadbalk Wheat Experiment.

	Cultivars, years grown and mean N uptake by grain + straw (kg ha^{-1} yr^{-1})										
Strip	Treatments[a] from 1968	C. Desprez 1970-78[b]	Flanders 1979-84	Treatments from 1985	Brimstone 1985-90	Apollo 1991-95	Hereward 1996-2000	Treatments from 2001	Hereward 2001-04	Hereward 2005-12	Crusoe 2013-18[c]
2.2	FYM	151	137	FYM	128	131	138	FYM	84	91	98
2.1	FYM N2	170	193	FYM N2	196	193	178	FYM N3[e]	145	203	210
01	FYM N2 PK	155	183	FYM N4 PK	215	232	214	(FYM) N4	190	204	200
03	Nil	44	47	Nil	36	24	33	Nil	17	24	24
05	PK(Na)Mg	52	50	PKMg	37	23	28	(P)KMg	20	25	22
06	N1 PK(Na)Mg	86	90	N1 PKMg	74	66	62	N1 (P)KMg	48	53	54
07	N2 PK(Na)Mg	117	134	N2 PKMg	118	120	104	N2 (P)KMg	86	89	90
08	N3 PK(Na)Mg	133	165	N3 PKMg	158	149	143	N3 (P)KMg	123	125	130
09	N4 PK(Na)Mg	140	187	N4 PKMg	173	174	173	N4 (P)KMg	157	172	167
15	N3 PK(Na)Mg	130	157	N5 PKMg	184	188	196	N5 (P)KMg	191	200	202
16	N2 PK(Na)Mg	113	128	N6 PKMg	201	194	214	N6 (P)KMg	206	225	228
19	C	102	96	(C)	78	39	41	N1+1+1 KMg	110	133	137
18	N2 ½[PK(Na)Mg]	119	150	N1+3 ½[PKMg](A)[d]	172	163	164	N1+2+1 PKMg	157	174	170
12	N2 P Na	103	119	N2 P Na	108	92	94	N1+3+1 (P)KMg2	170	198	198
17	N2 ½[PK(Na)Mg]	118	154	N0+3 ½[PKMg](A)[d]	161	154	146	N1+4+1 PKMg	202	223	241
10	N2	98	104	N2	84	106	99	N4	116	116	120
11	N2 P	97	117	N2 P	100	82	93	N4 P Mg	109	103	126
13	N2 PK	118	129	N2 PK	116	107	99	N4 PK	145	162	163
14	N2 PKMg*	118	130	N2 PKMg*	118	98	96	N4 PK*(Mg*)	143	157	151
20	N2 K(Na)Mg	-	-	N2 KMg	-	-	-	N4 KMg	-	-	-
	s.e.		**9.4**		**9.4**	**10.3**	**10.3**		**11.5**	**8.2**	**10.3**
	F(108,506) = 11.11, $p < 0.001$ $\varphi = 0.3566$ (0.0448)										

[a] See Table 1 for detailed description of treatments

[b] Although Cappelle Desprez was grown from 1968, the mean yields from 1970 - 1978 shown here, and in other tables, are to compare with the yields of the 1st wheat grown after a 2-year break which was not "in phase" until 1970 (see Appendix Table 1b). See Dyke et al. (1983) for s.e. of N uptake.

[c] Excludes spring wheat in 2015

[d] Between 1985 - 2000 the treatment on strips 17 and 18 alternated *i.e.* in one year the treatment included the application of autumn N, the following year it did not. Data shown for this period are NOT the mean yields on strips 17 or 18; rather they are the means of the years either without or with autumn N.

[e] FYM N2 until 2004

It can also be calculated as the % recovery of each increment of applied N.

On Broadbalk, this simple calculation is confounded by the fact that the fertilizer N treatments have been established for many years; N0, N1, N2, N3 since 1852, N4 since 1968, N5 and N6 since 1985. Increased amounts of N resulted in higher yields, larger residues of roots, root exudates and stubble and an increase in the % N in soil. More inorganic N is mineralized on soils with a larger N content, some of which will be available to the growing crop and some lost by leaching or denitrification. It is also possible that where the higher rates of N are applied some unused fertilizer N might remain in the soil, particularly if the yield is limited by disease or weather. In contrast, plots receiving no N for >170 years have had minimal inputs of organic matter as roots and stubble and consequently the amount of mineralized N available to the following crop will be limited. With these caveats the recovery of added N for selected treatment is shown in Table 12.

To determine the effect of these long-continued N applications, sub-plots (each 2.5 m × 6.0 m) were established on plots normally receiving PKMg plus N rates, N0–N6: these N applications were withheld in 1987–1990. Where N was withheld the results were variable, with interpretation being complicated by uptake of N by weeds. However, there was a clear trend for an increase in crop N uptake from N0 to N4 with 12–30 kg N ha^{-1} more on N3 and N4 sub-plots than on N0. At harvest 1988 and 1989 (i.e., 2 or 3 years after fertilizer N was last applied) the N3 and N4 sub-plots contained an extra 10–17 kg ha^{-1} of inorganic N in the topsoil compared with the N0 treatment. There were no differences between the withheld N areas and N0 in 1990. More inorganic N was found in 1989 and 1990 on plots receiving the usual N application, particularly those plots receiving the larger amounts of N. Laboratory incubations on soils from the withheld N areas measured higher mineralization rates on soils usually receiving larger rates of N (Glendining et al., 1996).

On the basis of these results, it was decided that when oats were introduced into the 5-course rotation in 1996, they would *not* receive fertilizer N *or* FYM. Measuring N uptake by the oats would allow an assessment of the effects of increased soil N on any additional mineralization and/or the carry-over of any residual fertilizer N. Table 13 shows the average annual yield and N uptake by oat grain plus straw from 1996 to 2017. Mean N uptake where PKMg but no fertilizer N has been applied since 1852 (strip 05) was 22–25 kg N ha^{-1}. Additional N taken up by the oats on plots from which N1–N6 was withheld in that year was *c.* 3, 6, 10, 16, 28 and 44 kg N ha^{-1}, respectively. On plots from which FYM or FYM + N was

Table 12 Mean % recovery of applied N by wheat grain plus straw, continuous wheat, Section 1, and 1st wheat after a 2-year break, selected treatments. Broadbalk Wheat Experiment.

	Cultivars, years grown and recovery of applied fertiliser N[a] (%)										
Strip	Treatments[b] from 1968	C. Desprez 1970-78[c]	Flanders 1979-84	Treatments from 1985	Brimstone 1985-90	Apollo 1991-95	Hereward 1996-2000	Treatments from 2001	Hereward 2001-04	Hereward 2005-12	Crusoe 2013-18[d]
					Continuous wheat, Section 1						
2.1	FYM N2	28	64	FYM N2	62	66	65	FYM N3[e]	46	52	50
06	N1 PK(Na)Mg	56	71	N1 PKMg	66	67	56	N1 (P)KMg	64	60	51
07	N2 PK(Na)Mg	69	98	N2 PKMg	83	82	83	N2 (P)KMg	61	77	60
08	N3 PK(Na)Mg	52	60	N3 PKMg	43	73	51	N3 (P)KMg	36	34	46
09	N4 PK(Na)Mg	31	47	N4 PKMg	36	30	82	N4 (P)KMg	84	65	55
15	N3 PK(Na)Mg	52	69	N5 PKMg	57	69	57	N5 (P)KMg	-15	38	56
16	N2 PK(Na)Mg	69	89	N6 PKMg	1	8	41	N6 (P)KMg	67	32	19
					1st wheat after a 2-year break						
2.1	FYM N2	20	58	FYM N2	71	65	41	FYM N3[e]	64	78	78
01	FYM N2 PK	4	48	FYM N4 PK	20	41	38	(FYM) N4	47	2	-22
06	N1 PK(Na)Mg	71	83	N1 PKMg	78	91	71	N1 (P)KMg	59	59	67
07	N2 PK(Na)Mg	65	93	N2 PKMg	92	112	86	N2 (P)KMg	78	74	76
08	N3 PK(Na)Mg	33	64	N3 PKMg	84	60	82	N3 (P)KMg	76	76	84
09	N4 PK(Na)Mg	15	45	N4 PKMg	31	51	63	N4 (P)KMg	71	97	76
15	N3 PK(Na)Mg	27	47	N5 PKMg	23	29	48	N5 (P)KMg	71	58	73
16	N2 PK(Na)Mg	56	80	N6 PKMg	35	13	37	N6 (P)KMg	33	51	54

[a] Calculated for each increment of applied fertiliser N (*e.g.* uptake by N3 minus uptake by N2 as % of 48 kg N ha^{-1}, or uptake by FYM N2 minus uptake by FYM as % of 96 or 144 kg N ha^{-1})

[b] See Table 1 for detailed description of treatments

[c] Although Cappelle Desprez was grown from 1968, the mean yields from 1970 - 1978 shown here, and in other tables, are to compare with the yields of the 1st wheat grown after a 2-year break which was not "in phase" until 1970 (see Appendix Table 1b).

[d] Excludes spring wheat in 2015

[e] FYM N2 until 2004

Table 13 Mean yield of oat grain, t ha^{-1} year^{-1} at 85% dry matter, and mean N uptake, kg ha^{-1} year^{-1}, by oat grain plus straw. Broadbalk Wheat Experiment.

		1996-2001			2002-2017	
Strip	Treatments to oats[a] 1996-2001	Grain yield (t ha^{-1})	N uptake grain + straw (kg ha^{-1})	Treatments to oats 2002-2017	Grain yield (t ha^{-1})	N uptake grain + straw (kg ha^{-1})
2.2	(FYM)	5.58	78	(FYM)	6.77	86
2.1	(FYM N2)	5.73	80	(FYM N3)	7.17	92
01	(FYM N4) PK	5.92	91	(FYM) (N4)	5.82	69
03	Nil	1.53	19	Nil	1.88	22
05	PKMg	1.75	22	(P)KMg	2.20	25
06	(N1) PKMg	1.96	25	(N1) (P)KMg	2.47	28
07	(N2) PKMg	2.28	27	(N2) (P)KMg	2.91	32
08	(N3) PKMg	2.51	30	(N3) (P)KMg	3.43	38
09	(N4) PKMg	2.95	37	(N4) (P)KMg	3.69	41
15	(N5) PKMg	3.82	51	(N5) (P)KMg	4.53	52
16	(N6) PKMg	4.89	66	(N6) (P)KMg	5.77	69
19	(C)	1.83	22	(N1+1+1) KMg	2.69	32
18	(N1+3) ½[PKMg](A)	2.78	34	(N1+2+1) PKMg	3.25	36
12	(N2) P Na	2.39	28	(N1+3+1) (P)KMg2	3.84	42
17	(N0+3) ½[PKMg](A)	2.98	36	{N1+4+1) PKMg	5.38	64
10	(N2)	2.41	30	(N4)	4.75	67
11	(N2) P	2.42	29	(N4) P Mg	5.24	62
13	(N2) PK	1.97	24	(N4) PK	3.50	40
14	(N2) PKMg*	1.96	25	(N4) PK*(Mg*)	3.57	40
20	(N2) KMg	-	-	(N4) KMg	-	-
	s.e.	**0.402**	**5.2**		**0.246**	**3.2**

For yield, F(18,315) = 7.25, $p < 0.001$ φ = 0.5747 (0.0537)

For N uptake, F(18,317) = 9.88, $p < 0.001$ φ = 0.5784 (0.0515)

[a] See Table 1 for detailed description of treatments but note that oats did not receive fertiliser N or FYM in the year that they were grown.

withheld, uptake by the oats was 78–92 kg N ha^{-1}; a very considerable amount of N was mineralized from the accumulated manure residues and taken up by the crop. However, if it is not taken up by the following autumn-sown crop much of the mineralized N will be subject to loss by leaching and/or denitrification. When measurements have been made at harvest or over-winter, there is almost always more inorganic N in the soil profile of the organic FYM treatments compared with plots receiving PKMg and high rates of inorganic N fertilizers (Goulding et al., 2000).

Previous analyses of grain and straw samples (often bulked over 10 years) were published by Lawes and Gilbert (1858, 1884), Gilbert (1895), Russell and Watson (1940) and Chambers (1953). Comparisons of data for different cultivars and earlier periods are difficult because of changes in management, e.g., form of N and time of application (Johnston, 1969a,b). However, because an old and a modern cultivar were grown side-by-side on selected treatments over 4 years (see above), a direct comparison is possible. Fig. 10A and B shows the differences in yield between the old long-straw cultivar, Squarehead's Master, and the modern short-straw cultivar, Brimstone. The data summarized in Table 14 show that grain % N was less in Brimstone because the yield was larger. Although % N in straw was similar for the two varieties, the larger yield of straw from the older long-straw cultivar meant that N uptake was greater. Overall, total N uptake by the two cultivars was the same.

4.2.2 Using ^{15}N-labeled fertilizer to investigate the fate of applied N

In 1979, Jenkinson, Powlson and colleagues began a series of experiments using the stable isotope of N to investigate the fate of ^{15}N-labeled fertilizer applied to arable crops and pasture. Their intention was to apply the

Table 14 Mean yields[a] and uptakes of N, P and K, by *cv.* Squarehead's Master and *cv.* Brimstone, 1988–90. Broadbalk Wheat Experiment.

	***cv.* Squarehead's Master**			***cv.* Brimstone**		
	Grain	**Straw**	**Total**	**Grain**	**Straw**	**Total**
Yield at 85% dry matter ($t\,ha^{-1}$)	4.30	5.01	9.31	6.64	2.67	9.31
% N	2.53	0.54	–	1.87	0.51	–
N uptake ($kg\,ha^{-1}$)	94	26	120	108	14	122
% P	0.39	0.06	–	0.29	0.06	–
P uptake ($kg\,ha^{-1}$)	14.0	2.7	16.8	16.4	1.6	18.0
% K	0.46	0.83	–	0.51	0.81	–
K uptake ($kg\,ha^{-1}$)	16.7	35.3	52.0	28.6	17.6	46.2

[a] Yields and uptakes of wheat grown as the 1st wheat after a 2-year break; mean of all treatments except those on strips 01, 2.1, 2.2 and 20.

labeled N to unconfined microplots in the field (rather than lysimeters or tubes inserted into the soil) to see how much N was taken up by the crop, how much remained in the soil, its fate over subsequent years and how much was lost. On Broadbalk, microplots (2 m × 2 m) were established on selected treatments in spring 1980, 1981, 1982 and 1983 to which labeled N was applied at the appropriate rate, as equal amounts $K^{15}NO_3$ and $(^{15}NH_4)_2SO_4$ or as $K^{15}NO_3$ or $(^{15}NH_4)_2SO_4$ separately. Where yield was not limited by lack of available P, 51–68% of the labeled N was recovered by the wheat, 14–36% remained in the soil and 14–30% was lost from the crop:soil system (Powlson et al., 1986a). More labeled N remained in the soil, mostly as organic N, when applied as NH_4-N and only 1% of that applied in spring remained as inorganic N in the soil at harvest (Macdonald et al., 1989). The fate of the labeled N residues remaining in the soil was monitored for the next 3 years (Hart et al., 1993). About 16% of the residue was mineralized and taken up by the following wheat crops, about 30% lost, but, 3 years later, 55% of the residue was still found in the soil. Modeling the spring-applied labeled N lost in the first season it was estimated that almost twice as much was lost by denitrification than by leaching (Addiscott, 2005; Addiscott and Powlson, 1992). At a time when losses of fertilizer N by leaching were being blamed for the eutrophication of water courses (Addiscott et al., 1991) the fact that only 1% of the spring applied N remained in the soil as inorganic N at harvest and thus at risk of loss by leaching helped to counter this claim. It was concluded that the overall arable system was responsible, with most nitrate leached being derived from mineralization of soil organic matter rather than from unused fertilizer (Addiscott et al., 1991; Macdonald et al., 1989). However, as seen above, fertilizer N can increase soil N which will, in turn, result in more inorganic N being mineralized and subject to loss. Labeled N was also applied in autumn 1980 and 1981 to plots on Broadbalk that received autumn N at that time. Only 16–32% of the labeled N was recovered by the crop, 21% remained in the soil and 46–64% was lost (Powlson et al., 1986b).

Similar ^{15}N studies were carried out on other long-term experiments at Rothamsted, including the Hoosfield Spring Barley Experiment (Glendining et al., 1997, 2001) and the Park Grass Experiment (Jenkinson et al., 2004). Over a 20+ year period this was one of the most comprehensive programs of research using ^{15}N-labeled fertilizer anywhere in the world and acted as a model for numerous other studies in a wide range of environments and cropping systems globally, e.g., Dourado-Neto et al. (2010).

4.2.3 Potassium

Dyke et al. (1983) gave data on K from 1968 to 1978, when the first modern short-strawed cultivar, Cappelle Desprez, was grown; some of that data are included here. Grain % K varied from *c*. 0.3% to 0.6% while % K in straw varied greatly, from as little as 0.1% to >2.0% K. Johnston et al. (2016a) reviewed the management of potassium in soils and crops and showed a clear correlation between % K in straw and the number of days between 1st August and harvest; the later the harvest, the lower straw % K (see Fig. 17 in Johnston et al., 2016a). It has been thought that K might be leached from the stems and leaves by rainfall but plotting rainfall against % K in straw did not improve the correlation. One possible explanation is that in the latter half of the growing season, K is translocated through the straw and exuded through the roots.

Because of the variability in the amount of K in the straw, the total K uptake by grain plus straw also varies greatly; Tables 15 and 16 show total K uptake by grain plus straw for wheat grown continuously or in rotation. Average uptakes by the 1st wheats were largest on the FYM treatments where soils had a high level of exchangeable K. On soils with PKMg and larger rates of N average K offtakes in grain plus straw exceeded the 90 kg ha^{-1} applied as fertilizer K in some years. Uptakes were less on the continuous wheat where average yields were smaller.

Concentrations of K in grain and straw from the short-straw cultivars grown since 1968 are similar to earlier periods although changes in analytical techniques make comparisons difficult. But, as with N, we do have a direct comparison when two varieties were grown side-by-side in 1988–90. Both grain yield and K uptake of Brimstone was greater than that of Squarehead's Master but the much larger yield of straw with Squarehead's Master contained more K. Overall, the total K uptake by the grain and straw of Squarehead's Master was greater than that of Brimstone (Table 14).

4.2.4 Phosphorus

Percentage P in grain varied from <0.2% where no P fertilizer was applied to >0.4% where fertilizer or FYM was applied (data not shown). Average total P uptake by grain plus straw was 2–9 kg ha^{-1} where no P was applied to wheat grown continuously, slightly more for wheat in rotation. With fertilizer P or FYM mean uptakes were up to 29 kg P ha^{-1} for continuous wheat and 37 kg P ha^{-1} for wheat in rotation (Tables 17 and 18). About 90–95% of the total P uptake was in the grain.

Table 15 Mean K uptake by grain plus straw, kg ha^{-1} year^{-1}, continuous wheat, Section 1. Broadbalk Wheat Experiment.

	Cultivars, years grown and mean K uptake by grain + straw (kg ha^{-1} yr^{-1})										
Strip	Treatments[a] from 1968	C. Desprez 1970-78[b]	Flanders 1979-84	Treatments from 1985	Brimstone 1986-90[c]	Apollo 1991-95	Hereward 1996-2000	Treatments from 2001	Hereward 2001-04	Hereward 2005-12	Crusoe 2013-18[d]
2.2	FYM	107	n.a.	FYM	68	66	62	FYM	36	45	33
2.1	FYM N2	133	n.a.	FYM N2	77	114	92	FYM N3[f]	51	65	57
01	FYM N2 PK	-	-	FYM N4 PK	-	-	-	(FYM) N4	-	-	-
03	Nil	15	n.a.	Nil	7	8	10	Nil	4	5	5
05	PK(Na)Mg	20	n.a.	PKMg	11	9	12	(P)KMg	6	7	7
06	N1 PK(Na)Mg	37	n.a.	N1 PKMg	30	30	29	N1 (P)KMg	21	21	17
07	N2 PK(Na)Mg	56	n.a.	N2 PKMg	40	48	49	N2 (P)KMg	30	35	27
08	N3 PK(Na)Mg	66	n.a.	N3 PKMg	41	59	55	N3 (P)KMg	34	36	30
09	N4 PK(Na)Mg	77	n.a.	N4 PKMg	51	62	63	N4 (P)KMg	37	41	33
15	N3 PK(Na)Mg	66	n.a.	N5 PKMg	53	81	81	N5 (P)KMg	41	50	42
16	N2 PK(Na)Mg	48	n.a.	N6 PKMg	55	83	83	N6 (P)KMg	44	52	41
19	C	36	n.a.	(C)	27	13	14	N1+1+1 KMg	30	34	27
18	N2 ½[PK(Na)Mg]	44	n.a.	N1+3 ½[PKMg](A)[e]	43	59	54	N1+2+1 PKMg	33	38	32
12	N2 P Na	33	n.a.	N2 P Na	22	18	19	N1+3+1 (P)KMg2	36	43	40
17	N2 ½[PK(Na)Mg]	40	n.a.	N0+3 ½[PKMg](A)[e]	40	54	50	N1+4+1 PKMg	42	47	41
10	N2	25	n.a.	N2	25	28	16	N4	10	10	9
11	N2 P	25	n.a.	N2 P	21	23	18	N4 P Mg	16	17	23
13	N2 PK	51	n.a.	N2 PK	35	42	39	N4 PK	39	40	36
14	N2 PKMg*	40	n.a.	N2 PKMg*	34	41	43	N4 PK*(Mg*)	36	40	31
20	N2 K(Na)Mg	33	n.a.	N2 KMg	16	29	24	N4 KMg	11	5	4
	s.e.				**6.1**	**6.1**	**6.1**		**6.8**	**4.8**	**6.1**

F(90,403) = 6.39, $p < 0.001$ $\varphi = 0.4820$ (0.0551)

[a] See Table 1 for detailed description of treatments

[b] Although Cappelle Desprez was grown from 1968, the mean yields from 1970 - 1978 shown here, and in other tables, are to compare with the yields of the 1st wheat grown after a 2-year break which was not "in phase" until 1970 (see Appendix Table 1b). See Dyke et al. (1983) for s.e. of K uptake.

[c] Not analysed for K in 1985

[d] Excludes spring wheat in 2015

[e] Between 1985-2000 the treatment on strips 17 and 18 alternated *i.e.* in one year the treatment included the application of autumn N, the following year it did not. Data shown for this period are NOT the mean yields on strips 17 or 18; rather they are the means of the years either without or with autumn N.

[f] FYM N2 until 2004

n.a. Not analysed for K

Table 16 Mean K uptake by grain plus straw, kg ha^{-1} year^{-1}, 1st wheat after a 2-year break. Broadbalk Wheat Experiment.

Cultivars, years grown and mean K uptake by grain + straw (kg ha^{-1} yr^{-1})

Strip	Treatments[a] from 1968	C. Desprez 1970-78[b]	Flanders 1979-84	Treatments from 1985	Brimstone 1986-90[c]	Apollo 1991-95	Hereward 1996-2000	Treatments from 2001	Hereward 2001-04	Hereward 2005-12	Crusoe 2013-18[d]
2.2	FYM	134	n.a.	FYM	60	94	70	FYM	39	48	46
2.1	FYM N2	159	n.a.	FYM N2	104	137	106	FYM N3[f]	64	92	79
01	FYM N2 PK	104	n.a.	FYM N4 PK	112	166	123	(FYM) N4	72	80	62
03	Nil	22	n.a.	Nil	15	12	13	Nil	6	10	8
05	PK(Na)Mg	32	n.a.	PKMg	15	12	15	(P)KMg	9	10	8
06	N1 PK(Na)Mg	53	n.a.	N1 PKMg	32	38	35	N1 (P)KMg	22	25	23
07	N2 PK(Na)Mg	71	n.a.	N2 PKMg	47	59	49	N2 (P)KMg	36	41	36
08	N3 PK(Na)Mg	88	n.a.	N3 PKMg	60	75	62	N3 (P)KMg	46	49	47
09	N4 PK(Na)Mg	93	n.a.	N4 PKMg	58	79	69	N4 (P)KMg	54	62	53
15	N3 PK(Na)Mg	81	n.a.	N5 PKMg	65	88	81	N5 (P)KMg	65	71	61
16	N2 PK(Na)Mg	63	n.a.	N6 PKMg	75	91	86	N6 (P)KMg	69	79	69
19	C	43	n.a.	(C)	27	18	16	N1+1+1 KMg	37	46	45
18	N2 ½[PK(Na)Mg]	62	n.a.	N1+3 ½[PKMg](A)[e]	59	73	60	N1+2+1 PKMg	49	60	55
12	N2 P Na	40	n.a.	N2 P Na	36	31	30	N1+3+1 (P)KMg2	50	63	59
17	N2 ½[PK(Na)Mg]	64	n.a.	N0+3 ½[PKMg](A)[e]	59	67	56	N1+4+1 PKMg	62	74	68
10	N2	32	n.a.	N2	26	37	31	N4	31	29	26
11	N2 P	38	n.a.	N2 P	31	27	29	N4 P Mg	23	23	27
13	N2 PK	73	n.a.	N2 PK	45	54	45	N4 PK	52	60	53
14	N2 PKMg*	56	n.a.	N2 PKMg*	44	48	44	N4 PK*(Mg*)	46	54	44
20	N2 K(Na)Mg	-	-	N2 KMg	-	-	-	N4 KMg	-	-	-
	s.e.				**9.0**	**9.0**	**9.0**		**10.0**	**7.1**	**9.0**

F(90,403) = 4.80, $p < 0.001$ $\varphi = 0.6105$ (0.0515)

[a] See Table 1 for detailed description of treatments

[b] Although Cappelle Desprez was grown from 1968, the mean yields from 1970 - 1978 shown here, and in other tables, are to compare with the yields of the 1st wheat grown after a 2-year break which was not "in phase" until 1970 (see Appendix Table 1b). See Dyke et al. (1983) for s.e. of K uptake.

[c] Not analysed for K in 1985

[d] Excludes spring wheat in 2015

[e] Between 1985-2000 the treatment on strips 17 and 18 alternated *i.e.* in one year the treatment included the application of autumn N, the following year it did not. Data shown for this period are NOT the mean yields on strips 17 or 18; rather they are the means of the years either without or with autumn N.

[f] FYM N2 until 2004

n.a. Not analysed for K

Table 17 Mean P uptake by grain plus straw, kg ha^{-1} year^{-1}, continuous wheat, Section 1. Broadbalk Wheat Experiment.

Cultivars, years grown and mean P uptake by grain + straw (kg ha^{-1} yr^{-1})

Strip	Treatments[a] from 1968	C. Desprez 1970-78[b]	Flanders 1979-84	Treatments from 1985	Brimstone 1986-90[c]	Apollo 1991-95	Hereward 1996-2000	Treatments from 2001	Hereward 2001-04	Hereward 2005-12	Crusoe 2013-18[d]
2.2	FYM	25	n.a.	FYM	21	24	22	FYM	15	16	15
2.1	FYM N2	25	n.a.	FYM N2	26	31	29	FYM N3[f]	22	22	21
01	FYM N2 PK	-	-	FYM N4 PK	-	-	-	(FYM) N4	-	-	-
03	Nil	6	n.a.	Nil	3	4	4	Nil	2	2	2
05	PK(Na)Mg	7	n.a.	PKMg	4	5	5	(P)KMg	3	4	3
06	N1 PK(Na)Mg	14	n.a.	N1 PKMg	10	12	11	N1 (P)KMg	9	9	7
07	N2 PK(Na)Mg	18	n.a.	N2 PKMg	16	19	17	N2 (P)KMg	13	14	11
08	N3 PK(Na)Mg	18	n.a.	N3 PKMg	16	22	19	N3 (P)KMg	13	13	12
09	N4 PK(Na)Mg	20	n.a.	N4 PKMg	18	22	21	N4 (P)KMg	15	14	12
15	N3 PK(Na)Mg	18	n.a.	N5 PKMg	20	27	24	N5 (P)KMg	15	16	15
16	N2 PK(Na)Mg	17	n.a.	N6 PKMg	19	25	24	N6 (P)KMg	17	16	14
19	C	14	n.a.	(C)	9	7	6	N1+1+1 KMg	10	10	8
18	N2 ½[PK(Na)Mg]	15	n.a.	N1+3 ½[PKMg](A)[e]	17	22	18	N1+2+1 PKMg	11	12	11
12	N2 P Na	17	n.a.	N2 P Na	12	12	12	N1+3+1 (P)KMg2	16	17	16
17	N2 ½[PK(Na)Mg]	15	n.a.	N0+3 ½[PKMg](A)[e]	16	20	17	N1+4+1 PKMg	14	14	14
10	N2	9	n.a.	N2	6	6	5	N4	3	3	3
11	N2 P	13	n.a.	N2 P	11	14	12	N4 P Mg	11	11	13
13	N2 PK	17	n.a.	N2 PK	16	17	14	N4 PK	15	15	15
14	N2 PKMg*	18	n.a.	N2 PKMg*	16	18	16	N4 PK*(Mg*)	16	17	14
20	N2 K(Na)Mg	8	n.a.	N2 KMg	4	6	4	N4 KMg	3	1	1
	s.e.				**1.4**	**1.4**	**1.4**		**1.6**	**1.1**	**1.4**

F(90,407) = 5.38, $p < 0.001$ φ = 0.4529 (0.0500)

[a] See Table 1 for detailed description of treatments

[b] Although Cappelle Desprez was grown from 1968, the mean yields from 1970 - 1978 shown here, and in other tables, are to compare with the yields of the 1st wheat grown after a 2-year break which was not "in phase" until 1970 (see Appendix Table 1b). See Dyke et al. (1983) for s.e. of P uptake.

[c] Not analysed for P in 1985

[d] Excludes spring wheat in 2015

[e] Between 1985-2000 the treatment on strips 17 and 18 alternated *i.e.* in one year the treatment included the application of autumn N, the following year it did not. Data shown for this period are NOT the mean yields on strips 17 or 18; rather they are the means of the years either without or with autumn N.

[f] FYM N2 until 2004

n.a. Not analysed for P

Table 18 Mean P uptake by grain plus straw, kg ha^{-1} year^{-1}, 1st wheat after a 2-year break. Broadbalk Wheat Experiment.

Cultivars, years grown and mean P uptake by grain + straw (kg ha^{-1} yr^{-1})

Strip	Treatments[a] from 1968	C. Desprez 1970-78[b]	Flanders 1979-84	Treatments from 1985	Brimstone 1986-90[c]	Apollo 1991-95	Hereward 1996-2000	Treatments from 2001	Hereward 2001-04	Hereward 2005-12	Crusoe 2013-18[d]
2.2	FYM	29	n.a.	FYM	25	30	27	FYM	18	21	23
2.1	FYM N2	27	n.a.	FYM N2	32	36	34	FYM N3[f]	29	34	33
01	FYM N2 PK	23	n.a.	FYM N4 PK	30	37	35	(FYM) N4	31	31	29
03	Nil	9	n.a.	Nil	7	6	6	Nil	4	5	5
05	PK(Na)Mg	12	n.a.	PKMg	8	6	7	(P)KMg	5	6	5
06	N1 PK(Na)Mg	19	n.a.	N1 PKMg	15	16	14	N1 (P)KMg	11	12	12
07	N2 PK(Na)Mg	22	n.a.	N2 PKMg	21	24	21	N2 (P)KMg	17	17	17
08	N3 PK(Na)Mg	23	n.a.	N3 PKMg	25	28	26	N3 (P)KMg	22	20	22
09	N4 PK(Na)Mg	21	n.a.	N4 PKMg	25	28	28	N4 (P)KMg	23	24	23
15	N3 PK(Na)Mg	22	n.a.	N5 PKMg	25	28	29	N5 (P)KMg	27	26	26
16	N2 PK(Na)Mg	21	n.a.	N6 PKMg	26	27	29	N6 (P)KMg	25	26	27
19	C	19	n.a.	(C)	14	9	8	N1+1+1 KMg	17	18	18
18	N2 ½[PK(Na)Mg]	21	n.a.	N1+3 ½[PKMg](A)[e]	24	25	24	N1+2+1 PKMg	22	23	23
12	N2 P Na	20	n.a.	N2 P Na	19	17	19	N1+3+1 (P)KMg2	24	25	26
17	N2 ½[PK(Na)Mg]	21	n.a.	N0+3 ½[PKMg](A)[e]	23	25	23	N1+4+1 PKMg	24	25	26
10	N2	13	n.a.	N2	12	15	15	N4	14	13	12
11	N2 P	18	n.a.	N2 P	17	15	18	N4 P Mg	16	15	19
13	N2 PK	22	n.a.	N2 PK	20	21	19	N4 PK	22	24	25
14	N2 PKMg*	23	n.a.	N2 PKMg*	21	21	19	N4 PK*(Mg*)	22	24	23
20	N2 K(Na)Mg	-	-	N2 KMg	-	-	-	N4 KMg	-	-	-
	s.e.				**1.8**	**1.8**	**1.8**		**2.0**	**1.4**	**1.8**

F(90,407) = 4.27, $p < 0.001$ φ = 0.4836 (0.0493)

[a] See Table 1 for detailed description of treatments

[b] Although Cappelle Desprez was grown from 1968, the mean yields from 1970 - 1978 shown here, and in other tables, are to compare with the yields of the 1st wheat grown after a 2-year break which was not "in phase" until 1970 (see Appendix Table 1b). See Dyke et al. (1983) for s.e. of P uptake.

[c] Not analysed for P in 1985

[d] Excludes spring wheat in 2015

[e] Between 1985-2000 the treatment on strips 17 and 18 alternated *i.e.* in one year the treatment included the application of autumn N, the following year it did not. Data shown for this period are NOT the mean yields on strips 17 or 18; rather they are the means of the years either without or with autumn N.

[f] FYM N2 until 2004

n.a. Not analysed for P

A direct comparison of the old and new cultivars (Table 14) shows that, although % P in the grain of the modern cultivar was lower than in the older cultivar, the large differences in grain and straw yield meant that the uptakes of P were the same.

4.2.5 Magnesium, calcium and sodium

Uptakes of Mg, Ca and Na are not shown here but are available through e-RA.

4.2.6 Grain quality

Most of the cultivars grown on Broadbalk have been considered suitable for bread-making provided certain criteria are met. For example: (a) the grain should be well filled and not shriveled; (b) the Hagberg Falling Number (HFN) should exceed 250; (c) the protein content should exceed 13%; (d) the hectoliter weight should exceed 76 kg L^{-1}; (e) the ratio of N:S should *not* exceed 17:1. A protein content of 13% is equivalent to 2.28% N in grain. In the 1970s/1980s, Benzian et al. (1983) showed that, with the cultivars grown at that time, it was difficult to have both a large grain yield and a sufficiently high concentration of N in the grain such that it was suitable for bread-making. They speculated that this would continue to pose a problem for farmers who needed to estimate their likely yield and how much fertilizer N was needed to achieve that yield and reach 13% protein. In the United Kingdom, there is a premium for bread-making wheat compared with feed wheat, so this is clearly an important management decision for the farmer. Fig. 11 shows the grain yield and % N in grain from 2001 to 2018 (excluding spring wheat in 2015) for two recent cultivars on Broadbalk, grown either as continuous wheat or the 1st wheat after a 2-year break and given amounts of N ranging from 144 to 288 kg ha^{-1} (N3–N6) as single or split applications. Fig. 11 shows that Benzian et al. (1983) were correct; it is not always possible to obtain a large yield with a high concentration of N in the grain. The higher yielding 1st wheats tended to have lower grain % N. For the 17 years and four N rates shown, only 45% of the 1st wheats exceeded 2.28% N compared with 66% for continuous wheat.

Hectoliter weights and HFN for the same group of years and treatments (136 examples for both continuous wheat and the 1st wheat in rotation; Fig. 12A and B) show that for the continuous wheat, 66% of the examples had hectoliter weights >76 kg L^{-1} and 57% had HFN values >250; only 52% met the criteria for both *but* a further 20% failed to reach the required protein content. Reaching the standards needed to satisfy the millers for the

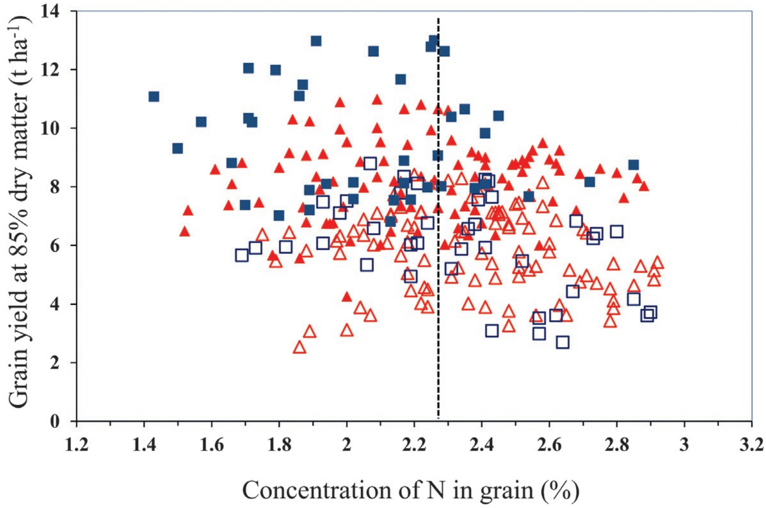

Fig. 11 Yield vs % N in grain for *c.v.* Hereward, 2001–12, and *c.v.* Crusoe, 2013–18 (excluding 2015), grown continuously or as the 1st wheat after a 2-year break and given (P)KMg plus fertilizer N ranging from 144 to 288 kg ha^{-1} as single or split applications. △, continuous Hereward; ▲, Hereward grown as a 1st wheat; □, continuous Crusoe; ■, Crusoe grown as a 1st wheat. The dashed line represents the minimum % N required for bread-making wheat. Broadbalk Wheat Experiment.

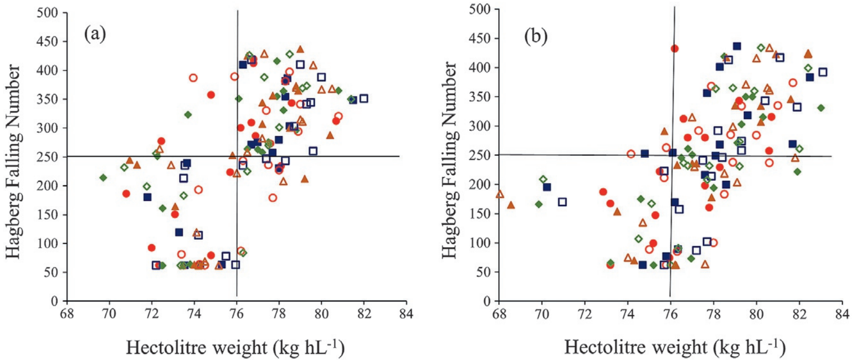

Fig. 12 Hagberg Falling Number vs Hectoliter weight for *c.v.* Hereward and *c.v.* Crusoe, 2001–18 (excluding 2015) grown (A) continuously or (B) as the 1st wheat after a 2-year break. Treatments shown are those receiving (P)KMg and 144, 192, 240 or 288 kg N ha^{-1} as single (●, ■, ♦, ▲) or split (○, □, ◇, △) applications. The horizontal and vertical lines represent the minimum Hagberg Falling Number and minimum hectoliter weight, respectively, required for bread-making wheat. Broadbalk Wheat Experiment.

1st wheat in rotation was even more difficult. Although 82% exceeded the value needed for hectoliter weight only 48% had HFN values >250; only 46% met the criteria for both and, of these, a further 22% failed to achieve the necessary protein content.

The N:S ratio in grain is also important for bread-making wheat as it influences the quality of the protein in the grain and should not exceed 17:1 (Zhao and McGrath, 2003). Since 2001, S-containing fertilizers have been withheld from strip 14. Compared with strip 9, which receives the same amount of N, K as K_2SO_4 rather than KCl, and adequate levels of P and Mg, the N:S ratio of wheat grown in rotation has increased slightly, but for wheat grown continuously the ratio has increased markedly as % S in the grain has declined. The yield of grain was less where no S in fertilizer was applied, although not always significantly so (strip 14 cf. strip 9; Tables 2–8). Grain % S and total uptake of S for continuous wheat and the 1st wheat after a 2-year break are given in Tables 19 and 20, respectively.

4.2.7 Other crops in rotation with wheat

The main reason for growing other crops in rotation with wheat since 1968 has been to provide a "disease break," but they also provide some additional agronomic information. The yields and nutrient offtakes of beans and potatoes grown in rotation with Cappelle Desprez were discussed by Dyke et al. (1983). Yields of potatoes grown between 1979 and 1984 are available from e-RA but are not discussed here. Potatoes and bare fallows provided the break from continuous wheat as part of a 5-year rotation between 1984 and 1996. In 1996 a revised 5-course rotation was phased-in, with oats and maize as the two break crops (Appendix Table A1b).

4.2.8 Potatoes, 1985–96

To allow the following wheat crop to be drilled at the appropriate time the potatoes were lifted earlier than usual after the tops had either died naturally or had been desiccated. Thus, yields were smaller than would be expected for main-crop potatoes. Potatoes exhibit much greater spatial variability than cereals and on Broadbalk they appear to show a trend across the field which means that standard errors need to be calculated on log transformed data (available through e-RA). Here, mean yields and offtakes for 1985–1996 are in Table 21. Largest yields were on plots receiving PKMg and the highest rate of N or FYM plus extra N. On the fertilizer plots receiving >144 kg N ha^{-1} (and sufficient P and Mg) average offtakes of K exceeded annual applications of 90 kg K ha^{-1}.

Table 19 Mean % S in grain and mean S uptake by grain plus straw, kg ha^{-1} year^{-1}, continuous wheat, Section 1. Broadbalk Wheat Experiment.

		Cultivars, years grown, % S in grain and mean S uptake by grain + straw (kg ha^{-1} yr^{-1})					
		% S in grain			Total S uptake by grain + straw, kg ha^{-1}		
	Treatments[a]	Hereward	Hereward	Crusoe	Hereward	Hereward	Crusoe
Strip	from 2001	2001-04[b]	2005-12	2013-18[c]	2001-04[b]	2005-12	2013-18[c]
2.2	FYM	0.131	0.114	0.115	5.9	6.6	5.9
2.1	FYM N3[d]	0.138	0.134	0.136	9.3	10.3	10.2
01	(FYM) N4	-	-	-	-	-	-
03	Nil	0.134	0.118	0.110	1.1	1.3	1.1
05	(P)KMg	0.131	0.116	0.113	1.7	1.8	1.4
06	N1 (P)KMg	0.120	0.119	0.116	5.9	5.7	3.3
07	N2 (P)KMg	0.124	0.128	0.123	6.5	7.1	5.6
08	N3 (P)KMg	0.146	0.141	0.135	8.6	8.5	7.2
09	N4 (P)KMg	0.160	0.150	0.147	10.6	10.4	9.1
15	N5 (P)KMg	0.152	0.156	0.153	10.0	11.1	11.2
16	N6 (P)KMg	0.153	0.158	0.156	11.3	12.2	11.5
19	N1+1+1 KMg	0.150	0.141	0.144	9.1	8.9	7.2
18	N1+2+1 PKMg	0.151	0.148	0.146	9.5	9.7	9.1
12	N1+3+1 (P)KMg2	0.155	0.152	0.155	11.5	11.9	11.7
17	N1+4+1 PKMg	0.158	0.153	0.154	11.4	11.7	11.9
10	N4	0.143	0.129	0.113	3.3	2.9	2.2
11	N4 P Mg	0.161	0.157	0.150	6.5	7.1	7.9
13	N4 PK	0.150	0.145	0.146	9.5	9.7	9.4
14	N4 PK*(Mg*)[f]	0.130	0.125	0.098	8.2	8.3	5.2
20	N4 KMg	0.152	0.143	0.146	3.3	1.7	1.2
	s.e.	**0.0086**	**0.0052**	**0.0066**	**1.14**	**0.70**	**0.88**
		F(36,201.9) = 2.01, p = 0.001			F(18,206.1) = 93.87, $p < 0.001$		
		φ = 0.5146 (0.0621)			φ = 0.5146 (0.0621) (Treatment effect only)		

[a] See Table 1 for detailed description of treatments

[b] Not analysed for S in 2002

[c] Excludes spring wheat in 2015

[d] FYM N2 until 2004

[f] K, as KCl, since 2001, *i.e.* no S applied.

4.2.9 Oats, 1996–2017

The oats did not receive fertilizer N or FYM. Thus, on plots where P and K are 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 mineralized from the SOM. Yields and N uptakes are in Table 13.

4.2.10 Maize, 1997–2017

Maize (*Zea mays*) is a C4 plant and the carbon it contains has a different ^{13}C "signature" than the C3 plants usually grown on Broadbalk. Thus, we can

Table 20 Mean % S in grain and mean S uptake by grain plus straw, kg ha^{-1} year^{-1}, 1st wheat after a 2-year break. Broadbalk Wheat Experiment.

		Cultivars, years grown, % S in grain and mean S uptake by grain + straw (kg ha^{-1} yr^{-1})					
		% S in grain			Total S uptake by grain + straw, kg ha^{-1}		
Strip	Treatments[a] from 2001	Hereward 2001-04[b]	Hereward 2005-12	Crusoe 2013-18[c]	Hereward 2001-04[b]	Hereward 2005-12	Crusoe 2013-18[c]
2.2	FYM	0.131	0.110	0.106	6.6	7.5	7.8
2.1	FYM N3[d]	0.129	0.134	0.132	10.7	13.4	14.8
01	(FYM) N4	0.154	0.141	0.133	14.3	15.0	13.5
03	Nil	0.129	0.114	0.108	1.3	1.8	1.9
05	(P)KMg	0.135	0.118	0.128	2.2	2.5	2.0
06	N1 (P)KMg	0.115	0.107	0.109	4.4	4.5	4.8
07	N2 (P)KMg	0.127	0.115	0.116	7.4	7.3	7.9
08	N3 (P)KMg	0.133	0.127	0.125	10.2	10.1	11.3
09	N4 (P)KMg	0.143	0.144	0.139	12.1	13.3	14.4
15	N5 (P)KMg	0.160	0.156	0.152	14.9	15.7	17.3
16	N6 (P)KMg	0.161	0.161	0.160	15.4	16.8	19.7
19	N1+1+1 KMg	0.133	0.132	0.136	8.8	10.1	11.9
18	N1+2+1 PKMg	0.153	0.145	0.140	13.5	14.1	14.7
12	N1+3+1 (P)KMg2	0.155	0.155	0.151	13.3	15.2	17.3
17	N1+4+1 PKMg	0.153	0.159	0.160	15.1	16.3	20.7
10	N4	0.137	0.130	0.129	6.8	7.7	7.3
11	N4 P Mg	0.152	0.156	0.149	8.2	8.6	10.6
13	N4 PK	0.150	0.149	0.137	11.4	12.7	13.5
14	N4 PK*(Mg*)	0.140	0.133	0.120	9.7	10.7	9.4
20	N4 KMg	-	-	-	-	-	-
	s.e.	**0.0081**	**0.0049**	**0.0062**	**1.34**	**0.82**	**1.03**
		F(36,201.9) = 1.56, p = 0.03			F(36,205) = 2.26, p < 0.001		
		φ = 0.4332 (0.0708)			φ = 0.5117 (0.0627)		

[a] See Table 1 for detailed description of treatments

[b] Not analysed for S in 2002

[c] Excludes spring wheat in 2015

[d] FYM N2 until 2004

distinguish maize-derived organic matter from that of organic matter already in the soil. When the opportunity arises, the intention is to use archived crop and soil samples to see where, within the soil structure, the maize carbon is being held and how quickly it is recycled. At Rothamsted in S.E. England the summers are not usually hot enough to guarantee that the cobs will ripen so the maize is harvested early for forage when dry matter content reaches *c.* 26–28%, thus allowing the following wheat crop to be drilled in good time. Mean yields and N offtakes are in Table 22. Most notably, where N, P, Mg and K was applied, average annual K offtakes exceeded the amount of fertilizer K applied.

Starting in 2018, a new 5-course rotation was phased-in but is not discussed here.

Table 21 Mean yield of potato tubers, total fresh weight, t ha^{-1} year^{-1}, and mean NPK offtakes, kg ha^{-1} year^{-1}, 1985–1996. Broadbalk Wheat Experiment.

Strip	Treatments[a] from 1985-1996	Fresh wt of tubers (t ha^{-1} yr^{-1})	N offtake (kg ha^{-1} yr^{-1})	P offtake[b] (t ha^{-1} yr^{-1})	K offtake[b] (kg ha^{-1} yr^{-1})
2.2	FYM	32.4	90	17.4	170
2.1	FYM N2	36.8	110	16.9	179
01	FYM N4 PK	32.9	105	14.4	168
03	Nil	7.0	20	2.7	30
05	PKMg	12.0	29	6.5	63
06	N1 PKMg	19.5	54	9.3	100
07	N2 PKMg	23.6	70	10.4	118
08	N3 PKMg	29.7	93	11.1	141
09	N4 PKMg	30.5	94	10.4	143
15	N5 PKMg	31.4	98	11.2	151
16	N6 PKMg	32.4	101	10.5	152
19	(C)	12.3	37	2.8	48
18	N3 ½[PKMg](A)	23.5	74	4.6	104
12	N2 P Na	9.3	36	5.1	25
17	N3 ½[PKMg](A)	20.1	63	5.8	88
10	N2	7.1	24	1.6	23
11	N2 P	7.9	30	3.6	22
13	N2 PK	16.2	51	7.6	79
14	N2 PKMg*	28.5	82.2	11.8	129
20	N4 KMg	-	-	-	-

[a] See Table 1 for detailed description of treatments

[b] Not analysed for P or K in 1985.

4.3 Soils

The years in which the soils of most plots on Broadbalk were sampled, and sub-samples analyzed and archived are in Appendix Table A2. Where possible the positions of earlier samples are related to the current sections. Unless stated otherwise, the data here, for soils sampled prior to 1966, are from archived soils which were sub-sampled in 2000 and re-analyzed.

4.3.1 Soil movement

In any long-term arable experiment, there is the possibility of soil movement across plot boundaries (Sibbesen, 1986), either by water or wind erosion or,

Table 22 Mean yields of maize, total dry weight, t ha^{-1} year^{-1}, and mean NPK offtakes, kg ha^{-1} year^{-1}, 1997–2017. Broadbalk Wheat Experiment.

		1997 - 2000					2001 - 2004				2005 - 2017[a]			
Strip	Treatments[b] from 1985	Mean yield (t ha^{-1} yr^{-1})	N uptake (kg ha^{-1} yr^{-1})	P uptake (t ha^{-1} yr^{-1})	K uptake (kg ha^{-1} yr^{-1})	Treatments from 2001	Mean yield (t ha^{-1} yr^{-1})	N uptake (kg ha^{-1} yr^{-1})	P uptake (t ha^{-1} yr^{-1})	K uptake (kg ha^{-1} yr^{-1})	Mean yield (t ha^{-1} yr^{-1})	N uptake (kg ha^{-1} yr^{-1})	P uptake (t ha^{-1} yr^{-1})	K uptake (kg ha^{-1} yr^{-1})
2.2	FYM	14.2	134	31.9	185	FYM	11.1	113	23.3	181	12.9	134	24.6	174
2.1	FYM N2	15.7	169	32.4	224	FYM N2	12.3	140	26.1	187	15.3	183	28.1	212
01	FYM N4 PK	16.2	193	34.3	228	(FYM) N4	14.0	168	31.2	193	13.5	163	24.9	173
03	Nil	2.9	19	5.7	31	Nil	2.1	17	2.9	26	2.0	20	2.9	21
05	PKMg	3.4	23	8.3	52	(P)KMg	2.1	15	4.3	37	3.7	30	6.5	55
06	N1 PKMg	8.3	55	16.0	111	N1 (P)KMg	6.5	56	12.0	99	6.8	57	10.9	91
07	N2 PKMg	12.4	95	21.6	170	N2 (P)KMg	10.4	103	20.4	149	9.2	95	14.6	123
08	N3 PKMg	14.0	135	26.8	177	N3 (P)KMg	11.3	131	22.2	147	9.8	110	16.3	120
09	N4 PKMg	14.8	172	29.1	176	N4 (P)KMg	11.7	145	22.1	149	9.7	121	15.6	115
15	N5 PKMg	13.7	162	28.2	177	N5 (P)KMg	10.3	141	22.5	137	10.1	126	16.9	126
16	N6 PKMg	14.5	185	30.5	173	N6 (P)KMg	10.7	146	21.9	146	9.9	124	15.5	119
19	(C)	3.5	25	7.5	36	N2+1 KMg	6.1	75	9.5	64	5.5	68	8.5	60
18	N3 ½[PKMg](A)	13.4	131	21.6	162	N2+2 PKMg	10.7	143	20.2	132	10.1	121	15.2	118
12	N2 P Na	7.3	77	16.9	38	N2+3 (P)KMg2	10.1	131	21.9	115	10.7	131	17.2	119
17	N3 ½[PKMg](A)	13.3	132	20.8	155	N2+4 PKMg	9.7	141	18.7	127	9.4	124	15.8	109
10	N2	6.2	69	9.5	42	N4	2.7	40	4.3	25	2.5	35	4.2	21
11	N2 P	5.9	60	14.5	29	N4 P Mg	5.7	79	17.5	32	5.6	74	14.4	30
13	N2 PK	11.2	88	19.8	148	N4 PK	10.3	126	21.1	142	10.4	123	18.4	136
14	N2 PKMg*	11.0	83	20.2	127	N4 PK*(Mg*)	11.1	147	25.0	143	10.9	125	20.2	131
20	N4 KMg	-	-	-	-		-	-	-	-	-	-	-	-
	s.e.	**1.33**	**14.8**	**2.6**	**17.0**		**1.33**	**14.8**	**2.6**	**17.0**	**0.77**	**8.5**	**2.6**	**9.8**

For yield, $F(36,270) = 2.83$, $p < 0.001$ $\varphi = 0.4626$ (0.0604)

For N uptake, $F(36,269) = 3.91$, $p < 0.001$ $\varphi = 0.3724$ (0.0617)

For P uptake, $F(36,272) = 2.99$, $p < 0.001$ $\varphi = 0.3718$ (0.0588)

For K uptake, $F(36,270) = 3.56$, $p < 0.001$ $\varphi = 0.4897$ (0.0594)

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[a] Excludes 2013 as yields were adversely affected by the accidental application of a residual herbicide.

[b] See Table 1 for detailed description of treatments

as here on Broadbalk, by cultivation. Any movement of soil from one treatment to another is of concern, particularly when one aim of the experiment is to look at long-term nutrient balances (i.e., inputs vs offtakes) and changes in measured soil parameters. The amount of movement will be affected by the size of the plots, the presence or absence of any discard area between them, the number and type of cultivation and the longevity of the experiment. As the soil on Broadbalk has been cultivated at least once (often two or three times) every year since the strips were first established and treatments applied in autumn 1843 this potential problem cannot be ignored. Until 1894 each treatment strip was plowed individually and any soil which fell outside the strip was manually forked back into the strip. After tractors were introduced, and as these became more powerful, plow depth increased, but was limited to $<$23 cm and the width of the slice to about 25–30 cm. Thus, one edge of the plow slice may be moved by *c.* 40–50 cm and to minimize soil movement the soil is turned to the north or south in alternate years and, for seed-bed preparation, cultivators which only move the soil a minimal distance are used. However, even though the paths between treatment strips are 1.5 m wide (1.9 m between the Nil and FYM strip) there has been some movement of soil across the paths and into adjacent treatment strips. To assess the degree of movement, two transects were taken in March 1990, across three treatments in Section 1. Soil samples, 0–15 cm (i.e., within the plow depth), were taken every 30 cm across plots 2.2, 03 and 05, FYM, Nil and PKMg, respectively. The individual samples were analyzed for total P, Olsen P, organic C, total N and exchangeable cations. Fig. 13 shows Olsen P across the three plots. There is a clear gradient across the paths extending by *c.* 1 m into the adjacent plots. Crucially, for each measured parameter, there is a plateau in the middle of each plot. Where P had been applied as fertilizer or in FYM for $>$140 years, the soil contained 100+ mg P kg^{-1}, but only 6 mg P kg^{-1} on the Nil plot (*c.* 1200 and 450 mg kg^{-1} of total P, respectively). These results give us confidence that the central area of each strip is representative of the treatment applied and that soil samples and yields taken from those areas will also be a true reflection of those treatments. However, in the future some alteration in cultivation practice may have to be considered to minimize soil movement and ensure the integrity of the experiment.

4.3.2 Soil weight

Lawes and Gilbert sampled Broadbalk very comprehensively in 1865, 1881 and 1893 (the 50th anniversary of the experiment). They found considerable variability in the parameters they measured, both within the field and

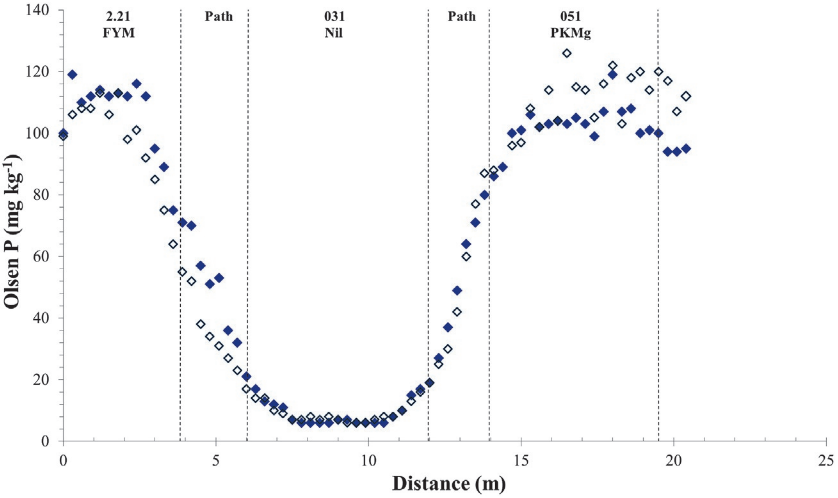


Fig. 13 Olsen P in soil taken across plots 2.21 (FYM), 031 (Nil) and 051 (PKMg) in spring 1990. Samples were taken at 30 cm intervals to a depth of 18 cm (i.e., within the plow layer); the two transects, ♦ and ◊, were 12 m apart. Broadbalk Wheat Experiment.

between the 3 years but, after discussion, agreed upon values for the weight of fine, dry soil passing through a 0.635 cm (¼ inch) sieve and for the weight of stones >0.635 cm, for the different treatments (Dyer, 1902). The weight of soil and stones, in both the 0–23 cm and 23–46 cm layers, were also determined in 1914, and in the 1970s/1980s on a very limited number of treatments. The weight of soil was not measured again until 2000 when only the topsoil, 0–23 cm, was measured. On plots receiving only inorganic fertilizers, the weight of soil has not changed since the 1890s and a mean weight of 2.88 M kg ha^{-1} in the 0–23 cm layer is used in any calculations (Appendix Table A3). On plots receiving FYM, the bulk density of the topsoil has decreased over the years and the soil weight is now 2.52 M kg ha^{-1} in the 0–23 cm layer. The weight of subsoil has only been measured on a very limited number of plots since 1914. For plots receiving inorganic fertilizers it is assumed that the weight of the various subsoil layers has not changed; values of 3.02 and 3.13 M kg ha^{-1} have been used for the 23–46 cm and 46–69 cm layers, respectively. From the few measurements done on FYM plots in the 1980s we have used values of 2.75 and 3.01 M kg ha^{-1} for the 23–46 cm and 46–69 cm layers, respectively. This difference from the value in plots not receiving FYM, particularly in the 23–46 cm layer, is evidence of some movement of FYM-derived organic matter moving down the soil profile either by direct mixing or through earthworm activity.

4.3.3 Particle size distribution

The soils of Broadbalk were classified by Avery and Bullock (1969) after taking, analyzing and describing representative profile pits. A more detailed picture of particle size distribution was made on 0–23 cm soil sampled in autumn 2000. The % of clay varied from 19% to 38%; a wider range than had previously been measured. A contour map of % clay on Broadbalk was given by Watts et al. (2006) in their paper examining the role of clay, organic matter and long-term management on plow draught.

4.3.4 Soil organic matter

Soils from Broadbalk and the other long-term experiments at Rothamsted and Woburn have been used extensively to study the role of SOM in agricultural systems (Dyer, 1902; Johnston et al., 2009). In particular, the data has been used to build and validate mathematical models which simulate the turnover of SOM in soil (Jenkinson, 1990; Jenkinson and Coleman, 2008; Jenkinson and Rayner, 1977; Jenkinson et al., 1992, 2008) and assess the degree by which land management might contribute to, or mitigate against, global warming (Jenkinson et al., 1991; Poulton et al., 2018; Powlson et al., 2018).

When discussing SOM, it must be remembered that the amount present at a given time depends on several factors including the quantity of organic matter added and its rate of oxidation, the rate at which existing SOM decomposes, soil texture and climate. Annual soil cultivation in the Rothamsted long-term experiments is by inversion plowing followed by surface cultivation to produce a seedbed.

It is now usual to quote organic C content of soils (SOC) as measured directly (see above) but for some purposes, especially for providing practical information to farmers or agronomic advisers, it is customary to convert SOC to SOM. This is done either by multiplying the % Org C by a factor of 1.724 to give % SOM (Mattingly et al., 1974) or by multiplying % N by 10 as many soils have a C:N ratio of about 10:1. When assessing long-term changes in SOC on Broadbalk it is possible to mean the data for the different treatments over all 10 sections but this can mask important differences. For example, Sections I–V had different numbers of fallows between 1926 and 1967 and the rotations that were introduced in 1968, included fallows, and spring planted/sown potatoes and maize crops up to 2017 (Appendix Tables A1a and A1b). FYM was *not* applied when the sections were fallowed, nor was FYM or fertilizer N applied to the oats from 1996 to 2017. If the mean topsoil % Org C (excluding strips 01 and 20) for each

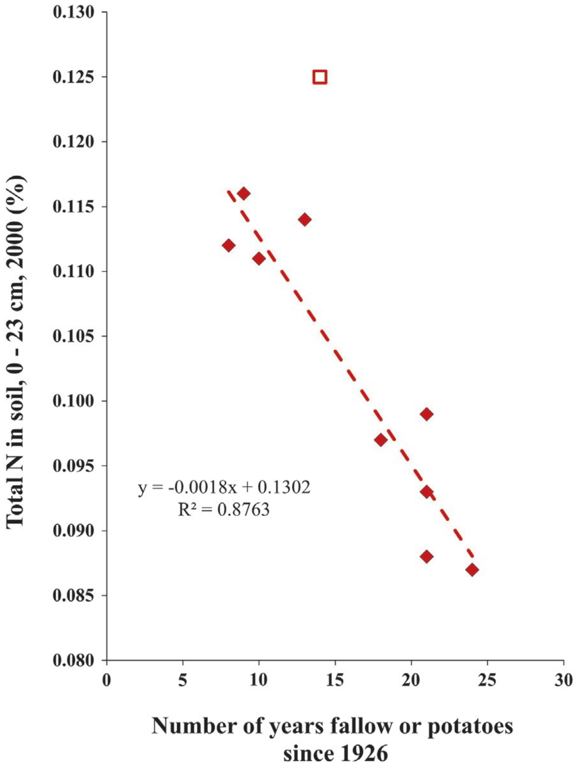


Fig. 14 Effect on total N in topsoil, 0–23 cm, of the number of years in which sections were fallowed or potatoes were grown between 1926 and 2000. ◆, sections 0–7, 9; □, section 8 (excluded from the correlation; see text). Broadbalk Wheat Experiment.

of the sections in 2000 is plotted against the number of years in which that section was in fallow, potatoes or maize there is a very clear effect on Org C (Fig. 14). Data from Section 8 is excluded from this correlation as this section has never received herbicides and has a large mass of weed root and stubble which is incorporated into the soil annually by plowing. Org C on Section 8 has increased steadily since 1968 (see Section 4.4).

The SOM data for Sections 0–9 can be regarded as two separate datasets, which have diverged since the 1920s when fallowing was introduced; these two sets are: (i) soils which have been mostly in continuous wheat since the 1960s ("Continuous"; Sections 1, 9 and 6) and (ii) soils that have been in rotation since 1968 ("Rotation"; Sections 2, 3, 4, 5 and 7) and which had previously been fallowed more often than other sections (Appendix Tables A1a and A1b). Section 8 is excluded for the reasons given above and Section 0 is excluded as straw has been incorporated on this section since autumn 1986. Straw is removed from the rest of the experiment. In 1944, samples were taken from four holes on each plot on each of the five sections at that time; equivalent to two holes per plot per current section. In 1966 soils were taken from Sections Ia, Ib, II, III, IV, Va and Vb and since 1986/87 from individual plots within each of the current sections. Appendix Table A2 shows the date and relationship between samples over time. In Fig. 15, we show % N in topsoil for two long-term treatments which have either been in "continuous" wheat with fewer fallows between 1926 and 1967 or had been fallowed more often and are now in "rotation." Fortunately, the 1944 soils were sampled in such a way that data from areas which were later divided into the 10 current sections can be plotted separately (Appendix Table A2). The figure shows that, by 1944, % N (and % Org C; not shown) had diverged. It is also clear that where the treatments were changed to test a higher rate of fertilizer N (i.e., from 48 to 192 kg N ha^{-1} in 1968 and from 144 and 96 kg N ha^{-1} to 240 and 288 kg N ha^{-1}, respectively, in 1985) this led to an increase in % Org C (and % N) in the soil, almost certainly because yields and thus organic residues were increased (Fig. 16). It is also clear that, during this period, 1966–2015, increases on sections in rotation were not so large, almost

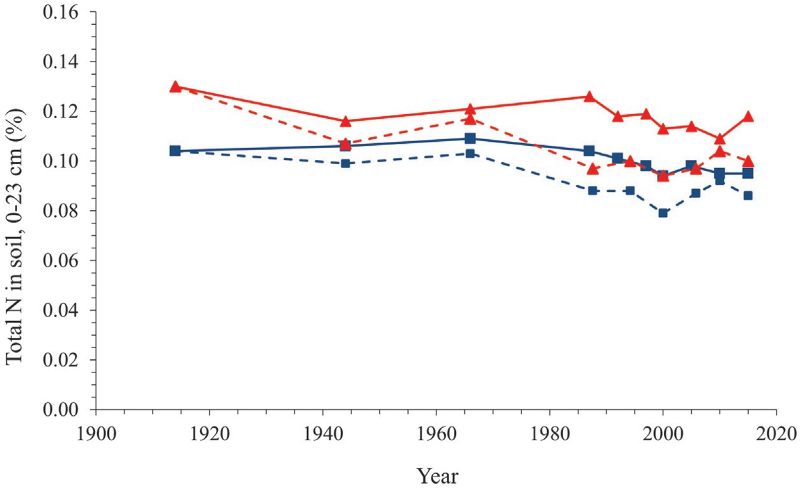


Fig. 15 Total N in topsoil, 0–23 cm, since 1920s on soil receiving: ■, (P)KMg; or ▲, N3(P) KMg since 1852. Sections in "continuous" wheat with fewer fallows (solid lines) compared with sections fallowed more often and later in rotations (dashed lines). Current treatments given; see Table 1 for earlier treatments. Broadbalk Wheat Experiment.

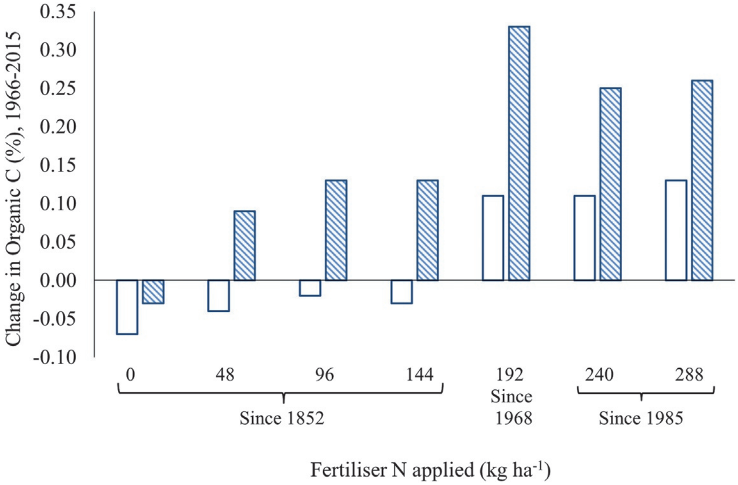


Fig. 16 Changes in % Organic C in topsoil, 0–23 cm, between 1966 and 2015 on treatments receiving (P)KMg and 0, 48, 96, 144, 192, 240 or 288 kg N ha^{-1}. Sections in "continuous" wheat with fewer fallows (hatched histograms) compared with sections fallowed more often and later in rotations (empty histograms). Current treatments given; see Table 1 for earlier treatments. Broadbalk Wheat Experiment.

certainly because fallows were part of the rotations between 1968 and 1996 and oats were part of the rotation between 1996 and 2016 (Appendix Table A1b); fertilizer N was not applied to either the fallows or oats.

To follow changes in the *amounts* of C or N in the soil over time (often termed C or N stock) the same weight of air-dried soil at the beginning and end of any particular period must be used. Thus, where the bulk density for the 0–23 cm depth has declined over time because of the addition of FYM we need to calculate how deeply the soil should have been sampled so that the same weight of soil is being considered; the amount of C or N in that "extra" soil needs to be added to that in the 0–23 cm depth (Jenkinson, 1971; Poulton et al., 2018).

Fig. 17 shows, for sections in continuous wheat, the amount of Org C in topsoil (0–23 cm) on selected treatments; the data has been adjusted to take account of the changes in soil weight on soils receiving FYM (Appendix Table A3). Lawes and Gilbert (1898) said that Broadbalk "…had been under arable cultivation for some centuries…" before the experiment started. Certainly the % Org C on the control strips on Broadbalk (and on the adjacent Hoos Barley experiment which started in 1852; Jenkinson and Johnston, 1977) is lower than in all other fields on Rothamsted Farm (Johnston et al., 1981) suggesting that this soil had been in arable cropping

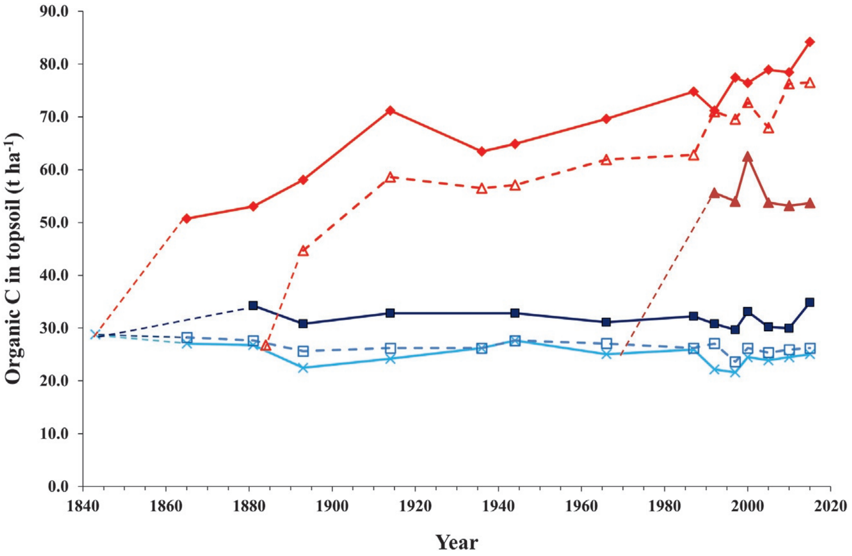


Fig. 17 Long-term changes in the amount of soil organic carbon in topsoil, 0–23 cm, of sections in "continuous" wheat since 1843. ×, Nil; □, (P)KMg; ■, N3(P)KMg; ♦, FYM; △, FYM N3; ▲, (FYM)N4. Current treatments given; see Table 1 for earlier treatments. Data are adjusted for changes in bulk density. Starting values for 1843, 1884 and 1968 are estimated. Broadbalk Wheat Experiment. Rothamsted Research (2021c).

for a considerable time. Our best estimates for % Org C and % N in the 0–23 cm depth at the start of the experiment are 1.0% and 0.11%, respectively, which equate to 28.8 t Org C ha^{-1} and 3.17 t N ha^{-1}, respectively. The Org C content of some soils in some treatments has changed little in 150+ years. By 1865, soil in plots receiving N3PKMgNa fertilizers had a little more Org C than soil in the Nil and PKMgNa-only plots because the better-fertilized crop gave not only more yield but left more stubble, roots and root exudate, to be plowed-in. Org C in plots receiving larger amounts of fertilizer N (192, 240 and 288 kg ha^{-1}) since 1968 or 1985, and where larger crops have been grown, is still tending to increase. On the FYM treatments, Org C increased, rapidly at first, then more slowly, and these soils now contains more than double the concentration than that in the Nil or fertilizer only soil. The decline in Org C 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.

In 2015, the "4 per 1000 initiative: Soils for Food Security and Climate" was launched prior to the Paris conference of the United Nations

Framework Convention on Climate Change (https://www.4p1000.org/4-1000-initiative-few-words). The aim of the initiative was to promote management practices that would increase the stock of SOC to a depth of 40 cm at a rate of 4‰ (0.4%) of the initial amount per year for 20 years. It was suggested that if this could be achieved globally it would cancel out the annual rise in CO_2 in the atmosphere and slow global warming. Although it was soon realized that this aim was unrealistic it was recognized that any increase in SOC was not only useful in combatting climate change but would also help improve the quality of many soils (Chabbi et al., 2017; Chambers et al., 2016; Lal, 2016; Minasny et al., 2017). Poulton et al. (2018) used data from16 long-term Rothamsted experiments to consider some of the options that might achieve this aim. On Broadbalk, the most obvious treatments were those which had received FYM since 1844 or 1885 or from 1968 to 2000, excluding the period from 1926 to 1967, when FYM was not applied to fallowed soils. Using a common time frame, a curve could be fitted to the accumulation of SOC in the topsoil (adjusted for changes in soil weight) and then the rate of increase at a particular time could be calculated. When FYM was first applied to soil with a low SOM content, the rate of increase was *c.* 1.0 t Org C ha^{-1} $year^{-1}$, but as the amount of SOM in the soil approached an equilibrium, the rate of increase declined to only *c.* 0.1 t Org C ha^{-1} $year^{-1}$. The 35 t FYM ha^{-1} application contains *c.* 8 t dry matter ha^{-1}. This equates to *c.* 3 t C ha^{-1} $year^{-1}$ and the increases in soil carbon represent *c.* 33% of the Org C in the FYM when applications started but only *c.* 3% as SOM neared equilibrium, i.e., almost all of the Org C (and N) added at this stage was lost. Of the N applied in the FYM, some would have been taken up by the crop, a small proportion would have been retained in the soil but much would have been lost by denitrification or leaching (see Section 4.7). For many years after the FYM was first applied, the 4‰ target was exceeded; but a large amount of FYM, 35 t ha^{-1} $year^{-1}$, was applied to achieve this increase. However, as discussed by Poulton et al. (2018) and many others, although this increase in soil C is undoubtedly beneficial for soil properties and functioning, it does not represent climate change mitigation. The C in FYM has been transferred from plants grown elsewhere and then passed through an animal rather than being *additional* C derived from the atmosphere through photosynthesis.

The N balance, 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 N offtakes by the crop were small and 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. More recently, inputs of N in FYM have been greater and although offtakes have been larger, N accumulation in the soil has been much less as it nears equilibrium, and *c.* 200 kg N ha^{-1} cannot be accounted for annually. Much N is lost by leaching as nitrate as shown by direct measurements of nitrate in drainage water (Goulding et al., 2000).

Where straw was plowed-in on Section 0, SOC was increased by *c.* 0.26 t ha^{-1} year^{-1} between 1988 and 2000 (mean of plots receiving 96, 144 or 192 kg N ha^{-1} + PKMg). An increase in the stock of SOC in the plow layer was also seen when the rate of applied fertilizer N was increased from 48 to 192 kg N ha^{-1} in 1968 and from 144 to 240 and 96 to 288 kg N ha^{-1} in 1985 (strips 09, 15 and 16, respectively). The increases in organic matter inputs in roots and stubble which came from the larger yields resulted in rates of increase ranging from 0.13 to 0.43 t Org C ha^{-1} year^{-1}. These results firmly repudiate the claims by Kahn et al. (2007) and Mulvaney et al. (2009) that the use of fertilizer N leads to a decline in SOM; see also Powlson et al. (2010) for a detailed discussion of this. A similar trend to that in Broadbalk (i.e., a small increase in SOC where N fertilizer is applied) is also observed in many other LTEs globally (Ladha et al., 2011).

One of the key effects of SOM on soil is its influence on soil physical properties. This has been the subject of several studies on Broadbalk soils, using contrasting approaches. An important finding has been that small changes in SOM can have disproportionately large impacts on a range of physical properties. Watts et al. (2006) measured the energy required to pull a plow through the soil in the different Broadbalk plots and expressed the results as soil-specific draught, *S*, in units of kPa. This value is regarded as a measure of the ease of workability of a soil and is affected by clay content. But a clear result was that the small increase in SOC between the treatment receiving no N fertilizer and that receiving 144 kg N ha^{-1} annually (a 31% increase) reduced the value of *S* by almost as much as in the FYM treatment where SOC was increased 233%. Blair et al. (2006) found that in-field measurements of unsaturated hydraulic conductivity (K_{unsat}), an indication of water infiltration rate, and aggregate stability as indicated by wet sieving, both increased markedly between the treatments receiving increasing annual N fertilizer rates and proportionately much more than the increases in SOC. Both were more strongly associated with a fraction of SOC termed labile C, based on mild chemical oxidation, than on total SOC. Chakraborty et al. (2014) measured the deformation characteristics of repacked soil from Broadbalk and a long-term straw incorporation experiment at Woburn Farm using a novel technique known as triaxial testing. The method provides information on the extent to which a soil resists compaction, leading to a loss of pore space, particularly when compaction occurs at different degrees of wetness. With Broadbalk soils having contrasting SOC content (FYM treatment cf. inorganic fertilizers) the deformation characteristics revealed by triaxial testing were more sensitive to the change in SOC than measurements of mean weight diameter derived from wet sieving, tensile strength or friability. With the long-term straw experiment on a sandy loam soil, differences in deformation characteristics between treatments could be detected even where increases in total SOC content from straw addition were barely detectable. Interpretation of triaxial testing data following compression in relation to loss of pore space, expressed as void ratio, was later refined using soils from Broadbalk and the Hoosfield Barley Experiment (Suravi et al., 2021).

4.3.5 Soil pH and $CaCO_3$

Unlike % Org C and % N in the soil we have not attempted to create two diverging datasets for soil pH as the observed differences are more closely related to the distribution of $CaCO_3$ applied before the experiment started.

In the area around Rothamsted the practice of sinking pits to dig out the underlying chalk and spread it on the surface of the acid soil to improve yield was described by Young (1813) and Russell (1916). The individuals specializing in this work were known as "chalk drawers." On Broadbalk, the remains of such pits can still be seen as shallow depressions, or "dells." Based on estimates of the decline in $CaCO_3$ over time, it is possible that as much as 250 t ha^{-1} of chalk was applied to Broadbalk *before* the experiment started, but it is unlikely that applications were uniform. The 1865 soil samples on the control strip contained from 2.6% to 6.8% $CaCO_3$, but by 1944, $CaCO_3$ had declined on all treatments. Fig. 18 shows the decline in $CaCO_3$ on selected treatments. This loss of $CaCO_3$ would have been due, in part, to crop growth and to acidifying inputs from the atmosphere but was greatest on plots receiving the higher rate of N (144 kg ha^{-1}). Before 1917, N was mostly applied as a mixture of ammonium chloride and ammonium sulfate and then from 1917 to 1967 as ammonium sulfate. Both salts had a significant acidifying effect on the soil, and by 1944, the amount of free $CaCO_3$ in the topsoil on a few sub-plots had declined to zero (Table 5.8 in Johnston, 1969a,b) and soil pH was as low as 5.2–5.5 (Table 23). By the early 1950s, the crop in these areas was showing symptoms of acidity. To correct this, ground chalk (12.6 t ha^{-1}) was applied to all of Section Vb in autumn 1954 and to all of Section Va and plot 19 in

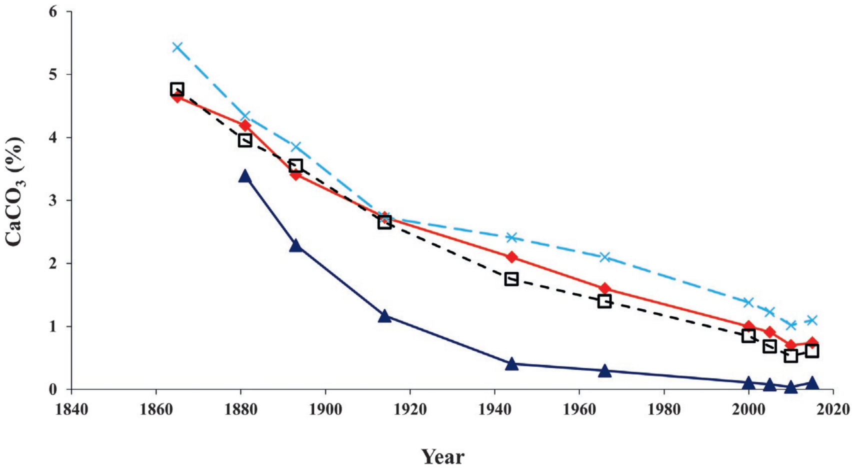


Fig. 18 Decline in $CaCO_3$ in topsoil, 0–23 cm, on selected treatments, 1860s–2015. ×, Nil (Strip 03); □, PKMg (Strip 05); ▲, N3(P)KMg (Strip 08); ♦, FYM (Strip 2.2). Current treatments given; see Table 1 for earlier treatments. Broadbalk Wheat Experiment.

Table 23 Topsoil, 0–23 cm, pH_{water}, 1944. Broadbalk Wheat Experiment.

		Section No. and Hole No. in 1944									
		I, 1&2	I, 3&4	II, 1&2	II, 3&4	III, 1&2	III, 3&4	IV, 1&2	IV, 3&4	V, 1&2	V, 3&4
	Treatment	Section No. from 1968 onwards									
Strip	in 1944	Section 0	Section 1	Section 2	Section 3	Section 4	Section 5	Section 6	Section 7	Section 8	Section 9
2.1	FYM since 1885	7.44	7.68	7.69	7.66	7.66	7.62	7.48	7.68	7.68	7.72
2.2	FYM	7.74	7.80	7.82	7.80	7.74	7.72	7.53	7.52	7.70	7.73
3	Nil	8.02	8.08	8.13	8.14	8.14	8.10	8.04	8.08	8.12	8.16
5	PKNaMg	8.10	8.14	8.18	8.17	8.20	8.11	8.09	8.09	8.09	8.08
6	N1 PKNaMg	8.00	8.04	8.07	8.06	8.09	8.06	7.94	7.74	7.88	8.04
7	N2 PKNaMg	8.10	7.87	8.10	8.13	8.13	7.96	7.72	7.77	7.48	7.56
8	N3 PKNaMg	7.74	7.14	7.98	8.01	8.06	7.70	7.13	6.16	6.06	6.63
9	N*1 PKNaMg	8.11	8.14	8.18	8.18	8.24	8.20	8.10	8.10	8.18	8.16
10	N2	7.50	7.44	7.42	7.56	7.60	7.44	7.24	7.06	6.94	7.40
11	N2 P	7.46	7.50	7.46	7.37	7.60	7.34	7.42	7.34	7.12	7.40
12	N2 P Na	7.25	7.43	7.74	7.51	7.70	7.68	7.50	7.12	6.86	7.42
13	N2 PK	7.60	7.70	7.66	7.62	7.46	7.48	7.40	7.04	6.24	7.26
14	N2 P Mg*	7.54	7.55	7.48	7.64	7.64	7.66	7.55	7.28	5.30	6.99
15	N2 PKNaMg	7.50	7.60	7.26	7.52	7.60	7.70	7.44	7.40	6.40	7.34
16	N*2 PKNaMg	8.12	8.14	8.18	8.15	8.18	8.19	8.08	8.07	8.12	8.10
17	N2 (A)	7.96	7.98	8.02	8.05	8.02	8.05	7.72	7.70	7.71	7.70
18	PKNaMg(A)	7.94	7.92	7.96	7.98	8.00	8.00	7.99	7.96	7.93	7.91
19	C	7.86	7.84	7.92	7.96	7.94	6.96	6.36	6.25	7.24	7.72
20	N2 KNaMg	7.86	7.99								

🟩	>8.01
🟦	7.71 - 8.00
🟨	7.41 - 7.70
🟪	7.11 - 7.40
🟥	<7.10

Note: data is shown in plot order as in the field

Section IV in autumn 1963. To prevent further acidity developing a scheme was introduced in autumn 1954 where chalk was applied annually to the stubble, except to the section that was to be fallowed. The amount applied was based on the acidifying effect of the fertilizer; 112 kg of $CaCO_3$ for every 15.7 kg of N as ammonium sulfate, and 56 kg of $CaCO_3$ for every 15.7 kg of N as castor meal (Bolton, 1972). The first applications, in autumn 1954, were double these amounts to increase soil pH more quickly. This scheme of regular liming continued until autumn 1967 (Glendining et al., 2022) with some plots in that year getting extra chalk to counteract acidity shown by soil analysis. Because it would not have been possible to test a range of liming treatments on Broadbalk (a "no lime" treatment, for example, would eventually have resulted in no growth of wheat on some plots) two new, long-term liming experiments were established in 1962 (Bolton, 1977; Holland et al., 2021). Interestingly, liming treatments were imposed on the long-term Park Grass experiment (Silvertown et al., 2006).

When Broadbalk was modified in 1968 the two forms of fertilizer N were replaced by calcium ammonium nitrate (Nitro-chalk) that contained calcium carbonate which helped to counteract the acidifying effect of the ammonium nitrate. No further chalk was given until autumn 1975 when a new scheme, of uniform chalk dressings, was introduced; this was revised in 1988 (Glendining et al., 2022). In 1986, the type of N fertilizer was again changed, this time to straight ammonium nitrate (Nitram®), the most commonly used form of N fertilizer in the United Kingdom. A year earlier, in 1985, the two highest rates of N currently tested on the experiment were introduced; 240 and 288 $kg\,N\,ha^{-1}$ on strips 15 and 16, respectively. The potential acidifying effect of these higher rates of N is considerable. Analysis of the soils taken in 1987/88 showed that soil pH was sufficiently high and chalk applications were stopped temporarily in 1992 when a cycle of dressings had been completed. By 2000, soil pH (Table 24) had changed little on most plots. However, the amount of $CaCO_3$ in the topsoil continued to decline and, in soils with little or no free $CaCO_3$, soil pH had also started to decline again; although none were less than pH 6.8. Further soil analysis in 2005/6, showed that there was as much as 1 unit of pH difference between sub-plots within any one section. Differential chalk dressings to selected plots re-commenced in autumn 2007 (Glendining et al., 2022) with the intention of raising pH to a minimum of *c.* 7.5; somewhat higher than needed for an arable soil but minimizing the range of pH values within each section; many plots do not need chalk. Soil pH is monitored regularly, and further corrective dressings are applied when needed.

Table 24 Topsoil, 0–23 cm, pH_{water}, 2000. Broadbalk Wheat Experiment.

Strip	Treatment in 2000	Section No. in 2000									
		Section 0	Section 1	Section 2	Section 3	Section 4	Section 5	Section 6	Section 7	Section 8	Section 9
1	FYM N4 PK			7.65	7.76	7.94	7.76	7.54	7.60		
2.1	FYM N2	7.72	7.70	7.94	7.80	7.90	7.74	7.60	7.78	7.62	7.64
2.2	FYM	7.90	7.82	7.79	7.76	7.91	7.80	7.58	7.66	7.65	7.59
3	Nil	8.26	8.14	8.23	8.26	8.24	8.19	8.10	8.12	7.98	7.98
5	PKMg	8.16	8.10	8.15	8.22	8.17	8.12	7.99	7.85	7.52	7.62
6	N1 PKMg	7.88	7.89	8.04	8.06	8.10	7.96	7.63	7.40	7.20	7.52
7	N2 PKMg	7.60	7.50	7.83	7.89	8.08	7.64	7.28	7.28	7.08	7.24
8	N3 PKMg	7.28	7.30	7.43	7.74	7.96	7.00	7.13	7.12	7.04	7.05
9	N4 PKMg	7.92	7.98	8.10	8.04	8.12	7.72	7.80	7.57	7.50	7.66
10	N2	7.92	7.93	8.21	8.15	8.16	7.41	7.51	7.59	7.49	7.45
11	N2 P	7.86	7.90	7.98	7.93	8.04	7.53	7.24	7.42	7.24	7.34
12	N2 P Na	7.98	8.00	8.10	7.92	7.98	7.48	7.44	7.36	7.22	7.26
13	N2 PK	7.95	8.00	8.10	7.96	7.74	7.42	7.55	7.24	7.06	7.14
14	N2 PKMg*	7.89	7.95	7.92	7.91	7.72	7.52	7.62	7.30	6.92	7.06
15	N5 PKMg	7.25	7.07	7.02	7.50	7.60	7.39	7.26	6.99	6.82	6.80
16	N6 PKMg	7.91	7.80	7.76	7.82	7.93	7.96	7.85	7.44	7.26	7.40
17	N0+3 ½[PKMg](A)	8.08	8.04	8.10	8.10	8.08	8.06	8.03	7.87	7.68	7.61
18	N1+3 ½[PKMg](A)	8.09	8.14	8.20	8.10	8.12	8.08	7.99	8.02	7.58	7.60
19	(C)	7.96	8.13	8.21	8.15	8.10	7.53	7.66	7.48	7.36	7.26
20	N2 KMg	8.09	8.17								

🟦	>8.01
🟩	7.71 - 8.00
🟨	7.41 - 7.70
🟪	7.11 - 7.40
🟥	<7.10

Note: data is shown in plot order as in the field

Compared with the 0–23 cm soil layer the subsoil contains much less $CaCO_3$. Typically, the 23–46 cm layer contains 0—*c.* 1.5% $CaCO_3$; there is least in strip 08 (which, for many years, received the largest N rate tested) and most in strips 2.1, 2.2, 03 and 05 (FYM + N, FYM, Nil and PKMg, respectively). The 46–69 cm and 69–91 cm layers contain between 0% and 0.3% $CaCO_3$, but are mostly <0–1%.

By 1944, soil pH in the 23–46 cm layer ranged from 7.0 to 7.9 with the lower values in soil with little or no free $CaCO_3$. By 2000, following many years of chalk application, soil pH in the 23–46 cm layer ranged from 7.4 to 8.2.

Data on declining amounts of chalk in the soil have been used by Rothamsted researchers to model such changes (RothLime) to predict the likely decline in % $CaCO_3$ in a range of farming scenarios (Goulding et al., 1989).

4.3.6 Plant nutrients

As with soil pH, and unlike % Org C and % N in soil, there is insufficient evidence to warrant creating diverging datasets for exchangeable cations and soil P. Although P, K, Mg fertilizers and FYM were not applied to fallows between 1927 and 1967 they have been applied to fallows since 1968.

4.3.7 Exchangeable K (K_{ex})

Table 25 shows the changes in K_{ex} in the topsoil since 1966. On the Nil treatment (strip 03) which has never received K fertilizer or organic manure, K_{ex} in the topsoil has changed little since the early years of the experiment (Fig. 19). Nor does the concentration of K_{ex} seem to have changed in the lower depths of soil (Table 26). As the offtake of K has probably totaled almost 1900 kg ha^{-1} year^{-1} from 1844 to 2018 (Chambers, 1953; Johnston, 1969a,b; Table 15 this paper) this strongly suggests that

Table 25 Exchangeable K, mg kg^{-1}, in topsoil[a], 0–23 cm. Broadbalk Wheat Experiment.

		Exchangeable K (mg kg^{-1})						
	Treatments[b]	Year sampled[c]						
Strip	from 2001	1966	1987/88[d]	1992-96[e]	2000	2005-06	2008-12	2013-17
2.2	FYM	647	664	688	596	590	554	592
2.1	FYM N3	630	595	679	579	568	517	556
01[f]	(FYM) N4	-	503	595	599	373	280	243
03	Nil	101	101	104	102	106	105	113
05	(P)KMg	361	337	382	374	397	401	418
06	N1 (P)KMg	360	315	353	328	368	378	395
07	N2 (P)KMg	331	283	304	288	324	330	352
08	N3 (P)KMg	288	250	273	255	288	302	339
09	N4 (P)KMg	314	254	266	261	289	306	334
15	N5 (P)KMg	355	274	300	274	309	322	342
16	N6 (P)KMg	314	261	291	258	301	315	343
19[g]	N1+1+1 KMg	114	105	121	80	147	180	229
18	N1+2+1 PKMg	255	188	211	176	237	257	295
12	N1+3+1 (P)KMg2	78	72	72	68	169	180	208
17	N1+4+1 PKMg	246	204	214	187	235	264	309
10	N4	86	81	82	73	84	85	87
11	N4 P Mg	80	74	71	67	73	75	74
13	N4 PK	316	274	307	293	309	317	336
14[h]	N4 PK*(Mg*)	87	161	205	220	234	246	270
20[i]	N4 KMg	321	332	384	368	384	390	397

[a] Sampled in autumn (unless noted) from compacted stubble. Analyses on air-dried soil < 2 mm.

[b] See Table 1 for details of treatment changes since 1966.

[c] See Appendix Table 2 for year each section was sampled; data are means of all sections, unless noted.

[d] Eight sections only; sections 6 and 8 not sampled.

[e] 1996 sampled in March

[f] Strip 1, sections 2-7 only; treatment started 1968.

[g] Castor meal until 1988

[h] K added since 1968

[i] Sections 0 and 1 only

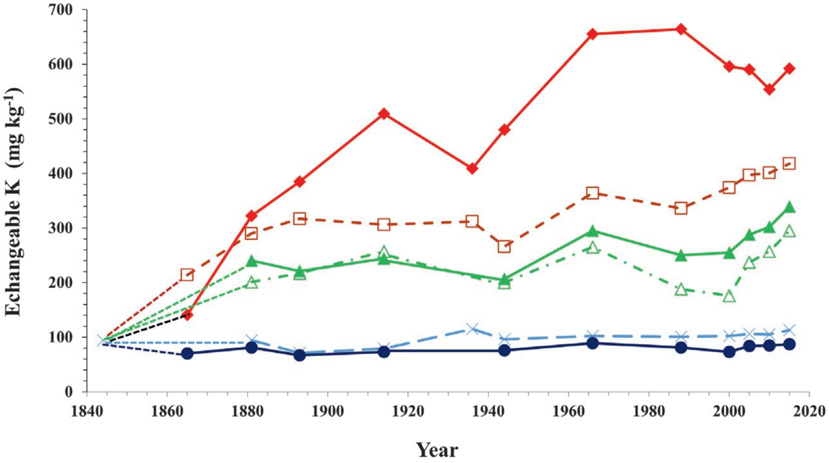


Fig. 19 Changes in exchangeable K in topsoil, 0–23 cm, since 1843. ×, Nil (Strip 03); □, PKMg (Strip 05); ▲, N3(P)KMg (Strip 08); ●, N4 (Strip 10); △, N1+2+1PKMg (Strip 18); ♦, FYM (Strip 2.2). Current treatments given; see Table 1 for earlier treatments. Starting values for 1843 and 1968 are estimated. Broadbalk Wheat Experiment.

the pool of K_{ex} is being "topped up" by K moving slowly from the large pools of less readily available forms (Blake et al., 1999; Catt, 1969; Johnston et al., 2016a). It is possible that some soil is being moved into the Nil strip from the two adjacent strips, both of which have higher concentrations of K_{ex} in the soil because of their treatment (see Section 4.3.1 about possible soil movement). Where nutrients, other than K, have been applied (N2, N2P, N2PNa (until 2000) on strips 10, 11 and 12, respectively) concentrations of K_{ex} are now lower than on the Nil strip; *c.* 70 mg kg^{-1} cf. 102 mg kg^{-1} (Fig. 19, Table 25) because of the larger yield, and hence greater removal of K, on these treatments compared to the control (Tables 15 and 16). Where K fertilizer has been applied at the full rate since the early years of the experiment, concentrations of K_{ex} have increased to levels at which yield would not be constrained. They vary widely and tend to reflect crop yield and K offtake. Where FYM, containing 333 kg K ha^{-1} $year^{-1}$ (mean 1968–2016), has been applied K_{ex} in the topsoil has increased greatly (Fig. 19, Table 25). The supply of K has far exceeded crop needs and there has been much movement of K_{ex} into the subsoil (Table 26). The different forms of K in Rothamsted soils, its availability to the crop and the response by the crop to applied K fertilizer was reviewed by Johnston et al. (2016a).

Table 26 Exchangeable cations in subsoil, in 2000; mean of selected treatments in all sections. Broadbalk Wheat Experiment.

	Treatments[a]	Exchangeable K (mg kg^{-1})			Exchangeable Mg (mg kg^{-1})			Exchangeable Ca (mg kg^{-1})		
Strip	from 1985-2000	23-46 cm	46-69 cm	69-91 cm	23-46 cm	46-69 cm	69-91 cm	23-46 cm	46-69 cm	69-91 cm
2.2	FYM	816	797	558	104	117	131	3680	3640	4110
2.1	FYM N2	712	743	518	89	110	120	3350	3540	3870
01	FYM N4 PK	742	539	222	76	70	62	3280	3860	4340
03	Nil	112	124	129	42	52	71	4130	4290	4430
05	PKMg	411	359	267	100	107	110	4250	4250	4380
08	N3 PKMg	268	193	155	90	93	89	3670	4420	4600
16	N6 PKMg	277	203	161	93	88	75	4140	4560	4840
19[b]	(C)	92	86	108	49	59	55	2350	2810	3320
18	N1+3 ½[PKMg](A)	192	157	142	61	61	60	4280	4380	4390
10	N2	112	123	128	41	43	54	4350	4800	5010
14[d]	N2 PKMg*	179	139	140	185	182	165	3780	4380	4630

[a] See Table 1 for treatments before 1985

[b] Strip 19 was only sampled on Section 9

4.3.8 Exchangeable Mg (Mg_{ex})

On those soils not receiving Mg fertilizer or manure the concentration of Mg_{ex} in the topsoil has changed little since the early years of the experiment. Strips 03 (Nil) and 10 (N4) still contain *c.* 40 mg Mg_{ex} kg^{-1} (Table 27) and, at this level would not be classed as deficient (RB209). Where Mg fertilizer (≡11–12 kg ha^{-1} $year^{-1}$) has been applied Mg_{ex} has increased approximately twofold. A larger rate of Mg application, *c.* 30 kg ha^{-1} $year^{-1}$, increased concentrations of Mg_{ex} to 164 mg kg^{-1} by 2000 (strip 14, mean of all sections). After Mg applications stopped on strip 14 in 2001, as part of the changes made to introduce a zero S treatment, Mg_{ex} has declined markedly (Table 27). Where FYM, containing *c.* 27 kg Mg ha^{-1} $year^{-1}$, has been applied since the 19th century, concentrations of Mg_{ex} are now c.110 mg kg^{-1}. There has been movement of Mg down the profile to at least 91 cm (Table 26).

4.3.9 Exchangeable Na (Na_{ex})

Measuring Na_{ex} is problematic; concentrations are usually very low and concentrations in the extractant solution (the "blank") can be relatively high. Applications of fertilizer Na on many of the plots stopped in 1973 (Table 1). On average, there is now very little difference in Na_{ex} between most of the treatment strips with values ranging from 8 to 18 mg kg^{-1}. Exceptions to this were on: (i) strip 9 which received N as $NaNO_3$ until 1967; in 1944 concentrations of Na_{ex} were at least double that on most other plots but by 1987/88, 20 years after the $NaNO_3$ treatment stopped, concentrations were no higher than on most other strips; (ii) on strip 12 which received a high rate of Na until 2000; in 2000 concentrations of Na_{ex} were about double that on other strips but by 2013–17 concentrations were no higher than on most other strips, and (iii) plots receiving FYM tended to contain slightly more Na_{ex}, *c.* 13–19 mg kg^{-1}.

4.3.10 Exchangeable Ca (Ca_{ex})

Because of the large, irregular dressings of chalk applied to Broadbalk before the experiment began concentrations of Ca_{ex} in the topsoil in the early years of the experiment were high, >5000 mg Ca kg^{-1}. Although free $CaCO_3$ declined on the whole experiment concentrations of Ca_{ex} remained high for many years on many treatments. However, on those soils receiving a greater acidifying input, e.g., strip 8, 15 and 10, free $CaCO_3$ declined more rapidly (see Section 4.3.5) and Ca_{ex} was not maintained. By 1944, free $CaCO_3$ had declined to zero on parts of some treatment strips, Ca_{ex} had declined markedly and the soil was becoming acid (see Section 4.3.5).

Table 27 Exchangeable Mg, mg kg^{-1}, in topsoil[a], 0–23 cm. Broadbalk Wheat Experiment.

		Exchangeable Mg (mg kg^{-1})					
	Treatments[b]	Year sampled[c]					
Strip	from 2001	1987/88[d]	1992-96[e]	2000	2005-06	2008-12	2013-17
2.2	FYM	113	112	110	117	121	139
2.1	FYM N3	101	107	106	108	111	129
01[f]	(FYM) N4	75	85	94	73	61	53
03	Nil	44	40	37	35	33	37
05	(P)KMg	78	81	75	80	81	89
06	N1 (P)KMg	72	78	72	83	85	93
07	N2 (P)KMg	65	72	67	79	81	89
08	N3 (P)KMg	63	70	66	81	83	91
09	N4 (P)KMg	73	75	70	75	76	87
15	N5 (P)KMg	68	72	73	86	87	95
16	N6 (P)KMg	74	77	66	76	78	86
19[g]	N1+1+1 KMg	73	64	53	64	68	78
18	N1+2+1 PKMg	61	60	50	62	65	75
12	N1+3+1 (P)KMg2	38	39	43	72	73	84
17	N1+4+1 PKMg	61	59	52	61	66	77
10	N4	38	38	38	41	44	44
11	N4 P Mg	39	41	43	58	67	83
13	N4 PK	32	42	34	35	37	38
14[h]	N4 PK*(Mg*)	140	152	164	134	121	112
20[i]	N4 KMg	90	92	80	81	77	84

[a] Sampled in autumn (unless noted) from compacted stubble. Analyses on air-dried soil < 2 mm.

[b] See Table 1 for details of treatment changes since 1966.

[c] See Appendix Table 2 for year each section was sampled; data are means of all sections, unless noted.

[d] Eight sections only; sections 6 and 8 not sampled.

[e] 1996 sampled in March

[f] Strip 1, sections 2-7 only; treatment started 1968.

[g] Castor meal until 1988

[h] K added since 1968

[i] Sections 0 and 1 only

In 1944, there was a clear correlation between the percentage of CaCO$_3$ remaining in the topsoil and the concentration of Ca$_{ex}$ (Fig. 20A) and between Ca$_{ex}$ and pH (Fig. 20B). Following the introduction of corrective, and then basal, chalk dressings (see Section 4.3.5) concentrations of Ca$_{ex}$ were

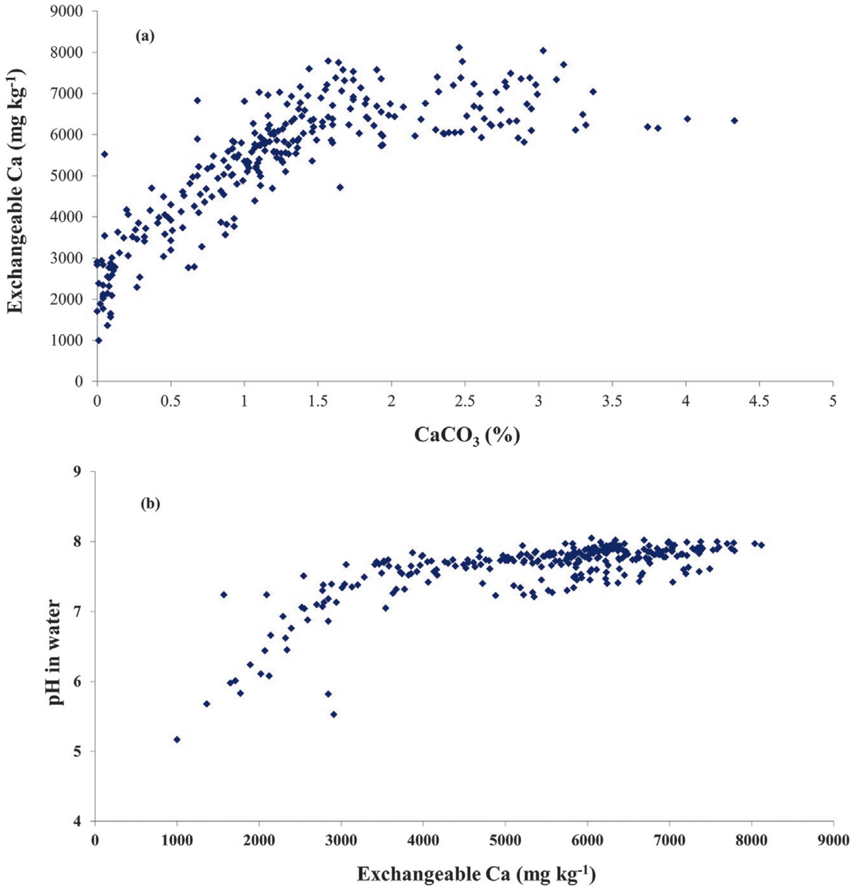


Fig. 20 $CaCO_3$, exchangeable Ca and pH_{water} in topsoil, 0–23 cm, 1944. (A) $CaCO_3$ vs exchangeable Ca; (B) exchangeable Ca vs pH. Broadbalk Wheat Experiment.

maintained or increased until the 1980s. When basal chalk applications stopped in 1992, Ca_{ex} levels declined. By 2013–17, few of the plots contained >1.5% $CaCO_3$ and more of them had lower concentrations of Ca_{ex} (Table 28), although, because of the corrective and basal chalk, none were as low as some plots had become in 1944. Amounts of free $CaCO_3$ and concentrations of Ca_{ex} continued to decline on most plots and, by 2013–17, soil pH had again started to fall on those plots with little or no free $CaCO_3$. As in 1944, there was a clear correlation between pH and Ca_{ex}.

Subsoils on Broadbalk contain between *c.* 3000–6000 mg kg^{-1} Ca_{ex} (Table 26) and there is little indication that this has changed since the start of the experiment or that it has been affected by treatment.

Table 28 Exchangeable Ca, mg kg^{-1}, in topsoil[a], 0–23 cm. Broadbalk Wheat Experiment.

		Exchangeable Ca (mg kg^{-1})					
		Year sampled[c]					
Strip	Treatments[b] from 2001	1987/88[d]	1992-96[e]	2000	2005-06	2008-12	2013-17
2.2	FYM	7040	5900	5250	5170	5150	5280
2.1	FYM N3	6540	5930	5420	4890	4790	4820
01[f]	(FYM) N4	5560	5120	4580	4470	4110	4130
03	Nil	7430	6480	6020	5590	4200	5610
05	(P)KMg	6220	5170	4760	4380	4200	4200
06	N1 (P)KMg	4690	3930	3610	3320	3210	3190
07	N2 (P)KMg	3880	3250	2980	2760	2730	2700
08	N3 (P)KMg	3570	3100	2570	2550	2580	2620
09	N4 (P)KMg	6060	5210	4650	4040	3890	3820
15	N5 (P)KMg	3570	3180	2630	2470	2530	2700
16	N6 (P)KMg	5470	4710	3540	3380	3070	3000
19[g]	N1+1+1 KMg	5060	4250	3590	3400	3290	3310
18	N1+2+1 PKMg	6560	5850	5220	4630	4330	4230
12	N1+3+1 (P)KMg2	4890	4430	3860	3480	3360	3380
17	N1+4+1 PKMg	6100	5340	4610	3980	3690	3540
10	N4	4700	4000	3560	3180	3130	3110
11	N4 P Mg	4850	4280	3800	3500	3430	3550
13	N4 PK	4570	3980	3230	3240	3170	3290
14[h]	N4 PK*(Mg*)	4410	3850	3170	3120	3070	3130
20[i]	N4 KMg	7620	7210	6480	5740	5930	5150

[a] Sampled in autumn (unless noted) from compacted stubble. Analyses on air-dried soil < 2 mm.

[b] See Table 1 for details of treatment changes since 1966.

[c] See Appendix Table 2 for year each section was sampled; data are means of all sections, unless noted.

[d] Eight sections only; sections 6 and 8 not sampled.

[e] 1996 sampled in March

[f] Strip 1, sections 2-7 only; treatment started 1968.

[g] Castor meal until 1988

[h] K added since 1968

[i] Sections 0 and 1 only

4.3.11 Phosphorus

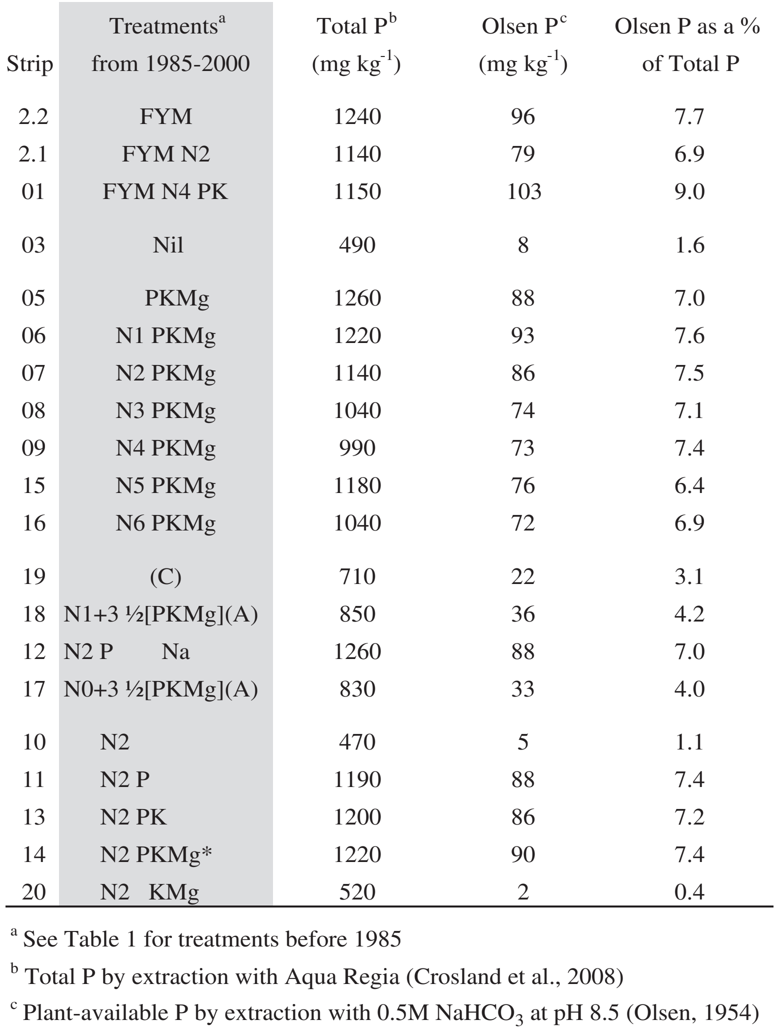
The role of phosphorus in agricultural systems, the importance of the long-term experiments at Rothamsted and the evaluation of the analytical techniques employed over 180 years has been discussed in many publications and the references therein (Dyer, 1902; Johnston et al., 2014; Johnston and Poulton, 2019; Lawes, 1847; Lawes and Gilbert, 1864; Lawes and Gilbert, 1885; Syers et al., 2008).

4.3.12 Total P

Until 2000 many of the strips on Broadbalk had received P fertilizer at 33–35 kg ha^{-1} year^{-1} since the start of the experiment. By 2000, the topsoil on those plots contained, on average, between 990 and 1260 mg kg^{-1} of total P (Table 29). Where FYM, currently supplying about 45 kg P ha^{-1} year^{-1} has been applied (together with fertilizer P on strip 01) the soil has a similar concentration of total P. Where fertilizer P had been applied every other year and subsequently at half-rate annually (strips 17 and 18) or at some time in the past (strip 19) amounts of total P are less. Only on two main strips, 03 and 10, and on strip 20 has no fertilizer P or manure been applied since 1852; a small amount of P was applied to strip 04 (now part of strip 03) in 1844–52. On these plots the concentrations of total P in the topsoil ranges from 440 to 560 mg kg^{-1} (Table 29).

By 2000, a considerable amount of P had moved down the soil profile, almost certainly through so-called by-pass flow in water moving through large pores formed by either earthworms or previous crop roots that have since decayed (Heckrath et al., 1995). On strips 03 and 10 (no P added) the concentration of total P in the 23–46 cm layer was, on average, 350 mg kg^{-1}, while on strips which had received P fertilizer or FYM mean concentrations ranged from 390 (excluding some plots on Section 9) to 560 mg kg^{-1} (Table 30). Soil variability across the experiment is such that these differences are not significant. In the 46–69 cm and 69–91 cm layers there are no clear differences between treatments. Exceptions to the above comments are in the south-east corner of the experiment, where the soil is classified as Charity-Notley series (see soil map in Avery and Catt, 1995). Although the topsoil is very similar to the rest of the experiment the subsoil has a gravelly layer within 80 cm depth. This layer will tend to impede through drainage in this area (John Catt; pers. comm). The subsoils on plots 14, 16, 18 and 19 of Section 9 have higher concentrations of total P than adjacent plots.

Table 29 Total P and Olsen P, in topsoil, 0–23 cm, in 2000; mean of all sections. Broadbalk Wheat Experiment.



Strip	Treatments[a] from 1985-2000	Total P[b] (mg kg^{-1})	Olsen P[c] (mg kg^{-1})	Olsen P as a % of Total P
2.2	FYM	1240	96	7.7
2.1	FYM N2	1140	79	6.9
01	FYM N4 PK	1150	103	9.0
03	Nil	490	8	1.6
05	PKMg	1260	88	7.0
06	N1 PKMg	1220	93	7.6
07	N2 PKMg	1140	86	7.5
08	N3 PKMg	1040	74	7.1
09	N4 PKMg	990	73	7.4
15	N5 PKMg	1180	76	6.4
16	N6 PKMg	1040	72	6.9
19	(C)	710	22	3.1
18	N1+3 ½[PKMg](A)	850	36	4.2
12	N2 P Na	1260	88	7.0
17	N0+3 ½[PKMg](A)	830	33	4.0
10	N2	470	5	1.1
11	N2 P	1190	88	7.4
13	N2 PK	1200	86	7.2
14	N2 PKMg*	1220	90	7.4
20	N2 KMg	520	2	0.4

[a] See Table 1 for treatments before 1985

[b] Total P by extraction with Aqua Regia (Crosland et al., 2008)

[c] Plant-available P by extraction with 0.5M $NaHCO_3$ at pH 8.5 (Olsen, 1954)

4.3.13 Plant-available P

Olsen P (extraction with 0.5 M $NaHCO_3$; Olsen et al., 1954) is a measure of the P in the soil that is considered readily available to the plants (Syers et al., 2008). Various extractants had been used previously (Johnston and Poulton, 2019) but Olsen's method has been used at Rothamsted since

Table 30 Total P and Olsen P in subsoil, in 2000; mean of selected treatments in all sections. Broadbalk Wheat Experiment.

	Treatments[a]	Total P[b] ($mg\ kg^{-1}$)			Olsen P[c] ($mg\ kg^{-1}$)		
Strip	from 1985-2000	23-46 cm	46-69 cm	69-91 cm	23-46 cm	46-69 cm	69-91 cm
2.2	FYM	562	375	346	25	3	2
2.1	FYM N2	516	348	336	17	2	2
01	FYM N4 PK	506	374	365	15	2	2
03	Nil	347	338	350	1	1	2
05	PKMg	457	381	363	7	2	2
08	N3 PKMg	433	394	388	6	1	2
16[d]	N6 PKMg	412 (632)	358 (517)	406 (628)	4 (15)	1 (6)	2 (3)
19[e]	(C)[e]	(700)	(545)	(422)	(12)	(7)	(4)
18[d]	N1+3 ½[PKMg](A)	392 (795)	346 (695)	374 (652)	2 (16)	1 (23)	2 (16)
10	N2	355	348	372	1	0	1
14[d]	N2 PKMg*	460 (616)	375 (438)	370 (398)	8 (18)	2 (4)	2 (2)

[a] See Table 1 for treatments before 1985

[b] Total P by extraction with Aqua Regia (Crosland et al., 2008)

[c] Olsen P by extraction with 0.5M $NaHCO_3$ at pH 8.5 (Olsen, 1954)

[d] On strips 14, 16 and 18 the mean of Sections 0-8 is given and, in brackets, Section 9

[e] Strip 19 was only sampled on Section 9

the 1950s and extensively in the United Kingdom since the 1960s. Jordan-Meille et al. (2012) discussed how Olsen P relates to other analytical techniques which measure plant-available P. As much as 85% of the P added as fertilizer or in manure will move into *non*-available pools of P in the soil. A proportion of these "reserves" will become available during the growing season (Johnston and Poulton, 2019), or over a longer time-scale (if fertilizer P is withheld), to re-supply the pool of readily available-P as P is taken up by the crop. Where P has been applied the Olsen P pool accounts for up to 10% of the total P in the topsoil. Where no P has been applied, concentrations of Olsen P in the topsoil are low, typically 2–12 $mg\,kg^{-1}$, and have changed little since the start of the experiment (Table 31). This represents about 2%, or less, of the total P in the soil. Where P fertilizer at the full rate or FYM was applied, concentrations of Olsen P increased rapidly to begin with but had reached a plateau, or even declined by 2000 (Fig. 21). Given that, in most cases, the crop is removing less P than is being applied some of the added P must either be moving into non-available pools or being lost from the soil. By 2000, it was clear that

Table 31 Olsen P, mg kg^{-1}, in topsoil[a], 0–23 cm. Broadbalk Wheat Experiment.

		Olsen P (mg kg^{-1})						
	Treatments[b]	Year sampled[c]						
Strip	from 2001	1966	1987/88[d]	1992-96[e]	2000	2005-06	2008-12	2013-17
2.2	FYM	99	101	104	96	104	107	111
2.1	FYM N3	78	80	90	79	84	85	84
01[f]	(FYM PK) N4	-	87	101	103	90	76	69
03	Nil	9	7	8	8	9	10	12
05	(P)KMg	81	82	89	88	78	76	71
06	N1 (P)KMg	90	88	94	93	83	78	73
07	N2 (P)KMg	90	90	94	86	76	72	65
08	N3 (P)KMg	81	80	82	74	63	61	56
09	N4 (P)KMg	81	71	79	73	64	58	52
15	N5 (P)KMg	88	83	84	76	65	64	60
16	N6 (P)KMg	68	75	75	72	61	58	53
19[g]	N1+1+1 KMg	47	27	26	22	19	19	19
18	N1+2+1 PKMg	56	38	39	36	40	48	52
12	N1+3+1 (P)KMg2	83	88	93	88	72	70	65
17	N1+4+1 PKMg	44	37	39	33	38	43	49
10	N4	8	6	6	5	5	6	6
11	N4 P Mg	79	83	93	88	82	87	89
13	N4 PK	81	89	92	86	85	91	91
14[h]	N4 PK*(Mg*)	87	90	97	90	88	93	96
20[i]	N4 KMg	6	2	4	2	4	3	5

[a] Sampled in autumn (unless noted) from compacted stubble. Analyses on air-dried soil < 2 mm.

[b] See Table 1 for details of treatment changes since 1966.

[c] See Appendix Table 2 for year each section was sampled; data are means of all sections, unless noted.

[d] Eight sections only; sections 6 and 8 not sampled.

[e] Section 3 sampled in March 1996

[f] Strip 1, sections 2-7 only; treatment started 1968.

[g] Castor meal until 1988

[h] K added since 1968

[i] Sections 0 and 1 only

advising farmers that there was no benefit to yield in maintaining their soils above 25–30 mg kg^{-1} Olsen P (Johnston et al., 2013; Poulton et al., 2013) while maintaining many soils on Broadbalk at >70 mg kg^{-1} was potentially confusing. It was decided therefore that, after more than 150 years, applications of fertilizer P should be withheld on some treatments (see Table 1) until concentrations of Olsen P declined to a more sensible agronomic value of *c.*

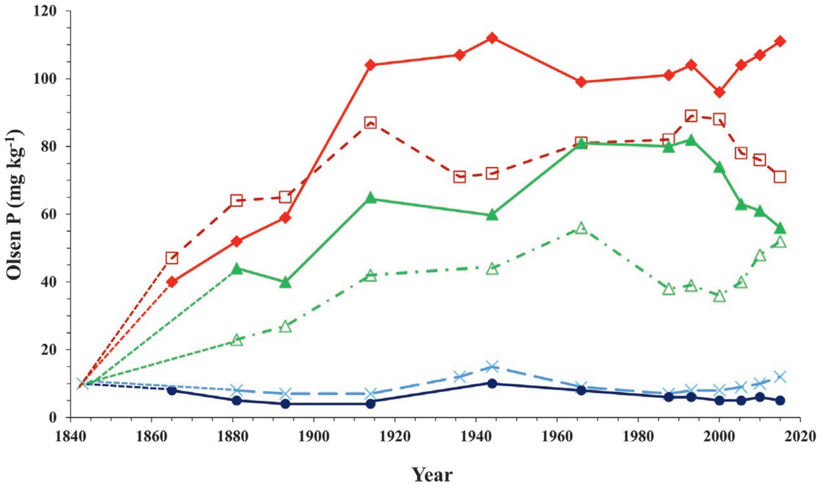


Fig. 21 Changes in Olsen P in topsoil, 0–23 cm, since 1843. ×, Nil (Strip 03); □, PKMg (Strip 05); ▲, N3(P)KMg (Strip 08); ●, N4 (Strip 10); △, N1+2+1PKMg (Strip 18); ♦, FYM (Strip 2.2). Current treatments given; see Table 1 for earlier treatments. Starting values for 1843 and 1968 are estimated. Broadbalk Wheat Experiment.

30 mg kg^{-1} Olsen P. It is likely that those treatments receiving higher rates of N and thus growing larger crops with a greater P offtake will reach that target earlier than other treatments, at which point *all* the treatments from which P has been withheld will start to receive P again. This will take many years. Changes in Olsen P between 1966 and 2013–17 are in Table 31. By 2013–17, the average decline in Olsen P on the eight fertilizer treatments where P had been withheld since 2000 was 19 mg kg^{-1}. At this rate of decline, it may take another 15–20 years to reach the target. This will be longer than the time taken for Olsen P to decline on other experiments when P applications were stopped (Johnston et al., 2016b) but most had not received P for such a long time. The slow decline in Olsen P on Broadbalk is analogous to that on the Hoosfield Continuous Barley experiment which received fertilizer P and/or castor meal between 1852 and 1979. Between 1982 and 2018, Olsen P declined from 128 to 69 mg kg^{-1}. On both experiments the amount of P moving into initially non-available forms but becoming available over time is considerable (Johnston et al., 2016a,b).

Table 32 shows, for selected treatments on Section 1, the change in Olsen P between 2000 and 2015 as a % of the P balance (P applied *minus* P removed by the crop). On plot 051, the offtakes without fertilizer N were small, the P balance was −58 kg ha^{-1} and the decline in

Table 32 Changes in plant-available P on selected treatments as a percentage of the P balance, 2000–2015. Continuous wheat, Section 1. Broadbalk Wheat Experiment.

Plot No.	Treatment since 2001	Olsen P in topsoil[a] (kg ha^{-1})		Change in Olsen P (kg ha^{-1}) 2000-2015	P balance (kg ha^{-1}) (P applied *minus* P removed) 2001-2015[b]	Change in Olsen P as a % of P balance 2000-2015
		Sept 2000	Sept 2015			
2.21	FYM	229	310	81	527	15
2.11	FYM N2[c]	149	169	20	440	5
031	Nil	14	32	17	-34	-
101	N4	9	14	6	-51	-
051	(P)KMg	274	213	-61	-58	104
061	N1(P)KMg	288	236	-52	-136	38
071	N2(P)KMg	291	216	-75	-207	36
081	N3(P)KMg	222	170	-52	-199	26
091	N4(P)KMg	210	144	-66	-213	31
151	N5(P)KMg	205	164	-40	-233	17
161	N6(P)KMg	193	138	-55	-235	23

[a] Assuming soil weight for 0 - 23cm topsoil layer of 2.88 M t ha^{-1} for Nil and fertiliser treatments, and 2.52 M t ha^{-1} for FYM treatments.

[b] Includes P removed by spring wheat in 2015

[c] FYM+N3 from 2005

Olsen P accounted for all of the change. Where N (and K, Mg) were applied the negative P balance was much larger and the change in Olsen P only accounted for 17–38% of that balance, i.e., 60% or more of the P removed by the crop came from pools of P in soil that were not, initially, readily available (Johnston and Poulton, 2019; Syers et al., 2008). On strip 01, where both FYM and P have been withheld since 2000 the decline was 34 mg kg^{-1}; on this strip we will continue to measure the residual benefit of the FYM (and PK) that was applied between 1968 and 2000. On strip 19, the intention is to withhold P indefinitely, which will, in time, provide a third full-length strip in which lack of P limits yield.

Concentrations of Olsen P in the subsoil are shown in Table 30. As with the total P data there is evidence that P has moved down the profile and this has led to losses of P in drainage water (Heckrath et al., 1995). This is most apparent on the plots receiving FYM. This is partly because the weight of soil in the 0–23 cm layer, has decreased over time (Appendix Table A3) and samples taken from the 23–46 cm layer now will include some soil which was part of the topsoil in previous years. As with total P, there are much higher concentrations of Olsen P at all depths in the south-east corner of the experiment (Table 30).

4.4 Weeds

The problems of controlling weeds when growing continuous wheat were discussed by Thurston (1969). Weeds were first recorded in 1854 and initially control was by hoeing or hand-pulling and later, by fallowing. Regular detailed visual weed surveys began in 1930 and continued until 1979. In 1957, herbicides were first tested on Section 1a (now Section 0) and, since 1964, they have been used on the whole experiment except Section Va (now Section 8). Thurston (1969) referenced results from the research of two pioneering female scientists at Rothamsted, Winifred Brenchley and Kathleen Warington, who, in a series of seminal papers, reported their findings on the effects of fallowing on the weed-seed population in the soil (Brenchley and Warington, 1930, 1933, 1936, 1945; Warington, 1958); their work was appraised by Moss et al. (2004). With the introduction of herbicides in 1957 their effectiveness in controlling weeds was compared with fallowing (Thurston, 1964, 1969, 1972).

In 1991, annual weed surveys resumed on Section 8 but with a change in methodology; weed species present in 25 random quadrats per plot were recorded; these surveys still continue. Since 1867, 130 plant species have been recorded on Broadbalk, but many occur only sporadically. Since 1991, about 50 plant species have been recorded in the annual surveys and about 30 of these are recorded every year (Moss et al., 2004). The most common species, which occur on many plots, are: black-grass (*Alopecurus myosuroides*), common poppy (*Papaver rhoeas*), common vetch (*Vicia sativa*), parsley piert (*Aphanes arvensis*) and scentless mayweed (*Tripleurospermum inodorum*). Moss et al. (2004) showed clearly how the frequencies of individual species are influenced by applications of inorganic N fertilizer. Common chickweed (*Stellaria media*) is greatly favored by increasing amounts of N from 0 to 288 kg N ha^{-1} but other species are strongly disadvantaged, e.g., black medick (*Medicago lupulina*), and field horsetail (*E. arvense*). The greatest weed diversity is observed on plots with intermediate fertility (96 kg N ha^{-1}), representing a habitat that as largely disappeared from the wider landscape because increasing amounts of N are now used in fields of commercial farms (Storkey et al., 2012).

During the late-1990s/early-2000s, the perennial weed, *E. arvense* became a problem across the experiment, particularly on plots receiving no N or only 48 kg N ha^{-1}, due to lack of competition from the wheat. *E. arvense* is a deep-rooted rhizomatous plant with aerial shots appearing in April or May which proved difficult to control with the usual herbicide regime then being used. After harvest 2002, Section 0 was left unploughed, wheat was not drilled and in summer 2003 a randomized, replicated experiment testing seven herbicides plus a control was made on plots 030, 050 and 190 of Section 0. The treatments were applied in June and July 2003 and the effects were assessed twice in 2003 and again in 2004 when the section was again left unploughed and uncropped. Two of the more promising herbicides were re-applied in July 2004 to determine the longer-term effect. The section was plowed and sown to wheat in autumn 2004 and the emergence of *E. arvense* shoots was again assessed in June 2005. Of the seven herbicides tested, Amitrole was most effective (Moss et al., 2007) and was adopted for use on the whole experiment, except Section 8.

Some of the rarest weeds in the United Kingdom can be found on Broadbalk (Moss et al., 2004). A revised atlas of British and Irish Flora (Stroh et al., 2023) includes a list of species which have shown the greatest relative decrease nationally since the 1930s. Three of the species found on Broadbalk are in the top 10 species in the list; corn cleavers (*Galium tricornutum*), corn buttercup (*Ranunculus arvensis*) and shepherd's needle (*Scandix pecten-veneris*). These species tend to be most abundant on plots with intermediate soil fertility. Of these, corn cleavers is one of Britain's rarest plants and Broadbalk is the only site where this species has been recorded in recent years.

Storkey et al. (2021) found that crops receiving most fertilizer N had a proportionately greater effect on weed growth, as did growing shorter cultivars and the trend toward warmer temperatures during the growing season. Samples of grain from the small-plot combines used to harvest Broadbalk and calculate yield are usually clean and free from any unwanted material apart from some broken grains and pieces of rachis. However, on Section 8, the combine will pick up, and not separate, much weed seed, which results in an elevated measure of grain yield. For many years, the sample from the combine has been laboriously cleaned to remove weed seeds, allowing a "cleaned" grain yield to be calculated; these corrected values are published periodically in the Yields of the Long-term Experiments (www.era.rothamsted.ac.uk/eradoc/books/2). Storkey et al. (2021) used a simple linear regression equation derived from this cleaning process to calculate weed-free grain yields for the six treatments that they considered; PKMg +48, 96, 144, 192, 240, 288 kg N ha^{-1}. They derived the following equation ($r^2 = 0.97$):

$$\text{clean yield} = 1.004 \times \text{combine yield} - 0.400$$

Using yields for all treatments and for 16 years between 1998 and 2018 (excluding years when Section 8 was fallow and 2004 when the combine was unable to harvest some plots) we derived the following equation ($r^2 = 0.98$):

$$\text{clean yield} = 0.944 \times \text{combine yield} - 0.210$$

The two regression coefficients are essentially the same. Considering just the 3 years when wheat followed a 1- or 2-year fallow (Appendix Table A1b) made no difference to the factor.

Table 33 shows the mean yields of grain before and after removing the weed seeds from Section 8 and compares the cleaned grain yield with yields on the adjacent Section 9 which receives herbicides. On most treatments, yields on Section 9 are more than twice those on Section 8. As reported by Storkey et al. (2021) losses on Section 8 are proportionately greater with higher rates of N because of selection for a more competitive, nitrophilous weed community (Storkey et al., 2016). The clear exceptions to this are on plots 03 and 05 which do not receive fertilizer N or FYM, where the yields on Section 8 are greater than those on Section 9. On these plots, the additional root mass from the weeds on Section 8 which is plowed-in has increased SOM considerably (Fig. 14). In addition, the flora on plots 03 and 05 on Section 8 contains a significant proportion of the legumes common vetch and medick which is undoubtedly supplying some N to the wheat together with mineralized N from the SOM.

Visually, the plots on Section 8 can vary dramatically from year-to-year because of variation in the relative abundance of different species. This is especially so when there is an abundance of common poppy which is particularly noticeable because of its striking red flowers; in some years the plots are a sea of red. An analysis of the management and environmental factors that explain these patterns identified sowing date and over winter and spring weather as important drivers of weed community dynamics. In the case of poppy, it was more abundant in cooler years and was replaced by scentless mayweed in years with milder winters and warmer springs. This observation supports the idea that environmental variation facilitates coexistence of species adapted to the same habitat (de Leon et al., 2014). An interesting hypothesis is whether, in the long-term, climate change will result in changes in weed communities. If so, this will be of fundamental ecological interest but also have implications for weed management in practical farming.

Table 33 Effect of weeds on the yield of wheat grain, 1998–2018[a], Section 8 compared with Section 9, Broadbalk Wheat Experiment.

		Section 8[b]		Section 9[c]
		Combine grain yield	Clean[d] grain yield	Combine grain yield
Strip	Treatments[e] from 2001	Mean t ha^{-1} yr^{-1}	Mean t ha^{-1} yr^{-1}	Mean t ha^{-1} yr^{-1}
2.2	FYM	3.12	2.69	5.53
2.1	FYM N3[f]	3.31	2.86	7.39
01	(FYM) N4	-	-	-
03	Nil	1.40	1.23	0.70
05	(P)KMg	2.18	1.66	1.11
06	N1 (P)KMg	2.21	1.82	3.00
07	N2 (P)KMg	2.47	2.14	4.30
08	N3 (P)KMg	3.06	2.60	5.36
09	N4 (P)KMg	3.75	3.39	6.15
15	N5 (P)KMg	2.87	2.51	6.51
16	N6 (P)KMg	2.93	2.54	6.89
19	N1+1+1 KMg	2.23	1.83	4.43
18	N1+2+1 PKMg	2.85	2.54	6.00
12	N1+3+1 (P)KMg2	3.13	2.78	6.02
17	N1+4+1 PKMg	2.67	2.41	6.50
10	N4	1.70	1.49	1.72
11	N4 P Mg	2.58	2.24	4.16
13	N4 PK	3.00	2.66	5.93
14	N4 PK*(Mg*)	3.34	2.92	5.97
20	N4 KMg	-	-	-

[a] Excludes 2001, 2004, 2008, 2015, 2016 when Section 8 was fallowed or it was not possible to combine some plots.

[b] Section 8 does not receive herbicides.

[c] Section 9 does receive herbicides

[d] Calculated yield of grain after the removal of weed seeds from a sample of combined grain.

[e] For treatments before 2000 see Table 1.

[f] FYM N2 until 2004.

The management of Section 8 is atypical. No farmer would try and grow wheat with only the occasional fallow to control weeds. However, Section 8 is extremely useful for two reasons. First, the striking differences in species dynamics, frequency and genetic diversity between plots in close proximity clearly shows the ecological adaptation of species to soil fertility (Cavan et al., 2000). Second, as the problem of herbicide resistance becomes more widespread (Hull et al., 2014) the fact that Section 8 has never received herbicides means that it is a valuable source of plant material which can be used as a susceptible control in herbicide resistance trials (Hicks et al., 2018).

4.5 Root and stem base diseases

Take-all, caused by the fungus *Gaeumannomyces tritici* (formerly *Gaeumannomyces graminis* var. *tritici*; previously *Ophiobolus graminis* Sacc.) damages the roots of wheat and other susceptible cereals thereby limiting uptake of water and nutrients and decreasing yield (Gutteridge et al., 2003). It is the most damaging root disease of wheat worldwide and, in the United Kingdom, it is thought to result in an annual yield loss of 5–20% (Palma-Guerrero et al., 2021). It was first identified on Broadbalk in 1930 although its presence had been suggested by observations in the 1860s. The occurrence of take-all on Broadbalk prior to 1967 and the effects of fertilizer treatments and soil pH on its severity were discussed by Glynne (1969) and Etheridge (1969). Although rarely a problem in the first wheat crop following a non-susceptible crop, take-all can have an adverse effect where sequences of susceptible crops like wheat are grown without a break. However, following several successive crops of wheat, a natural form of disease suppression can develop, known as take-all decline, which decreases the severity of the disease and its effect on yield (Hornby, 1998; Slope et al., 1969). Between 1985 and 2009, the severity of take-all was assessed on the roots of plants sampled at about Growth Stage 69 (Zadoks et al., 1974) and used to calculate a take-all rating (TAR), which ranges from 0 (no disease) to 300 (all plants with severe disease). In most years, there was little or no take-all present in the 1st wheat after a 2-year break but for continuous wheat and the 2nd and 3rd wheat crops after a break the severity of take-all differed greatly from year-to-year. Table 34 shows the TAR meaned over 15 years; it was largest in the 3rd wheat, with some 30–50% of plants affected, and slightly less in the preceding 2nd wheat and in continuous wheat that followed. The extent by which fertilizer or manure

Table 34 Take-all rating for continuous wheat and the 1st, 2nd and 3rd wheat crops grown after a 2-year break, mean 1985–2009. Broadbalk Wheat Experiment.

	Treatment[b]		Take-all rating[a]			
Strip	1985-2000	2001-2009	1st wheat[c]	2nd wheat[c]	3rd wheat[c]	Cont. wheat[d]
2.1	FYM N2	FYM N3	1	63	103	67
07	N2PKMg	N2(P)KMg	3	94	138	107
15	N5PKMg	N5(P)KMg	2	83	116	81
10	N2	N4	3	144	155	134
11	N2P	N4P Mg	2	42	94	74
13	N2PK	N4PK	7	89	122	99

[a] The take-all rating is is a measure of the severity of the take-all fungus affecting the crop. Wheat plants are sampled in late-May/early-June and the root system is assessed as follows: 0 = no infection; 1 = < 25% of root system affected (slight take-all); 2 = 25-75 % of roots affected (moderate take-all); 3 = > 75 % of roots affected (severe take-all). A take-all rating on a scale of 0 (no take-all) to 300 (severe take-all on all plants) is then determined (Gutteridge et al., 2003). It is calculated as follows:- (1 x % plants with slight infection) + (2 x % with moderate infection) + (3 x % with severe infection)

[b] Treatments from 1985-2009. See Table 1 for details.

[c] Plants from Sections 2, 3, 4, 5 and 7

[d] Plants from Section 9

treatments affect take-all is not fully understood, although the amount of readily plant-available P in the soil has a noticeable effect on the incidence of take-all especially if the movement of phosphate ions through the soil by diffusion is restricted (Johnston et al., 2014). When a plant's root system is compromised by take-all, the effect on yield can be considerable. Fig. 22A–F shows the effects of take-all and P on the yields of continuous wheat and of the 2nd and 3rd wheats after a 2-year break given fertilizer N and either without or with fertilizer P. For the continuous, 2nd and 3rd wheat crops with N but no P, take-all was severe in some years and grain yields were only *c.* 1 t ha^{-1} or less. Where both N and P were applied there were fewer years when take-all was severe and yields, although still very variable, were not affected to the same extent. These results are in line with earlier work on the Exhaustion Land experiment at Rothamsted which showed that take-all was less severe where fresh P fertilizer had been applied or where there were residues of previous P applications (Gutteridge et al., 1996; Mattingly et al., 1980).

In a recent paper, Rothamsted scientists reviewed advances in take-all research (Palma-Guerrero et al., 2021). These include the identification

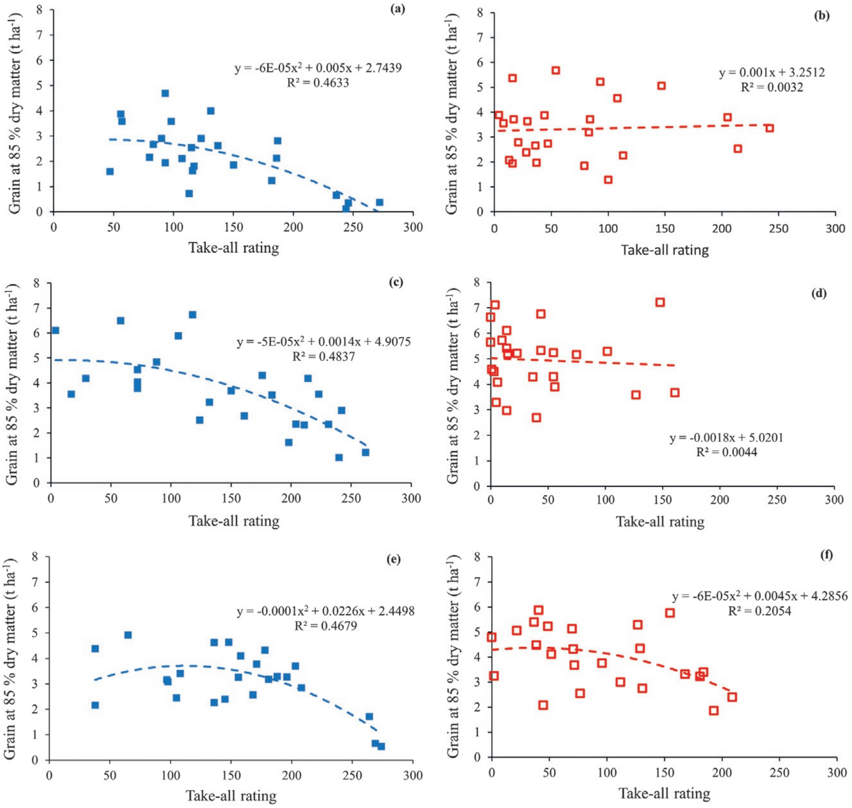


Fig. 22 Effect of P on take-all and yields, 1985–2009, of: (A) and (B), continuous wheat (Section 9); (C) and (D), 2nd wheat after a 2-year break; (E) and (F) 3rd wheat after a 2-year break. Plots receiving ■, N4 (Strip 10) or □, N4PMg (Strip 11). Current treatments given; see Table 1 for earlier treatments. See text for explanation of take-all rating. Broadbalk Wheat Experiment.

of new sources of genetic resistance and the possibility that resistance might be successfully introduced into wheat. There is also a better understanding of the interaction between the soil, the soil microbial community and the development of the disease in different wheat cultivars which might lead to improved management practices. However, they also speculate on how climate change may affect the disease. For example, will an increase in air temperature favor the crop, the disease or soil organisms antagonistic to take-all?

The incidence and severity of brown foot rot (BFR) caused by *Fusarium* spp. were also assessed between 1992 and 2009 (Pradhan and Glendining, 2021). An air-borne fungal disease which affects the stem bases, it has been recorded on Broadbalk since 1933 (Glynne, 1969) and seems to have been most prevalent in hot, dry summers. Severe symptoms were seen on >10% of plants in a few treatments in 4 years, most notably in 2001, when the crop had been planted very late (Pradhan and Glendining, 2021). In most years and treatments, there was no severe infection. The percentages of plants with slight disease are shown in Table 35. On treatments without P and/or K, yields were poor, but there was little BFR. With sufficient P and K, and 96–192 kg N ha^{-1}, yields were larger but there was more infection. Higher rates of N or FYM + N, gave the largest yields but also had the highest level of slight infections. Infections were lowest in the 1st wheat in rotation, higher in the 2nd and 3rd wheats and in continuous wheat. In the treatments with larger amounts of N there was a suggestion that more plants with slight infection resulted in a yield penalty, but this is misleading because the 1st wheat after a break had least take-all and the largest yields. There was no clear correlation with rainfall or temperature during the summer months. In the 1990s, Bateman and Coskun (1995) found more *F. culmorum* on plots receiving FYM or higher rates of fertilizer N but there was no consistent effect of incorporating straw since autumn 1986.

The incidence and effects of other diseases, particularly eyespot (*Pseudocercosporella herpotrichoides*) were discussed in detail by Glynne (1969).

Table 35 Percentage of plants with slight Brown Foot Rot; continuous wheat and the 1st, 2nd and 3rd wheat crops grown after a 2-year break, mean 1992–2009. Broadbalk Wheat Experiment.

			Plants with slight Brown Foot Rot[a] (%)				
	Treatment[b]		1st	2nd	3rd	Cont.	
Strip	1992-2000	2001-2009	wheat[c]	wheat[c]	wheat[c]	wheat[d]	Mean
10	N2	N4	3.7	5.1	5.3	4.9	4.8
11	N2 P	N4 P Mg	6.0	3.8	5.6	5.6	5.3
13	N2 PK	N4 PK	7.8	13.3	15.9	14.3	12.8
7	N2 PKMg	N2 (P)KMg	6.5	8.4	13.8	13.7	10.6
15	N5 PKMg	N5 (P)KMg	15.7	20.1	26.2	23.4	21.4
2.1	FYM N2	FYM N3	12.8	17.5	21.0	21.3	18.2
Mean			8.8	11.4	14.6	13.9	

[a] The % of plants with a slight infection of Brown Foot Rot was assessed on plants sampled in late-June/early-July.

[b] Treatments from 1992-2009. See Table 1 for details.

[c] Plants from Sections 2, 3, 4, 5 and 7

[d] Plants from Section 9

4.6 The effects of weather and global change on yield

In addition to the applied treatments, management practice, weeds, diseases and underlying soil structure, year-to-year variability in weather, particularly temperature and rainfall at key times in the year, also influences grain yield. In the longer term, the continued rise in temperature and the expected increase in extreme rainfall events will have an impact on our ability to maintain or increase yield.

Lawes and Gilbert (1864, 1871, 1880, 1885) attempted to explain differences in yields in terms of the prevailing weather. Although they could explain major differences between, e.g., the lowest yielding year (1879; very cold winter followed by a cold wet spring and summer; see Fig. 4) and the highest yielding year, up until that time, (1863; mild winter and early spring, sufficient but not excessive rainfall and a cool summer) they could not explain smaller, more subtle differences in yield (Lawes and Gilbert, 1885). One of the reasons that Lawes and Gilbert continued Broadbalk, and other experiments, is probably because they thought that by gathering data over more seasons, they might better understand the effects of the weather on yield. In 1919, RA Fisher was appointed to see if more could be made of the large amount of yield and weather data that had accumulated since 1843. Often considered the founder of modern statistical science, Fisher published "Studies in crop variation" in 1921 (Fisher, 1921), his first application of the analysis of variance (ANOVA). A second paper on the effects of rainfall on wheat yields followed in 1924 (Fisher, 1924). While at Rothamsted, he also popularized the concept of the *P*-value, specifically $P=0.05$, as a limit for statistical significance. Reviewing attempts by Fisher and later by Buck (1961) and others to assess the effects of weather on yield Yates (1969) concluded that "The results that have emerged from this immense amount of arithmetic on the Broadbalk yields are therefore somewhat meagre. All that can be said with confidence is that they are larger in dry years than in wet ones, that variations in sunshine had little effect, and variations in temperature none." Later, Chmielewski and Potts (1995) looked at data from 1854 to 1967 and found that grain yields were smallest in wet years and largest more often in dry or cooler years.

All the above authors were considering yields prior to 1968. Addy et al. (2020) looked at the effects of weather on the yields of wheat since 1968, when modern short-strawed cultivars were introduced. They fitted yield vs fertilizer N response curves to the data for each year which were modified to include explanatory variables for monthly rainfall and mean monthly temperature. Generally, correlation between asymptotic maximum yields and weather variables was low, suggesting that other factors such as cultivar and the amount of N applied had a greater impact. Nonetheless, variability in the monthly rainfall and mean monthly temperature did influence the crops response to N and thus final yield. For example, higher rainfall in October and February tended to reduce yield, as did warmer temperatures in May and dry weather in June. Although cultivar explained a certain degree of variability, Addy et al. (2020) suggested that variability might be confounded by pests and diseases which might, in turn, be affected by weather, and by the rate of N applied, to a greater or lesser extent than the cultivar grown.

Other confounding factors would include the increase in atmospheric CO_2 and the related increase in temperature, which might be expected to affect yield. Since the late-1980s when the increase in mean annual temperature became clearer (Fig. 4), successive cultivars have been chosen for their higher yield potential. The introduction of fungicides in 1979 helped to protect that potential and higher rates of N since 1985 helped to exploit that potential. However, since the 1980s we have also seen declines in the input of atmospheric N and S and a decrease in the acidity of rainfall. These confounding factors (and the year-to-year variability in weather) means that it is difficult to discern any consistent increase or decrease in yield that could be attributed to global change. Study of the annual data suggests that the year-to-year variability in the yields of some treatments is increasing. Macholdt et al. (2020), looking at yields from 1986 to 2017, found that, given sufficient N fertilizer, yields were more stable and that the risk of yield loss was less in the 1st wheat after a 2-year break. Seasonal variability was greater and the risk of not achieving the expected yield was greater in continuous wheat with less N or FYM only. Although the 1st wheat receiving FYM plus extra fertilizer N in spring gave the largest yield it was also, perhaps surprisingly, the most variable. Further work is needed to look at the interaction between yield stability, maintaining yield expectations, organic matter and fertilizer inputs, management scenarios, soil type and the changing climate.

Addy et al. (2021) used principal components analysis and a *K*-means clustering procedure to identify patterns in temperature, rainfall and sunlight data collected from 1892 to 2016. The data could be clustered into 10 distinct groups. The three clusters which represented many of the years since 1968 are typified by either Cluster 1) higher temperatures, higher rainfall in autumn/winter but drier June; Cluster 9) warm July to September, dry July and August; or Cluster 7) warm March to June, dry spring. Total biomass yield (grain plus straw) tended to be lower in those years represented in Cluster 1.

Although temperature is by no means the only parameter affecting crop yield it is perhaps the most tangible, especially in countries used to a more temperate climate. Fig. 4 shows how the average annual temperature has changed at Rothamsted since the late-1980s. Of the 28 warmest years on record (1 °C or more above the long-term average of 9.0 °C, 1878–1988), 25 have occurred in the last 34 years, six of those years have been >1.5 °C above the long-term average and three have exceeded that average by >2 °C. Currently, yields in the United Kingdom are being maintained; in 2022 mean yield was 8.6 t ha^{-1}, slightly higher than previous years (www.gov.uk). However, if this warming trend in south-east England continues, the important question is for how long can yields be maintained at that level? Drought conditions during stem elongation, high temperatures at anthesis and heat stress during grain filling will all tend to reduce yield (Barber et al., 2017). It seems likely that at some point farmers will have to change to cultivars that might be considered more suited to Mediterranean conditions.

4.7 Broadbalk drains

The drains installed in 1849 were not intended for experimental use, but in 1866 they were opened, and drainage water collected and analyzed by Voelcker (1871). He found that it contained very little P even though *c.* 600 kg P ha^{-1} had been applied by that time. Although ammonium (NH_4), K, Mg and Na salts were all added to the soil, the biggest losses were of Ca which increased with increasing amounts of NH_4 salts. These observations in the field confirmed the theory of cation exchange in soils developed by Way (1850, 1852). Way (1850) considered that both P absorption and Ca—K exchange took place on the clay fractions of the soil. The drainage also contained nitrate (NO_3), the concentrations increasing with the amount of NH_4 salts added.

In the 1980s/1990s, the losses of NO_3-N and P from agricultural soils into water courses and their adverse effect on the wider environment was causing concern (Addiscott, 2005; Addiscott et al., 1991). The original drains were still operational and losses of NO_3-N and P were measured. However, because the experiment had been divided into Sections growing different crops, and because some drains ran intermittently it was unclear where the drainage was coming from. It was therefore decided that new drains would be installed on Section 9 (nearest the drainage ditch) 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 each old drain at 75 cm depth. Analysis of drainage water continued. Because many soils have the capacity to retain P, vertical movement of P through the soil profile is generally considered to be of little agronomic importance. However, by the 1990s, the soils with different treatments contained between 5 and 100 mg kg^{-1} of Olsen P (Table 31). Measurements of P (mainly dissolved reactive P) in drainage showed that there was a critical level, above which the P concentration in the drainage water increased rapidly; the value was *c.* 60 mg kg^{-1} Olsen P on this soil type (Heckrath et al., 1995). This movement was almost certainly via preferential or "bypass" flow through water moving downwards through large pores and having minimal contact with soil particles, thus avoiding retention by adsorption in soil surfaces. This finding was a significant development leading to a change in understanding regarding P fertilization. While it is important to maintain soils above an Olsen-P concentration necessary to avoid yield loss through P limitation, it is now realized that allowing soils to increase greatly above an appropriate threshold (in this case, 30 mg kg^{-1}) is not only wasteful but also carries a significant risk of water pollution. This study on Broadbalk led to investigations on others soil types: it was found that the critical Olsen P concentration for P loss varied and an indicator for the risk of P loss was developed (Hesketh and Brookes, 2000).

Goulding et al. (2000) reported amounts of NO_3-N lost through the drains in the 1990s and showed that the greatest losses were from soils receiving FYM. Even where no N fertilizer had been applied for more than 150 years about 10 kg ha^{-1} of NO_3-N was lost each year. Most N was lost where the amount of fertilizer N applied exceeded that needed for "optimum" yield or where FYM has been applied for many years. The EU limit (CEC, 1980) for the maximum concentration of N allowed in potable waters (11.3 mg N L^{-1}) was usually exceeded where the larger amounts of fertilizer N or FYM had 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.

4.8 Broadbalk Wilderness

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 uncultivated. The germinating shed grain did not compete well with the weeds, and after

4 years the few self-sown wheat plants that could be found were stunted and barely recognizable as cultivated wheat. One half of the area has remained untouched since then and is now woodland dominated by ash (*Fraxinus excelsior*), sycamore (*Acer pseudoplatanus*) and hawthorn (*Crataegus monogyna*); the ground is covered with ivy (*Hedera helix*) in the densest shade, and with dog's mercury (*M. perennis*) and other species present in less shaded areas (Harmer et al., 2001). On the other half, woody species were cut down annually since *c.* 1900. This area was itself divided in 1957, with part continuing to have the woody species cut down, and part grazed by sheep or mown.

Although not an experiment in the accepted sense, this small area of regenerating woodland has been of great value, especially in recent years, with the on-going debate about the sequestration of carbon in soils and vegetation (Poulton et al., 2018). The development of the "Wilderness" on Broadbalk is complemented by that of the Geescroft Wilderness (Poulton et al., 2003). Both areas had grown arable crops for many years but while Broadbalk had previously been heavily chalked and soil pH is *c.* 7.0, Geescroft had not been chalked and soil pH fell from 7.1 in 1883 to 4.4 in 1999, probably because acidifying atmospheric inputs were trapped by leaves and washed down into the soil.

On both sites, much C has been sequestered in trees and soil since the 1880s. Broadbalk Wilderness has gained, on average, 3.39 t Org C ha^{-1} $year^{-1}$ (0.54 t in soil, plus an estimated 2.85 t in trees), 49.6 kg N ha^{-1} $year^{-1}$ (36.8 kg in soil, plus 12.8 kg in trees). Some of the N required for plant growth will have come from inputs in rain and dry deposition. Broadbalk accumulated C and N in the wooded area faster than Geescroft probably because, as it is a relatively narrow area, 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 the nearby covered yards in which bullocks were housed during winter. By 1999/2001, Broadbalk "Wilderness" had accumulated more Org C in the topsoil since 1882 than the arable strip receiving 35 t FYM ha^{-1} $year^{-1}$ since 1844, 78 t ha^{-1} cf. 74 t ha^{-1}, respectively, plus an estimated 407 t C ha^{-1} in the trees (Poulton et al., 2003, 2018).

5. Sample and data archive

5.1 Rothamsted Sample Archive

The Rothamsted Sample Archive (Fig. 23) is unique. It comprises >300,000 samples of dried grain, straw, herbage, soil, fertilizers and manures. From Broadbalk, there are unground samples of grain and straw from every year

Fig. 23 Rothamsted Sample Archive contains >300,000 crop, soil, organic manure and fertilizer samples from 1843 to 2023.

since the first harvest in 1844. Since 1968 (when Broadbalk was divided into 188 plots) unground samples have been kept from the continuous wheat on Section 1, from the first wheat in rotation and from other crops grown in rotation, i.e., beans, potatoes, oats and maize. Sub-samples from these and other sections that have been ground for chemical analysis have also been retained. Soils have not been sampled and archived so often (Appendix Table A2). Early samples were taken with a box sampler (Dyer, 1902) which provided a large (>5 kg) bulk of soil. Later soils were sampled more regularly but the retained samples were not so large. Samples of fertilizers (except N) and chalk, together with dried samples of castor meal and FYM applied to the experiment have also been archived since the 1940s; ground sub-samples have been analyzed. Samples continue to be archived.

A problem with long running experiments is that analytical techniques change. Comprehensive checks are needed to ensure that new techniques give the same results as the previous ones, or whether a factor can be calculated to convert results from one to the other. Grahmann et al. (2023) highlighted the problems associated with changes over a 40-year period in the combustion methods used to measure SOC. Unfortunately, we are looking at changes in techniques over a much longer period. Most methods have been modified or changed altogether (see Appendix) while others have remained in use for many years. For example, the Kjeldahl (1883) method for determining N in soils replaced a Soda Lime method in the 1890s (results from the two methods was reported by Dyer, 1902) and was, in turn, replaced by a combustion technique in the 1990s, after extensive comparison of the old and new methods. As new analytical techniques are developed these can be applied retrospectively to archived samples; a development foreseen by Lawes and Gilbert in the 1860s when they said "…if our knowledge of the chemistry of soils should progress as rapidly as it has in the last twenty years, the analysis of a soil will ere long become much more significant than it is at present" (Lawes and Gilbert, 1864). However, this assumes that there has been no change in the measured parameter during long-term storage. Blake et al. (2000) found no difference in total C and N in soils stored for many years, minor changes in exchangeable K and Ca but problems with exchangeable Na and manganese. They found that soils had become more acid by up to 0.4 pH unit. Although some changes have been seen after long-term storage it is probable that there will have been significant changes in some parameters when crop and soil samples were initially oven-dried or air-dried.

Despite the potential problems the analysis of archived material allows us to look back over time and investigate changes, some of which may occur so slowly that they take decades to become apparent. Examples include the build-up and/or decline of pollutants in the crop or soil, changes in the mineral components of the crop and changes in SOM and nutrient availability in the soil. Sub-samples from the Sample Archive are available to scientists from universities and institutes in the United Kingdom and around the world, if they have a strong scientific case for the proposed research.

5.2 Electronic Rothamsted Archive (e-RA)

Since the early 1990s, much of the vast amount of data and descriptive information related to Broadbalk and other long-term experiments has gradually been entered into an actively managed, searchable electronic database (Perryman et al., 2018). The database contains some open-access datasets, all of the meteorological data and a bibliography of all published papers from the long-term experiments; it is accessed through the Rothamsted website: http://www.era.rothamsted.ac.uk/. Many historical documents have been scanned, given digital object identifiers (DOIs) and are also accessible through e-RA; these include Annual Reports, Yield Books and experiment plans. The e-RA database has been improved by adopting protocols developed by the Global Long-term Agricultural Experiments Network (GLTEN). The aim of this network of scientists/organizations who manage LTEs is to raise the profile of the experiments and to improve accessibility to, and understanding of, the data available and of the experiments themselves (Ostler et al., 2023).

6. Broadbalk as a scientific resource

Long-term experiments like Broadbalk are a resource on which other, often short-term, studies can be made. Indeed, to ensure continued funding, it is often essential that new ideas are tested and additional measurements made, sometimes involving small changes to the treatments provided these are compatible with the long-term integrity of the experiment. Such studies can lead to published papers within a relatively short time and are important to demonstrate the continuing value of an LTE. Funding bodies do not want to be told that we have marvelous experiments but that it will be another 20 years before they see any results. But, the effects of some treatments or particular management practice may take many years to become apparent. At Rothamsted, and our satellite field sites, we are fortunate to have several complementary long-term experiments which justify their continuation by giving interesting results worthy of publication. Broadbalk is the most widely known of these LTEs, and about which we get most enquiries, whether this is for data which is available through e-RA, fresh or archived crop and/or soil samples or access to the experiment to carry out in situ measurements. Since the major changes were made in 1968, more than 450 papers have been published which, to a greater or lesser extent, have made use of data or samples from Broadbalk. Most have been published in peer-reviewed journals, others in books or conference proceedings and some have been published "in-house" by the LAT. A bibliography of published papers can be found in e-RA. Some have been referenced in the work reported here; others are listed below.

Hütsch et al. (1993, 1994) and Powlson et al. (1997) reported on the soil's ability to act as a sink or a source for methane, an important greenhouse gas, especially how the sink strength of the soil is influenced by land use, soil pH and fertilizer or manure applications. Goulding et al. (1998), Yamulki et al. (1995) and Bradbury et al. (1993) measured gaseous N fluxes, N cycling and modeled the fate of N. The diversity of the microbial population involved in these processes has been considered by Ogilvie et al. (2008), Clark et al. (2012) and Zhalnina et al. (2013) using soil samples from Broadbalk, while Jenkinson and Powlson (1976), Powlson and Jenkinson (1976), Patra et al. (1990), Brookes et al. (1982, 1985) and Shen et al. (1989) used Broadbalk soils to help develop techniques to measure the quantities of C, N and P in the total population of soil microbes, termed the microbial biomass, and changes over time. Jenkinson (1990) and Jenkinson and Coleman (2008) measured SOC and its ^{14}C content to help build and validate RothC, a computer model which simulates the turnover of SOM in both the topsoil and subsoil. In a series of papers, van Bergen and others (Bull et al., 2000; van Bergen et al., 1997) examined various components of SOM; in particular they looked at its total lipid content and followed the fate of lipids contained in the initial organic input. Poirier et al. (2005) used Broadbalk soil to test a range of spectroscopic methods for identifying chemical groups within physically separated fractions. Similarly, Sohi et al. (2005) used ^{13}C NMR for this purpose to elucidate chemical groups of differing stability and compared data from Broadbalk soil with that from seven other LTEs globally.

Jones et al. (1994) reviewed many of the papers examining the build-up and/or decline in soils of atmospheric pollutants such as polynuclear aromatic hydrocarbons (PAHs), polychlorinated dibenzo-*p*-dioxins and -furans (PCDD/Fs) and PCBs. This work was only possible because of the existence of the Rothamsted Sample Archive. Sulfur, another atmospheric input, declined from a maximum of *c.* 65 kg ha^{-1} year^{-1} in the 1980s to *c.* 5 kg ha^{-1} year^{-1} now. Zhao et al. (2003) measured the ratio of ^{34}S/^{32}S in grain and straw from Broadbalk from 1845 to 1999 and showed how S inputs mirrored the increased deposition from industry and its subsequent decline. Zhao et al. (2001) also measured the δ^{13}C in Broadbalk grain and straw from 1845. Both showed a decreasing trend, particularly since the 1960s, which was in line with the trend in the δ^{13}C of atmospheric CO_2.

Bearchell et al. (2005) and Shaw et al. (2007) extracted DNA material from *Phaeosphaeria nodorum* and *Mycosphaerrella graminicola* found in archived grain and straw samples from Broadbalk. The ratio of these two Septoria diseases of wheat, both of which cause yield loss by decreasing green leaf area, was determined. The dominance of one disease over the other was related to the changes in national SO_2 emissions. Clark and Hirsch (2008) looked at the survival of bacteria and bacterial DNA in archived soils dating back to 1868. They found that bacterial DNA survived the archiving process and long-term storage better than culturable bacteria.

Iron, zinc, copper and magnesium are important for human health, but their intake by the UK population has declined. Wheat is an important source of these minerals in the UK diet. Fan et al. (2008) analyzed grain from Broadbalk from 1845 to 2005 and showed that concentrations of these minerals remained constant until the 1960s but declined following the introduction of short-strawed, higher grain yielding cultivars even though concentrations in the soil did not decline. Because of the great increase in grain yield with short-straw varieties, the concentration of these minerals in grain was diluted while the total quantities absorbed by the crop remained approximately constant. Selenium (Se) is another element essential for good human health; its intake by the UK population has also declined since the 1970s. However, concentrations in Broadbalk wheat grain have not declined even after the introduction of higher yielding cultivars in the 1960s. Se concentrations in the soil have tended to increase since the

1840s (Fan et al., 2007). In a comparative study using archived samples from 16 countries Ben Mariem et al. (2020) looked at changes in the nutritional quality of grain over 166 years.

Lu et al. (2005) extracted total RNA from wheat grain grown with inorganic fertilizer N or with organically-derived N (i.e., from FYM) and identified differentially expressed genes. Many genes are involved in N metabolism and protein synthesis and analysis showed that specific genes had different expression levels according to the source of N.

Stroud (2019) found that the earthworm population was reduced in soils which had received fertilizers for >160 years compared with soils which had receiving FYM for many years. This confirmed findings by Edwards and Lofty (1982) that all species of earthworms were more numerous in soils given FYM.

7. The future

Any discussion about the value of the Broadbalk wheat experiment in the coming years must include climate change. Although there was an agreement by 195 countries to limit global temperature rise to 1.5 °C (IPCC, 2023) it seems certain that concentrations of CO_2 and other major greenhouse gases will continue to increase for some decades, with the temperature goal very likely to be exceeded. This trend has serious implications for global climate, regional weather patterns and food security. In recent years, we have seen long-term droughts, catastrophic forest fires and extensive flooding in Australia, Europe, the USA and elsewhere. Despite this, yields in many parts of the world have increased (Ritchie et al., 2023), but this will have been due, at least in part, to the introduction of new varieties and improvements in management. We do not know the extent to which such changes will be able to counter negative effects of climate change in different climatic regions. In a recent modeling exercise, Jägermeyr et al. (2021) found that although yields of some major crops such as maize were likely to decline in many parts of the world, wheat yields in higher latitude regions were projected to increase over the next 20–30 years. In temperate countries like the United Kingdom, which have typically been able to achieve high cereal yields, perhaps it will be possible to maintain those high yields as CO_2 concentrations and temperatures keep rising; at least for the next few decades. Clearly, long-term experiments like Broadbalk are a "benchmark" against which to measure the effects of global change on crop yields and associated changes in soils and the dynamics of pests, diseases and weeds. In addition, we expect that Broadbalk and the associated data in e-RA will continue to provide valuable information on slow changes in soil properties to aid mechanistic understanding and modeling. These goals will increasingly be facilitated by collaboration with scientists managing other LTEs under different climates and cropping systems globally, thus increasing the value of Broadbalk as a resource for global agriculture, agricultural/environmental interactions, and fundamental understanding of crop/soil systems (Ostler et al., 2023).

There is also no doubt that the Sample Archive will continue to be of great scientific value. Visitors often ask "What are you going to analyse the samples for next?" The answer is, we don't know, but if past experience tells us anything it is that the Sample Archive *will* be useful in the future, we just don't necessarily know what for! We can, of course, speculate. In a recent paper, Rotchell et al. (2023) reported the presence of microplastics in human blood and tissue. One route by which these may get into the body is through the food chain following inputs to soil such as through sewage sludge (Frost et al., 2022). Previous work using archived samples from Broadbalk and other LTEs has shown how the concentration of pollutants such as polychlorinated biphenyls (PCBs) had increased in wheat grain since they were first manufactured in the 1920s (Jones et al., 1991). It would be interesting to see if microplastics could also be detected in wheat grain from Broadbalk and for how long they have been present. It is also likely that researchers will make more use of stable and radio-active isotope analyses, DNA and gene analyses to study, e.g., the turnover of SOM, the way in which the crop might respond to different inputs or to stress such as excess heat or drought, the structure of the microbial community or the incidence of different pests and diseases.

At Rothamsted, our aim is to further raise the profile of Broadbalk and the other long-term experiments and exploit their full potential (Ostler et al., 2023).

8. Conclusions

The Broadbalk experiment shows that it is possible to maintain or increase yields of wheat over very many years with either inorganic fertilizers or organic manure. However, to achieve this, changes in management have been needed to ensure that soil acidity, weeds and diseases do not compromise the experiment. The introduction of a short-straw cultivar in

1968 led to immediate large increases in grain yield. Growing that cultivar as the 1st crop after a 2-year break, thus minimizing the effects of take-all, gave additional increases in yield. Successive cultivars which had a greater yield potential also resulted in further increases when that potential was exploited by adding larger amounts of fertilizer N and protected by the responsible use of fungicides and herbicides. The largest yields now exceed 12 t ha^{-1}. However, where FYM has been applied for many years or where the largest amounts of fertilizer N have been added, the risk of unacceptable losses of NO_3-N into the drainage system is high.

On a soil that had probably been in arable cropping for centuries before the experiment began, SOC was low at *c.* 1.0%. Adding FYM for many years increased stocks of C greatly. Increasing amounts of fertilizer N resulted in larger crops and more stubble, root and root exudate being plowed-in, leading to increases in soil C toward new equilibria. SOM in some treatments has been in equilibrium for many years.

The experiment and the data from it, together with the archive of crop and soil samples, continue to provide scientists with a valuable resource for fundamental understanding of agricultural systems as well as a sound basis for practical management strategies for improving sustainability.

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Conflict of interest

The authors declare no conflicts of interest.

Appendix

A.1 Analytical techniques

We give here, a brief description of the techniques used for routine crop, soil, fertilizer, manure and drainage water analyses since the 1960s. With one or two exceptions we have not attempted to give details of earlier techniques nor of the less routine analyses done on many fresh and archive samples. Some of these can be found in the original papers although details in some 19th century publications are sometimes limited.

A.1.1 Crops

Crops are oven-dried and ground $<0.5\,\text{mm}$ and usually analyzed for N, P, K, Ca, Na and since 2000, for Si.

Total N in plant material was estimated by Kjeldahl (1883) until the 1990s and is now determined by combustion analysis based on the Dumas combustion method (TruMac CN Analyzer, Leco Corporation, St. Joseph, Michigan, USA). Total P was determined after dry ashing (Piper, 1942), on a Spekker, Technicon AutoAnalyzer or using Alpkem Flow Injection Analysis using the method of Fogg and Wilkinson (1958) until the 1990s and now using the method of Murphy and Riley (1962) by Continuous segmented colorimetric flow analyzer (Skalar SAN^{PLUS}, Skalar Analytical BV, Breda, The Netherlands). Cations were measured after dry ashing, by emission (K, Na, Ca) or atomic absorption (Mg) spectrophotometry (Unicam SP 90A Series 2 Atomic Absorption Spectrophotometer and Shandon Southern, Baird Atomic A 3400 Atomic Absorption Spectrophotometer) and now by nitric perchloric digestion (Zarcinas et al., 1987) and analysis by Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES) (Optima 7300 DV ICP-OES, Perkin Elmer Life and Analytical Sciences, 710 Bridgeport Avenue, Shelton, CT 06484 USA).

A.1.2 Soils

Soils are air-dried, ground and sieved to $<2\,\text{mm}$ and routinely analyzed for pH in water, exchangeable cations and plant-available P (Olsen P). A sub-sample is more finely ground, <44 mesh, for organic C, or Total C and inorganic C, Total N, and occasionally for Total P.

Soil pH is measured in boiled deionized H_2O.

Exchangeable cations are leached from soil with *N* ammonium acetate (Metson, 1956) and determined by Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES) (Optima 7300 DV ICP-OES, Perkin Elmer Life and Analytical Sciences, 710 Bridgeport Avenue, Shelton, CT 06484 USA). Plant-available P is measured after extraction with 0.5 M $NaHCO_3$ (Olsen et al., 1954) using a modified method of Murphy and Riley (1962) on a continuous segmented colorimetric flow analyzer

(Skalar SAN^{PLUS}, Skalar Analytical BV, Breda, The Netherlands). Total P in soil was determined by fusion with sodium carbonate (Mattingly, 1970) or by aqua regia digestion (Crosland et al., 2008). Major cations including Total P is now determined using aqua regia (McGrath and Cunliffe, 1985).

Organic C was determined by the Tinsley (1950) method described by Bremner and Jenkinson (1960); previously by Walkley and Black (1934) with a factor to make them equivalent to Tinsley. Since the 1990s inorganic carbon was determined using a manual manometer and calcimeter, and more recently by a carbon flexible solid sample analyzer (Primacs$^{SNC-100}$ Carbon/Nitrogen analyzer, Skalar Analytical BV, Breda, The Netherlands). Inorganic C is subtracted from Total C to give Organic C.

Since 1990, Total Carbon has been determined by combustion analysis (TruMac CN Analyzer, Leco Corporation, St. Joseph, Michigan, USA).

Total N was by Kjeldahl (1883) until the early 1990s, and is now by combustion (TruMac CN Analyzer, Leco Corporation, St. Joseph, Michigan, USA).

A.1.3 Fertilizers

Cations are determined using the aqua regia digestion method (McGrath and Cunliffe, 1985) and determined by Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES) (Optima 7300 DV ICP-OES, Perkin Elmer Life and Analytical Sciences, 710 Bridgeport Avenue, Shelton, CT 06484 USA).

A.1.4 Farmyard manure (FYM)

Total N in FYM is determined on "fresh" material by Kjeldahl (1883) using the method of Crooke and Simpson (1971).

P and cations on a dried ground sample was by atomic absorption and is now by nitric/perchloric digestion (Zarcinas et al., 1987) and ICP-OES analysis by Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES) (Optima 7300 DV ICP-OES, Perkin Elmer Life and Analytical Sciences, 710 Bridgeport Avenue, Shelton, CT 06484 USA).

A.1.5 Chalk

The total neutralizing value of chalk/limestone is measured using the method of Shoemaker et al. (1961).

A.1.6 Drainage water

Anions, nitrate-N and ammonium-N were analyzed colorimetrically by Technicon AutoAnalyzer until the 1990s and now by Continuous segmented colorimetric flow analyzer (Henriksen and Selmer-Olsen, 1970) and (Krom, 1980). (Skalar SAN^{PLUS}, Skalar Analytical BV, Breda, The Netherlands).

Cations have been analyzed by ICP-OES since the 1980s and are currently determined using Optima 7300 DV ICP-OES (Perkin Elmer Life and Analytical Sciences, 710 Bridgeport Avenue, Shelton, CT 06484 USA).

More information regarding analytical facilities and instrumentation can be found at: https://www.rothamsted.ac.uk/analytical-chemistry-unit and at https://www.rothamsted.ac.uk/analytical-chemistry-unit/facilities

Table A1a Cropping 1925–1967. Broadbalk Wheat Experiment.

		Old Section Number[a] (1925 – 1967)									
Year[b]	Wheat Cultivar[c]	Ia	Ib	II	II	III	III	IV	IV	Va	Vb
1925	Red Standard	W	W	W	W	W	W	W	W	W	W
1926	"	F	F	F	F	F	F	W	W	W	W
1927	"	F	F	F	F	F	F	W	W	W	W
1928	"	W	W	W	W	F	F	F	F	F	F
1929	Squarehead's Master	W	W	W	W	F	F	F	F	F	F
1930	Red Standard	W	W	W	W	W	W	W	W	W	W
1931	"	F	F	W	W	W	W	W	W	W	W
1932	"	W	W	F	F	W	W	W	W	W	W
1933	"	W	W	W	W	W	W	W	W	F	F
1934	"	W	W	W	W	W	W	F	F	W	W
1935	"	W	W	W	W	F	F	W	W	W	W
1936	"	F	F	W	W	W	W	W	W	W	W
1937	"	W	W	F	F	W	W	W	W	W	W
1938	"	W	W	W	W	W	W	W	W	F	F
1939	"	W	W	W	W	W	W	F	F	W	W
1940	Squarehead's Master	W	W	W	W	F	F	W	W	W	W
1941	"	F	F	W	W	W	W	W	W	W	W
1942	Stand Up	W	W	F	F	W	W	W	W	W	W
1943	Squarehead's Master	W	W	W	W	W	W	W	W	F	F
1944	Red Standard	W	W	W	W	W	W	F	F	W	W
1945	"	W	W	W	W	F	F	W	W	W	W
1946	Squarehead's Master	F	F	W	W	W	W	W	W	W	W
1947	"	W	W	F	F	W	W	W	W	W	W
1948	"	W	W	W	W	W	W	W	W	F	F
1949	"	W	W	W	W	W	W	F	F	W	W
1950	"	W	W	W	W	F	F	W	W	W	W
1951	"	F	F	W	W	W	W	W	W	W	W
1952	"	W	W	F	F	W	W	W	W	W	W
1953	"	W	W	W	W	W	W	W	W	F	F
1954	"	W	W	W	W	W	W	F	F	W	W
1955	"	W	W	W	W	F	F	W	W	W	W
1956	"	W	F	W	W	W	W	W	W	W	W
1957	"	W	W	F	F	W	W	W	W	W	W
1958	"	W	W	W	W	W	W	W	W	F	F
1959	"	W	W	W	W	W	W	F	F	W	W
1960	"	W	W	W	W	F	F	W	W	W	W
1961	"	W	F	W	W	W	W	W	W	W	W
1962	"	W	W	F	F	W	W	W	W	W	W
1963	"	W	W	W	W	W	W	W	W	F	W
1964	"	W	W	W	W	W	W	F	F	W	W
1965	"	W	W	W	W	F	F	W	W	W	W
1966	"	W	F	W	W	W	W	W	W	W	W
1967	"	W	W	F	F	W	W	W	W	W	W
		New Section Number (1968 –)									
		0	1	2	3	4	5	6	7	8	9

Table A1b Cropping 1968–2018. Broadbalk Wheat Experiment.

		Section Number since 1968									
		Continuous wheat					Rotational wheat				
Year[b]	Wheat Cultivar[c]	1	9	0*	8**	6***	5	3	7	4	2
1968	Cappelle Desprez	W	W	W	W	F	W	W	P	W	BE
1969	"	W	W	W	W	W	F	W	BE	P	W
1970	"	W	W	W	W	W	W	F	W	BE	P
1971	"	W	W	W	W	F	W	W	P	W	BE
1972	"	W	W	W	F	W	F	W	BE	P	W
1973	"	W	W	W	W	W	W	F	W	BE	P
1974	"	W	W	W	W	F	W	W	P	W	BE
1975	"	W	W	W	W	W	F	W	BE	P	W
1976	"	W	W	W	W	W	W	F	W	Be	P
1977	"	W	W	W	W	F	W	W	P	W	BE
1978	"	W	W	W	W	W	F	W	BE	P	W
1979	Flanders	W	W	W	W	W	W	F	W	P	F
1980	"	W	W	W	W	W	W	W	F	W	P
1981	"	W	W	W	F	W	W	W	P	F	W
1982	"	W	W	W	W	W	W	W	W	P	F
1983	"	W	W	W	W	W	W	W	F	W	P
1984	"	W	W	W	W	W	W	W	P	F	W
1985	Brimstone	W	W	W	W	W	F	W	W	P	W
1986	"	W	W	W	W	W	P	F	W	W	W
1987	"	W	W	W	W	W[d]	W	P	W	W	F
1988	"	W	W[d]	W	F	W[d]	W	W[d]	F	W	P
1989	"	W	W[d]	W	W	W[d]	W	W	P	F	W[d]
1990	"	W	W[d]	W	W	W[d]	F	W	W[d]	P	W
1991	Apollo	W	W	W	W	W	P	F	W	W	W
1992	"	W	W	W	W	W	W	P	W	W	F
1993	"	W	W	W	W	W	W	W	F	W	P
1994	"	W	W	W	F	W	W	W	P	F	W
1995	"	W	W	W	W	W	F	W	W	P	W
1996	Hereward	W	W	W	W	W	P	O	W	W	W
1997	"	W	W	W	W	W	W	M	W	W	O
1998	"	W	W	W	W	W	W	W	O	W	M
1999	"	W	W	W	W	W	W	W	M	O	W
2000	"	W	W	W	W	W	O	W	W	M	W
2001	"	W	W	W	F	W	M	O	W	W	W
2002	"	W	W	W	W	W	W	M	W	W	O
2003	"	W	W	F	W	W	W	W	O	W	M
2004	"	W	W	F	W	W	W	W	M	O	W
2005	"	W	W	W	W	W	O	W	W	M	W
2006	"	W	W	W	W	W	M	O	W	W	W
2007	"	W	W	W	W	W	W	M	W	W	O
2008	"	W	W	W	F	W	W	W	O	W	M
2009	"	W	W	W	W	W	W	W	M	O	W
2010	"	W	W	W	W	W	O	W	W	M	W
2011	"	W	W	W	W	W	M	O	W	W	W
2012	"	W	W	W	W	W	W	M	W	W	O
2013	Crusoe	W	W	W	W	W	W	W	O	W	M
2014	"	W	W	W	W	W	W	W	M	O	W
2015	Mulika[e]	W	W	W	F	W	O	W	W	M	W
2016	Crusoe	W	W	W	F	W	M	O	W	W	W
2017	"	W	W	W	W	W	W	M	W	W	O
2018	"	W	W	W	W	W	W	W	New rotation begins		

[a] The five sections shown in Appendix Table 1a were not divided until autumn 1954 when Section V was divided for a test of liming and Section I was divided (for the harvest year of 1955) with Section Ia reverting to continuous wheat with hebicides from 1957. Sections II, III and IV were not divided until autumn 1967 (for the harvest year of 1968).

[b] Year refers to the year in which the crop was harvested

[c] The winter wheat varieties are selected primarily for their suitability for bread-making (except Apollo which was a feed wheat).

[d] Comparison of Brimstone and Squarehead's Master cultivars in 1987-1990 on sections indicated (Brimstone on all other sections)

[e] Conditions in autumn/early winter 2014/15 prevented the drilling of winter wheat; spring wheat variety (Mulika) sown on 9 March 2015

Crops
W = w. wheat; P = potatoes; BE = s. beans; F = fallow; O = w. oats; M = forage maize.
First wheat indicated with grey highlight

Sections and treatments
* = straw incorporated since autumn 1986; ** = no herbicides; *** = restricted pesticide use since 1985
Section 0 fallowed (uncultivated) in 2003 and 2004. Various herbicides were tested in an attempt to control *Equisetum arvense.*
No organic manures or fertilisers applied to the fallows between 1925 and 1967
Organic manures and autumn fertilisers (PK *etc*) applied to fallows but no N fertilisers.
N applied to spring beans, 1968-1978.
No N or FYM applied to oats, 1996-2017.

Table A2 Major soil sampling dates, topsoil, 0–23 cm, and the relative position of each set of samples over time. Broadbalk Wheat Experiment.

1865	1881[a]	1893[h]	1914[i]	Section number since 1926	1936	1944[j]	Section number since 1954	1966	Section number since 1968	1987/8	1992-96	1997-99	2000	2001-04	2005/6	2008-12	2013-17
						Holes 1&2	**Ia**	X	**0**	X	X	X	X		X	X	X
				I	X												
	Hole 6[b]	Hole 4?	Hole 1?			Holes 3&4	**Ib**	X	**1**	X	X	X	X		X	X	X
8 holes from each selected treatment strip. Positions unknown. Samples bulked to give one sample per strip																	
	Hole 5[c]		**Top of field**			Holes 1&2			**2**	X	X		X	X	X	X	X
			(West end)	**II**	X		**II**	X									
		Hole 3?				Holes 3&4			**3**	X	X		X		X	X	X
			Hole 2?														
	Hole 4[d]					Holes 1&2			**4**	X	X	X	X	X	X	X	X
				III	X		**III**	X									
						Holes 3&4			**5**	X	X	X	X	X	X	X	X
	Hole 3[e]		Hole 1?														
		Hole 2?				Holes 1&2			**6**		X	X	X		X	X	X
			Bottom of field	**IV**	X		**IV**	X									
	Hole 2[f]		(East end)			Holes 3&4			**7**	X	X		X	X	X	X	X
	Hole 1[g]	Hole 1?	Hole 2?			Holes 1&2	**Va**	X	**8**		X	X	X		X	X	X
				V	X												
						Holes 3&4	**Vb**	X	**9**	X	X	X	X		X	X	X

Broadbalk has been sampled on many occasions over the years. However, because the method of sampling has changed and the experiment has been divided, initially into two halves, then into five sections (I - V) (two of which, I and V, were divided in two) and finally into ten sections (0 - 9), it is not always advisable to directly compare one sampling with another without careful thought. The table shows (where possible) how samples taken over time relate to each other. Selected plots and depths have been sampled on many other occasions; most samples still exist in the Archive.

Sample "Holes" were taken with a 15.2 x 15.2 x 22.9 cm (or larger) metal box (Dyer, 1902), except 1944 when they were taken by spade.

In those years indicated by "X" a large number (10 - 20) of cores were taken with narrow diameter semi-cylindrical gouge auger from plots within each section; cores were bulked to give one sample for each plot.

[a] For 1881, a sampling plan still exists.

[b] Hole 6 was on the top (western) edge of current Section 1.

[c] Hole 5 was in what is now Section 2.

[d] Hole 4 was in the discard between current Sections 3 & 4, just off the top edge of Section 4.

[e] Hole 3 on strips 9a, 9b, 10a, 10b, 11a were on current Section 6, others on Section 5.

[f] Hole 2 was in what is now Section 7.

[g] Hole 1 on strips 13a, 14a, 15a were at top edge of current Section 8, others were within current Section 8.

[h] The positions of the 4 holes sampled in 1893 is unknown; they are assumed to be numbered from the bottom (eastern) end of the field as in 1881.

[i] Two holes taken from the "Top" of the field, two from the "Bottom"; positions unknown.

[j] For 1944, a sampling plan still exists; four holes taken from each of the (then) five sections; holes 1 & 2 were on current Section 0, holes 3 & 4 on current Section 1 *etc.*

Table A3 Summary of agreed soil weights (all sections), Broadbalk Wheat Experiment.

		FYM[b]	**FYM**[b]	**FYM**[c]
	Inorganic[a]	Since 1844	Since 1885	1968–2000
	Strips 03–19	Strip 2.2 (2b)	Strip 2.1 (2a)	Strip 01
	$\mathrm{Mkg\,ha^{-1}}$ of oven-dry fine soil, 0–23 cm			
1843	(2.88)	(2.88)		
1865	2.88	2.78		
1881	2.88	2.69		
1884	–	–	(2.88)	
1893	2.88	2.62	2.81	
1914	2.88	2.60	2.75	
1967	–	–	–	(2.88)
2000	2.88	2.52	2.52	2.52
	$\mathrm{Mkg\,ha^{-1}}$ of oven-dry fine soil, 23–46 cm[d]			
All years	3.0	3.0	3.0	3.0
	$\mathrm{Mkg\,ha^{-1}}$ of oven-dry fine soil, 46–69 cm[e]			
All years	3.1	3.1	3.1	3.1
	$\mathrm{Mkg\,ha^{-1}}$ of oven-dry fine soil, 69–91 cm[e]			
All years	3.1	3.1	3.1	3.1

[a] Plots receiving no fertilizer or manure, inorganic fertilizer only or rape cake/castor meal. Data is the mean of comprehensive measurements of soil weight made in 1865, 1881, 1893, 1914 and 2000.
[b] Assume no further change in bulk density (BD)/soil weight on plots 2.2 and 2.1 after 2000. However, BD may increase slightly on plots in rotation as FYM is NOT applied to the oats.
[c] BD is likely to increase on plot 01 as applications of FYM stopped in 2000.
[d] Mean of all plots measured in 1865, 1881, 1893 and 1914.
[e] Mean of all plots measured in 1865, 1881 and 1893. See Dyer (1902) for 1865, 1881 & 1893 data and Watts et al. (2006) for 2000 data. 1914 data is previously unpublished.
Starting values in brackets are assumed.

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