Johnston, A. E. and Mattingly, G. E. G. 1976. Experiments on continuous growth of arable crops at Rothamsted and Woburn-Experimental-Stations - effects of treatments on crop yields and soil analyses and recent modifications in purpose and design. *Annales Agronomiques.* 27 (5-6), pp. 927-956.

Ann. agron., 1976, **27** (5-6), 927-956.

EXPERIMENTS ON THE CONTINUOUS GROWTH OF ARABLE CROPS AT ROTHAMSTED AND WOBURN EXPERIMENTAL STATIONS : EFFECTS OF TREATMENTS ON CROP YIELDS AND SOIL ANALYSES AND RECENT MODIFICATIONS IN PURPOSE AND DESIGN

A. E. JOHNSTON and G. E. G. MATTINGLY

Rothamsted Experimental Station, Harpenden, Herts. AL5 2JQ (England)

SUMMARY

This paper describes six field experiments started during 1843-77. All, with various modifications, still continue and results for various periods between 1843 and 1975 are given. Originally the experiments investigated the nutrient requirements of wheat, barley and root crops, each crop grown in monoculture. Yields on unmanured and farmyard manure treated soils were measured and compared with those given by N P K Na Mg Si supplied in inorganic compounds and tested singly and in various combinations. These experiments soon demonstrated that fertilisers could give the same yields as farmyard manure and showed the relative importance of N, P and K for the various crops.

All manures tested supplied more nutrients than were removed in the crops. Nearly all the fertiliser N residues have been lost from the soil ; some N has accumulated in soils given farmyard manure but even on these soils much has been lost. Most of the P residues have remained in the plough layer but some K has moved into the subsoil. The P and K residues can be detected by increases in the bicarbonate soluble-P and the exchangeable K but neither method of soil analysis gives an estimate of the total amount of plant available P and K in the soil. However, field experiments show that the residues are available to a wide range of crops. In some comparisons yields were always better on soils with residues than on those without, even when much new fertiliser was tested.

Soils which have received annual dressings of farmyard manure for more than 100 years now contain more organic matter than soils with fertilisers only. During recent years varieties with a high yield potential, and improved cultural techniques, including weed, pest and disease control have been introduced. In this period yields of root crops and cereals grown in rotation have been larger on farmyard manure-than on fertiliser-treated soils. This difference cannot be explained in terms of spring applied fertiliser N dressings ; further investigations are being undertaken.

INTRODUCTION

In the 1830s, when BOUSSINGAULT was making experiments in Alsace on the nutrient balance of crop rotations, Lawes was experimenting on the effects of various substances on plants grown in pots and on small plots at Rothamsted. He was impressed by the effects of 'earthy phosphates decomposed by sulphuric acid', which later led to his patent for superphosphate manufacture and the start of his manure business. These early experiments apparently convinced Lawes of two things :

1. The need to grow the same crop year after year on the same land to understand the nutrient requirements of that crop. Complementary experiments could be made on crops grown in rotation.

2. The need to make experiments on large plots. This decision has proved of supreme importance, not only because the early results were an acceptable demonstration to farmers but because it has allowed the plots to be subdivided in later years to increase their usefulness.

LAWES started the first field experiment on large plots in spring 1843 just before he appointed Gilbert as chemist in June.

This paper describes results from four of their experiments at Rothamsted. All are on arable crops grown in monoculture ; winter wheat on Broadbalk (1844), spring barley on Hoosfield (1852), root crops on Barnfield (1843), and cereals on the Exhaustion Land (1856). Two, in which LAWES and GILBERT had great interest, are at Woburn, one each on winter wheat and spring barley (1877). Much has been written about each experiment ; references are given later to detailed accounts.

THE SOIL ON WHICH THE EXPERIMENTS WERE MADE

The soils have been described by the Soil Survey of England and Wales ; those at Rothamsted (Rothamsted Experimental Station, 1974) are leached brown soils (Sols lessivés). The surface soils are mainly developed in drift overlying Clay-with-flints on Upper Chalk. All belong to the Batcombe or closely related series ; much of Broadbalk and Hoosfield are on flinty loam or deep silt loam while Barnfield and Agdell (MATTINGLY and JOHNSTON, this Conference) are on shallow flinty clay loam. The soils contain 20-28 p. 100 clay ; COOKE (this Conference) gives a typical mechanical analysis. The natural topsoils are moderately or strongly acid (pH values 4.0-5.5) but much arable land has a neutral or alkaline reaction and contains some calcium carbonate (1-3 p. 100). In former times the underlying chalk was spread on the arable fields (YOUNG, 1813 ; RUSSELL, 1916) and some soils at Rothamsted have probably been cultivated for some centuries. The soils are seldom waterlogged though drainage may be impeded to some extent by the slow permeability of the Clay-with-flints.

At Woburn two soils, both developed in drift over Lower Greensand, are recognised on Stackyard Field where experiments on cereals started in 1876. One is classified as Cottenham Series, the topsoil (0-23 cm) is a loamy sand ; the other, which has a coarser texture, belongs to the Stackyard Series, the topsoil is a sandy loam. Both soils are free draining and, at the start of the experiments, were slightly acid. At both Rothamsted and Woburn arable land is now ploughed to a depth of about 23 cm.

THE TREATMENTS TESTED

In each experiment yields without manure and with farmyard manure (FYM) were measured and compared with those given by inorganic compounds containing : nitrogen, N ; phosphorus, P ; potassium, K ; sodium, Na ; and magnesium, Mg. These inorganic fertilisers were tested alone and in various combinations.

TABLE I

Details of treatments (1), *Barnfield, Broadbalk, Hoosfield, Exhaustion Land* (2) *and Woburn* (3)

(All nutrients kg element ha^{-1})

Nitrogen : Various fertilisers to supply 48, 96, 144 and 192 kg N (N_1 N_2 N_3 N_4). Before 1967 N applied either as ammonium-N (NH_4-N), mainly ammonium sulphate, or as nitrate-N (NO_3-N), sodium nitrate. Since 1968 'Nitro-Chalk' (ammonium nitrate-calcium carbonate mixture) has been used. In this paper when ammonium- and nitrate-N are compared N* is used to denote nitrate-N. Other rates of N used are given in the text.

Phosphorus : Superphosphate to supply 32-34 kg P. Before 1889 the superphosphate was made on Rothamsted Farm from calcined bone dust and sulphuric acid. Since 1889 factory made superphosphate (almost certainly from rock phosphate) was used. During the late 1890s and until 1902, 448 kg basic slag replaced superphosphate in some years.

Potassium : Potassium sulphate to supply 90 kg K for cereals, 135 kg K for potatoes on Exhaustion Land and 225 kg K for root crops on Barnfield.

Sodium : Sodium sulphate to supply 15 kg Na on cereals and potatoes ; sodium chloride to supply 88 kg Na for root crops on Barnfield. Na was also given when sodium nitrate was used to supply N.

Magnesium : Magnesium sulphate to supply 11 kg Mg for cereals and potatoes; 22 kg Mg for root crops on Barnfield.

Farmyard manure : 35 t FYM made on Rothamsted Farm. The amount of the dressing was intended to supply 224 kg total N. Between the 1850s and 1960s the dressing probably supplied on average 220 kg N, 36 kg P, 165 kg K. From 1968 to 1975 35 t ha^{-1} has supplied 240 kg N, 43 kg P, 330 kg K. Smaller dressings were given at Woburn, 19.7 t ha^{-1} during 1877-1906 ; 14.8 t ha^{-1} during 1907-1926.

Rape cake : 1 120 kg on Hoosfield, 2 110 kg on Broadbalk, 2 240 kg on Barnfield. Rape cake, on average, contained 5.5 p. 100 N, 0.96 p. 100 P, 1.05 p. 100 K. In 1941 castor meal replaced rape cake and from 1955 the weight applied was adjusted to supply 48 or 96 kg N ha^{-1}. Not applied on Barnfield after 1959 nor on Hoosfield after 1967.

(1) Only the principal treatments are given, for details of changes and exceptions see : BARNFIELD, WARREN and JOHNSTON (1962) ; BROADBALK, JOHNSTON and GARNER (1969) ; HOOSFIELD, WARREN and JOHNSTON (1967) ; EXHAUSTION LAND, WARREN and JOHNSTON (1960) and JOHNSTON (1970); WOBURN, JOHNSTON (1975).

(2) EXHAUSTION LAND, 1856-1901 only, see text for later changes.

(3) WOBURN, 1877-1906 only, see text for later changes.

Another organic manure, rape cake, was also tested, it supplied both N and C and a little P and K.

Table 1 shows the main treatments; the fertiliser dressings were generous. N was often tested at two or more amounts and both ammonium salts (NH_4-N) and sodium nitrate (NO_3-N) were compared. Throughout this paper N* denotes the use of sodium nitrate. More K was given for root crops than for cereals.

The conventions adopted in this paper

All data are given in metric units per hectare (ha^{-1}). Most have been converted from Imperial units and rounded up where this makes no gross error. Yields of grain and straw are at 85 p. 100 dry matter, yields of root crops are fresh washed roots except sugar beet where sugar yields are sometimes given. Fertiliser applications and nutrient uptakes are given as kg element ha^{-1}.

Methods of analysis

Methods of analysis used for crops and soils are those given by MATTINGLY and JOHNSTON (this Conference).

THE ORIGINAL DESIGN OF THE EXPERIMENTS

LAWES and GILBERT gave considerable thought to the design of their experiments, as the improvements made between 1843 and 1856 show.

Although the practice was discontinued later, fields at Rothamsted were ploughed in the 1840s so that the soil was left in ridges and furrows, the ground, about 3.8 m, between the furrows was known as a 'land'. In 1843 each plot on Broadbalk and Barnfield was the length of the field and one 'land' wide. A different treatment was tested on each plot. On Broadbalk two of these 'single land' plots were combined, each continued to test a different treatment, and subsequently there has been little change in their size.

On Barnfield three 'single land' plots were made into one plot and in 1845 the P K Na Mg treatments were assigned to these strips which ran the full length of the field. Nitrogen treatments crossed all strips at right angles. In 1852 the barley experiment on Hoosfield was also designed with P K Na Mg treatments in strips crossed at right angles by N treatments; an FYM and second unmanured plot, were placed to one side of the experiment. In 1856 further modifications were made on Barnfield when FYM and FYM plus P (later PK) were introduced as main strip treatments and crossed by the N treatments. The main fertiliser treatment not tested on Barnfield was KNaMg with and without N. The importance of this was probably not appreciated in 1845 and it was not included in 1856 probably because there was no land left and no wish to change any other strip treatment.

The experiments at Woburn were set out similarly to that on Hoosfield, PK treatments in strips were crossed at right angles by N treatments with plots testing FYM at the side of the experiment. The history of the Woburn experiments is discussed later.

CHANGES IN THE EXPERIMENTS AT ROTHAMSTED

1903-1906. At Rothamsted there was little change in the arrangement of the treatments after 1856 until HALL, who was Director 1902-1912, made a few modifications in 1903-06. He added plots to Broadbalk, Barnfield and Park Grass to test NKNaMg (*i. e.* P was omitted). He also started the test of applying chalk every fourth year to half plots on Park Grass (THURSTON, WILLIAMS and JOHNSTON, this Conference).

1926. On Broadbalk, weeds, always a problem in continuous cereal growing, had been controlled by hand hoeing though occasionally parts of the field were fallowed for a whole year. Hand hoeing became increasingly expensive and in 1926 regular fallowing was introduced. Broadbalk was divided into five sections, each fallowed in turn; after the fallow year four wheat crops were grown. Although this scheme was introduced to control weeds, it nevertheless led to the start of four important research programmes. These were:

1. The effect of fallowing and manurial treatments on the abundance of weed species (THURSTON, 1969).
2. The effect of fallow on the incidence of Wheat Bulb fly (JOHNSON, LOFTY and CROSS, 1969).
3. The effect of fallow on the yield of subsequent crops (GARNER and DYKE, 1969).
4. Studies on the incidence of soil-borne diseases particularly eyespot (*Cercosporella herpotrichoides*, FRON), first recorded in Britain on Broadbalk, and take-all (*Gaeumannomyces graminis*) (GLYNNE, 1969).

1959-1975. Recent modifications aim to make the results of the experiments more relevant to modern farming. They are intended to explain recent observations that some crops yield better when grown in rotation than in monoculture and that yields on some soils well supplied with organic matter are larger than on soils with little organic matter.

Changes in manuring introduced in 1968 and since

FYM and PK manuring have not been altered since 1974. The small annual dressing of Mg as $MgSO_4 . 7 H_2O$ (table 1) has been replaced by a dressing of $MgSO_4 . H_2O$ given every third year but supplying three times the original annual dressing. Sodium was not applied after 1973 except to the plot on Broadbalk where the amount is chemically equivalent to the K dressing. Castor meal, which replaced rape cake in 1941, is now given only to one plot on Broadbalk.

The most important changes have been in nitrogen manuring. LAWES and GILBERT originally tested both NO_3-N and NH_4-N; at equivalent N dressings there was little difference in yield provided the timing of the dressings was correct. However, ammonium sulphate and sodium nitrate had very different effects on the soil. On some plots on Broadbalk, Hoosfield and Barnfield ammonium sulphate acidified the soil so much that by the late 1940s yields were decreased. The pH of these acid soils was increased by applying chalk in the 1950s ; subsequently, the comparison of ammonium sulphate and sodium nitrate in these experiments ceased. N is now applied as « Nitro-Chalk ».

Changes in cropping

On Barnfield growing root crops every year ceased after 1959 ; recent modifications are discussed later.

Major changes on Broadbalk and Hoosfield were made in 1968. Much of Broadbalk and Hoosfield continues to grow only wheat and barley but the yields are now compared with those obtained by growing the cereals in rotations in which soil-borne pests and diseases are lessened. Because the modifications had to be made on existing plots it was only possible to test a three-course rotation : potatoes, beans, wheat on Broadbalk ; potatoes, beans, barley on Hoosfield. One advantage of having a rotation is that new varieties of cereals can be phased into the cropping sequences.

During 1926-67 weeds were controlled on Broadbalk by fallowing. However, in 1952 and again in 1959, continuous winter wheat was reintroduced on two small sections and a test of weed control by herbicides was started. This test was generally successful and in 1968 it was decided to use herbicides on all but one-tenth of the experiment. Fallowing was not abandoned but could only be tested on three-tenths of the experiment, so the cropping sequence is : fallow, wheat, wheat. Because of these changes there is now a good test of the effects of rotation and fallow on weeds not easily controlled by herbicides.

On Hoosfield sprays were first used to control weeds in 1944 and all crops are now sprayed when necessary. There is no test of fallowing.

BARNFIELD 1843-1975

Root crops were drilled on Barnfield every year from 1843-1959, except when barley was grown during 1853-55. Swedes, turnips, mangolds and sugar beet were all grown during various periods. Within the first two or three years LAWES a[nd] GILBERT destroyed the belief that the large leaves of turnips, swedes and sugar beet could absorb enough ammonia from the air for the plants to produce large yields. They were also convinced that phosphate was needed for these root crops so they mostly tested FYM, K, Na and Mg and forms of N. Changes in the design of the experiment before 1856 have been mentioned. WARREN and JOHNSTON (1962) gave references to detailed accounts of the early results. Here we briefly discuss yields of: 1) mangolds grown each year from 1876 to 1959 ; 2) sugar beet grown on a part, but always the same part, of each plot during 1946-59 ; 3) cereals and root crops grown during 1962-73.

1876-1959. FYM, P, K, Na and Mg treatments are in table 1 ; both NO_3-N and NH_4-N at 96 kg N ha^{-1} and rape cake at 2 240 kg ha^{-1} were tested. WATSON and RUSSELL (1943) discussed the yields of mangolds for two periods, 1876-94 and 1904-40 because there were some changes of treatment in 1904 ; potassium was

withheld from some plots and given to others for the first time. However, on plots with unchanged manuring average yields of mangolds were much the same in both periods. The only exceptions were small, but consistent decreases in yield (2.5 to 5.0 t ha^{-1}) in the second period on soils not manured with K, Na or FYM ; the decreases were probably due to exhaustion of soil K. P or PK fertilisers given alone increased yield little (table 2) ; N gave much larger increases, especially sodium nitrate which supplied two nutrients, N and Na. All combinations of N, P and K increased yield as did FYM. Before 1930 FYM was applied in spring and yields with NPKNaMg, N*PKNaMg and FYM alone were approximately the same, 38.9, 46.0 and 42.2 t ha^{-1} (table 2). However, yields were even larger, about 60 t ha^{-1}, with FYM plus inorganic N fertiliser and NPKNaMg fertilisers plus rape cake.

TABLE 2

Yields of mangolds, roots t ha^{-1}, Barnfield, 1876-1894
(WATSON and RUSSELL, 1943)

Other treatment	No nitrogen	N applied as			
		ammonium sulphate	sodium nitrate	rape cake	rape cake plus ammonium sulphate
Unmanured	9.5	15.1	25.6	25.6	25.4
P	12.6	20.8	39.4	30.1	28.1
PK	11.3	34.4	38.9	45.2	55.5
PKNaMg ..	13.3	38.9	46.0	52.0	62.8
FYM.......	42.2	55.5	58.3	59.3	61.5

TABLE 3

Yields of mangolds, 1941-59, and sugar beet, 1946-59, roots only, t ha^{-1}, Barnfield
(WARREN and JOHNSTON, 1962)

Other treatment	No nitrogen		N applied as			
			sodium nitrate		rape cake plus ammonium sulphate	
	mangolds	sugar beet	mangolds	sugar beet	mangolds	sugar beet
Unmanured	3.8	3.8	20.3	12.6	20.3	16.1
P	5.5	4.8	29.4	16.8	23.4	18.1
PK	5.3	4.0	30.9	15.6	47.5	23.9
PKNaMg ..	6.8	4.5	36.2	20.1	48.0	25.9
FYM.......	22.3	15.6	50.2	27.9	50.0	28.6
FYM + PK	28.4	14.8	54.5	24.9	59.0	25.9

Yields of mangolds decreased considerably after the early 1940s even though fertilisers and FYM were still applied at the same rates. Whether there was a build up of some soil-borne pests or diseases or a deterioration in soil physical conditions after growing root crops continuously for 100 years is not known. Although mangold yields were much smaller in 1941-59 than in 1876-94, WARREN and JOHNSTON (1962) showed that N increased yield by the same amount, about 26 t ha^{-1}, in both periods. However, responses to P, K and Na fertilisers and to FYM were much smaller in the 1940s than in the 1880s.

Yields of sugar beet, 1946-59, and mangolds, 1941-59 are in table 3; the effects of the manurial treatments were much the same on both crops. Sodium nitrate and

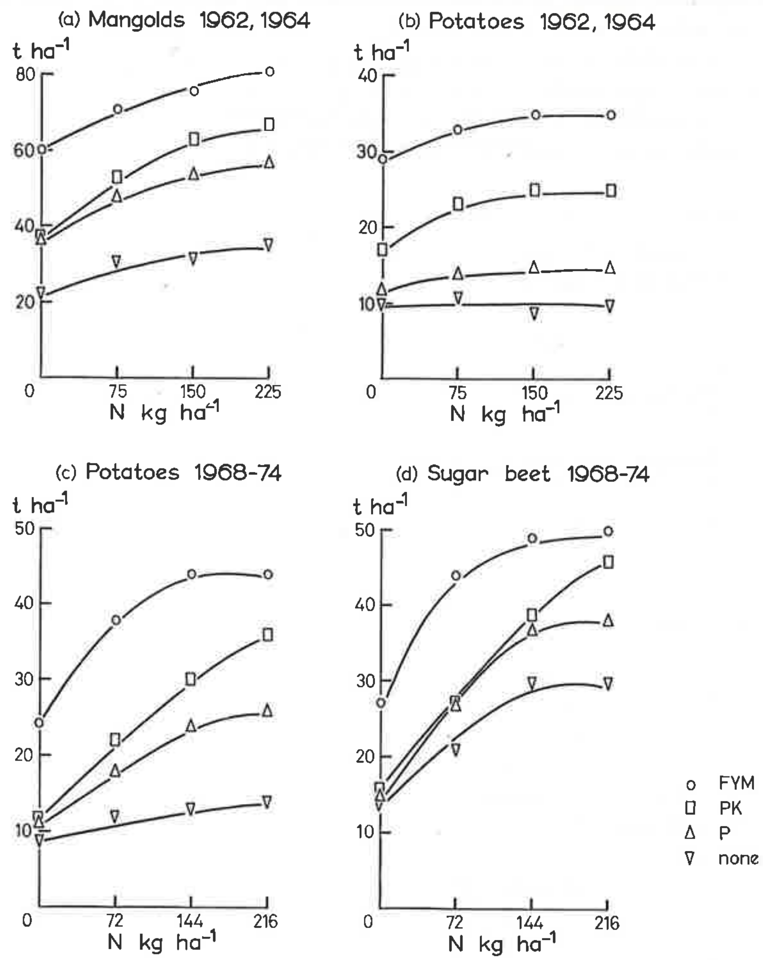

FIG. 1. — *Relationship between yields of mangolds, potatoes and sugar beet and fertiliser N applied to soils treated with farmyard manure*, ○ ; PK fertilisers, □ ; P fertilisers, △ ; or unmanured, ▽ ; during 1962-73, Barnfield.

a) Mangolds grown in 1962 and 1964
b) Potatoes grown in 1962 and 1964
c) Potatoes grown in 1969, 1971 and 1973
d) Sugar beet grown in 1969, 1971 and 1973

ammonium sulphate increased the yield of sugar beet roots by the same amount, 11.5 t ha^{-1}, when PK fertilisers were given. During 1941-59 NPKNaMg fertilisers gave larger yields than FYM, probably because the FYM was applied in autumn and ploughed in. When fertiliser N was given with FYM yields were larger than with FYM alone. Sugar beet yielded less roots than mangolds but produced more tops; consequently total dry matter yields (tops plus roots) were larger with sugar beet than with mangolds.

1962-1964. Because yields had declined so much by the 1950s it was decided to stop growing root crops continuously in 1959 and the field was fallowed in 1960-61. However the large increases in yield from adding N fertiliser to soils treated with FYM had not been explained and it was decided to test four amounts of N (0, 75, 150, 225 kg N ha^{-1} as 'Nitro-Chalk') on potatoes and mangolds grown on all plots. Yields in 1962 and 1964 are summarised in figure 1. Mangolds (fig. 1 *a*) yielded as much in 1962-64 as in 1876-94 (table 2). Yields were always larger on FYM- than on PK-treated soils at all amounts of N tested. Potatoes (fig. 1 *b*), a crop not previously grown on Barnfield, also yielded well and, like mangolds, yields were larger on FYM-treated soils. For both potatoes and mangolds the shape of the response curves to N suggested that yields on PK-treated soils would not have equalled those on FYM-treated soils no matter how much N was applied. Responses to N on soils without PK or with P only, figures 1 *a* and 1 *b*, show that potatoes were much more susceptible to shortage of P or K than were mangolds.

1968-1973. During this period potatoes, barley, sugar beet and spring wheat were grown in rotation starting with the two cereal crops on half plots in 1968. Four amounts of N were again tested : 0, 72, 144, 216 kg N ha^{-1} for root crops; 0, 48, 96, 144 kg N ha^{-1} for cereals. Potatoes in 1968-73 (fig. 1 *c*) yielded more than in 1962-64 (fig. 1 *b*), best yields were about 10 t ha^{-1} larger in 1968-73. Sugar beet (fig. 1 *d*) also yielded well during 1968-74, best yields were nearly twice those in 1946-59 (table 3). Both sugar beet and potatoes yielded more on FYM than on

TABLE 4

Yields of barley and spring wheat, Barnfield, 1968-73 (1)
(grain, t ha^{-1}, at 85 p. 100 dry matter)

Treatment	N dressing, kg N ha^{-1}							
	Barley				Spring wheat			
	0	48	96	144	0	48	96	144
FYM	4.18	5.40	5.16	5.08	2.44	3.73	3.92	3.79
PK	1.85	3.74	4.83	4.92	1.46	2.97	3.53	4.12
P	1.82	4.22	4.96	4.95	1.57	3.22	3.77	4.20
Unmanured	2.10	3.75	4.96	4.67	1.70	3.07	3.44	4.09

(1) Cereals were grown in 1968, 1970 and 1972.

PK-treated soil, but the effect was smaller with sugar beet (4 t ha⁻¹) than with potatoes (7.8 t ha⁻¹) when 216 kg N ha⁻¹ was given. Sugar beet, like mangolds in 1962-64, responded more to N on soils without PK or without K than did potatoes.

With optimum fertiliser N barley yielded a little more and spring wheat slightly less when grown on FYM-treated soil than on PK-treated soil (table 4). Yields of both barley and spring wheat were not increased by giving potassium (table 4), agreeing with other results on the heavier soils at Rothamsted. This suggests that the amount of K released each year by weathering is still sufficient to supply the needs of a spring cereal yielding up to 5 t grain ha⁻¹. An apparently unexpected result in table 4 is that cereals yielded so well on soil without PK; these soils, however, contain much more bicarbonate soluble-P (table 16) than similarly unmanured soils at Rothamsted. This is partly because LAWES and GILBERT applied some P to these soils during 1843-52 and partly because the tops of the root crops were left on the plots to be ploughed in so returning nutrients to the soil.

1967-1975. Field beans (tic) were grown on all plots in 1967. Yields on FYM- and PK-treated soils were 4.52 and 1.58 t grain ha⁻¹ respectively. Subsequently beans have been grown on the same fifth of the field each year and experiments made during these years have shown that the large difference in yield in 1967 was due to an interaction between soil organic matter and the selective herbicide (simazine) used to control weeds. Simazine applied at the recommended rate per hectare did not damage beans on FYM-treated soil, because it contained enough organic matter to retain the simazine near the surface and prevent it washing down through the soil.

BROADBALK 1844-1975

Winter wheat has been sown on all or part of Broadbalk every year since autumn 1843. The experiment has always attracted much attention because it demonstrated that wheat, a staple food for many people, could, if given sufficient nutrients, be grown on the same land year after year. LAWES and GILBERT described the results on many occasions, the last (LAWES and GILBERT, 1895) summarised the first 50 years; subsequently, RUSSELL and WATSON (1940) considered the results up to the late 1930s. In 1968 the first volume of Part 2 of the Rothamsted Report contained nine papers, each summarising one aspect of the studies made on Broadbalk.

Initially the main plots were as long as the field (about 350 m) and each had a different treatment. The treatments (table 1) were not randomised; the first six plots then received in order: FYM, nothing, PKNaMg, N_1PKNaMg, N_2PKNaMg and N_3PKNaMg, and the effects of the manures on growth were (and still are) visually very striking. Originally 172 kg N ha⁻¹ was also tested but was abandoned because the varieties of wheat then grown always lodged badly when given this much N. Table 5 shows yields for two decades, 1852-61 and 1902-11, and for 1970-75. Where wheat has been grown for more than 120 years yields have not diminished; in 1970-75 they were more than doubled compared to any other period because a better variety (*Cappelle Desprez*) was grown and cultivations and weed and pest control have improved.

TABLE 5

Effect of fertilisers and FYM on yields of winter wheat grown continuously, Broadbalk (grain, t ha⁻¹, at 85 p. 100 dry matter)

Treatment	Period and Variety		
	1852-61 *Red Rostock*	1902-11 *Squarehead's Master*	1970-75 *Cappelle Desprez*
Unmanured	1.12	0.80	1.70
FYM	2.41	2.62	5.80
PKNaMg	1.29	1.00	2.09
N_1PKNaMg	1.91	1.58	3.99
N_2PKNaMg	2.42	2.28	5.23
N_3PKNaMg	2.52	2.76	5.47
N_4PKNaMg	—	—	5.48

Yields in 1844 showed that N was more important than PKNaMg for wheat at Rothamsted; this was still true in 1970-75, yields on unmanured soil and those given PKNaMg, N_2 and N_2PKNaMg were 1.70, 2.09, 2.83 and 5.23 t ha⁻¹ respectively. Table 5 shows how N increased yields of wheat grown continuously; 48 and 96 kg N ha⁻¹ gave large increases, 144 kg N ha⁻¹ always gave maximum yield, but 172 kg N ha⁻¹ did not increase yield further in 1970-75 (or in 1852-64 when N_4 was still tested). Both FYM and optimum fertilisers gave much the same yield in the earlier periods but during 1970-75 yields were about 0.3 t ha⁻¹ more on FYM-treated soils.

LAWES and GILBERT tested both forms and times of application of N fertilisers. The results led them to apply all NO_3-N in spring but NH_4-N was applied part in autumn (24 kg N ha⁻¹ irrespective of total dressing) and the remainder in spring. Used in this way NO_3-N increased grain yield by about 10 p. 100 before fallowing was started in 1926.

Another important result quickly learnt and long demonstrated was that for wheat there was no residual effect of the 96 kg N ha⁻¹ dressing. This test was made by alternating the treatments on two plots so that each year wheat was grown with fresh N and residual PKNaMg and with residual N and fresh PKNaMg. During 1852-1967 fresh N gave 2.11 t ha⁻¹, residual N 1.03 t ha⁻¹; for comparison soils receiving N_2PKNaMg and PKNaMg each year gave yields of 2.22 and 1.13 t ha⁻¹ respectively.

There were also tests of P and K when 96 kg N ha⁻¹ (N_2) was given. During 1852-1967 yields with N_2, N_2P and N_2PK were 1.58, 1.67 and 2.12 t ha⁻¹ respectively. P had a very small effect, K, in the presence of P, a much larger one, 0.45 t ha⁻¹. These effects of P and K on wheat are quite different from those on barley on Hoosfield; on barley P had a large effect, K a small one.

In a test unique to Broadbalk Na and Mg were applied separately at rates chemically equivalent to the amount of K applied. Yields with N_2PNa and N_2PMg were 2.03 and 2.02 t ha⁻¹ respectively, only slightly less than the yield given by N_2PK (2.12 t ha^{-1}). This effect of Na and Mg is interesting; the crops grown on these two soils both contained appreciably more K than that on N_2P-treated soil. Possibly the Na and Mg released extra soil K which benefited the wheat. Since 1968 this test is continued only on the N_2PNa plot.

1968-1975. Changes introduced in 1968 have already been described. Yields of wheat grown continuously can now be compared with those of wheat grown after fallow and in the rotation, potatoes, beans, wheat (table 6). Yields were affected

TABLE 6

Effect of treatment, fallowing and crop rotation on winter wheat yields, Broadbalk 1970-75

(grain, t ha^{-1}, at 85 p. 100 dry matter)

Treatment	Wheat grown			
	Continuously	1st crop after fallow	In rotation after beans	2nd crop after fallow
Unmanured	1.70	3.13	2.67	1.40
FYM	5.80	6.48	6.76	5.88
PKNaMg	2.09	3.76	3.16	1.58
N_1PKNaMg	3.99	4.88	5.36	3.76
N_2PKNaMg	5.23	5.16	6.19	5.35
N_3PKNaMg	5.47	4.98	5.78	5.85
N_4PKNaMg	5.48	4.97	5.60	5.92

by the interaction of at least three factors, nitrogen supply, soil-borne disease and lodging. The one-year fallow lessened the inoculum of soil-borne fungi (especially the take-all fungus, *Gaeumannomyces graminis*) and increased the amount of crop-available soil N. For the first crop after fallow the optimum N dressing was not the largest amount tested, and where large dressings were given yields decreased because of lodging. The second crop after fallow got no benefit from extra N in the soil and maximum yield was given by the largest amount of N tested. The two-year break of potatoes and beans left very little take-all and 96 kg N ha^{-1} gave the best yield with fertilisers; where more N was given yield was lost due to lodging. Table 6 also shows that during 1970-75 wheat following beans or fallow yielded more on soils for long treated with FYM than on fertiliser-treated soils. The reason for this is being investigated; the response by these crops to spring applied fertiliser N suggests that giving more N in spring would not eliminate the difference. Giving extra fertiliser N (96 kg N ha^{-1} in spring as 'Nitro-Chalk') to soils treated with FYM increased straw but not grain yields. Grain yields were often less because the crop lodged.

Potatoes have been grown on Broadbalk since 1968 and, in contrast to wheat, potato yields were increased by giving 96 kg N ha^{-1} with the FYM. During 1970-75 yields with FYM alone and with N_3PKNaMg were almost identical, 39.7 and 39.4 t ha^{-1}; N_4PKNaMg gave 41.4 t ha^{-1} and FYM + N_2 45.4 t ha^{-1}.

HOOSFIELD BARLEY 1852-1975

1852-1967. Spring barley has been grown on 1.8 ha of Hoosfield every year since 1852. The only exceptions were 1912, 1933, 1943 and 1967 when the whole field was fallowed; weed control by mechanical cultivations was much easier in spring sown barley than in autumn sown wheat. LAWES and GILBERT (1895) described results for the first 30 years. RUSSELL and WATSON (1938) discussed yields, crop composition and grain quality. WARREN and JOHNSTON (1967) summarised results, including crop and soil analyses, to 1966 and listed other published work.

The original design of the experiment has been mentioned; treatments are in table 1. Originally two amounts of N, 48 and 96 kg N ha^{-1}, were tested but the larger amount invariably lodged the crop and decreased yield so the test was abandoned in 1857. Between 1868 and 1967 48 kg N ha^{-1} was given as ammonium sulphate, sodium nitrate or rape cake. Since 1968, N as 'Nitro-Chalk' was tested at 48, 96 and 144 kg N ha^{-1}.

Yields during three decades, 1852-61, 1902-11, 1952-61 and in 1970-75 (table 7) varied little on unmanured soil, especially after readily mineralised soil organic N was exhausted. FYM doubled yield during the first ten years and then as the soil became richer in FYM residues, yields were increased fourfold by the combined effect of fresh dressings and residues. PKNaMg fertilisers alone gave small increases in yield. All three N fertilisers given with PKNaMg increased yield by between 1.0 and 1.5 t ha^{-1} during the first three decades. No one form of N was obviously best suggesting that organic N in rape cake was rapidly mineralised. In the first

TABLE 7

Effect of fertilisers and FYM on the yield of barley, Hoosfield, 1852-1975

(grain, t ha^{-1}, at 85 p. 100 dry matter)

Treatment [1]	Period and Variety			
	1852-61 Chevalier	1902-11 Archers Stiff Strawed	1952-61 Plumage Archer	1970-75 Julia
Unmanured	1.43	0.65	0.93	1.19
FYM	2.85	2.96	3.51	5.02
PKNaMg	1.92	1.05	1.37	1.34
NPKNaMg	2.91	2.52	2.37	3.64
N*PKNaMg	(*a*)	2.48	2.50	3.97
CPKNaMg	2.99	2.50	2.51	4.13

[1] 48 kg N ha^{-1} applied as:
N, ammonium sulphate; N*, sodium nitrate, (started 1868); C, rape cake. All nitrogen given as 'Nitro-Chalk' since 1968.

period yields were larger with fertilisers than with FYM; later FYM gave larger yields as FYM residues accumulated in soil.

Best yields in 1970-75 were nearly 1.5 t ha^{-1} more than in 1952-61 on soils adequately manured. Change in variety, better cultivations, chemical control of weeds and foliar diseases were all responsible for the extra yield.

The effects of P, KNaMg, and PKNaMg fertilisers were tested in the presence and absence of N. During the first 110 years 48 kg N ha^{-1} gave an average annual yield of 1.49 t grain ha^{-1}. Given this amount of N, KNaMg increased yield by only 0.15 t ha^{-1} but P gave an extra 0.88 t ha^{-1} while PKNaMg yielded 0.98 t ha^{-1} more. These results showed the importance of adequate P manuring for barley and the small response to K on Rothamsted soil. Recent results, when yields have been larger, confirm these conclusions.

1968-1975. Reasons for the modifications made in 1968 have been given. Yields of barley grown continuously are compared with those after a two year break of potatoes and beans. On soils well supplied with P and K, barley yielded well during 1970-75; 96 kg N ha^{-1} gave 5.16 t grain ha^{-1}; an extra 48 kg N ha^{-1} only increased yield by a further 0.2 t ha^{-1} (table 8). Barley given a fresh dressing of FYM (35 t ha^{-1}), on soil long treated with FYM, yielded 5.02 t grain ha^{-1} and adding 48 kg N ha^{-1} as fertiliser N increased yield by an extra 0.53 t ha^{-1}. Larger dressings of fertiliser N on FYM-treated soils decreased yields. During 1970-75 FYM was ploughed in in autumn and any nitrate in the manure or produced by mineralisation during late autumn could be leached during winter. This may explain why 48 kg ha^{-1} fertiliser N gave a worthwhile increase in yield. On soils without P or K since 1852, N increased yield little, 144 kg N ha^{-1} gave only 2.53 t grain ha^{-1}.

TABLE 8

Effect of nitrogen on the yield of barley, Hoosfield, 1970-75
(grain, t ha^{-1}, at 85 p. 100 dry matter)

Treatment	N dressing, kg N ha^{-1}			
	0	48	96	144
Unmanured	1.30	2.06	2.34	2.53
PKNaMg	1.69	3.64	5.16	5.36
FYM............	5.02	5.55	5.39	5.24

Barley grown continuously and in rotation can only be compared on PK-treated soils. Barley grown in rotation yielded more than barley grown continuously at each amount of N tested, but with 96 or 144 kg N ha^{-1} differences in yield were small (table 9). Yields of barley grown continuously, given in tables 8 and 9, are not identical because the comparison between continuous and rotation barley was made on soils treated with castor meal from 1852 to 1966. With the smaller amounts of N yields were larger on soils with castor meal residues than on those without. However, Julia barley grown continuously and given sufficient N yielded almost the same on soils with and without castor meal residues.

When no N was given, barley after beans in the three-course rotation yielded 1.6 t ha^{-1} more than barley grown continuously (table 9). The N residues from beans cannot, however, be valued in terms of a fresh N dressing because barley after beans was probably less affected by any soil-borne pathogens than barley grown continuously.

TABLE 9

Effect of N on yields of barley grown continuously and in rotation (1), *Hoosfield, 1970-75*
(grain, t ha^{-1}, at 85 p. 100 dry matter)

Barley grown	N dressing, kg N/ha^{-1}			
	0	48	96	144
Continuously	2.39	4.13	5.45	5.45
In rotation	4.00	5.23	5.68	5.76

(1) For PK dressings see table 1.

THE EXHAUSTION LAND 1852-1974

1852-1901. JOHNSTON (1970) summarised the results from many short period tests made by LAWES and GILBERT which valued residues of fertiliser and FYM dressings. However, the most outstanding experiment on the value of P and K residues started in 1902 on the Exhaustion Land and still continues. Experiments made on the site from 1852 to 1901 were described by WARREN and JOHNSTON (1960). Between 1856 and 1874 various combinations of N, P and K fertilisers were tested on winter wheat. In 1876 extra fertiliser treatments were included and a test of FYM introduced. Potatoes were grown each year from 1876 to 1901. Estimates of total amounts of P and K applied in fertilisers and FYM between 1856 and 1901 are in table 10. The residual values of these nutrients have been tested since 1902.

1902-1940. No fertilisers were applied and cereals were grown except on plots 5 to 10 which grew legumes during 1905-11. Cereal yields were increased in the first year or two where inorganic N was given before 1902; there were larger effects, which persisted longer, from residues of FYM. Subsequently yields were recorded only between 1917-22 and during this period neither fertiliser nor FYM residues increased yields; presumably too little N was mineralised from any extra organic matter in the soil.

1941-1974. Barley, given N only, was grown each year, N dressings were 63 kg ha^{-1} during 1941-62 and 88 kg ha^{-1} during 1963-74. Soil analyses in 1951 and

1974 are in table 10 as are yields of three varieties of barley grown between 1949-74. In 1949-62 yields of Plumage Archer were almost doubled by the combined effect of P and K residues from either fertilisers or FYM which had, by then, been in the

TABLE 10

Yields of barley during 1949-74, P and K in soil and estimated total amounts of P and K given during 1856-1901, Exhaustion Land

		Treatment		
		No P No K (1)	Residues of PK fertilisers 1856-1901 (2)	Residues of FYM 1876-1901 (3)
P and K applied 1856-1901				
P kg ha^{-1}		0	1 410	1 260
K kg ha^{-1}		0	5 070	3 920
Soil analysis 0-23 cm depth				
Total P mg kg^{-1}	1951	570	748	761
	1974	535	657	675
$NaHCO_3$-soluble P mg kg^{-1}	1951	7	23	27
	1974	2	8	12
Exchangeable K mg kg^{-1}	1951	74	131	106
	1974	69	96	87
Barley grain, t ha^{-1}, at 85 p. 100 dry matter				
1949-62	*Plumage Archer* (4)	1.76	2.90	3.13
1964-69	*Maris Badger* (5)	1.73	3.62	4.29
1970-74	*Julia* (6)	1.83	4.32	4.75

(1) Average of 4 plots, one of which was given very small dressings of P and K in 1876-81.
(2) Average of 3 plots.
(3) Average of 2 plots.
(4) Average of 10 crops each given 63 kg N ha^{-1}.
(5) Average of 6 crops each given 88 kg N ha^{-1}.
(6) Average of 5 crops each given 88 kg N ha^{-1}.

soil for between 50 and 100 years. Since then yields have been much the same each year on soils without residues. Newer varieties, *Maris Badger* and *Julia*, have yielded *more* than *Plumage Archer* on soils with residues (table 10). Soils with PK residues now yield about as much grain per hectare as the average of all barley crops grown in England and Wales. Results for one plot (9) are excluded from the averages given in table 10 because less K was applied during 1856-1901 than on other fertiliser plots. However, yields on plot 9 during 1970-74 were only about 0.5 t grain ha^{-1} less than on PK residue plots, suggesting that the residues acted mainly through the P they supplied.

1957-1958. To test whether the PK residues would increase yields of crops other than barley six crops were grown each year in 1957 and 1958. P and K were tested separately, dressings of NK were given where P was tested and NP where K was tested. In addition, the effects of new dressings of P and K were also measured. Table 11 summarises the yields, they were discussed in detail by JOHNSTON, WARREN and PENNY (1970).

TABLE 11

Effect of P and K residues and dressings of new P and K on six crops, Exhaustion Land, 1957-58 (1)

Crop	Experiments testing P				Experiments testing K			
	P given kg ha^{-1}	Yield on soil		Effect of P residues	K given kg ha^{-1}	Yield on soil		Effect of K residues
		without residues	with residues			without residues	with residues	
Barley grain t ha^{-1}	0	2.03	3.11	1.08	0	3.34	3.54	0.20
	56	3.49	3.48	— 0.01	63	3.56	3.56	0
	response	1.46	0.37		response	0.22	0.02	
Spring wheat grain t ha^{-1}	0	2.38	2.81	0.43	0	3.31	2.99	— 0.32
	56	3.29	3.01	— 0.28	63	3.23	2.99	— 0.24
	response	0.91	0.20		response	— 0.08	0	
Potatoes tubers t ha^{-1}	0	12.8	21.1	8.3	0	17.1	27.6	10.5
	56	32.6	32.6	0	126	31.1	36.7	5.6
	response	19.8	11.5		response	14.0	9.1	
Sugar beet sugar t ha^{-1}	0	3.84	5.67	1.83	0	4.87	6.15	1.28
	56	5.72	6.00	0.28	126	5.67	5.43	— 0.24
	response	1.88	0.33		response	0.80	— 0.72	
Swedes roots t ha^{-1}	0	21.3	38.9	17.6	0	37.7	46.7	9.0
	56	44.7	44.9	0.2	63	40.2	47.7	7.5
	response	23.4	6.0		response	2.5	1.0	
Kale t ha^{-1}	0	37.2	48.2	11.0	0	50.7	53.0	2.3
	56	50.5	53.7	3.2	126	45.7	57.2	11.5
	response	13.3	5.5		response	4.2	4.2	

(1) From JOHNSTON, WARREN and PENNY (1970).

Where P was tested all six crops yielded more on soils with P residues than on soils without; 56 kg P ha^{-1} as a fresh dressing increased yields of all crops and yields were much the same on soils with and without residues. This result contrasts with that given by MATTINGLY and JOHNSTON (this Conference, table 3) for the Agdell experiment. A single dressing of new P to starved and enriched soils did not give the same yield on both; soils with residues always yielded more. Why crops responded differently on the Exhaustion Land is not known. The soil is comparatively easy to cultivate and may possess some physical property that allows roots to grow readily. Freshly applied nutrients may therefore be more accessible on this soil than on a more 'difficult' soil like that on Agdell. A similar explanation could also account for the large benefit in recent years of the old PK residues.

There were large increases in potato yields due to K residues in soil and to freshly applied K, but cereal yields were increased hardly at all. However, barley yields were not large during 1957-58 and newer varieties now grown might give small responses to K. Yields of swedes, sugar beet and kale were all larger on soils with K residues than on soils without, responses to fresh K were more variable.

EXPERIMENTS ON WHEAT AND BARLEY GROWN EACH YEAR AT WOBURN

In 1876 the Duke of Bedford made available a farm at Woburn in Bedfordshire for agricultural experiments ; initially there were two, one tested the residual value of animal feedingstuffs (Mattingly and Johnston, this Conference), the other the effects of fertilisers and FYM on wheat and barley grown each year. They were supervised by the Royal Agricultural Society of England. The results were discussed in detail by Russell and Voelcker (1936) and were summarised by Johnston (1975) The Woburn Experimental Station has been supervised from Rothamsted since 1921.

1877-1926. During 1877-1906 the amounts of fertilisers tested were the same as on cereals at Rothamsted ; except that the larger amounts of N were not tested on wheat and FYM dressings were less. Thus the effects of fertilisers on cereals grown on clay loam soils at Rothamsted and on sandy loam at Woburn could be compared. During 1877-86 yields of both wheat and barley were much the same as they had

TABLE 12

Yields of wheat and barley grown in the Continuous Wheat and Barley experiments, Woburn (1)

(grain, t ha^{-1}, at 85 p. 100 dry matter)

Treatment	Wheat 1877-86	Wheat 1917-26	Barley 1877-86	Barley 1917-26
Unmanured	1.08	0.46	1.56	0.49
PKNaMg	1.13	0.56	1.35	0.59
N	1.63	0.04	2.30	0.09
N*	1.50	1.02	2.35	0.67
NPK	2.04	0.64	2.57	0.30
N*PK	2.12	1.08	2.73	0.97
FYM	1.76	1.20	2.39	1.54

(1) From Johnston, 1975.

been in the first decade of the comparable experiments on Broadbalk and Hoosfield. The effects of the manures were much the same too ; PK fertilisers alone had little effect but N increased yield considerably. NPK fertilisers gave the largest yield, larger than FYM, probably because the small dressing, 20 t ha^{-1}, supplied too little N. As at Rothamsted the residual effect of fertiliser N dressings, applied in alternate years, was small.

The fertiliser dressings were considerably decreased after the first 30 years ; this decision was probably taken because yields in the early 1900s were poor and the amounts tested in earlier years probably appeared excessive relative to those used by farmers on light soil. From 1907 N dressings were halved, P was decreased to about two-thirds and K to a quarter of the original dressings. The FYM dressing was also decreased and Na and Mg no longer applied. Yields of wheat and barley during 1877-86 and 1917-26 in table 12 show how large was the decline, though it was less on FYM-treated soil than on soils given fertilisers. However, it is impossible to tell how much yields were affected by the decreased fertiliser dressings and how much they diminished because of increasing soil acidity.

We now understand more clearly why yields declined at Woburn in the 1890s but, at that time, little was known about the concept of acidity or how to measure it. Johnston and Chater (1975) recently re-analysed soil samples taken during 1876-1959 and showed how acidity gradually increased in all soils, especially quickly where ammonium sulphate was given. Increasing acidity and competition from weeds tolerant of the acid conditions decreased cereal yields considerably. Field tests of liming started in 1898. Chalk, 10 t ha^{-1}, applied to the most acid soils increased yields of wheat from 0.36 to 1.25 t grain ha^{-1} and of barley from 0.22 to 1.3 t grain ha^{-1} during 1907-16. Studies on soil acidity continued and Voelcker (1923) concluded that the research at Woburn was the first to yield results on the effects of soil acidity and the use of lime to remedy this.

1927-1955. No P, K or FYM were applied after 1926 except for a few very small dressings on some plots (Johnston, 1975). However winter wheat and spring barley were still grown during 1927-55 to measure the effects of fallowing and test different amounts of N as 'Nitro-Chalk'. During 1943-55 soils previously given ammonium sulphate were so acid that crops were not sown and on other plots crops failed in some years. The best crops grown in this period were, however, only a little larger than those in 1877-86.

1955-1974. In 1953 it was decided to lime all soils to about pH 6 (in water) their soil reaction in 1876. The first chalk dressings were applied in 1955. Johnston and Chater (1975) described changes in soil pH, amounts of chalk applied and losses of chalk from the surface soils between 1954 and 1959. By 1959 the pH of all surface soils ranged from 5.7 to 5.9.

Yields during 1943-54 showed some residual effects from PK applied either as fertilisers or FYM during 1877-1926. So, on part of the experiments, between 1960 and 1962 the value of the residues were tested for potatoes, sugar beet and barley as they had been at Rothamsted on the Exhaustion Land and Agdell ; Johnston, Warren and Penny (1970) discussed the results in detail, they were more like those on Agdell than on the Exhaustion Land. Crops were always larger on soils with residues than on those without, even when new dressings of P and K were given.

Wheat and barley, both given 112 kg N ha⁻¹, were grown on the remaining plots during 1959-62, yields were about double the best in 1943-54. Liming had been beneficial.

1966-1974. Although cereal yields had been increased by liming, a new experiment was started in 1966 on a third of each site to attempt to increase yields still further. Wheat was still grown on the wheat site, barley followed barley. Cereals grown continuously were compared with those in a five-course rotation : one-year grass ley followed by potatoes and three cereal crops. Generous dressings of P (57 kg P ha^{-1}) and K (215 kg K ha^{-1}) were given each year, magnesian limestone was applied regularly to prevent serious acidity developing and four amounts of N were tested. Yields of both cereals were much better than any grown previously (table 13).

TABLE 13

Effect of nitrogen on yields of wheat and barley grown both continuously and in rotation, 1969-74, Woburn

(grain, t ha^{-1}, at 85 p. 100 dry matter)

Wheat	N dressing kg N ha^{-1}: 63	126	189	252
1st wheat after potatoes	3.44	4.50	4.52	4.28
2nd wheat after potatoes	2.51	3.50	3.42	3.28
3rd wheat after potatoes	1.92	2.92	3.07	3.11
Wheat grown each year	2.40	3.11	3.40	2.95

Barley	N dressing kg N ha^{-1}: 50	100	150	200
1st barley after potatoes	3.98	4.93	5.09	4.82
2nd barley after potatoes	3.44	4.82	4.91	4.90
3rd barley after potatoes	3.32	4.63	4.71	4.66
Barley grown each year	2.74	4.06	4.58	4.69

Best yields were given by crops immediately following potatoes but the optimum N dressing was not always the largest amount tested. When barley yields in the different crop sequences were compared, barley grown continuously yielded least except when most N was given. The best yield of continuous wheat was larger than that of the third wheat after the break. Both N and crop sequence affected yield ; the differences may be explained when data for the incidence of soil-borne pathogens on these crops are summarised.

PLANT NUTRIENTS IN CROPS

Amounts of N P K Na Ca Mg at harvest in well-manured crops grown in the 1950s-1960s are in table 14 ; detailed results are elsewhere : Broadbalk (JOHNSTON, 1969 *a*), Hoosfield (WARREN and JOHNSTON, 1967) and Barnfield (WARREN and JOHNSTON, 1962). The amounts are those in grain plus straw and in tops plus roots.

TABLE 14

Amounts of N, P, K, Na, Ca, Mg in crops at harvest on Broadbalk, Hoosfield and Barnfield

Experiment and year	Crop	Treatment	kg element ha^{-1} (1) N	P	K	Na	Ca	Mg
Broadbalk 1966-67 (2)	Continuous wheat	FYM	63	13	38	0.7	7	4.9
		N_3PKNaMg	76	15	39	0.7	10	5.7
	1st wheat after fallow	FYM	121	21	80	1.0	16	9.1
		N_3PKNaMg	90	15	44	1.0	14	7.1
Hoosfield 1964 and 1966 (3)	Continuous barley	FYM	79	21	66	1.9	11	6.7
		N_2PKNaMg	83	20	55	1.7	11	7.0
Barnfield 1958-59 (4)	Mangolds	FYM	54	13	137	27	18	6.6
		N_2PKNaMg	85	16	194	43	17	8.5
	Sugar beet	FYM	69	12	109	21	26	11.2
		N_2PKNaMg	85	12	128	24	23	10.1

(1) In grain plus straw of cereals and tops plus roots of root crops.
(2) From JOHNSTON, 1969 *a*, variety *Squareheads' Master*.
(3) From WARREN and JOHNSTON, 1967, variety *Maris Badger*.
(4) From WARREN and JOHNSTON, 1962.

Grain and straw were always removed from the plots but tops of root crops on Barnfield were left to be ploughed in. Cereals, except those grown continuously, contained more N, P and K on FYM- than on PK-treated soils. Root crops on Barnfield removed more N and K from PK- than from FYM-treated soil. All crops removed much the same amount of Mg ; there was a little more Ca in the root crops. Cereals contained little Na, there was much more in the root crops grown on Barnfield, 88 kg Na ha^{-1} was given with the fertiliser dressings but no extra Na was given with FYM.

The percentage recovery of added nutrients is calculated as :

$$\frac{\text{amount in treated crop } \textit{minus} \text{ amount in untreated crop}}{\text{amount applied}} \times 100$$

this is often used as a measure of fertiliser efficiency. Percentage recoveries of P and K are usually small, less than 20 p. 100, because these nutrients are not very mobile in soil and soil reserves supply much of the plant's requirements. For elements not readily lost from soil by leaching it is often more important to consider amounts removed in relation to amounts applied. If the amount applied exceeds that removed then measurable residues accumulate in soil. Results given earlier, especially for the Exhaustion Land, show that these residues can be used by crops. If removals exceed supply the excess must be at the expense of soil reserves and this may diminish yield of following crops.

At present little is known about the fate of N not taken up by the crop for which it was given. Little of the residual N remains in soil for long. JOHNSTON (1976) calculated that after 130 years of manuring on Broadbalk extra soil N accounted for less than 5 p. 100 of residual fertiliser N and less than 15 p. 100 of residual FYM-N. He also showed that recovery of added N in these experiments at Rothamsted was often very much larger than in other long-term experiments. This was because crops grown on soil given no N for so long removed only small amounts, wheat, barley, potatoes, sugar beet and grass have all removed between 30 and 35 kg N ha^{-1} each year since the mid-1960s.

PLANT NUTRIENTS IN SOILS

Plant nutrients in the soils have been progressively impoverished or enriched depending on manuring and cropping. Detailed soil analyses have been given for Broadbalk (JOHNSTON, 1969 *b*), Barnfield (WARREN and JOHNSTON, 1962), Hoosfield (WARREN and JOHNSTON, 1967), Woburn (JOHNSTON and CHATER, 1975 and MATTINGLY, CHATER and JOHNSTON, 1975) and the Exhaustion Land (JOHNSTON and POULTON, 1977).

Nitrogen. Broadbalk and Hoosfield soils were sampled by LAWES and GILBERT and samples have been taken since. Figure 2 *a* and *b* show changes in soil N with time for Broadbalk and Hoosfield respectively. After the first few years N percentage in the unmanured soils changed little and adding PK fertiliser had little effect. On Broadbalk soil, N increased by 0.015 percentage N during the first 20 years where $N_2PKNaMg$ fertiliser was given, p. 100 N then remained remarkably constant. Five plots on Broadbalk have comparable manuring and yield similarly, all five soils contained 0.114 ± 0.001 p. 100 N in 1966. The increase in N content is thought to come from the N in the larger plant residues returned each year to the soil rather than from inorganic N accumulations. Similar small increases occurred on Hoosfield. Soil N increased much more where annual dressings of 35 t ha^{-1} FYM were applied. FYM-treated soil contained 0.25 p. 100 and 0.29 p. 100 N on Broadbalk and Hoosfield respectively in the 1960s.

Much of the variability in percentage N in unmanured and fertiliser treated soil reflects changes in methods of sampling and analysis (JOHNSTON, 1969 *b*). However, on Broadbalk some of the decline in percentage N of FYM-treated soil between 1914 and 1936 must be due to extra fallowing for weed control during 1926-29. Once the fallowing cycle (one year in five) was established in 1931 soil N increased

again. More N accumulated in soils where continuous wheat was reintroduced in 1952 than in soils which continued to be fallowed (JOHNSTON, 1969 *b*).

The effects on soil N of fertiliser and FYM treatments lasting more than 100 years are summarised in table 15 for the Broadbalk, Hoosfield and Barnfield experiments.

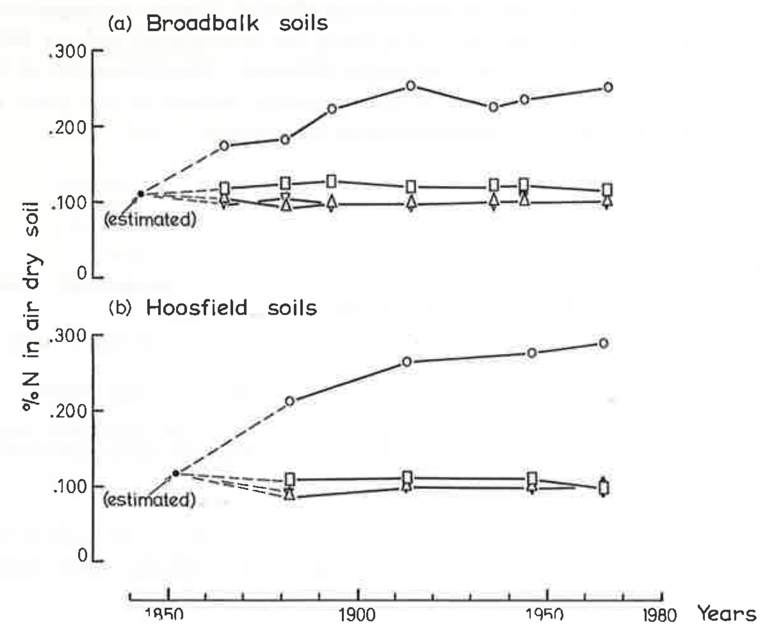

FIG. 2. — *Changes in the nitrogen content of Broadbalk and Hoosfield soils treated with:* farmyard manure, ○ ; NPK fertilisers, □ ; PK fertiliser, △ ; or unmanured, ▽.
a) Broadbalk soils
b) Hoosfield soils

TABLE 15

Effect of manuring on the total N content of soil, Broadbalk, Hoosfield and Barnfield

(JOHNSTON, 1976)

Experiment		Broadbalk	Hoosfield	Barnfield	Mean of three experiments
Year started Year sampled		1844 1966	1852 1965	1843 1958	
Treatment and effect		Percentage N in air dry soil 0 to 23 cm depth			
Unmanured		0.099	0.101	0.092	0.097
Effect of	N	+ 0.007	+ 0.007	+ 0.006	+ 0.007
	PK	+ 0.008	+ 0.009	— 0.004	+ 0.004
	NPK	+ 0.016	— 0.001	+ 0.004	+ 0.006
	FYM	+ 0.152	+ 0.181	+ 0.138	+ 0.157

Soil N changed much more dramatically with time on the light soil at Woburn (MATTINGLY, CHATER and JOHNSTON, 1975). On all soils without FYM percentage N decreased from 0.135 p. 100 N in 1888 to 0.103 p. 100 N in 1927. FYM, 19.7 t ha^{-1}, applied between 1877 and 1906 slightly increased soil N by 1888. Then, in 1907 the FYM dressing was decreased to 14.8 t ha^{-1} and by 1927 FYM-treated soil contained less N than in 1876 when the experiment started. Figure 3 compares changes in N content of some Woburn soils with those on unmanured soil on Broadbalk (taken from fig. 2 *a*). The lines are strikingly different. The N content of Woburn soil, about 0.156 p. 100 N in 1876, has approximately halved in 100 years whereas in the Rothamsted soil it has remained almost unchanged.

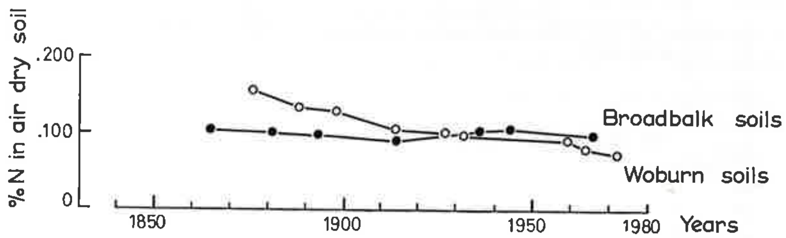

FIG. 3. — *Changes in nitrogen content of unmanured soil, • from Broadbalk, Rothamsted compared with those in unmanured or N only treated soil, o, from the Continuous Wheat and Barley experiments, Woburn* (from MATTINGLY, CHATER and JOHNSTON, 1975).

These results from Woburn are relevant to the problem of maintaining the organic matter content of light land used for all-arable cropping. They suggest that only very large amounts of FYM would maintain soil N content.

Phosphorus

Readily soluble P is now extracted from soils using 0.5*M*-$NaHCO_3$ (pH 8.5). Unmanured Broadbalk and Hoosfield soil contains about the same amount of soluble P (table 16) but the amounts are larger than in similarly unmanured soils on Agdell or at Saxmundham (MATTINGLY and JOHNSTON, this Conference). Results from Agdell and Saxmundham suggest that at the level of soluble P in unmanured Broadbalk and Hoosfield soil cereals would respond to fresh P fertiliser. There is much more P on the unmanured Barnfield soil because some P was applied during 1843-52. These residues, which have been in the soil for more than 100 years still increase soluble P compared with the amounts on Broadbalk and Hoosfield.

Where P has been added as fertiliser or FYM, which supplied similar amounts of P (table 1), the soil now contains much soluble P. On Barnfield soils treated with N_2PKNaMg and N_2*PKNaMg both contain much the same amount of total P, 1 170 and 1 200 mg P kg^{-1}, but very different amounts of bicarbonate-soluble P, 99 and 56 mg P kg^{-1} respectively. Soils treated with N_2PKNaMg had become quite acid by the early 1950s and were limed to pH 7 ; the acidity appears to have enhanced the bicarbonate-soluble P.

Differences in the amounts of bicarbonate-soluble P in P-treated soils which have remained neutral or calcareous in these three experiments probably reflect differences in the buffering capacities of the soils.

TABLE 16

Bicarbonate-soluble P and exchangeable K in soils from Broadbalk (1), *Hoosfield* (2) *and Barnfield* (3)

Experiment Year	Broadbalk 1966	Hoosfield 1965	Barnfield 1958
Treatment	P, mg kg^{-1}, soluble in 0.5*M*-$NaHCO_3$		
Unmanured	8	5	23
PKNaMg	80	126	59
N PKNaMg	88	103	99
N*PKNaMg	67	110	56
FYM	97	102	83
	K, mg kg^{-1}, soluble in 1*N*-ammonium acetate		
Unmanured	102	87	180
PKNaMg	364	433	620
N PKNaMg	341	362	480
N*PKNaMg	319	410	450
FYM	655	758	540

(1) From JOHNSTON, 1969 *b*.
(2) From WARREN and JOHNSTON, 1967.
(3) From WARREN and JOHNSTON, 1962.

Responses by cereals to soil P (MATTINGLY and JOHNSTON, this Conference) suggest that there would be no response to fresh P on any of the P-treated soils in these experiments. Modifications to be made on Barnfield in 1977 will test this.

Potassium

The exchangeable K content of some soils from three experiments are in table 16. The unmanured soils on Broadbalk and Hoosfield contain less exchangeable K than similar soils on Barnfield which contain more clay. More than twice as much fertiliser K was applied on Barnfield than on Broadbalk or Hoosfield so fertiliser treated soils on Barnfield contain more exchangeable K. Dressings of FYM however were the same in all three experiments and more K was removed in the roots from Barnfield than in the grain and straw of the cereals on Broadbalk and Hoosfield. There is now less exchangeable K in FYM-treated soils on Barnfield than in similarly treated soils on Broadbalk and Hoosfield.

Reçu pour publication en mai 1976.

RÉSUMÉ

EXPÉRIENCES DE FERTILISATION DE LONGUE DURÉE SUR MONOCULTURE DANS LES STATIONS EXPÉRIMENTALES DE ROTHAMSTED ET DE WOBURN : EFFETS DES TRAITEMENTS SUR LES RENDEMENTS ET L'ANALYSE DES SOLS, ET BUT ET PLAN DES MODIFICATIONS INTRODUITES RÉCEMMENT

Ce mémoire fait l'historique de six expériences de longue durée et discute les effets des traitements sur les rendements et sur les sols, ainsi que le but des modifications introduites récemment. Quatre de ces expériences sont situées à Rothamsted, et les deux autres à Woburn. Les cultures sont les suivantes : blé d'hiver sur le champ désigné par 'Broadbalk', 1844-1975 ; plantes racines sur 'Barnfield', 1843-1975 ; orge de printemps sur 'Hoosfield', 1852-1975 ; céréales sur 'l'Exhaustion Land', 1856-1975 ; et blé et orge à 'Woburn', 1876-1975.

Jusqu'à tout récemment les mêmes cultures se succédaient tous les ans sur les mêmes parcelles. Quoique la pratique de l'assolement fût bien établie dans les années 1840, LAWES et GILBERT avaient considéré qu'en rompant avec la tradition et en cultivant une plante en monoculture, il serait possible de comprendre ses besoins nutritionnels.

Les expériences de Rothamsted sont établies sur sol limono-argileux (20 à 28 p. 100 d'argile) contenant un peu de $CaCO_3$ (1 à 3 p. 100) et celles de Woburn sur sol sablo-limoneux (10 p. 100 d'argile) légèrement acide à l'origine.

Les rendements des parcelles sans engrais ou avec fumier de ferme ont été mesurés et comparés à ceux des parcelles recevant des substances inorganiques contenant NPKNaMgSi, appliquées seules ou en combinaisons variées. En général, on n'a testé qu'une seule dose de fumier et de PKNaMg, mais plus de K était apporté aux plantes racines qu'aux céréales. La quantité d'éléments fertilisants apportée par les engrais et le fumier excédait celle prélevée par les meilleures récoltes. On a comparé plusieurs doses d'azote, ainsi que les formes de l'azote apporté (nitrique et ammoniacal). A la suite de modifications récentes, les mêmes doses de fumier et de PKMg ont été maintenues, mais tout l'azote est apporté maintenant sous la forme de 'Nitro-Chalk' et on compare aussi des doses d'azote plus élevées.

Les premiers résultats ont démontré de façon concluante que les engrais minéraux pouvaient produire le même rendement que le fumier, que l'azote était plus important que PKNaMg, et qu'une nouvelle dose d'engrais azoté était nécessaire tous les ans. P s'est révélé plus important que K pour l'orge sur le sol plus lourd de Rothamsted. L'altération des minéraux argileux fournit probablement encore assez de K pour une récolte de céréale atteignant environ 5 t de grains à l'hectare. Sur Broadbalk, on a testé K, Na et Mg appliqués séparément et à doses équivalentes ; les rendements ont peu varié, sans doute parce que Na et Mg ont provoqué une libération additionnelle de K dont le blé a pu bénéficier.

Le sulfate d'ammoniaque qui a été, depuis longtemps, une source importante d'engrais azoté, a provoqué une augmentation des pertes de $CaCO_3$ dans les couches supérieures du sol. Les sols qui en ont reçu les doses les plus fortes, particulièrement ceux qui contenaient peu de $CaCO_3$, ont subi une telle acidification que les récoltes en ont été réduites. On utilise aujourd'hui peu de sulfate d'ammoniaque mais les sols continuent à perdre du $CaCO_3$. Les résultats de ces expériences ont démontré comment l'acidification des sols peut provoquer une sérieuse réduction des récoltes, alors que c'est là un des phénomènes les plus faciles et les moins coûteux à corriger.

Le désherbage a toujours été un problème, particulièrement en ce qui concerne les céréales semées en automne. Jusqu'à la première moitié des années 1920, même les céréales étaient régulièrement soumises à un binage manuel, mais cette pratique devint trop coûteuse et, sur Broadbalk, un cinquième du champ fut tour à tour mis en jachère une fois tous les cinq ans. En ce qui concerne l'orge de printemps, le désherbage était plus facile, les plantules de mauvaises herbes étant éliminées par les façons culturales de la fin du printemps. On utilise maintenant des herbicides sur la totalité du champ de Broadbalk, exception faite pour une toute petite partie. Quoique sur Broadbalk la jachère fut introduite par nécessité, elle conduisit au développement de quatre programmes de recherche importants : la biologie des plantes adventices, les insectes nuisibles, l'effet de la jachère sur la fourniture d'azote et sur les rendements, et l'incidence des maladies cryptogamiques sur le blé.

Même au cours des premières années, LAWES et GILBERT avaient prélevé des échantillons de sol, et les changements dans le taux des éléments fertilisants ont pu être ainsi mesurés. Les sols recevant des engrais minéraux ont accumulé très peu d'azote à Rothamsted et en ont perdu beaucoup à Woburn ; c'est seulement dans les sols ayant reçu annuellement de fortes doses de fumier qu'on a pu noter un accroissement de la teneur en azote. Jusqu'à tout récemment, sur Broadbalk, environ 40 p. 100 seulement de l'azote apporté par les engrais minéraux et moins de 20 p. 100 de celui amené par le fumier étaient exportés par les récoltes. Même après 130 ans, moins de 5 p. 100 de l'azote provenant des engrais azotés et moins de 15 p. 100 de l'azote du fumier se retrouvent dans le sol.

Dans les parcelles ayant reçu du superphosphate, tout le P résiduel se trouve dans la couche arable du sol ; dans les parcelles avec fumier, une légère quantité de P est passée dans le sous-sol. En ce qui concerne le K, son accumulation dans le sol a varié avec la quantité de K apportée, la culture et la quantité de K prélevée par cette culture.

On a évalué les effets résiduels de P et K sur une série de cultures. Les sols contenant P ou K résiduels ont toujours donné des rendements supérieurs à ceux des sols qui n'en contenaient pas, à la condition que tous les autres éléments fertilisants y aient été présents en quantité suffisante. En général P s'est révélé plus efficace que K surtout à Rothamsted où les sols libèrent encore un peu de K tous les ans. L'introduction de nouvelles applications de P ou de K dans l'essai a produit des résultats plus variables. Dans certains sols, une nouvelle application d'engrais à un sol appauvri n'a pas élevé les rendements comparativement à ceux obtenus dans un sol enrichi mais sans nouvelle addition d'engrais. Dans d'autres sols, une nouvelle application d'engrais a produit les mêmes rendements sur sol appauvri comme sur sol enrichi. On ignore les raisons pour lesquelles ces sols se comportent différemment ; des différences de structure pourraient être invoquées.

Le résultat le plus important de ces expériences est peut-être le fait que les rendements, particulièrement en ce qui concerne les céréales, n'ont pas diminué après plus de cent ans de culture continue. Les derniers rendements ont été les plus forts, en partie parce que les variétés utilisées aujourd'hui donnent de meilleurs rendements, et en partie en raison de l'amélioration des façons culturales, y compris meilleur désherbage et meilleur contrôle des parasites et des maladies. Les maladies et les parasites transmis aux plantes par l'intermédiaire du sol n'ont été étudiés systématiquement que tout récemment. On était à peine averti de leur importance au cours des années 1840, quoique nous sachions aujourd'hui que le succès de l'assolement était dû au contrôle que les rotations exerçaient sur eux. On compare maintenant les rendements du blé et de l'orge en culture continue et en rotation sur Broadbalk et sur Hoosfield. En général, les rendements maxima sont produits par les cultures en rotation, et la dose optimum d'azote se trouve généralement inférieure à celle requise par les céréales en culture continue.

Une autre modification récente consiste à apporter de l'azote minéral aux parcelles avec fumier. Ces parcelles, ayant reçu du fumier pendant de nombreuses années, contiennent plus de matière organique que celles traitées aux engrais minéraux. Le rendement des plantes racines est notablement plus élevé sur les parcelles avec fumier et azote minéral que sur les parcelles ne recevant que des engrais minéraux ; mais il y a peu de différence dans le rendement des variétés modernes de céréales sur les deux sols à la dose optimum de N. On se propose aussi d'étudier ultérieurement l'effet de l'accroissement de la matière organique du sol sur des prairies temporaires de durée variée.

ZUSAMMENFASSUNG

VERSUCHE BEZÜGLICH DES FORTLAUFENDEN WACHSTUMS BESTELLBAREN KULTUREN IN DEN VERSUCHSZENTREN VON ROTHAMSTED UND WOBURN : WIRKUNGEN DER BEHANDLUNGEN AUF DIE KULTURERTRÄGE UND BODENANALYSEN UND NEUE VERÄNDERUNGEN VOM ZIEL UND PLAN

In dieser Mitteilung werden sechs Feldversuche beschrieben, die zwischen 1843 und 1877 angefangen worden sind Alle gehen noch mit verschiedenen Veränderungen weiter und die Ergebnisse für verschiedene zwischen 1843 und 1975 erfassten Perioden sind gegeben. Die Versuche betrafen zuerst den Nährstoffbedarf von Weizen-, Gerste- und Rübemonokulturen. Die Erträge mit und ohne Stallmist werden bestimmt und mit den mit getrennten oder verschieden kombinierten mineralischen NPKNaMgSI Gaben erzielten Erträgen verglichen. Diese Versuche zeigten bald dass die chemischen Dünger die selben Erträge wie der Stallmist ergeben und lassten die relative Bedeutung von N, P und K für die verschiedenen Kulturen hervortreten.

Alle die studierten Dünger lieferten mehr Nährstoffe als die Kulturen davon ausnutzzten. Fast alle die Rückstände der N-Düngung wurden aus dem Boden weggenommen ; etwas N hat sich in den mit Stallmistdüngung angereicherten Böden angehaüft, aber davon ist auch in diesen,

Böden viel verlorengegangen. Das meiste der P-Rückstände ist in der Ackerkrume geblieben, aber etwas K wanderte in den Untergrund. Die P und K Rückstände können durch Zunahmen, vom bicarbonatlöslichen P und vom austauschbaren K nachgewiesen sein, aber keine dieser Methoden zur Bodenanalyse erlaubt eine Schätzung de gesamten Bodengehalts an pflanzenaufnehmbaren P und K. Doch zeigten die Feldversuche dass die Rückstände für eine ganze Reihe von Kulturen verfügbar sind. Im laufe gewisser Vergleichsuntersuchungen waren die Erträge auf Böden mit Rückständen immer besser als auf Böden ohne Rückständen, auch wenn ein ganz neues Düngemittel studiert war.

Die Böden, denen jährlich eine Stallmistschicht während mehr als 100 Jahre verabreicht wurde, enthalten heute mehr organische Stoffe als die, denen nur chemische Dünger verabreicht wurden. In den letzten Jahren wurden Sorten mit höher Ertragsleistung und verbesserte Kulturtechniken mit Unkraut-, Schädlings- und Krankheitsbekämpfung eingeführt. Während dieser Periode waren die Erträge der Rüben- und Getreidekulturen in Fruchtfolge auf die mit Stallmist angereicherten Böden besser als auf die mit chemischen Düngern angereicherten Böden. Diese Differenz kann nicht mit den im Frühling verabreichten N-Düngerschichten erkluärt werden ; nähere Untersuchungen werden unternommen.

РЕЗЮМЕ

Опыты монокультуры временных культур на экспериментальных станциях в Ротхемштете и Вобэрне. Действие различных обработок на урожайность и анализы почв. Недавние изменения целей и организации экспериментов.

А. Е. ДЖОНСТОН, Г.Е.Г. МЭТТИНГЛИ.

В данной работе описываются 6 полевых опытов, заложенных между 1843-м и 1877-м годом. Все эти опыты продолжаются до сих пор с некоторыми изменениями, и в этом труде даются результаты, полученные в различные периоды с 1843-го до 1975-го года. Сначала в этих опытах изучались нужды монокультур пшеницы, ячменя и пропашных культур в питательных элементах. Урожайность на почвах без удобрений и удобренных навозом, определялась и сравнивалась с урожайностью на почвах получавших N, P, K, Na, Mg, Si в форме минеральных соединений, внесенных по отдельности, или в различных комбинациях. Опыты эти очень скоро показали, что применение минеральных удобрений давало возможность получать урожаи того-же уровня, что и применение навоза, и что для некоторых культур применение минеральных удобрений играет довольно важную роль.

Все испробованные удобрения приносили в почву количества питательных элементов большие чем те, которые выносились урожаями. Неиспользованный остаточный азот был почти полностью потерян почвой; некоторые количества этого элемента накоплялись, правда, в почвах получавших навоз, но даже в этом случае большая часть азота терялась. Большая часть остаточного фосфора оставалась в пахотном слое, но некоторое количество калия мигрировало в под-почву. Остаточные количества P и K можно определить по увеличению содержания растворимого фосфора в бикарбонате и по увеличению содержания обменного калия; но не существует метода определения общего количества усвояемых (растениями) P и K в почве. Полевые опыты показали однако, что остаточные количества этих элементов могут быть усвоены большим числом культур. В некоторых сравнительных изучениях урожайность всегда была повышенной на почвах содержавших остаточные количества питательных элементов, даже тогда, когда в эксперименте испробывалась повышенная доза какого-нибудь нового удобрения.

Почвы, получавшие ежегодно навоз, в течении более ста лет, содержали более крупные запасы органического вещества, чем почвы обрабатывавшиеся с помощью только минеральных удобрений. Недавно в опыты были введены более продуктивные сорта, улучшена практическая сторона обработок, введена была также борьба с сорняками, вредителями и болезнями. В течении этого нового периода урожайность культивируемых в севооборотах пропашных и злаков больше увеличилась на почвах получавших навоз, чем на почвах получавших минеральное удобрение. Эту разницу невозможно об' яснить весенними подкормками азотом, и поэтому в настоящее время начаты новые исследования для выяснения этого вопроса.

REFERENCES

Cooke G. W. (this Conference). *Long term fertiliser experiments in England : The significance of their results for agricultural science and for practical farming.*

Garner H. V., Dyke G. V., 1969. The Broadbalk Yields. *Rep. Rothamsted exp. Stn for* 1968, Pt, **2**, 26-49.

Glynne M. D., 1969. Fungus diseases of wheat on Broadbalk 1843-1967. *Rep. Rothamsted exp. Stn for* 1968, Pt **2**, 116-140.

Johnson C. G., Lofty J. R., Cross D. J., 1969. Insect Pests on Broadbalk. *Rep. Rothamsted exp. Stn for* 1968, Pt **2**, 141-156.

Johnston A. E., 1969 *a*. Plant nutrients in crops grown on Broadbalk. *Rep. Rothamsted exp. Stn for* 1968, Pt **2**, 50-62.

Johnston A. E., 1969 *b*. Plant nutrients in Broadbalk soils. *Rep. Rothamsted exp. Stn for* 1968, Pt **2**, 93-112.

Johnston A. E., 1970. The value of residues from long-period manuring at Rothamsted and Woburn. III. The experiments made from 1957 to 1962, the soils and histories of the sites on which they were made. *Rep. Rothamsted exp. Stn for* 1969, Pt **2**, 22-38.

Johnston A. E., 1975. Experiments made on Stackyard Field, Woburn, 1876-1974. I. History of the Field. Details of the Cropping and Manuring and the Yields of the Continuous Wheat and Barley experiments. *Rep. Rothamsted exp. Stn for* 1974, Pt **2**, 29-44.

Johnston A. E., 1976. Additions and removals of nitrogen and phosphorus in long-term experiments at Rothamsted and Woburn and the effect of the residues on total soil nitrogen and phosphorus. In : *Agriculture and Water Quality. Tech. Bull. Minist. Agric. Fish. Fd* No. 32, 111-144.

Johnston A. E., Garner H. V., 1969. The Broadbalk Wheat Experiment : Historical Introduction. *Rep. Rothamsted exp. Stn for* 1968, Pt **2**, 12-25.

Johnston A. E., Chater M., 1975. Experiments made on Stackyard Field, Woburn, 1876-1974. II. Effects of treatments on soil pH, P and K in the Continuous Wheat and Barley experiments. *Rep. Rothamsted exp. Stn for* 1974, Pt **2**, 45-60.

Johnston A. E., Poulton P. R., 1977. Yields on the Exhaustion Land and changes in the NPK content of the soils due to cropping and manuring 1852-1974. *Rep. Rothamsted exp. Stn for* 1976, Pt **2**, (in press).

Johnston A. E., Warren R. G., Penny A., 1970. The value of residues from long-period manuring at Rothamsted and Woburn. IV. The value to arable crops of residues accumulated from superphosphate. V. The value to arable crops of residues accumulated from potassium fertilisers. *Rep. Rothamsted exp. Stn for* 1969, Pt **2**, 39-90.

Lawes J. B., Gilbert J. H., 1895. The Rothamsted Experiments. *Trans. R. Highld. agric. Soc. Scotl.*, Ser 5, **7**, 11-354.

Liebig J., 1843. *Organic chemistry in its application to agriculture and physiology.* 3rd edition London : Taylor and Walton, 387 pp.

Mattingly G. E. G., Chater M., Johnston A. E., 1975. Experiments made on Stackyard Field, Woburn, 1876-1974. III. Effects of NPK fertilisers and farmyard manure on soil carbon, nitrogen and organic phosphorus. *Rep. Rothamsted exp. Stn for* 1974, Pt **2**, 61-77.

Mattingly G. E. G., Johnston A. E. (this Conference). Long term rotation experiments at Rothamsted and Saxmundham Experimental Stations : The effects of treatments on crop yields and soil analyses and recent modifications in purpose and design.

ROTHAMSTED EXPERIMENTAL STATION, 1974. Guide, Harpenden : 78 pp.

RUSSELL E. J., 1916. Chalking : a useful improvement for clays overlying the chalk. *J. Bd Agric. Fish.*, **23**, 625-633.

RUSSELL E. J., VOELCKER J. A. (ed.), 1936. *Fifty years of field experiments at the Woburn Experimental Station.* London : Longmans Green and Co., 392 pp.

RUSSELL E. J., WATSON D. J., 1938. The Rothamsted field experiments on barley, 1852-1937. Pt I, II and III. *Emp. J. exp. Agric.*, **6**, 268-292, 293-314 ; **7**, 193-220.

RUSSELL E. J., WATSON D. J., 1940. The Rothamsted field experiments on the growth of wheat. *Tech. commun. imp. Bur. Soil Sci.*, No, 40.

THURSTON J. M., 1969. Weed studies on Broadbalk. *Rep. Rothamsted exp. Stn for* 1968, Pt **2**, 186-208.

THURSTON J. M., WILLIAM E. D., JOHNSTON A. E. (this Conference). Modern developments in an experiment on permanent grassland, started in 1856 : Effects of fertilisers and lime on botanical composition and crop and soil analyses.

VOELCKER J. A., 1923. The Woburn Experimental Farm and its work, 1876-1921. *Jl R. Agric. Soc.*, **84**, 110-166.

WARREN R. G., JOHNSTON A. E., 1960. The Exhaustion Land Site. *Rep. Rothamsted exp. Stn for* 1959, 230-239.

WARREN R. G., JOHNSTON A. E., 1962. Barnfield. *Rep. Rothamsted exp. Stn for* 1961, 228-247.

WARREN R. G., JOHNSTON A. E., 1967. Hoosfield Continuous Barley. *Rep. Rothamsted exp. Stn for* 1966, 320-338.

WATSON D. J., RUSSELL E. J., 1943. The Rothamsted experiments on mangolds, 1876-1940. I. Effect of manures on yield of roots. *Emp. J. exp. Agric.*, **11**, 49-64.

YOUNG A., 1813. *General view of the agriculture of Hertfordshire*, London, 236 pp.