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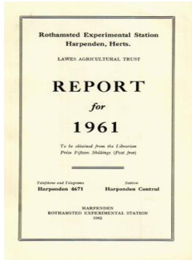
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MICROBIOLOGICAL OBSERVATIONS ON THE CLASSICAL FIELDS AT ROTHAMSTED

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The Rothamsted field experiments offer great opportunities for the study of Soil Microbiology. Here, as nowhere else, the effects of long-continued treatments of the same soil on its population of micro-organisms can be observed. Perhaps the opportunities have not been fully exploited, but several fundamental discoveries of the true nature of the microscopic population of soils have been made, notably that Protozoa are true soil inhabitants, and that the total population must be reckoned in thousands of millions per gram of soil. (Much work has also been done on soil-borne plant pathogens in the Rothamsted fields, but this has been most ably reviewed by others (see, for instance, Glynne & Salt, 1957), and little would be gained by repeating what has been better done already.)

The earliest microbiological observations on Rothamsted soils were made by Robert Warington in 1883. In that year he took soil samples at different depths on Agdell field, which at that time carried a long-term experiment on two four-course rotations (turnips, barley, bare fallow, wheat; turnips, barley, clover, wheat) and found that surface soil, and soil down to but not below 18 inches, contained nitrifying bacteria. He repeated the work the next year, when he failed to find nitrifiers at a depth greater than 9 inches (Warington, 1884).

There was then a gap of more than twenty years before Ashby (1907) examined a series of soils collected at Rothamsted for the then recently discovered bacterium, *Azotobacter chroococcum*, which could fix nitrogen from the air. He found that it was abundant in the soil of Broadbalk Wilderness, and fairly abundant in the Drain Gauges. In Agdell it was present in the limed but not the unlimed plots, and it could not be found in three Park Grass plots (1, 4 and 9) or in Geescroft Wilderness (which has a more acid soil than the Broadbalk Wilderness).

Two years later, in 1909, appeared the first of a series of papers by Russell and Hutchinson on the effects of partial sterilisation of soil on crop growth and on the numbers of bacteria. Their first experiments were made with unmanured soil taken from the headland of Barnfield. They treated this soil with steam, and with toluene, and counted the bacteria by the plate method on nutrient gelatine. The count in the untreated soil was 5–9 million bacteria/g.; treatment with steam or toluene diminished the count to about half this value at first, but 10 days later the count had risen to 40 million bacteria/g. The same gelatine plate method showed bacterial numbers of 14–77 millions/g. in the dunged plot of Barnfield, but only 12 millions/g.

in Hoos Field unmanured plot (Russell and Hutchinson, 1909, 1913; Hutchinson, 1913). Partial sterilisation thus increased crop yields and bacterial numbers after a temporary fall; from these results Russell and Hutchinson concluded that there was some factor in soil which limited both bacterial growth and soil fertility, and which was removed by partial sterilisation. As they succeeded in growing the ciliate Protozoon *Colpoda* in hay infusion inoculated with soil, they thought that it must be the soil Protozoa that were the harmful factor. Goodey (1911) found several species of Protozoa, mostly ciliates but some amoebae, in fresh and in old stored soil samples taken from Barnfield and Hoosfield unmanured plots. Critics of his work suggested that the Protozoa were not true soil inhabitants, but were accidentally blown into the soil in their encysted stage, and remained encysted. Martin and Lewin (1915), however, discovered that Protozoa lived in the soil as active forms, mobile and able to feed, and not only as cysts. They examined samples taken from Broadbalk plots 2 and 3 (FYM and unmanured), and from Agdell fallow.

In 1917 Russell and Appleyard published counts made on gelatine plates of bacteria from soil samples collected during a whole year from Broadbalk plots 2 and 3 (and from Great Harpenden field). Numbers fluctuated on all the plots and their attempt to relate the fluctuations to the nitrate content of the samples (not surprisingly) failed. The fluctuations were not related to soil temperature or soil moisture, and Russell and Appleyard said that they might have been caused by the predatory activities of soil Protozoa. The carbon dioxide output of incubated soil samples was shown to be related to the numbers of bacteria in them, and the output of carbon dioxide has been used since by many workers as a convenient index of microbial activity in soils. This paper also includes one of the earliest estimations of the amount of nitrate lost from the soil in autumn by leaching and otherwise.

In 1920 Cutler published a method for counting total numbers of Protozoa, and also the numbers of active (i.e., not encysted) Protozoa in soil samples. This method, which depended on the development of Protozoa on peptone–meat-extract–agar plates inoculated with dilutions of a soil suspension, was used by Crump (1920) to study the soil Protozoa in plots 2 and 3 of Broadbalk, the dunged plot (1–0) of Barnfield and an unmanured plot on Great Harpenden. She found that the most numerous Protozoa were small flagellates, which varied in numbers from 1,000 to 100,000/g. of soil. Amoebae were fewer, from 100 to 50,000/g., and ciliates were not always present, and never more than 1,000/g. Very few Protozoa were found deeper than 6 inches below the soil surface. In surface samples there were more Protozoa in dunged plots than in unmanured plots. In all the plots the numbers fluctuated similarly, with peaks at the same time of year; the fluctuations could not be correlated with changes in soil temperature or moisture, or with rainfall, but there was some indication that they went in the opposite direction to changes in the plate count of bacteria.

This point was investigated further by Cutler and Crump (1920), who found that the numbers of active forms of three common soil flagellates (*Oicomonas*, *Cercomonas* and *Bodo* spp.) in the soil of

Broadbalk plot 2 fluctuated from day to day. Once again, these changes could not be related to soil moisture or temperature. In the same soil the numbers of active amoebae varied inversely with the plate counts of bacteria. A year later a really heroic experiment was undertaken by Cutler, Crump and Sandon (1922). They took a soil sample from the dunged plot (1–0) of Barnfield on every one of the 365 days from 5 July 1920 to 4 July 1921, and from these samples they obtained plate counts of bacteria on Thornton's agar (Thornton, 1922), and counted total and active Protozoa by Cutler's method. The results were examined in great detail, and showed that, on many occasions, the bacterial numbers were low when the Protozoa numbers were high, and vice versa. A common picture was to see a sudden rise in the bacterial count followed two or three days later by a rise in the numbers of one or other of the Protozoa. These results seemed at the time to indicate that the predatory action of the Protozoa was limiting the numbers of bacteria in soils; but subsequent work showed that knowledge of both the predators and the prey was far from complete. (See Thornton and Crump, 1952.)

It had become apparent for some time that the counts of bacteria obtained by plate methods were gross underestimates of the real soil population. No agar medium, however " unselective ", permits every bacterial species to develop, and it was obvious that anaerobic bacteria, and autotrophs, were not being included in the counts. Just how gross the underestimate was, however, came as a surprise to most bacteriologists. The plate counts, even on a better medium than the nutrient gelatine used by Russell and Hutchinson, estimated the bacterial population of a fertile soil at some tens of millions per gram. The first method of total counts, the ratio method of Thornton and Gray (1934), showed that the real bacterial population might be more than a hundred times as great. In this method a known small quantity of soil was mixed with a suspension of indigo containing a known number of indigo particles per ml., and drops of the mixture spread on microscope slides and stained with a red dye. The bacteria appeared as red dots and the indigo particles as blue dots, and comparing the numbers of each in random microscope fields gave an estimate of the soil population, of the order of thousands of millions per gram of soil. For instance, counts on Barnfield soil ranged from 1,900 to 2,900 millions/g. on different plots, and counts on Hoosfield from 1,700 millions on plot 1–0 (unmanured) up to 3,700 millions on plot 4-AA (nitrate of soda, phosphate and potash).

Another total counting method, the agar-film method of Jones and Mollison (1948), gives estimates of the same order of numbers. Counts done on Broadbalk by this method showed that Plot 2 (FYM) had the most bacteria and actinomycetes, and Plots 3 (unmanured) and 7 (ammonium sulphate and minerals) had similar numbers. The average count by the direct method was 2,500 million cells/g. of soil, and the average plate count 50 millions/g., $\frac{1}{50}$ of the direct count (Skinner, Jones and Mollison, 1952).

As well as the total numbers, several particular groups of micro-organisms have been counted at Rothamsted. Algae were counted in samples from Broadbalk plots 2 and 3 by Bristol Roach (1927), who found the same species on both plots, but more numerous on the dunged plot 2. J. Singh (1937) made plate counts of fungi and actinomycetes, on an agar medium, pH 5·2, that was not really favourable to either group. On both Broadbalk and Barnfield he found most in the plots with organic manures, and fewest in the unmanured plots. Skinner (1951) found that the high numbers of actinomycetes in Broadbalk plots 2, 3 and 7 were nearly all in the spore stage at the time of counting, with very little mycelium present.

Jensen (1931) used soil from two plots on Park Grass to study the decomposition of farmyard manure. In the limed soil from plot 1, pH 7, he found that the numbers of bacteria and actinomycetes were increased when the soil was incubated with farmyard manure and straw; but in the acid unlimed soil, pH 3·8, from plot 14, the same treatment increased only the numbers of fungi. From the soil of plot 1 he isolated a cellulose-decomposing bacterium, a species of Vibrio, which appeared to be the most numerous cellulose decomposer at pH 7. From the acid plot 14 he isolated cellulose decomposing fungi; and from Hoosfield soil, of intermediate acidity (pH 6·3), he obtained the Vibrio, and also the Myxobacterium *Sporocytophaga*, which had been discovered at Rothamsted by Hutchinson and Clayton in 1919 (Jensen, 1931b). From the Hoosfield soil Jensen also isolated two actinomycetes active in breaking down keratin (Jensen, 1930) and two species of fungi able to decompose chitin (Jensen, 1932).

In 1946 B. N. Singh described an improved method of counting Protozoa in soils. This was based on his discovery that the Protozoa were selective in their choice of food, eating some species of bacteria readily and others not at all. Small circles of an edible bacterium were spread inside glass rings embedded in plain agar, and inoculated with serial dilutions of the soil sample. As the Protozoa developed they ate the bacterial circle, and the different kinds were easy to detect in the small space. Singh (1949), by this method, counted amoebae in plots on Barnfield and Broadbalk. On both fields numbers were highest in the dunged plot and lowest in the unmanured, with a plot with sulphate of ammonia and minerals giving a count between the two (see Table 1).

TABLE 1

Numbers of amoebae per gram dry soil (Singh, 1949)

Barnfield (mean of 9 observations)			
Unmanured (8–0)	FYM (1–0)	Ammonium sulphate and minerals	
8,000	34,000	26,000	(4 A)
Broadbalk (mean of 6 observations)			
Unmanured (3)	FYM (2)	Ammonium sulphate and minerals	
17,000	72,000	48,000	(7)

Singh also discovered, by this same method, that several micropredators, once thought to be rare, were in fact widely distributed and numerous in soils. Some of these, the Acrasieae, for instance, were thought to live in dung only, and not to be true soil inhabitants. But Singh found that the Acrasian *Dictyostelium*, the gigantic amoeboid predator *Leptomyxa reticulata*, and the higher Myxobacteria *Myxococcus*, *Chondrococcus* and *Archangium*, were all present and quite numerous in the soil of Broadbalk Plot 3, which has received no manure of any kind for more than a hundred years (Singh, 1947a, 1947b, 1948).

Some specialised groups of bacteria have also been counted in the Rothamsted classical fields. In the autumn of 1930 and 1931 Ziemięcka (1932) took a series of soil samples, and used Winogradsky's method of crumbs of soil on silica gel to count the nitrogen fixer *Azotobacter chroococcum*, and also the ammonia-oxidising bacteria in them. Her counts of Azotobacter, given in Table 2, show more in plots without added nitrogen.

TABLE 2

Azotobacter: cells per gram dry soil (Ziemięcka, 1932)

	Mean Nos. of Azotobacter
Unmanured (6 observations)	
Broadbalk 3, Hoosfield 1–0 and 7–1, Agdell 5 and 6 ...	852
P, K, *no* N (6 observations)	
Broadbalk 5, Hoosfield 4–0, Agdell 3 and 4, Barnfield 4–0	2,382
N: *Ammonium sulphate* (10 observations)	
Broadbalk 6, 7, 8, 10, 11, 12, 13, 14, Hoosfield 4–1 ...	231
N: *Sodium nitrate* (7 observations)	
Broadbalk 9 and 16, Hoosfield 3–AA and 4–AA, Barnfield 4–N	568
N: *Organic* (7 observations)	
Broadbalk 2 and 19, Hoosfield 3–0, 4–0 and 7–2	550
All plots without nitrogen (12 observations)	1,617
All plots with nitrogen (24 observations)	423

The ammonia oxidisers, by contrast, seemed to be most numerous in the plots with added organic nitrogen (farmyard manure or rape cake) (Table 3). Ammonia-oxidising bacteria have now been isolated from Broadbalk Plot 2, and identified as *Nitrosomonas europaea* Winogradsky (Meiklejohn, 1949).

TABLE 3

Ammonia oxidisers: cells per gram dry soil (Ziemięcka, 1932)

	Broadbalk	Barnfield
Unmanured	252	384
P, K, no N	406	334
Ammonium sulphate	1,949	252
Sodium nitrate	—	987
Rape cake	1,336	3,687
Farmyard manure	2,243	3,198

The results in these two tables are based on single observations. Recently I have counted *Azotobacter chroococcum* at intervals over a period of 3½ years in samples taken from eight plots on Broadbalk (Meiklejohn, 1962). The number of cells always fluctuated from sample to sample, but in spite of this there were real differences between plots. In general, the plots which showed the greatest increase in the yield of wheat after fallowing had the most Azotobacter. Plot 10, for instance, which receives sulphate of ammonia only (no P or K), and has an average increase in yield of 3 cwt. of grain/acre, has consistently fewer Azotobacter than Plot 5, receiving P and K but no N, which has an average yield increase of 9 cwt./acre after fallow. Table 4 shows the average counts of Azotobacter for eight Broadbalk plots.

TABLE 4

Azotobacter: cells per gram dry soil (*Meiklejohn, 1962*)

(*Broadbalk*)

Plot	Treatment	Number of observations	Mean No. of Azotobacter
3	Unmanured	56	167
5	Minerals (P, K, no N)	49	178
7	Ammonium sulphate, P, K	50	107
10	Ammonium sulphate only	52	77
11	Ammonium sulphate, P	35	140
13	Ammonium sulphate, P, K	35	139
17 & 18	Alternate years: P, K, no N	50	220
17 & 18	Alternate years: Ammonium sulphate	50	199

Few Azotobacter were found, probably because of the medium used, which has since been found to underestimate the numbers of Azotobacter. The error, however, appears to affect all counts in the same proportion, so that, though the real numbers are all higher than those shown, plots 17 and 18, for instance, really have more Azotobacter than plot 10. And in any case, Azotobacter is not the only nitrogen fixer in the Broadbalk soil. It is not even the most numerous. A few counts made of the anaerobic nitrogen-fixing bacterium *Clostridium pasteurianum* show consistently higher numbers than those of Azotobacter. In all the eight plots sampled, nitrogen-fixing Clostridia were found to amount to 100,000/g. or more on at least one occasion, and very few counts numbered fewer than 1,000 cells/g. of soil. There were not enough data for any differences between plots to be detected (Meiklejohn, 1956).

It is obvious, I think, that much remains to be done before the Rothamsted classical fields can be said to be adequately studied. The work already done has disclosed that the population of micro-organisms in cultivated soils must be numbered in thousands of millions per gram, and has given some indication of the complexity of this population. Future advances in useful knowledge are, however, more likely to be made not by attempting to study the "whole" soil population, but by more detailed study of the groups of micro-organisms responsible for particular processes important to soil fertility. The best line of approach is indicated by the work of Jensen. In his study of the decomposition of manure he was able to use two soils, from Park Grass plots 1 and 14, that had been changed by fertiliser treatment so that one was neutral and the other very acid, and so to find out that soils of different acidity contain different groups of cellulose decomposers. Further studies of this kind on the classical fields, where the soil properties are so well known, and all the yields are recorded, would take some useful advantage of the unique opportunities offered by the Rothamsted classical fields.

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BARNFIELD

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Lawes and Gilbert started a manurial experiment on mangolds on Barnfield in 1876, the same year they began to study the manuring of potatoes on what is now the Exhaustion Land. Except for a few years when the crops failed, mangolds have been grown on Barnfield each year from 1876 to 1959. From 1946 to 1959 a part of each plot, the same part each year, was sown with sugar beet. The results up to 1894 were summarised by Lawes and Gilbert[1] in 1895, and in 1902 Hall[2] discussed the results in detail. The next account of the experiment was by Watson and Russell[3,4,5,6,7] in five papers examining the results up to 1940. Our account gives results since 1940, and in addition to the mean yields for mangolds from 1941 to 1959 and sugar beet from 1946 to 1959, chemical analyses are given of crop and soil samples taken in 1958 and 1959.

At the time the experiment began mangolds were widely grown. Knowledge on its culture and manuring was derived from the experience of farmers and from field experiments. Salt gave good increases in yield, and fertilisers such as sodium nitrate and potassium nitrate were especially effective. The effect of phosphates on mangolds was small. Lawes and Gilbert's chief object in studying mangolds was to extend the range of crops in their investigations on the sources from which plants obtained nitrogen. They had already destroyed the belief that the large leaves of turnips, swedes and sugar beet could absorb enough ammonia from the air to meet their requirements. Even the application of a "starter" dose of nitrogen (about 8 lb. N/acre as ammonium salts) given to increase leaf area in the early stages of the plant's growth did not succeed.

The Mangold Experiment followed experiments with swedes and sugar beet on the same site, and the manuring was mainly a continuation of the schemes of these earlier experiments. There were eight long strips of land, side by side, each about $\frac{9}{10}$ acre, which were given the following treatments: (1) FYM; (2) FYM, P—from 1895 K also given; (3) unmanured—discarded in 1903 because it was very narrow; (4) P, K, Na, Mg; (5) P; (6) P, K; (7) N, P, K—the N was a small dose, about 8 lb. N/acre—from 1903 this strip received P, Na, Mg; (8) unmanured. This scheme did not provide a satisfactory test of P, as no strip received K only. Because Mg was always accompanied by Na there was no test of Mg, and the strip comparison of Na and K was also affected. Across the Strip treatments there were five Series treatments, no nitrogen (O), sodium nitrate (N), ammonium sulphate (A), ammonium sulphate and rape cake (AC) and rape cake (C). In 1941 rape cake was unobtainable, and in that year and since castor bean meal was used. After Strip 3 (unmanured) was discarded the Strip and Series scheme contained thirty-five main plots, one per treatment. In the layout in the field there was a gap, not under experiment, between Series O

TABLE 1

Crops and manures, Barnfield, 1843–1959

Period	Crop	Strip treatments 1	2	3	4	5	6	7	8	Series treatments [1]
1843–44	Turnips	See note [2]								None
1845–48	Turnips	P [3]	P	None	P, K, Na, Mg	P	PK	PK	P	O [4] A AC C
1849–52	Swedes	P [3]	P	None	P, K, Na, Mg	P	PK	PK	P	O [4] A AC C
1853–55	Barley	Manures not applied in these years [5]								
1856–60	Swedes	FYM	FYM, P	None	P, K, Na, Mg	P	PK	PK [6]	None	O N A AC C
1861–70	Swedes	FYM	FYM, P	None	P	P	P	P	None	O N A AC C
1871–75	Sugar beet	FYM	FYM, P	None	P, K, Na, Mg	P	PK	PK [6]	None	O N A AC C
1876–1902 [7]	Mangolds	FYM	FYM, P [8]	None [9]	P, K, Na, Mg	P	PK	PK [6]	None	O N A AC C
1903–59	Mangolds [10]	FYM	FYM, P, K		P, K, Na, Mg [11]	P	PK	PNaMg	None	O N A AC C

(1) Nitrogen cross dressings, O, none; A, ammonium salts; C, 1856–60 sawdust, 1861–1939 rape cake, 1940–59 castor bean meal; AC, treatments A and C combined; N, 1856–60 sawdust and nitric acid containing as much nitrogen as applied in Series A; 1861–1959 sodium nitrate.

(2) In 1843–44 there were 24 strips to which various manures were applied including FYM, guanos and combinations of N, P, K, Na, Mg. See *J. R. agric. Soc.* 1847, **8**, 494. These were later combined to make 8 strips.

(3) Parts of the plot received rape cake and farmyard manure.

(4) In " The Valley " between the O and A Series a number of manures, including phosphates and guanos, were applied. Subsequently Series N occupied part of this valley.

(5) In 1854 400 lb ammonium salts were applied to the valley sections of Strips 4, 5, 6, 7 to evaluate nitrogen residues on main plots.

(6) 36·5 lb. ammonium salts also applied. These contained 7·8 lb. N equal to the amount of nitrogen applied in the sawdust on Series N.

(7) An additional plot (9) which was not part of the main scheme of Strip and Series manuring was started in 1876 on the triangular piece of land on the East side of the experimental area. This plot received per acre in 1876–1902, FYM 14 tons, superphosphate, 350 lb. till 1887, 392 lb. 1888–1902; 400 lb. ammonium salts; 1903–1959, 500 lb. potassium sulphate, 200 lb. sodium chloride, 200 lb. magnesium sulphate, 550 lb. sodium nitrate.

(8) FYM, P changed to FYM, PK in 1895.

(9) Strip 3 was very narrow and yields have not been recorded since 1902 (manured and cropped as " commercial " since 1927).

(10) From 1946 4 rows sugar beet replaced 4 rows mangolds on each plot, the same part each year.

(11) From 1903 plot 4N split 4Na (west) was manured as the rest of the strip, 4Nb received no sodium but nitrate as mixed KNO_3 $CaNO_3$ and $CaCl_2$ to balance chloride in the sodium chloride on 4Na.

TABLE 2

Details of Strip and Series treatments, Barnfield, 1845–1959

Treatment symbol	FYM	P	K	Na	Mg	Series A	Series N	Series C	Series AC
	Amounts of manures[14] per acre, annual application								
Period	Farmyard manure (tons)	Super-phosphate (lb.)	Potassium sulphate (lb.)	Sodium chloride (lb.)	Magnesium sulphate (lb.)	Ammonium salts[1] (lb.)	Sodium nitrate[2] (lb.)	Rape cake[3]	Ammonium salts (A) + rape cake (C)
1845–52		275[4]	334[5]	88[6]	75	200[7]		2000[7]	A + C[7]
1856–60	14	350	300	200[8]	100	200	See Note 2	See Note 3	A + C[3]
1861–70	14	350				400	550	2000	A + C
1871–75	14[9]	350	460	200	180	400[9]	550[9]	2000[9]	A + C[9]
1876–1902	14	350 392[10]	500	200	200	400	550	2000	A + C
1903–59[13]	14	392	500[11]	200	200[11]	400[12] 420[15]	550[12]	2000	A + C

(1) Applied as equal weights ammonium sulphate and ammonium chloride to 1916 (except 1887, ammonium sulphate only), from 1917 all as ammonium sulphate.

(2) 1856–60 3,000 lb. sawdust + nitric acid containing as much nitrogen as applied in Series A.

(3) 1856–60 3,000 lb. sawdust replaced rape cake, 1861–1939 rape cake (not applied 1917–20), 1940–59, castor bean meal, 1955 and since weight/acre adjusted from analysis so that total nitrogen applied equalled 86 lb./acre.

(4) Strip 4 370 lb.; Strip 5 345 lb.; Strip 8 in 1843–52 was divided lengthwise into 3 equal strips, the total application of superphosphate to each strip was west strip 1,000 lb., central strip 4,800 lb., east strip 500 lb.

(5) Applied as pearl ash, strip 4 received only 228 lb.

(6) As soda ash.

(7) No nitrogen in 1851, 1852.

(8) As sodium sulphate.

(9) No FYM or nitrogen cross dressings in 1874, 1875.

(10) 350 lb. to 1887, from 1888 392 lb. of superphosphate supplied to the Farm already made (probably Works made). 1896–1902 superphosphate replaced by 400 lb. basic slag.

(11) K, Mg omitted 1917, 1918.

(12) No nitrogen applied 1874, 1875, 1884, 1901, 1903.

(13) To correct acidity that had developed on Series A and AC ground chalk (5 tons/acre) was applied in spring 1956. To prevent further acidity developing a scheme of quinquennial chalk applications was introduced, the amount being based on the acidifying effect of the ammonium sulphate and rape cake (Series A 31·6, AC 47·4, C 15·8 cwt. $CaCO_3$/acre).

(14) Nitrogen: 86 lb. N/acre in 400 lb. ammonium salts, 420 lb. ammonium sulphate, 550 lb. sodium nitrate; 98 lb. N/acre was assumed to be supplied by 2,000 lb. rape cake; castor bean meal from 1955 supplied 86 lb. N.

Phosphorus: 1845–58 21 lb. P supplied by 275 lb. superphosphate, from 1856 29–30 lb. P supplied each year.

Potassium: 40·7% K in potassium sulphate, 45% K in pearl ash.*

Sodium: 39·3% Na in sodium chloride, 34% Na in soda ash.*

Magnesium: 10·0% Mg in magnesium sulphate.

* *J. R. agric. Soc.* 1852, **13**, 449.

(15) Cultivation and application of manures. 1871–1929 mangold leaves ploughed in in autumn, land reploughed in spring, harrowed, the land bouted (1888–1929 the bouts split back). From 1930 land ploughed in autumn only. To 1895 the seed was dibbled in, then drilled 26 inches between rows on ridges till 1929, on the flat from 1930. On plot 9, 1876–1902, the seed was drilled on the flat rows 22 inches apart, from 1903 as the remainder of the experiment. Lawes and Gilbert loosened 2 inches of the subsoil (between 6 and 8 inches) on several occasions by running a plough without mouldboard along the furrow bottom. In the winter of 1929–30 steam tackle was used to move a cultivator working at 12–15 inches through the soil and this brought some subsoil to the surface.

N: Till 1895 the N fertilisers were sown at the same time as the minerals (except 1892 when half was applied as a top dressing). 1896–1912 applied as a top dressing, by hand, between the rows. From 1913 one-third applied to the seedbed, remainder as a top dressing.

P: 1845–81 superphosphate drilled along each planting ridge. From 1882 broadcast with the K, Na, Mg.

K Na Mg fertilisers and rape cake applied in the spring and worked into the seedbed.

FYM: 1845–87 put on the flat in spring prior to bouting, 1888–1929 put between the bouts after the first bouting then covered in by the second bouting. 1930–59 applied just before autumn ploughing.

and Series N because of a depression in the land, known as " the valley ".

Before proceeding to discuss the results of the experiment, some features in the history of the site before the experiment need mention (fuller details of this period and of the period of the experiment are in Tables 1 and 2). Although the Mangold Experiment began in 1876, many of the plots had received the same treatment since 1861; some had received the same manures since 1845, though the amounts had often varied. Series O, A, AC and C (no nitrogen, ammonium sulphate and rape cake with and without ammonium sulphate) were started in the turnip experiment 1845, but Series N (sodium nitrate) came later in the swede experiment 1856–70. To make room for Series N, Lawes and Gilbert shortened the total width of Series A, AC and C and took in land at the upper part of the south slope of " the valley ". Before this the whole of " the valley " was used for experiments in which various manures, e.g., guano and phosphates, were applied. There is indeed a record in one of Lawes' notebooks of one material used that may have been the forerunner of ammoniated superphosphate; it was superphosphate " partially neutralised " with gas liquor. Parts of Strip 8 (unmanured) received phosphate in 1843–52. The effects on the chemical analyses of the soil of some of the treatments given before the Mangold Experiment began were still detectable in soil samples taken from the field in 1958.

Yields of Mangolds

Watson and Russell gave the mean yields of mangolds for two periods of the experiment, 1876–94 and 1904–40, because there were treatment changes in 1903 but none in each of the periods selected. Table 3 gives their figures and those for the last period, 1941–59. The outstanding feature of the table is the decrease in the yields of nearly all plots in the last period compared with either the first or second period. Except for the yields of the plots on Strips 2 and 7, where changes were made in 1903 in the mineral manuring, there was good agreement between the two earlier periods, and the only consistent differences were small (1–2 tons roots/acre less in the second period). These differences occurred where no K, Na or farmyard manure was supplied, and they therefore probably reflect the exhaustion of soil potassium. Although the dressing of rape cake supplied about 30 lb. K/acre, this was not enough to prevent a similar decrease in the second period on those rape-cake plots that received no fertiliser K, Na or farmyard manure. The differences between the yields of the second and third period were much greater. The yields of roots of the plots which received only inorganic fertiliser were 4–6 tons/acre lower in the last period, even where N, P, K; N, P, Na; and N, P, K, Na were applied, and on the farmyard manure plots they were 8 tons roots/acre lower. No loss of yield occurred with rape cake, alone or with ammonium sulphate only, but at the higher levels of yield obtained when P, K; P, Na; or P, K, Na fertilisers were added with the rape cake, the decreases for the third period were similar to those for the plots which received inorganic fertilisers only.

TABLE 3

Mangolds, Barnfield: mean yield of roots (tons/acre)

Series:	O			A			N			C			AC		
	No nitrogen			Ammonium sulphate			Sodium nitrate			Rape cake			Rape cake + Ammonium sulphate		
Strip	1876–94	1904–40	1941–59	1876–94	1904–40	1941–59	1876–94	1904–40	1941–59	1876–94	1904–40	1941–59	1876–94	1904–40	1941–59
8 No P or K	3·8	3·0	1·5	6·0	5·6	5·8	10·2	10·6	8·1	10·2	8·3	8·4	10·1	7·5	8·1
5 P	5·0	4·0	2·2	8·3	6·8	7·4	15·7	16·1	11·7	12·0	9·4	9·8	11·2	8·8	9·3
6 P, K	4·5	3·8	2·1	13·7	14·5	11·7	15·5	16·8	12·3	18·0	17·6	14·4	22·1	22·0	18·9
7 P, Na, Mg [1] ...	(5·9)	4·0	2·2	(15·0)	16·1	12·2	(15·9)	18·4	12·4	(18·9)	19·2	15·1	(22·0)	21·5	17·0
4 P, K, Na, Mg ...	5·3	4·2	2·7	15·5	15·5	12·8	18·3	19·0	14·4	20·7	20·7	15·8	25·0	26·4	19·1
1 FYM	16·8	17·4	8·9	22·1	22·0	18·1	23·2	28·0	20·0	23·6	23·0	17·9	24·5	23·2	19·9
2 FYM, P, K * ...	(17·0)	19·9	11·3	(21·4)	26·9	19·6	(24·2)	29·4	21·7	(23·3)	27·8	20·7	(23·5)	29·4	23·5

* The figures in brackets are means for the period, but the treatments differed from that given later. See Table 1 (notes 6 and 8).

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The lower yields in the last period of the experiment were mainly because responses to P, K and Na fertilisers, and to farmyard manure, were much smaller. Farmyard manure decreased the responses to PK fertilisers (N fertilisers present) by nearly the same amount in the second and third periods, 5½ tons 1904–40 and 5 tons 1941–59. This suggests that the activity of the PK nutrients in farmyard manure remained constant, while the activity of the same nutrients in the form of fertilisers was considerably less in the last period. The response to N, however, was not less, indeed on the farmyard manure strip (Strip 1) it was greater in 1941–59. Tables 4 and 5 show the effects of the nutrients added as fertilisers on yield for the periods when comparison is possible.

TABLE 4

Increase of yield of roots by N fertilisers in the absence of farmyard manure
(Barnfield—tons/acre)

	Minerals		
86 lb. N/acre applied as	P, K	P, Na, Mg	P, K, Na, Mg
Ammonium sulphate			
1876–94	9·2	—	10·2
1904–40	10·8	12·2	11·3
1941–59	9·6	10·0	10·1
Sodium nitrate			
1876–94	11·1	—	13·0
1904–40	13·1	14·5	14·8
1941–59	10·2	10·2	11·7

TABLE 5

Increase of yield of roots by K, Na and Mg in absence of farmyard manure
(Barnfield—tons/acre)

		N applied, lb./acre			
		86	86	98	184
		Sodium nitrate	Ammonium sulphate	Rape cake	Rape cake + ammonium sulphate
K	1876–94	−0·2	5·4	6·0	11·0
	1904–40	0·8	7·7	8·1	13·2
	1941–59	0·6	4·3	4·6	9·6
Na + Mg ...	1904–40	2·4	9·3	10·9	12·7
	1941–59	0·7	4·8	5·3	7·7
K, Na + Mg	1876–94	2·6	7·2	8·7	13·9
	1904–40	2·9	8·7	11·2	17·6
	1941–59	2·7	5·4	6·0	9·8

Tables 6 and 7 compare the effects of N and PK fertilisers with and without farmyard manure.

The total effect of farmyard manure was much less in the last period (Table 8). Applied alone or with PK fertilisers, it increased yield by only half as much as in the preceding period, a fall in response of 7 tons roots/acre. Applied with N fertilisers, the mean effect of farmyard manure was increased by 4 tons in the third period, compared with 1·5 tons in the second period. Because in the third period the response to farmyard manure fell by more than

TABLE 6

Increase of yield of roots by N fertilisers alone and in presence of farmyard manure and PK fertilisers
(Barnfield—tons/acre)

			In presence of					
	O		PK		FYM		FYM + PK	
Effect of	1904–40	1941–59	1904–40	1941–59	1904–40	1941–59	1904–40	1941–59
Ammonium sulphate	2·6	4·3	10·8	9·6	4·6	9·2	8·0	8·3
Sodium nitrate ...	7·6	6·6	13·1	10·2	10·6	11·1	9·4	10·4
Rape cake	5·3	6·9	13·8	12·3	5·6	9·0	7·8	9·4
Rape cake and ammonium sulphate ...	4·5	6·6	18·2	16·8	5·8	11·0	9·5	12·2

TABLE 7

Increase in yield of roots by PK fertilisers alone and in presence of farmyard manure
(Barnfield—tons/acre)

	Ammonium sulphate	Sodium nitrate	Rape cake	Rape cake + ammonium sulphate
1904–40				
No FYM	8·9	6·3	9·3	14·5
FYM	4·9	1·4	4·8	6·2
Difference	4·0	4·9	4·5	8·3
1941–59				
No FYM	5·9	4·2	6·0	10·8
FYM	0·5	1·7	2·8	3·6
Difference	5·4	2·5	3·2	7·2

TABLE 8

Increase of yield of roots by farmyard manure in absence and presence of other fertilisers
(Barnfield—tons/acre)

			N Fertilisers			
		O	Ammonium sulphate 86 lb. N	Sodium nitrate 86 lb. N	Rape cake 98 lb. N	Rape cake + ammonium sulphate 184 lb. N
No minerals	1904–40	14·4	16·4	17·4	14·7	15·7
	1941–59	7·4	12·3	11·9	9·9	11·8
PK ...	1904–40	16·2	12·4	12·5	10·2	7·4
	1941–59	9·2	7·9	9·4	6·3	4·6

did the response to K or Na, there was a change in the relation between the yields with farmyard manure and with fertilisers. Without rape cake in the first and second periods, farmyard manure gave 1 ton roots/acre more than PK fertilisers when the N fertiliser was ammonium sulphate (86 lb. N/acre), but 1 ton less when it was sodium nitrate. In the last period both forms of N (with PK) gave better yields than farmyard manure. The extra yields were:

Ammonium sulphate + PK . . . 2·8 tons roots/acre
Sodium nitrate + PK . . . . 3·4 tons roots/acre

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Other than the differences mentioned, the general conclusions about the effects of fertilisers, rape cake and farmyard manure on the yields of mangolds in the Barnfield experiment are substantially the same for the three periods (Table 3). In addition to the main Strip and Series scheme, there were two other treatments, one on plot 9 and the other on half of plot 4N (see footnotes 7 and 11, Table 1). Plot 9, where the treatment was changed in 1903 to provide a test of P in the presence of K, Na, Mg, does not give a valid measure of the P response because of residues from the treatment during 1876–1902. Plot 4Nb has received no sodium since 1903 (for full treatments on plots 4Na and 4Nb see Table 1). As mean yields on 4Na and 4Nb are similar, sodium as such seems inessential with the existing manurial treatments.

Kalamkar[8] examined the variations in yield from 1876 to 1930, and separated the variations into three kinds: (1) steady diminution of yield, ascribable to soil deterioration; (2) other slow changes, ascribable to factors that vary regularly from year to year; (3) the residual variation, called the annual variation, ascribable to factors which vary irregularly from year to year, including seasonal weather conditions, experimental errors, etc.

Deterioration and slow changes accounted for only very small fractions of the total variation. Since then, however, response to K, Na fertilisers and to farmyard manure has become much smaller. The composition of farmyard manure may fluctuate from year to year, but longer-period changes are also possible, for example, from 1939 to 1946, when concentrates for feeding animals were scarce. The behaviour of N fertilisers in the presence and absence of farmyard manure for the two periods 1904–40 and 1941–59 (Table 6) indicates that the composition of the manure may have changed. The variations in responses to N fertilisers are best determined by comparing yields in the presence of PK fertilisers and of farmyard manure alone, not FYM + PK, as FYM itself supplies much P and K. During 1904–40 the responses to N fertilisers (omitting $NaNO_3$, because it provides an additional nutrient, Na) were 10·8–18·2 tons/acre in the presence of PK fertilisers but only 4·6–5·8 tons when farmyard manure was present, a loss which can be attributed to the effect of the N in the farmyard manure. In the third period farmyard manure had very little effect on the responses to the N fertilisers except at the very high level of N (184 lb. N/acre in rape cake + ammonium sulphate). These results indicate that the farmyard manure in the third period contained less available N on average than in the preceding period, and this is why response to farmyard manure was smaller. Table 6 also shows that even the "richer" farmyard manures in the second period had little effect on the responses to N fertilisers, provided that extra PK was supplied. In previous accounts of the Barnfield Experiment the figures for the composition of farmyard manure were average values from the Rothamsted Farm. Table 9 contains the average contents of total N, P and K in 14 tons of farmyard manure at different times in the history of the field.

Since 1941, the farmyard manures contained less nitrogen than previously, confirming the deduction already made about those used between 1941 and 1959. The amounts of P and K also changed,

TABLE 9

Composition of farmyard manures at Rothamsted

	N	P	K
	lb./14 tons of manure		
1850–60	200	35	140
1860–80	200	35	195
1900–10	200	35	85
1930–40	200	45	205
1941–50	170	40	160
1951–59	160	25	140

but these changes were not reflected in the influence of farmyard manure on the effects of PK fertilisers. This could be expected, because the PK residues from earlier applications of richer manures would remain active for a longer period than residues of organic nitrogen. Mineral nitrogen is produced slowly from old organic residues. A further factor, recorded in Table 2, Note 15, may have contributed to the lower effectiveness of farmyard manure in the last period of the experiment. Up to 1929 the farmyard manure was applied in March–April, but since then it has been ploughed in during late autumn or early winter. Comparisons of winter and spring applications of farmyard manure in other experiments at Rothamsted show a small gain of about 1 ton of potatoes/acre in favour of the spring applications.

The yields from Barnfield, however, provide no clue to the reason or reasons for responses to K and Na fertiliser also becoming less. The grades of the potassium sulphate and sodium chloride were not lower at the end of the experiment; nor was the time of application changed.

YIELDS OF SUGAR BEET

Four rows of sugar beet were grown on each plot of the Mangold Experiment during the last 14 years, except 1948 and 1956, when crops failed. For mangolds the ratio of tops to roots is small ($\frac{1}{4}$–$\frac{1}{5}$) but the ratio is much larger for sugar beet (1), and in Table 10, therefore, the mean yields for tops and for roots of sugar beet are given. In this set of results no comparison is possible between sodium nitrate and ammonium sulphate in the presence of the full

TABLE 10

Sugar beet, Barnfield: Mean yields, tons/acre, 1946–59

Series:	O		A		N		C		AC	
	No Nitrogen		Ammonium sulphate		Sodium nitrate		Rape cake		Rape cake + ammonium sulphate	
Strip	Tops	Roots	Tops	Roots	Tops	Roots	Tops	Roots	Tops	Roots
8 No P or K ...	2·0	1·5	4·9	4·2	6·1	5·0	7·5	5·6	9·0	6·4
5 P	2·1	1·9	4·8	5·0	7·4	6·7	6·6	6·9	9·3	7·2
6 PK	1·9	1·6	5·3	6·6	6·6	6·2	6·8	8·2	10·4	9·5
7 P Na Mg ...	2·1	1·8	6·4	7·2	7·8	7·2	8·4	7·7	11·7	9·0
4 P K Na Mg	2·0	1·8	5·8	7·2	7·5	8·0 *	7·5	9·1	10·2	10·3
1 FYM ...	5·2	6·2	12·2	11·5	10·6	11·1	10·3	11·4	12·1	11·4
2 FYM P K ...	5·5	5·9	9·0	8·6	11·0	9·9	9·8	9·8	11·2	10·3

* Sodium nitrate replaced by a mixture of potassium and calcium nitrates.

complement of minerals (P, K, Na, Mg) because the manuring of the half plot of 4N, on part of which the sugar beet was grown, was changed in 1903. Sodium was replaced by calcium, and the nitrogen was applied as calcium and potassium nitrates.

The general pattern of the effects of the manurial treatments on the yields of sugar beet was similar to the pattern for the mangolds in the third period. For sugar-beet roots ammonium and nitrate nitrogen at an equal rate of N (86 lb./acre) gave the same increase, 5 tons/acre, in the presence of PK or P, Na fertilisers. Higher levels of N gave greater increases. Potassium, as potassium sulphate, and sodium, as sodium chloride, each increased the yield by 2 tons/acre where ammonium sulphate was used, but neither fertiliser had an effect when the nitrogen was supplied as sodium nitrate. NPK fertilisers containing 86 lb. N/acre as ammonium or nitrate gave 1–2 tons more roots per acre than farmyard manure.

The yields of sugar beet from the treatment farmyard manure + PK fertilisers show a new feature for Barnfield. Where N fertilisers and farmyard manure were applied, adding PK fertilisers decreased (1–3 tons) the yield of sugar beet but not of mangolds. Table 11 gives the effects of PK fertilisers in the presence and absence of farmyard manure for sugar beet and mangolds (third period). Effects on plots which received sodium nitrate are omitted for the reason stated when discussing Table 6.

TABLE 11

Effect of PK *fertilisers, Barnfield: Roots tons/acre*

	In presence of		
Effect of PK	Ammonium sulphate	Rape cake	Rape cake + ammonium sulphate
		Sugar beet 1946–59	
No FYM	2·4	2·6	3·1
FYM	−2·9	−1·6	−1·1
		Mangolds 1941–59	
No FYM	5·9	6·0	10·8
FYM	1·5	2·8	3·6

TABLE 12

Increase of yield of sugar beet and mangolds by N *fertilisers in the presence and absence of farmyard manure and* PK *fertilisers*

Barnfield (*roots tons/acre*)

	In presence of					
	PK		FYM		PK + FYM	
Effect of	Mangolds	Sugar beet	Mangolds	Sugar beet	Mangolds	Sugar beet
Ammonium sulphate	9·6	5·0	9·2	5·2	8·3	2·7
Rape cake	12·3	6·5	9·0	5·2	9·4	3·9
Rape cake + ammonium sulphate ...	16·8	7·9	11·0	5·2	12·2	4·4

Mangolds 1941–59. Sugar beet 1946–59.

Without farmyard manure, the PK fertilisers increased the yields of both crops, but only of mangolds with farmyard manure. The increases were greater, and the decreases less, at the higher levels of nitrogen. Farmyard manure has behaved consistently with sugar beet and mangolds in decreasing for each crop the responses to PK fertilisers, but with sugar beet by enough to de-

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crease yield. This effect must not be attributed solely to either source of P and K (fertilisers or farmyard manure), but to the total amount of P and K from the two sources. At the levels of N used, the total was excessive for sugar beet and near the level for maximum yield for mangolds. The effect on sugar beet of PK fertilisers + FYM was therefore an intensification of the effect on mangolds. This difference between the two crops is also reflected in the responses to N fertilisers (Table 12).

Sugar beet responded much less to N fertilisers in the presence of PK fertilisers + FYM than with either alone, whereas mangolds gave similar responses.

Sugar percentages were determined only in the last six crops of beet. The mean for the experiment was 16·7, and the main effects of the manurial treatments were:

	Changes in percentage of sugar
Nitrogen fertilisers	−0·4
Potassium sulphate	+0·3
Sodium chloride + magnesium sulphate ...	+0·4

Nutrient Contents of the Crops

Chemical analyses were not made of the mangolds from 1904 to 1940, and previous accounts of Barnfield dealt with analyses made in some years between 1876 and 1902. Those published by Lawes and Gilbert did not include all plots, and full sets of analyses, tops and roots separately, were first made in the last 2 years of the experiment, 1958 and 1959. The sugar beet were also analysed. Results for the 2 years are not adequate to represent the period 1941–59, but they do provide a good indication of the main treatment differences, because treatment effects on yield in the 2 years resembled those for the longer period.

Although the concentrations of nutrients in plants are important, there is too little information about mangolds (and many other crops) for the results to be interpreted satisfactorily in terms of levels of deficiency, excess or toxicity. The discussion here is mainly on the effects of the manurial treatments on the amounts per acre of each nutrient in the crops, with only an occasional reference to percentages in the crops and to the distribution of nutrients between tops and roots.

Table 13 gives the yields of dry matter and the nitrogen and phosphorus contents of plants from some of the main manurial treatments.

Although farmyard manure contained nearly twice as much nitrogen as each of the N fertilisers, the crop on the plot receiving FYM only took up little more than half as much nitrogen as the crop receiving N fertilisers. This is different from the early years 1876–1900, when the amounts of N taken up from the two sources of N were nearly equal. In the early years and at the end of the experiment more nitrogen was taken up by mangolds from sodium nitrate than from ammonium sulphate; the extra showed more in the percentage of nitrogen in the crop than in increase in yield. The figures in Table 13 cannot be used to determine precisely what

TABLE 13

Dry-matter yields and N *and* P *contents of mangolds and sugar beet, Barnfield 1958–59 means*

	cwt./acre			lb. element/acre					
	Dry matter			Nitrogen			Phosphorus		
Series:	O	N	A	O	N	A	O	N	A
Strip	Mangolds tops + roots								
1 FYM	32	60	62	48	142	136	11	22	23
2 FYM, P, K ...	34	59	54	56	151	137	12	20	23
4 P, K, Na, Mg ...	15	49	42	18	102	76	4	16	16
6 P, K	12	40	42	14	89	72	3	13	15
7 P, Na, Mg	14	43	41	15	86	74	4	13	15
	Sugar beet, tops + roots								
1 FYM	51	80	77	62	140	148	10	16	18
2 FYM, P, K ...	44	72	70	56	136	140	9	16	20
4 P, K, Na, Mg ...	15	63	54	18	102	76	3	11	11
6 P, K	13	51	54	15	80	76	2	9	10
7 P, Na, Mg	17	67	60	18	122	83	3	12	10

percentage was recovered by the crop of the nitrogen applied in a single dressing of N fertiliser or FYM. In this experiment the tops of the crop are ploughed back into the soil each autumn, and how much nitrogen this makes available to the crop in the next year is not known. Also, FYM and N fertiliser dressings exceeding 0·5 cwt. N/acre leave nitrogen residues in the soil, the availabilities of which cannot be estimated in this experiment.

The crops contained only about $\frac{1}{6}$ as much phosphorus as nitrogen. The percentages of P in the crops grown with ammonium sulphate were consistently higher than with sodium nitrate (mean increase 0·02% P), but the P removed per acre was almost identical for the two N fertilisers. The figures in Table 13 confirm that farmyard manure provides enough P for mangolds and sugar beet, and superphosphate applied to the farmyard-manure plots did not increase the amounts of P in the crops. Further, applying an N fertiliser to the farmyard-manure plots, which doubled the yield of dry matter, also doubled the uptake of P per acre. The farmyard manure (14 tons/acre) contained 25 lb. P and the superphosphate ($3\frac{1}{2}$ cwt./acre) 30 lb. P. At this level of application together with the P residues in the soil from previous applications the crops took up similar amounts of P from the organic manure and the inorganic fertiliser. The availability of the phosphorus in the two materials needs testing with smaller dressings, but their similar behaviour on Barnfield accords with the analysis of Rothamsted farmyard manure, in which about $\frac{1}{3}$ of the P is water-soluble.

Table 14 shows the potassium, sodium and magnesium contents of mangold and sugar-beet crops from plots which received no farmyard manure. The mineral manure treatments were the four combinations of (1) potassium sulphate (204 lb. K/acre) and (2) sodium chloride with magnesium sulphate (78 lb. Na and 20 lb. Mg/acre); all plots received N and P fertilisers.

The figures in the table are averages of three of the Series treatments, A (ammonium sulphate), C (rape cake) and AC (ammonium sulphate and rape cake). Each Series treatment crossed all the mineral manure Strip treatments, but Series N (sodium nitrate)

TABLE 14

Contents of* K, Na *and* Mg *in mangolds and sugar beet, Barnfield means for 1958–59*

Strip	K Man-golds	K Sugar beet	Na Man-golds	Na Sugar beet	Mg Man-golds	Mg Sugar beet
	lb. element/acre in tops + roots					
4, K, Na + Mg ...	192	134	58	39	10	12
5 —	71 †	80 †	20	21	7	13
6 K	187	138	22	19	8	11
7 Na + Mg ...	79	60	99	74	11	13

K 204 lb. K/acre as potassium sulphate.
Na 78 lb. Na/acre as sodium chloride.
* Means of three series: ammonium sulphate, rape cake, ammonium sulphate + rape cake. All plots received P as superphosphate.
† Rape cake supplied 25–30 lb. K/acre and K contents on Strip 5 are therefore greater than the amounts of K released from soil minerals.

and Series O (no nitrogen) were omitted from the averages, the first because it supplied sodium and the second because very poor crops are produced on this soil when nitrogen is withheld.

With potassium sulphate, the mangolds contained 40% more K than the sugar beet, but without contained similar amounts. Similarly, mangolds contained more Na than sugar beet where sodium chloride was given, but not otherwise.

Table 15 shows increases in K, Na and Mg produced by the fertilisers.

TABLE 15

Effect of potassium sulphate and sodium chloride on the uptakes of K *and* Na *by mangolds and sugar beet, Barnfield means 1958 and 1959*

Effect of *	Mangolds K	Mangolds Na	Mangolds Mg	Sugar beet K	Sugar beet Na	Sugar beet Mg
	lb. element/acre (tops + roots)					
K in absence of Na + Mg	116	2	1	58	−2	−2
Na + Mg in absence of K	8	80	4	−20	53	0
K and Na + Mg present ...	121	38	3	54	18	1

* In the presence of N and P
K at 204 lb./acre
Na at 78 lb./acre
Mg at 20 lb./acre

The extra amounts of K in the crops were for mangolds equal to one-half and for sugar beet one-quarter of the 204-lb. dressing of fertiliser K. Where Na fertiliser was applied without K, the extra amount of Na in the mangolds equalled all the 78 lb. of Na applied as sodium chloride; for sugar beet the extra was two-thirds of the dressing. The Mg changes in lb./acre were small. A main feature of the results in Table 15 is the contrast in behaviour of K and Na in the presence of each other. For each crop the extra amount of K from K fertiliser was the same with and without Na fertiliser (mangolds 116 lb. and 121 lb., sugar beet 58 lb. and 54 lb.), but the extra amount of Na from Na fertiliser was only one-half for mangolds, and one-third for sugar beet, with K fertiliser as without (mangolds 38 lb. and 80 lb., sugar beet 18 lb. and 53 lb.). This comparison

(K_2SO_4 *v.* NaCl) could not be made in the early years because Strip 7 was treated differently since 1903 than previously. By comparing the uptakes in the early years (1878–83) of K and Na from the sodium nitrate and ammonium sulphate sections of the mineral manure strips, Watson showed that K and Na each depressed the uptake of the other. This result was true for the same plots in 1958–59, but the Na depressed K uptake less at the end of the experiment than in the early years. The differences between the two comparisons (NaCl *v.* K_2SO_4 and $NaNO_3$ *v.* K_2SO_4 + $(NH_4)_2SO_4$), in the effect of one ion on the other, however, are not inconsistent. They reflect differences in the Na : K ratios produced in the soil by the different Na fertilisers. The $NaNO_3$ dressing supplied twice as much Na as the sodium chloride dressing. K residues from K_2SO_4 accumulated in the soil, but excess Na was almost wholly leached out, so that the difference in Na : K ratio between the two sets of plots widened as the experiment continued.

Of the total potassium in farmyard manures from the Rothamsted Farm, 70–80% is soluble in water and over 90% in ammonium acetate solution. Nearly all the sodium is water-soluble. The simple design of the Barnfield Experiment does not provide a satisfactory comparison of the effectiveness of potassium in the two forms, fertiliser and farmyard manure, as they operated in the presence of different amounts of nitrogen. Good comparisons require well-established N response curves and K uptakes. However, an approximate adjustment to the K uptake for the difference in N levels indicated that the availabilities of the K from the two sources were similar. For similar reasons an approximate value only, 15 lb. Na/acre, can be given for the uptake of sodium by mangolds from farmyard manure.

Mg fertiliser is thought to affect yields of mangolds on Barnfield little, but leaf symptoms of magnesium deficiency have been seen on some of the plots of the sodium nitrate series. The percentages of magnesium in the leaves of mangolds and sugar beet 1958–59, were less for all plots with sodium nitrate than with ammonium sulphate, except where farmyard manure was applied. The mean values, per cent magnesium in dry matter for each series, were:

Leaves	Sodium nitrate	Ammonium sulphate
	Mg % in dry matter	
Mangold	0·28	0·43
Sugar beet	0·17	0·24

Table 16 gives the uptakes by mangolds (tops + roots) of Mg on both nitrogen series, for plots with and without Mg fertiliser, and without farmyard manure.

The difference between the series was small with Mg fertiliser (0·5 lb. Mg/acre), but much larger without (1·8 lb. Mg). The NH_4 ion and Na ion apparently affected the uptake of the Mg ion similarly where there was adequate available Mg, but ammonium sulphate and sodium nitrate probably differed in their action on the non-exchangeable Mg in the soil. The difference (1·8 lb. Mg) on the plots without Mg fertiliser can be accounted for by the acidifying action of ammonium sulphate. Local chalk contains 0·4% Mg, and

1·5–2 lb. Mg would be released from the chalk in the soil by the dressing of ammonium sulphate (420 lb./acre). The uptakes for sugar beet on the two series differ as with mangolds, 0·1 lb. Mg/acre with and 1·8 without Mg fertiliser. Table 16 shows no effect on uptake by mangolds of Mg by K fertiliser but with sugar beet K decreased uptake by 1 lb. Mg/acre.

About 2 lb. Mg/acre were taken up from the farmyard manure.

TABLE 16

Uptake of Mg *by mangolds on ammonium sulphate and sodium nitrate series in presence and absence of* Mg *and* K, *Barnfield 1958–59*

	Strip 4 (P, K, Na, Mg)	Strip 7 (P, Na, Mg)	Strip 5 (P)	Strip 6 (P, K)	Effect of Na, Mg
	lb. Mg/acre				
Ammonium sulphate	7·7	7·6	6·4	6·4	1·3
Sodium nitrate ...	7·2	7·2	4·6	4·7	2·6
Difference	0·5	0·4	1·8	1·7	

EFFECT OF THE MANURIAL TREATMENTS ON THE SOIL

In the classification of the soils of the Rothamsted Farm by the Soil Survey of England and Wales, the soil of Barnfield, except " the valley ", belongs to the Batcombe Series, with a flinty clay loam surface soil and a yellow-red flinty clay subsoil with vari-coloured mottling at varying depths below 9 inches. In " the valley " the soil belongs to the Charity Series, which differs from the Batcombe Series mainly in the subsoil. The subsoil of the Charity Series is a brown flinty loam or clay loam down to at least 24 inches. About half of each plot which received sodium nitrate is in the Charity Series.

A pH survey of Barnfield in 1953–54 showed that areas within the ammonium sulphate and ammonium sulphate + rape cake series (A and AC) were acid (pH 5 in water). The soils of the other nitrogen series contained chalk, up to 2% $CaCO_3$. A dressing of ground chalk, 5 tons/acre, was applied to Series A and AC in 1956. In 1958, when soil samples were taken for detailed chemical analysis, the pH values for all plots were between 7 and 8. Table 17 gives analysis of the soils for total N, soluble and total P; ammonium acetate-soluble K and Na for the 0–9-inch depth. Soils from other depths (9–12, 12–18, 18–21 inches) were also analysed, and references to the results are made in the text.

Nitrogen

The nitrogen content of the surface soil of Barnfield unmanured plots was 0·01% N lower than the comparable soils of the Broadbalk Wheat and Hoosfield Barley experiments. The effect of inorganic fertilisers (N, P, K) on the N content of the soil was the same in the three experiments, a small gain of 0·01% N. Although the mangold experiment began in 1876, farmyard manure was applied to the site of Strips 1 and 2 from 1856 and the gain in soil nitrogen in 1958 over the unmanured soil was 0·14% N. This increase is less than on

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TABLE 17

Analyses of surface soil, 0–9 inches, Barnfield, 1958

	Strip						
	1	2	4	5	6	7	8
Series	FYM	FYM, PK	P, K, Na, Mg	P	P, K	P, Na, Mg	O
			Total N %				
O ...	0·230	0·237	0·088	0·092	0·087	0·088	0·092
N ...	0·240	0·242	0·101	0·098	0·096	0·096	0·096
A ...	0·258	0·252	0·096	0·094	0·092	0·098	0·098
AC ...	0·286	0·277	0·121	0·116	0·123	0·124	0·116
C ...	0·282	0·274	0·111	0·118	0·119	0·121	0·120
			Total P mg./100 g.				
O ...	124	195	122	120	122	123	78
N ...	122	184	120	128	132	135	61
A ...	133	185	117	115	110	117	61
AC ...	154	205	135	144	141	154	94
C ...	155	217	140	153	156	163	94
			P soluble in 0·01M-$CaCl_2$ g. mols. per litre $\times 10^{-6}$				
O ...	13·2	14·9	2·0	1·5	1·9	1·9	0·6
N ...	10·0	20·0	2·4	2·1	2·0	2·7	0·4
A ...	15·2	32·3	7·3	4·2	4·5	4·5	0·5
AC ...	17·9	34·0	20·1	9·6	14·3	12·4	5·4
C ...	19·9	44·8	7·0	3·7	4·5	5·4	4·1
			P soluble in 0·5M-$NaHCO_3$ mg./100 g.				
O ...	8·3	14·0	5·9	6·1	6·6	6·1	2·3
N ...	7·4	13·2	5·6	5·9	5·4	5·7	1·3
A ...	10·2	16·3	9·9	8·7	8·6	8·0	1·7
AC ...	13·0	17·3	11·7	12·3	15·0	12·2	6·2
C ...	12·8	19·8	9·8	8·8	9·3	9·3	5·6
			P soluble in acetic acid–sodium acetate, pH 4·8 mg./100 g.				
O ...	4·5	8·5	2·0	1·5	2·0	1·4	0·3
N ...	3·0	7·5	2·1	2·0	2·5	2·2	0·2
A ...	3·7	5·9	2·1	1·7	1·6	1·6	0·2
Ac ...	3·4	4·5	2·1	2·8	3·2	3·6	1·3
C ...	4·8	8·0	4·5	3·6	4·1	3·5	1·6
			P soluble in 0·3N-HCl mg./100 g.				
O ...	25	91	35	41	39	36	10
N ...	28	74	38	45	32	37	6
A ...	31	44	26	29	25	22	2
AC ...	37	54	22	41	37	54	12
C ...	40	81	40	23	60	63	13
			K soluble in N-ammonium acetate mg./100 g.				
O ...	54	89	62	17	65	35	18
N ...	33	76	45	13	58	15	12
A ...	24	67	48	12	43	11	10
AC ...	26	64	39	13	35	12	11
C ...	31	84	53	13	53	13	10
			Na soluble in N-ammonium acetate mg./100 g.				
O ...	2·0	1·9	2·0	1·1	0·9	2·6	1·0
N ...	5·8	5·3	4·8	4·1	3·9	5·0	3·8
A ...	1·0	1·0	2·2	0·6	0·7	2·6	0·6
AC ...	1·0	1·2	2·2	0·6	0·6	1·7	0·4
C ...	1·5	1·3	2·2	0·6	0·7	2·3	0·6

O, no nitrogen; N, sodium nitrate; A, ammonium sulphate; AC, ammonium sulphate + rape cake; C, rape cake.

Hoosfield (0·17% N), partly because of the wider row spacing of the crop on Barnfield and partly because of the deep cultivation in 1929–30 to about 12 inches. The still smaller increase (0·13% N) on

Broadbalk with a narrow row crop was caused by the fallowing scheme introduced into the experiment. The extra nitrogen in the soil of the farmyard-manure plots on Barnfield was equal to about one-quarter of the amount applied in the organic manure. On Barnfield, rape cake gave an increase in soil nitrogen similar to the increases on Broadbalk and Hoosfield (0·03% N). The extra nitrogen in the rape-cake plots of Barnfield and of Broadbalk was equal to one-tenth of the nitrogen applied; on Hoosfield the fraction was one-fifth, as the dressing of rape cake was half that of the other fields.

Phosphorus

The site of the no P strip (8) of the Mangold Experiment received phosphate between 1843 and 1852 (Table 2, footnote 4), more than 30 years before this experiment began. At the end of the experiment no part of this strip was as exhausted of P as the no-P plots of the Agdell and Exhaustion Land Experiments. Even on the parts of this strip where sodium nitrate and ammonium sulphate were applied, the total P and $NaHCO_3$-soluble P values of the soil were only a little less than those of the P-residue plots of the Exhaustion Land Experiment, on which the responses by crops to P fertiliser in 1957–58 were small except for potatoes. As two-fifths of Strip 8 also received P, contained in the rape-cake dressing, each year from 1845 to 1959, there is now on Barnfield only a little land at moderately low levels of P and none at very low levels.

Although the sodium nitrate series started in 1861, after the other nitrogen series, the site had received the same amounts of strip manures, because from 1843 these manures had been applied in " the valley " from Series O to Series A. From 1843 to 1852 Lawes and Gilbert used " the valley " land for other experiments in which phosphate manures were applied as dressings across Strips 4–7. In 1958 there were large P residues in the soil from the early cross dressings. The mean value for total P for Strips 4, 5, 6 and 7 of the nitrate series was 128 mg./100 g.; the corresponding values for the ammonium sulphate (Series A) and the no-nitrogen plots (Series O) were 115 mg. and 122 mg. The P uptake by the crops in 1958–59 for the two series (A and N) were almost identical, and therefore none of the extra total P in the soils of the nitrate series should be attributed to the two N fertilisers affecting uptake differently. The soils of the ammonium sulphate plots, however, contained more $CaCl_2$-soluble and $NaHCO_3$-soluble P than the sodium nitrate plots, even though they contained less total P (Strips 4–7). The differences were equally large for P derived from superphosphate and from farmyard manure, but the difference in $CaCl_2$-soluble P on the no-P plots was very small. In contrast to the neutral and alkaline extractants, two acid extractants, $CH_3COOH–CH_3COONa$ (pH 4·8) and 0·3*N*-HCl, dissolved more P from the sodium nitrate plots than from the ammonium sulphate plots. Apparently none of the extractants correctly assessed the available P, but mangolds and sugar beet may be sensitive only to drastic changes in soluble P at very high levels, such as the levels in the P fertiliser and farmyard-manure plots.

There were other differences in the effects of manurial treatments on soluble P, such as the higher values on the farmyard-manure plots than on the superphosphate plots for the same increase in total P (Series O, N, C). There were also further differences between extractants, but it is not possible to decide from the yield and uptake figures in this experiment whether the differences in soluble P by any one method or the differences between methods are important.

Potassium

The Mangold Experiment was the only Classical experiment in which fertilisers were applied to farmyard-manure plots. Much more K consequently accumulated in these plots than elsewhere. Table 17 shows the amounts of K soluble in ammonium acetate for all the surface soil samples (0–9 inches) taken in 1958. The highest values (up to 89 mg. K/100 g. soil) were in the soils of the FYM + PK plots (Strip 2), the next highest were the K fertiliser plots and then the plots with farmyard manure only. The unmanured plot on Barnfield contained more soluble K than the corresponding plots on Broadbalk, Hoosfield, Exhaustion Land and Agdell (Barnfield 18, the other fields 8–10 mg. K/100 g. soil). Strip 7, where from 1903 the fertiliser treatment was P, Na, Mg but earlier included K, had a large residue of fertiliser K (17 mg. K/100 g. soil) in the plot without N fertiliser, but not where nitrogen was applied.

The effects of sodium chloride and sodium nitrate on the amounts of soluble K in the soils which received potassium sulphate were in accord with the uptakes of potassium by the crops. At the high level of soluble K in these plots, applying sodium chloride (78 lb. Na/acre) did not change the amount of soluble K accumulated from the annual dressings of K fertiliser. The increases in soluble K, with and without added sodium (means of Series A, C and AC) were:

Increase in soluble K *on* K *fertiliser plots* (*mg./100 g. soil*)

	Sodium chloride	
Soil depth (in.)	Present	Absent
0–9	34·8	35·0
0–21	20·8	19·2

As on Broadbalk and Hoosfield, considerable K passed into the subsoil on Barnfield, but adding sodium chloride did not affect its distribution. Where more sodium was applied as sodium nitrate (141 lb. Na/acre), the soluble K differed from the ammonium sulphate plots:

Differences between sodium nitrate (*Series N*) *and ammonium sulphate* (*Series A*) *plots in* K *uptakes and soil* K

	Series N–A	
Strip	K uptake (lb./acre)	Soil K soluble in ammonium acetate 0–21 in. (mg./100 g.)
1 (FYM)	−70	4
2 (FYM, P, K)	−38	10
4 (P, K, Na, Mg)	16	−7
6 (P, K)	−27	5

Three of the four sodium nitrate plots had more soluble K, but the fourth on Strip 4 had less. The different result for Strip 4 is consistent with the uptake results, for more K was taken up on this strip with sodium nitrate but less on the other strips. At the lower levels of soluble K in the soils of plots without K fertiliser, sodium nitrate had smaller effects, an increase of 3 mg. soluble K in the surface soil but a small decrease of 1 mg. for full depth 0–21 inches. The crops from two short periods only were analysed, the very early years and the last 2 years, and a satisfactory balance sheet for potassium in this experiment cannot be made. However, at the end of the experiment there was a good linear relation between the amounts of K removed in the roots of the five nitrogen series (leaves are ploughed in) and the amounts of soluble K in the soils for each of the three treatments FYM, K fertiliser and FYM + K fertiliser. The ratio of K uptake by crop to soluble K in the soil differed for each treatment because the amounts of K applied differed. The ratio for each treatment probably changed only gradually during the course of the experiment, because the much soluble K in the soils in 1958 could only come from the accumulation of K residues over a long period. The very small uptake of K on the no-nitrogen series of the K fertiliser treatment allows an estimate to be made of the increase in soluble K were no crop present. The average increase for the surface soil + subsoil would be 40–45 mg. K/100 g. soil. This is only one-seventh of the K applied during the years 1845–1959, the difference is loss by " fixation " in the soil and loss in drainage water. Unfortunately the important comparison of the reactions of farmyard-manure K and fertiliser K with soil cannot be obtained in this experiment, mainly because only one rate of each material was tested, and each supplied a different amount of potassium. There is no information on the proportion of K " fixed " in the soil in the presence of organic matter, but experiments in the laboratory showed that the extra organic matter in the soils of the farmyard-manure plots had no significant effect, in soil-water suspensions, on the equilibrium between water-soluble K and exchangeable K. The ratio was indeed nearly the same for all the soils containing 15–80 mg. K, soluble in ammonium acetate, per 100 g. soil; at the higher levels the ratio increased slightly.

Sodium

The results of soil analysis for sodium and potassium illustrate the difference in the retention of the ions of the two elements by the soil. Even on the no-nitrogen series, where very little sodium was removed by carting off the roots, the extra sodium in the soil from annual applications of sodium chloride for a century was only 1–1·5 mg. Na soluble in ammonium acetate per 100 g. soil. On the sodium nitrate plots, where nearly twice the amount of sodium was applied, the increase in soluble sodium over the ammonium sulphate plots was 3·5 mg. Na/100 g. soil. On the farmyard-manure plots also there was a small increase in sodium, 0·5–1·0 mg. Na compared with the fertiliser plots which had not received sodium chloride or sodium nitrate. The average content of sodium in the farmyard manure used in the experiment is not known, but in samples from the

Rothamsted Farm during the past 3 years, the amount in a 14-ton dressing was 15–20 lb.

Extending the Use of the Barnfield Site

In the Mangold Experiment the two comparisons of sodium (as sodium chloride and sodium nitrate) with potassium each had a defect. Magnesium sulphate was always applied where sodium chloride was given, and no separate test of magnesium was made. Without either Mg fertiliser or the acidifying action of ammonium sulphate, only 5 lb. Mg/acre were taken up by mangolds and 7 lb. by sugar beet. The latter figure is low even for medium yields of sugar beet, so that the effect of magnesium on yield cannot be dismissed as negligible for either crop. With sodium nitrate the possibility of a difference in the effects of ammonium and nitrate nitrogen on yield may have interfered with the comparison of sodium and potassium. More nitrogen was taken up by the crops from the nitrate than the ammonium salt, and as the dressing 86 lb. N/acre was not high, the extra nitrogen in the crops may not have been merely luxury uptake.

Barnfield contains soils differing widely in the amounts of readily soluble potassium, and so provides an opportunity for extending the work on the value for different crops of K residues in the soil.

On the FYM + PK strip the levels of soluble P and K in the soil were very high, and these, together with the amounts in new dressings of FYM + PK fertiliser (60 lb. P, 350 lb. K), adversely affected the yield of sugar beet. Whether this effect can be reversed by increasing the rate of application of nitrogen can only be decided by further experiment. Though mangolds were not affected in the same way as sugar beet, larger yields might be obtained by giving more nitrogen.

The highest yields on Barnfield were on the FYM + N fertiliser plots, but increasing levels of inorganic nitrogen were not tested to see whether this form of nitrogen only could give equally high yields. Several characteristics of farmyard manure have not been assessed, such as the value of the sodium and magnesium it contains and the higher solubility of the P (in $CaCl_2$ and $NaHCO_3$) in the soil from the farmyard-manure plots than from the superphosphate plots on the no-nitrogen and sodium nitrate series.

Proposals for modifying the cropping and manuring scheme on Barnfield were considered by the Field Plots Committee, and consent to make changes was given by the Lawes Trust Committee. Two changes are proposed for the first stage in extending the scope of the investigations. They are the substitution of several rates of nitrogen as ammonium sulphate and sodium nitrate for the single rate, and growing potatoes on half plots alongside the mangolds.

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