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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

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SUMMARY

This paper describes the results from, and recent modifications to, three rotation experiments in Southern England. The oldest experiment, the Agdell rotation, started at Rothamsted Experimental Station in 1848 and continued, almost unchanged, until 1951. It compared two four-course rotations *a*) swedes, barley, clover (or beans) and winter wheat ; *b*) swedes, barley, fallow and winter wheat. The manurial treatments were : unmanured, PKNaMg fertilisers and NPKNaMg fertilisers applied once every four years to the swedes. There were only six plots and one crop was present each year. From 1952-57 the site was either fallowed or cropped uniformly while acid soils were chalked. Since 1958, the plots have been sub-divided to test, in micro-plot experiments, the value of the P and K residues remaining in the soil.

Two rotation experiments were started in 1899 at Saxmundham Experimental Station, Suffolk. The first (Rotation I) consisted of a four-course rotation of wheat, mangolds, barley and a legume (beans, peas or clover). Manurial treatments, applied each year, included farmyard manure, bonemeal and all combinations of N, P and K fertilisers. There were four replicates of ten treatments and each crop was present each year. The experiment, which continued unchanged until 1965, was modified, between 1966-69, to test the value of larger amounts of farmyard manure and N, P and K fertilisers for the same four arable crops. It was further modified, from 1970 onwards, to compare the production of grass and lucerne and the rates of removals of N and K from the soil.

The Rotation II experiment at Saxmundham tested the same four-course rotation as Rotation I but the treatments varied according to the crop grown. It was designed to determine how limited amounts of farmyard manure and N and P fertilisers could most profitably be used by the four arable crops. It continued unchanged until 1952 and some of the plots were cropped with the original manuring until 1964. From 1965-74 these plots have been used for experiments, which are described briefly, on the value of the residues of phosphate fertilisers for barley, potatoes and sugar beet.

INTRODUCTION

This paper describes three arable rotation experiments, one at Rothamsted and two at Saxmundham, Suffolk (Rotations I and II). These experiments are sited on clay loams (Rothamsted) and sandy clay loams (Saxmundham). Brief descriptions of their physical properties are given by Cooke (this Conference).

The main purpose of this paper is : i) to summarize yields of the crops during the years when the experiments remained unchanged ; ii) to describe the reasons for modifying the treatments in the last 25 years (or less) and the yields that have resulted from these changes ; iii) to relate yields to the amounts of nutrients supplied to the crops and iv) to construct balance sheets which relate net gains by or losses of nutrients from the soils with changes in the available nutrients in the soils.

The following conventions are adopted in this paper. Data are in metric units derived, by conversion, from the original Imperial units. Grain and straw yields are at 85 p. 100 dry matter, grass at 100 p. 100 dry matter. Yields of root crops (in tonnes per hectare, t ha^{-1}) are of fresh clean roots, sugar from beet is given as t sugar ha^{-1}. Nutrients are always given as kg element ha^{-1}.

EXPERIMENTAL METHODS AND MATERIALS USED

Many methods of both crop and soil analyses have changed during the past 25 years. Those given below have been used most widely and any important modifications are described in the text.

Crop analysis

Nitrogen was estimated by Kjeldahl digestion using H_2SO_4-K_2SO_4 and $CuSO_4$ as a catalyst; ammonia was determined by steam distillation or on the Technicon Auto-Analyzer using the method of VARLEY (1966).

Phosphorus was determined, after dry ashing, by either colorimetric estimation with ammonium vanadomolybdate (HANSON, 1950) or on the Technicon AutoAnalyzer using SALT'S (1968) adaptation of the method of FOGG and WILKINSON (1958).

Potassium was determined, after dry ashing, by emission spectrometry using an EEL or Unicam flame spectrophotometer.

Calcium, magnesium and sodium were measured, also after dry ashing, by emission (Ca, Na) or atomic (Mg) spectrometry on a Unicam SP 900 flame spectrometer (SALT, 1967).

Soil analysis

Total nitrogen was determined by Kjeldahl digestion using $CuSO_4$ and Se as catalysts (BREMNER, 1960) ; ammonia released was determined after distillation.

Organic carbon was measured on soil ground < 0.5 mm by the rapid method described by WALKLEY (1947) using a correction factor of 1.35 or by the method of TINSLEY (1950).

Total phosphorus was determined on some early samples by digestion with $HClO_4$ (60 p. 100) ; most determinations were made, after fusion with Na_2CO_3 (MATTINGLY, 1970), by colorimetric estimations either manually (FOGG and WILKINSON, 1958) or by SALT'S (1968) adaptation of the method of MURPHY and RILEY (1962).

Bicarbonate-soluble P was measured after extraction with 0.5*M* $NaHCO_3$ (OLSEN *et al.*, 1954) either manually, after neutralisation, by the $SnCl_2$-molybdate method (TRUOG and MEYER, 1929) or on the Technicon AutoAnalyzer (SALT, 1968).

0.01M calcium chloride soluble P was measured (usually using a 1:10 soil : solution ratio) as described by SCHOFIELD (1955) ; P was estimated either manually (TRUOG and MEYER, 1929) or on the Technicon AutoAnalyzer (SALT, 1968).

Exchangeable K and Mg were extracted from soils with N-ammonium acetate by the semi-micro method of METSON (1956) and K measured by emission and Mg by atomic absorption spectrometry on a Unicam SP 900 flame spectrophotometer. Exchangeable K was measured on some samples by successively extracting 6.25 g soil with N-ammonium acetate (250 ml).

Calcium carbonate was estimated manometrically (COLLINS, 1906 ; WILLIAMS, 1948) or, on a few samples containing little $CaCO_3$, by the method of TINSLEY, TAYLOR and MOORE (1951).

pH was measured using a glass electrode and a 1:2.5 soil : solution ratio either in water or 0.01 M $CaCl_2$.

RESULTS

The Agdell rotation experiment, Rothamsted

a) *Manuring and yields*

1848-1951. JOHNSTON and MATTINGLY (this Conference) have given reasons why LAWES and GILBERT made many of their experiments on crops grown in monoculture. However, in 1848, they started on Agdell field at Rothamsted an experiment which tested two crop rotations and three manurial treatments. There were six main plots, three each for the two rotations. One rotation was the traditional Norfolk four-course with swedes, barley, clover (or beans) and winter wheat (the 'clover rotation') ; in the other rotation a fallow replaced the legume crop (the 'fallow rotation '). Only one crop of the rotation was grown each year.

The manurial treatments were unmanured, P (changed to PKNaMg in 1884) and NPKNaMg ; the manures were applied once in four years to the swede crop. Nitrogen was applied as a mixture of ammonium salts and rape cake. Each fertiliser dressing supplied the following nutrients :

N, as ammonium salts, 48 kg N ha^{-1}.

N, as rape cake, 112 kg N ha^{-1} (in addition, each rape cake dressing supplied 22 kg P ha^{-1} and 22 kg K ha^{-1}).

P, as superphosphate, 32 kg P/ha^{-1} in 1848-95 and 42 kg P ha^{-1} in 1904-51, except in 1896 and 1900 when basic slag, 50 kg P ha^{-1}, was used.

K, as potassium sulphate, 130 kg ha^{-1} in 1848-95 and 220 kg K ha^{-1} in 1896-1951.

In addition, small dressings of Na and Mg, on average 22 kg Na ha^{-1} and 18 kg Mg ha^{-1}, were applied whenever K was given.

The traditional farming practice of the early 1800s was to let sheep eat the roots on the land when soil conditions permitted, thereby returning most of the nutrients for the benefit of the following crop of barley. The value of this practice was tested during 1848-1903 by halving the plots and removing the roots from one half while sheep ate those on the other half. LAWES and GILBERT (1894) discussed the results of this test.

Where ammonium salts were applied, the soils gradually lost $CaCO_3$ and became progressively more acid. After the 1930s yields of swedes were seriously diminished by clubroot (*Plasmodiophora brassicae*), which first appeared on the acid NPK treated plots but gradually spread to the other plots. Because of this disease, and the irrelevance of the manuring to farming in the 1950s, the rotation experiment ceased after the barley harvest of 1951. WARREN (1958) described the experiment up to 1957.

Table 1 gives average yields of the five crops for three periods. The very poor yields of swedes in 1936-51 show how badly they were affected by disease. The two rotations gave similar yields of roots and cereals, the main advantage of the clover rotation being the extra produce as beans or clover.

TABLE I

Agdell rotation : mean yields, 1848-1951

(WARREN, 1958 ; JOHNSTON and PENNY, 1972)

Period and crop	Fertiliser treatment and rotation					
	Unmanured		PK		NPK	
	Fallow	Clover	Fallow	Clover	Fallow	Clover
Swedes (roots, t ha^{-1})						
1852-99	3.2	1.8	20.6	21.5	37.4	36.5
1900-19	2.9	1.0	21.6	28.2	49.0	36.2
1936-51	1.3	0.4	7.8	8.2	7.1	4.9
Barley (1) (grain, t ha^{-1})						
1852-99	1.58	1.51	1.63	1.86	2.35	2.52
1900-19	0.98	0.93	1.18	1.44	1.43	1.96
1936-51	1.08	0.80	1.81	1.99	1.94	1.43
Clover hay (dry matter, t ha^{-1})						
1852-99	—	1.69	—	5.01	—	5.91
1900-19	—	0.71	—	2.73	—	1.55
1936-51	—	1.13	—	3.71	—	1.92
Beans (2) (grain, t ha^{-1})						
1852-99	—	0.93	—	1.24	—	1.66
Wheat (1) (grain, t ha^{-1})						
1852-99	1.98	1.77	2.28	2.38	2.33	2.50
1900-19	1.10	1.14	1.52	1.92	1.70	1.61
1936-51	1.84	1.49	2.43	2.45	2.09	2.43

(1) In all tables, yields of wheat and barley have been corrected to 85 p. 100 dry matter.
(2) Beans were only grown when the clover, undersown in the preceding barley, failed to grow satisfactorily.

In contrast to the small effect of crop rotation on yield there were large responses to the manurial treatments. Until 1919 PK fertilisers alone increased swede yields by 17-27 t ha^{-1}; adding N fertiliser gave further increases between 8-27 t ha^{-1}. Residues of N increased yields of barley which followed the roots by about 0.7 t ha^{-1} in 1852-99 and 0.4 t ha^{-1} in 1900-19 ; the effect was larger in the first period because the yields given are averages of those obtained after feeding and after carting off the root crop. There were no residual effects of N on the winter wheat, the last crop grown after the application of manures to the swedes, but wheat obtained as much N from the soil after a fallow as it did from the residues of a bean or clover crop. Wheat yields were increased by the PK residues by between 0.3 and 0.6 t ha^{-1} (table 1).

1952-59. In this period no further P and K were given. Soil acidity was corrected by differential chalk dressings, the first given in winter 1953-54. Smaller dressings, applied in 1959 and 1967, raised the pH of the soil (in water) to pH 7.0 or more.

Good crops of beans were grown in 1956 without manures and of potatoes in 1957 with a uniform dressing of N on all plots (table 2). Residues from previous manuring increased bean yields by 1.76 t grain ha^{-1} and potato yields by 23.8 t ha^{-1}. (The design of the original experiment did not make it possible to separate the residual effects of P and K in these two years). In five of the six comparisons between the rotation with fallow and the rotation with clover the latter gave lower yields in the residual years, probably because less P and K remained in these soils due to the extra uptake by the legume crop. Arnold and Close (1961) measured the release of non-exhangeable K from soils from the Agdell rotation in a glasshouse experiment using soils sampled in 1958.

TABLE 2

The effects, measured in 1956 and 1957, of the accumulated residues of fertilisers applied in the Agdell rotation experiment, 1848-1951

(Warren, 1958)

Year	Crop	Fertiliser treatment and rotation, 1848-1951					
		Unmanured		PK		NPK	
		Fallow	Clover	Fallow	Clover	Fallow	Clover
1956	Beans (grain, t ha^{-1})	1.07	0.65	3.29	2.51	2.28	2.41
1957	Potatoes (total tubers, t ha^{-1})	11.0	7.5	36.2	21.6	38.9	35.4

1958-70. Because the PK residues increased yields of beans and potatoes so much their effects were investigated in greater detail. In 1958 each plot was halved and on one half, the value of both the P and K residues for grass was measured during 1958-70 (Johnston and Penny, 1972). On the other half-plot the effects of the P residues on the yields of barley, potatoes and sugar beet were measured during 1959-62 (Johnston, Warren and Penny, 1970).

The experiment with arable crops measured only the P residues ; all crops were adequately manured with N and K. The yields for 1959-60 are summarised in table 3 ; in 1961-62 various methods of incorporating fresh dressings of new P were tested ;

the results were given in detail by JOHNSTON, WARREN and PENNY (1970) and are not discussed further here. The P residues more than doubled the yields of barley and potatoes and increased the yield of sugar by 70 p. 100 (table 3).

TABLE 3

Effect of P residues in the soil and a new dressing of 55 kg P ha^{-1} *on the yield of barley, potatoes and sugar beet grown on soils with and without P residues : Agdell rotation, 1959-60*

(JOHNSTON, WARREN and PENNY, 1970)

	Soil unmanured since 1848	Soil enriched with P residues	Effect of P residues
Barley (grain, t ha^{-1})			
Without new P	1.54	3.41	1.87
With new P (1)	2.89	3.88	0.99
Response to new P	1.35	0.47	—
Potatoes (total tubers, t ha^{-1})			
Without new P	12.0	29.9	17.9
With new P(1)	25.4	38.2	12.8
Response to new P	13.4	8.3	—
Sugar beet (sugar, t ha^{-1})			
Without new P	3.38	5.77	2.39
With new P(1)	4.79	6.00	1.21
Response to new P	1.41	0.23	—

(1) New P 55 kg P ha^{-1}.

Fresh P dressings increased yield more on the impoverished than on the enriched soil *but* giving new P to the poor soils did not increase yields to equal those on enriched soils without new P.

The experiment with grass can be divided into two periods ; during the first, 1958-63, grass was given only N fertiliser. In the second, 1964-70, half-plots were divided to test fresh dressings of both P and K ; subplots testing P received basal dressings of N and K, subplots testing K received basal dressings of N and P. P was applied at 220, 440 and 880 kg P ha^{-1}, K at 260, 520 and 1 040 kg K ha^{-1}. Yields in 1963 were very small because the severe winter of 1962-63 killed much of the grass and they are omitted from the averages given in table 4. The P test ceased in autumn 1969, the K test in autumn 1970. During 1958-62 the grass yielded more on the fallow rotation plots than on the clover rotation plots because the fallow plots lost less P and K between 1848-1951. The annual gain from the PK residues, averaged over all treatments, was 3.47 t ha^{-1} of dry grass between 1958-62, *i.e.* PK residues doubled the yield obtained on the unmanured plots.

Results for 1964-70 show that when K but no P and P but no K were given, treatments NP_0K_4 and NP_4K_0 respectively, the yields on the unmanured and PK plots had been restricted more by shortage of P than by K (table 4). The smallest dressings of fresh P and K both gave large increases in yield, ranging from 0.9 to 4.8 t ha^{-1} for the P dressing and 1.2 to 2.7 t ha^{-1} for the K dressing. When very large dressings of P and K were given (NP_4K_4), yields of grass on the old unmanured and PK plots were almost identical; the slightly larger yield on the old NPK plots was probably due to these plots being wetter than the rest of the field.

TABLE 4

Effect of P and K residues and fresh dressings of P and K on the yield of dry grass (t ha^{-1}) : *Agdell rotation, 1958-70*

(JOHNSTON and PENNY, 1972)

Period and treatment (1)	Fertiliser treatment and rotation, 1848-1951					
	Unmanured		PK		NPK	
	Fallow	Clover	Fallow	Clover	Fallow	Clover
1958-62						
N only	4.08	3.22	6.93	6.58	7.81	7.14
1964-70 (2)						
$N P_0 K_4$	4.18	3.09	6.10	5.10	8.04	6.64
$N P_4 K_0$	6.35	5.84	6.59	7.50	7.19	6.04
$N P_1 K_4$	7.81	7.88	8.38	8.27	8.96	8.67
$N P_4 K_1$	8.23	8.21	8.12	8.71	8.68	8.76
$N P_4 K_4$	8.36	8.24	8.31	8.53	9.16	8.98

(1) Treatments : N, 100 kg N ha^{-1} for each cut of grass,
P_1 and P_4, 220 and 880 kg P ha^{-1},
K_1 and K_4, 260 and 1 040 kg K ha^{-1}.
These dressings of P and K were applied only once, in spring 1964, but the amounts of P and K removed in the grass each year where P_1 P_4 K_1 K_4 treatments were given were replaced by equivalent P and K as fertilisers.

(2) The P test was stopped after the last cut of grass in 1969; the K test after the last cut in 1970.

1970-72. In 1964, when the large dressings of P and K were applied to subplots on the grass half of each plot, similar dressings were applied to subplots on the arable/fallow half-plots. These dressings equilibrated with the soil P and K during 1964-69. In addition, between 1958-69, soil organic matter increased in soils growing grass and decreased in soils which grew arable crops or were fallowed. The original six plots on Agdell had been sub-divided, by the end of 1969, into two groups, each of 48 subplots. The soils in one group contained different amounts of bicarbonate-soluble P, those in the other group contained different amounts of exchangeable K. The 48 plots in each group were divided into two sets, each of 24. In one set, the soils contained, on average, 1.4 p. 100 C, in the other 0.9 p. 100 C.

During 1970-72, an experiment was made on the soils with different amounts of soluble P, which ranged from 3 to 70 mg P kg^{-1}, to investigate relationships between yields of barley, potatoes and sugar beet and the bicarbonate-soluble P in soil and to measure responses of each crop to a dressing of fresh P. Two crops were grown each year and the dressings of fresh P, tested on sub-plots, were 27.5, 55 and 83 kg P ha^{-1} for the barley, sugar beet and potatoes respectively; these dressings were applied cumulatively to the plots during 1970-72. Results for the three crops grown on soils with most organic matter (1.4 p. 100 C) are in figure 1. The results show that there was a well-defined relationship between yield and amount of soluble P in soil for all three crops. Yields increased with increasing soil P up to about 20-25 mg

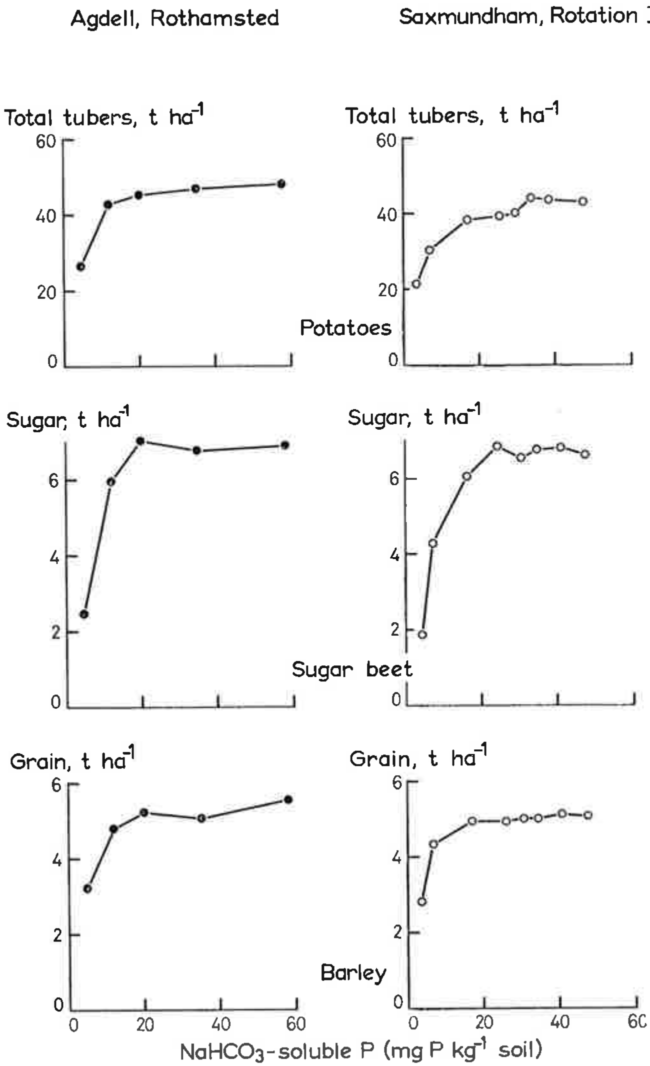

FIG. 1. — *Relationships between mean yields of potatoes, sugar and barley grain and $NaHCO_3$-soluble P in soils of the Agdell Rotation, Rothamsted* (1970-72) *and of Rotation II Saxmundham* (1969-74).

P kg^{-1}; above this level of soil P barley and sugar yields increased little but there were some further small increases in yields of potatoes. Table 5 gives the mean increases in yield from superphosphate applied before planting or sowing.

TABLE 5

Agdell rotation : increases in yields of potatoes, sugar and barley grain (1970-72) *from P applied as superphosphate* (1)

(Mean soil carbon = 1.4 p. 100 C)

$NaHCO_3$-soluble P in soil (mg P kg^{-1})	Increase (t ha^{-1}) in yield of		
	Potatoes	Sugar	Barley
4	+ 19.1	+ 3.46	+ 0.99
12	+ 5.2	+ 0.51	+ 0.30
.0	+ 3.5	+ 0.13	+ 0.09
35	+ 2.1	+ 0.04	+ 0.14
58	+ 5.5	— 0.18	— 0.21

(1) P applied = 83 kg P ha^{-1} (potatoes), 55 kg P ha^{-1} (sugar beet), 27.5 kg P ha^{-1} (barley).

On soils with less organic matter (0.9 p. 100 C) yields of barley on the old NPK plots were considerably smaller at all but the lowest levels of soil P, whereas yields of potatoes and sugar beet were not affected at either level of soil organic matter. We have already suggested that grass grown from 1964-69 probably yielded more on those soils than on others on Agdell because they were wetter. Differences between barley, and potatoes and sugar beet may be explained in the same way. Because soils of the old NPK plots tended to be wetter, barley grown on those plots was often drilled into a wetter seedbed than on the rest of the field and never recovered from this disadvantage. Potatoes and sugar beet, however, were always planted later when the soil had dried more and seedbeds were more uniform over the whole field.

b) *Nutrient removals.*

JOHNSTON and PENNY (1972) estimated the P and K additions to and removals from the soils of the Agdell experiment during 1848-1957. The balance, additions minus removals, and the mean annual change for each treatment are in table 6.

During 1959-60, when the value of the P residues for arable crops was tested, barley and potatoes took up 4.2 and 3.4 kg P ha^{-1} each year from the unmanured soils, about as much as had been taken up by the arable crops in the rotation experiment. The sugar beet removed rather more, about 7.8 kg P ha^{-1}, probably because it has a longer growing season and may remove P from the subsoil. All three crops took up more P from soils with residues and the extra P taken up (average 7.6 kg P ha^{-1}) represents an annual recovery of about 1.5 p. 100 of the P residues in the soil at the end of the rotation experiment. It was impossible to estimate how much K might have been recovered from the residues because the crops received basal dressings of N and K.

TABLE 6

Gains and losses of P and K from Agdell soils, 1848-1951
(JOHNSTON and PENNY, 1972)

Gains and losses of P and K	Fertiliser treatment and rotation, 1848-1951					
	Unmanured		PK		NPK	
	Fallow	Clover	Fallow	Clover	Fallow	Clover
P (kg ha^{-1})						
Additions minus removals	— 325	— 356	+ 436	+ 217	+ 785	+ 632
Mean annual change	— 3.0	— 3.2	+ 4.0	+ 2.0	+ 7.1	+ 5.7
K (kg ha^{-1})						
Additions minus removals	— 1 199	— 1 454	+ 1 576	+ 595	+ 1 445	+ 788
Mean annual change	— 10.9	— 13.2	+ 14.3	+ 5.4	+ 13.1	+ 7.2

Growing grass during 1958-69, at first with N only, but later with NK dressings where P was tested and NP dressings where K was tested, provided an opportunity to estimate how much P and K these soils released over 12 years.

P removed.

Grass took up about as much P (4.6 kg ha^{-1}) from the unmanured soils in both periods; this result agrees well with uptakes by arable crops. Much more P was taken up from the residues, on average 50.6 and 41.4 kg P ha^{-1} in the first and second six years respectively. The extra P (7.5 kg P ha^{-1}) taken up annually from the residues agrees well with the amount (7.6 kg P ha^{-1}) recovered by the arable crops in 1959-62. The annual recovery averaged about 1.6 p. 100 suggesting that, at this rate of release, the residues would last for about 60 years.

K removed.

Rather more K was removed in the second period than in the first (67 and 57 kg K ha^{-1} respectively) from the unmanured soil, probably because the grass benefited from the basal P fertiliser applied to these plots in the second period. However, the similarity between the K removals suggests that grass removed all the K available to it and that this soil, unmanured for more than 110 years, released about 60 kg K ha^{-1} annually. There were large differences in the amounts of K taken up from the residues in the two periods. On average, an extra 77 kg K ha^{-1} was taken up each year during the first six years but only 23 kg K ha^{-1} during the second seven-year period. In the second period the amounts of K removed were limited only by lack of K because at least twice as much K was removed from soils given fresh K dressings in this period. It seemed unlikely, therefore, that much more of the K residues would have been recovered if the experiment had continued, because the grass removed so much less of them during 1964-70 than previously. However, only about 65 p. 100 of the estimated K residues were recovered by the grass and, if the size of the residues was reasonably estimated, the fate of this K requires explaining. It may simply have been leached out of the range of the roots. Alternatively, as release and fixation of K in soils are reversible reactions, some may have become fixed so that its rate of release is now no faster than of 'native' soil-K. A pot experiment, in which surface soils (0-23 cm) from the Agdell experiment, sampled in spring 1967, were cropped exhaustively with ryegrass showed that only about 70 p. 100 of the estimated K residues were recovered by ryegrass in 1289 days. These results (JOHNSTON and MITCHELL, 1974) are in good agreement with those obtained in the field experiment.

c) *Soil analysis and balance sheets.*

The manuring and cropping treatments have produced measurable differences in the N, P and K contents of the soils.

Nitrogen and carbon.

Table 7 gives the N contents of the soils (0-23 cm deep) in 1867, 1913 and 1958.

TABLE 7

Percentage total nitrogen in 0-23 cm depth of Agdell soil

Year	Treatment and rotation 1848-1951					
	Unmanured		PK		NPK	
	Fallow	Clover	Fallow	Clover	Fallow	Clover
1867	0.127	0.130	0.123	0.135	0.129	0.130
1913	0.118	0.141	0.122	0.148	0.127	0.147
1958	0.120	0.145	0.125	0.150	0.115	0.137

On soils of the fallow rotation the effects of time and manuring are similar to those on the Broadbalk soils (JOHNSTON and MATTINGLY, this Conference) with comparable fertiliser treatments, but the levels of soil nitrogen are all slightly larger on Agdell than on Broadbalk. The N content of the unmanured and PK-treated soils of the fallow rotation changed little over nearly 100 years. By 1913 there was a small increase in soil N (0.007 p. 100 N) on the NPK-treated soil partly due to the extra plant residues ploughed in each year, partly because some of the N was applied as rape cake. However, this increase in soil N was not maintained and, by 1958, this soil contained less N than the soil which had been unmanured for 90 years. Between 1913 and 1958 NPK-treated soils in the fallow and clover rotations lost 0.012 and 0.010 p. 100 N respectively. The reason is not known but may be related to the acidity which developed on these soils between 1913 and 1958.

Growing clover or beans once in four years, rather than fallowing the land, consistently increased soil N on both manured and unmanured soils (table 6). Twenty years after the start of the experiment the increase in soil N was small, on average only 0.005 p. 100 N; during the next 47 years there was a further build up of soil N and, in 1913, there was, on average, an extra 0.023 p. 100 N in the clover rotation soils. Between 1913 and 1958, no further soil N accumulated and, in 1958, soils from the clover rotation still contained an extra 0.024 p. 100 N. This probably represents an equilibrium value for the extra N in Rothamsted soil cropped with a legume rather than fallowed for one year in four. This extra N appears, however, to be present in very stable compounds which mineralize slowly because yields of barley, on soils receiving PK but no N fertilisers, were only increased slightly (0.14 t ha^{-1}) although the extra total N in soils from the clover rotation was 650 kg N ha^{-1}.

	PK plots	
	Fallow rotation	Clover rotation
Percentage N in soil, mean of 1913 and 1958 soils	0.124	0.149
Barley, grain t ha^{-1}, mean of 10 rotations 1913-51	1.32	1.46

After 12 years under grass the soil contained an extra 0.22 p. 100 C in the 0-23 cm depth of soil, an increase of 20 p. 100 on the 1958 values. Soils which grew arable crops for four years, and were then fallowed for eight, lost soil carbon, which decreased by about 24 p. 100 over 12 years, probably due to fallowing. Even in 1969 the carbon content of the soils was still smaller on the fallow than on the clover rotation.

A rotation experiment, not described here, compared the value of manures produced by animals given two different types of feed for crops grown in rotation at Woburn Experimental Station, Bedfordshire, from 1876-1911. The manures were compared with fertiliser dressings supplying equivalent amounts of NPKMg; the experiment was considerably modified in 1911 and stopped in 1937. The results were described by VOELCKER (1936). The subsequent history of the site is known in detail and much has been learnt about changes in soil organic matter in this sandy loam soil due to cropping and manuring for nearly 100 years (MATTINGLY, CHATER and JOHNSTON, 1975). Unlike the Rothamsted soils in which the organic matter content has changed slowly or not at all, there has been a marked decrease in the organic matter in the light land at Woburn.

Phosphorus and potassium.

The mean annual P and K balance, additions of P or K minus removals of P or K, for the Agdell soils from 1848 to 1957 has already been given (page 752). These results are related to the bicarbonate-soluble P and the exchangeable K in soil respectively in fig. 2 which also compares other results from experiments at Rothamsted, Saxmundham and Woburn. These results are discussed further later in the paper.

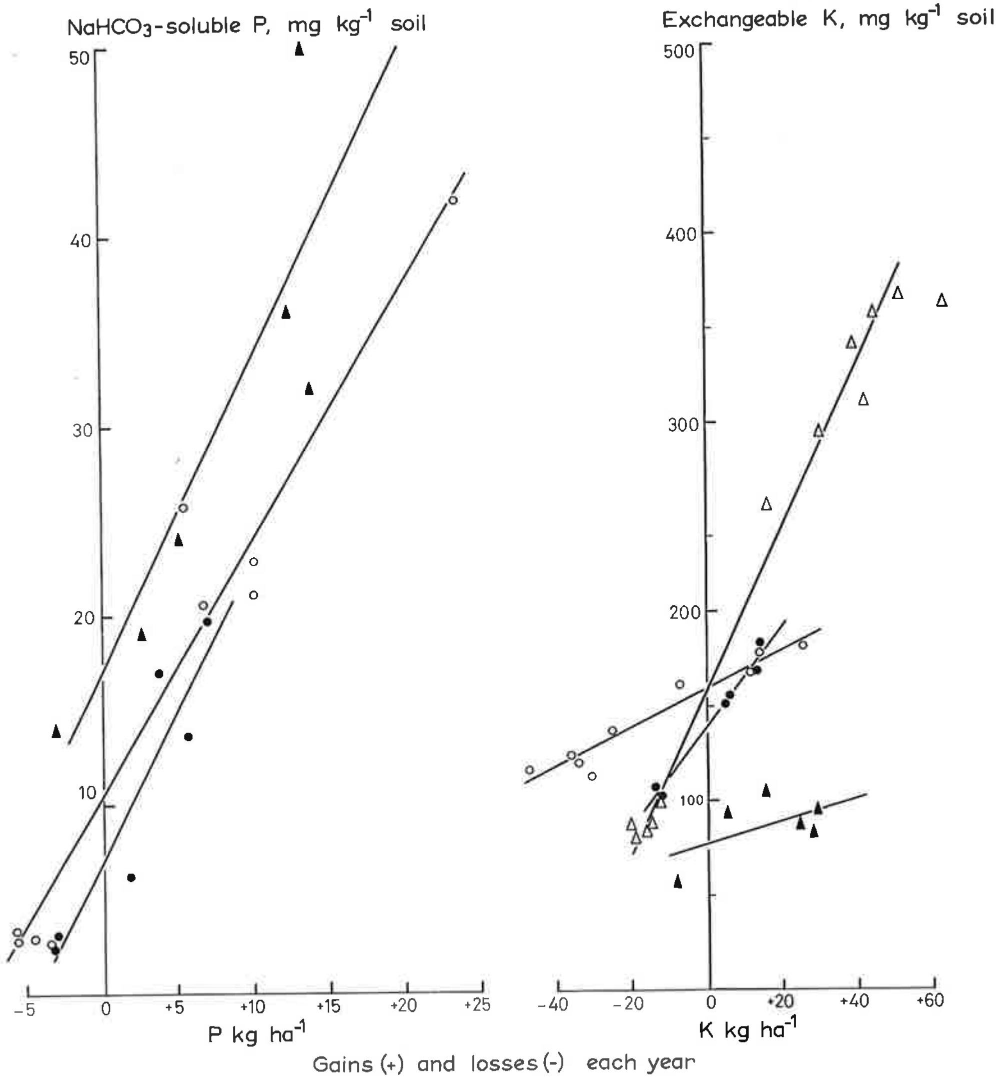

FIG. 2. — *Relationships between annual gains and losses of phosphorus and potassium* (kg ha^{-1}) *and $NaHCO_3$-soluble P and exchangeable K in soils* (0·23 cm) *from*

○ Saxmundham Rotation I, sampled in 1969
● Agdell Rotation, sampled in 1958
△ Broadbalk, Rothamsted, sampled in 1966
▲ Continuous Wheat and Barley, Woburn, sampled in 1956

Saxmundham, Rotation I

Manuring, yields and soil analyses.

1899-1965. This experiment tested all factorial combinations of N × P × K, together with plots given farmyard manure or bonemeal. The ten treatments occurred once in each block ; there were four blocks and each crop in a rotation of mangolds, winter wheat, a legume (beans, peas or clover) and barley was grown every year. Detailed results of the experiment, given by OLDERSHAW (1941), BOYD and TRIST (1966) and WILLIAMS and COOKE (1971), are summarized below. Mean yields from the experiment and the fertilisers tested are in table 8 and soil analyses, as means of the four blocks, are in table 9.

Plots given NPK fertilisers yielded slightly more wheat, barley and mangolds than farmyard manure, supplying about the same quantities of *available* nutrients as the NPK plots, but slightly less beans and 2 t ha^{-1} less clover. Bonemeal, which supplied more than twice as much P as superphosphate, together with about 14-16 kg N ha^{-1}, gave similar yields to superphosphate.

This experiment convincingly demonstrated the importance of superphosphate on this P-deficient calcareous soil and the value of N fertilisers for cereals. N, however, had little effect on yields of mangolds or sugar beet unless P was also applied ; the benefits from K were negligible for the cereals and sugar beet but increased the yields of mangolds, beans, peas and clover.

TABLE 8

Saxmundham, Rotation I : mean yields
(TRIST and BOYD, 1966 ; WILLIAMS and COOKE, 1971)

Treatment	Manuring (1)	Mean yields (t/ha^{-1})					
		Winter wheat (2)	Barley (2)	Mangolds (3)	Beans and peas (4)	Clover (5)	Sugar beet (6) clean roots
1	FYM	2.37	2.03	42.7	2.72	9.98	32.9
2	Bonemeal	1.79	1.34	29.1	1.92	7.08	18.1
3	N	1.74	1.37	12.3	1.42	3.93	7.5
4	P	1.73	1.26	28.4	2.13	7.44	15.6
5	K	1.27	1.00	10.5	1.43	4.47	7.0
6	—	1.28	1.03	10.5	1.37	4.30	5.8
7	PK	1.83	1.39	30.4	2.52	8.47	15.1
8	NK	1.88	1.53	14.1	1.52	4.81	6.0
9	NP	2.38	2.13	42.7	2.12	7.10	24.1
10	NPK	2.43	2.26	45.2	2.61	7.84	25.1
Standard error		± 0.085	± 0.112	± 2.23	± 0.120	—	—
Mean		1.87	1.53	26.6	1.98	6.54	15.7

(1) FYM : 15 t ha^{-1} ; Bonemeal : 500 kg ha^{-1} ; N : sodium nitrate, 39 kg N ha^{-1} ; P : superphosphate 18 kg P ha^{-1} ; K : potassium chloride, 53 kg K ha^{-1}. (2) 1900-61 ; (3) 1906-61 ; (4) grown for 45 years between 1905-61 ; (5) grown for 15 years between 1902-47 ; (6) 1956-65.

During the first 50 years of the experiment yields of barley, wheat and mangolds grown with farmyard manure (treatment 1) or with full NPK manuring (treatment 10) were similar to, or better than, average yields in East Suffolk. Since 1950, however, yields declined, relative to the best yields obtained commercially, and the experiment stopped in 1964.

TABLE 9

Saxmundham, Rotation I : soil analysis, 0-23 cm, 1957
(COOKE, MATTINGLY and WILLIAMS, 1958)

Manuring (1)	$CaCO_3$ (%)	C (2) (%)	N (%)	P (3) (mg kg^{-1})	$NaHCO_3$-soluble P (mg kg^{-1})	Exchangeable K (mg kg^{-1})
FYM	0.72	2.09	0.199	748	33.4	268
Bonemeal	0.74	1.36	0.149	923	7.6	109
N	0.76	1.24	0.136	455	2.8	124
P	0.74	1.34	0.139	601	22.7	116
K	0.88	1.28	0.137	448	2.4	235
—	0.83	1.27	0.135	454	2.5	137
PK	0.91	1.36	0.142	596	19.5	180
NK	0.89	1.28	0.139	446	2.4	205
NP	0.82	1.40	0.146	602	20.8	110
NPK	1.01	1.36	0.144	603	18.8	154
Mean	0.83	1.40	0.147	588	13.3	164

(1) See table 8; (2) P. 100 C : 1.35 × (WALKLEY, 1947) value; (3) corrected to values by fusion analysis (MATTINGLY, 1970).

TABLE 10

Saxmundham, Rotation I : mean yields, 1966-69
(WILLIAMS and COOKE, 1971)

Treatment	Manuring (1)	Mean yields (t ha^{-1})			
		Winter wheat	Barley	Sugar	Beans
1	FYM (2)	4.42	3.63	6.89	3.10
2	Bonemeal	1.93	1.29	2.25	1.77
3	N_2P_2	4.19	3.78	6.76	2.06
4	N_1P_1	3.65	3.16	5.33	2.02
5	N_1P_2K	3.58	2.79	5.38	2.01
6	N_1P_2	3.45	3.09	5.62	2.11
7	N_1P_1K	3.79	3.15	6.31	2.61
8	N_2P_2K	4.69	3.68	6.73	2.54
9	N_2P_1	4.35	4.00	6.74	2.12
10	N_2P_1K	4.42	3.80	6.73	2.67
Mean	—	3.85	3.24	5.87	2.30

(1) FYM : 30 t ha^{-1}; bonemeal : 500 kg ha^{-1}; N : ammonium nitrate-limestone, N_1 and N_2 : 63 and 126 kg N ha^{-1}; P as superphosphate, P_1 and P_2 : 22 and 44 kg P ha^{-1}; K as potassium chloride : 104 kg K ha^{-1}.

(2) In all years, except 1966, 63 kg N ha^{-1} was applied in addition to FYM.

(N manuring included one or two top dressings in 1967-69, see WILLIAMS and COOKE, 1971).

1966-69. The experiment was redesigned in 1965-66 but the original manuring was retained on a small area (30 m^2) of each main plot. WILLIAMS and COOKE (1971) state : « In 1965 we saw no point in continuing the demonstration on whole plots that unfertilised crops at Saxmundham yield little, that phosphate fertiliser is essential and that nitrogen is needed for all crops but legumes ». Nine out of ten main-plot treatments were modified but the amount of bonemeal (treatment 2) remained unchanged to provide a control plot. Yields between 1966-69 on the small areas of each plot which were cropped with unchanged manuring were similar to long-term averages (table 8), and are not given here. Table 10 gives the new treatments and the yields they produced between 1966-69.

The new manuring tested from 1966-69 raised yields of wheat, barley and sugar beet up to and, in several years, well above national average yields. Most of the benefit came from the larger amounts of N and P applied between 1966-69 ; 44 kg P ha^{-1} applied to plots where none had been given before 1965 gave almost as large crops (table 10) as plots which had received 22 kg P ha^{-1} since 1899. At least 126 kg N ha^{-1}, applied late in March or early in April, was needed by wheat, barley and sugar beet and these crops benefited, in the wet summers of 1967 and 1969, from top-dressings providing 63 kg N ha^{-1}. Potassium fertilisers had little effect on yields of wheat and barley but, as in 1899-1965, they slightly increased the yield of beans.

WILLIAMS and COOKE (1971) comment that the seasonal variations in yield did not seem to be related to differences in air temperature in different years and that poor yield seemed associated with i) wet autumns which delayed ploughing and resulted in poor soil conditions and ii) wet springs which leached nitrate. The problems of cultivations and soil structure on the Chalky-Boulder clay soils at Saxmundham are discussed elsewhere (COOKE and WILLIAMS, 1972). The influence of rainfall on nutrient losses from the soils at Saxmundham is described by WILLIAMS (1976).

Yields of grass and lucerne.

1970-76. All plots were divided transversely and one-half of each plot was sown in spring, 1970 with lucerne and the other with a mixture of timothy and meadow fescue. The P and K manuring during the period 1970-74 was the same as in 1966-69. All treatments growing grass were given 100 kg N ha^{-1} for each cut (usually two each year) ; no N was given to lucerne. Mean yields of grass and lucerne were remarkably similar (table 11) and ranged from 8.6-12.1 t ha^{-1} for grass and from 8.5-13.0 t ha^{-1} for lucerne over four years. The mean increase in yield from K was 0.64 t ha^{-1} for grass and 0.86 t ha^{-1} for lucerne. Phosphorus had no effect on yields of grass but slightly increased lucerne yields by 0.16 t ha^{-1}. Fresh dressings (1970-74) plus residues from previous phosphate manuring (1966-69) which, by 1969, had increased the amounts of soluble P in the soils to 11 mg P kg^{-1}, were adequate to maintain yields. The mean exchangeable K in soils previously unmanured, was 126 mg K kg^{-1} and yields of both crops were increased by 6-9 p. 100 from freshly applied potassium chloride.

Nutrient uptakes by grass and lucerne.

The total amounts of N removed by grass were little affected by the amounts of P and K applied ; about 150 kg N ha^{-1} was removed each year in grass on plots given fertilisers and about 180 kg N ha^{-1} from the plot given farmyard manure.

Grass recovered about 60 p. 100 of the applied fertiliser nitrogen. The lucerne crop removed about 260 kg N ha^{-1} and, without any fertiliser N, slightly outyielded the grass. Neither P nor K fertilisers affected the uptake of nitrogen.

TABLE II

Saxmundham Rotation I : mean yields of, and uptakes of N and K by, grass and lucerne, 1971-74

Treatments	Manuring (1)	Yields (t ha^{-1})		Uptakes (kg ha^{-1})			
				Grass		Lucerne	
		Grass	Lucerne	N	K	N	K
1	FYM	11.17	11.10	181	281	273	209
2	Bonemeal	9.16	9.43	150	176	254	118
4 and 9	P_1	9.36	9.28	154	181	259	113
3 and 6	P_2	9.36	9.41	153	185	260	114
7 and 10	P_1K	10.00	10.12	157	250	271	197
5 and 8	P_2K	10.00	10.30	152	256	268	210
Mean		9.78	9.88	156	220	264	160

(1) FYM : 60 t/ha^{-1} applied in 1970 ; bonemeal : 500 kg/ha^{-1} ; for P and K manuring, see table 10. N manuring (to grass only) : 100 kg N ha^{-1} for each cut.

Grass grown on soil which had received no K for 70 years took up, on average, 180 kg K ha^{-1}, about three times the amount removed annually by grass grown for 12 years on unmanured soils of the Agdell Rotation at Rothamsted. A major objective of the present modification of the Rotation I experiment at Saxmundham is to establish how long this Chalky-Boulder clay soil, typical of many in Eastern England, continues to release so much potassium. The annual application of 104 kg K ha^{-1} increased grass yields by 0.64 t ha^{-1} and K uptakes to about 250 kg K ha^{-1}, an apparent recovery of 70 p. 100. More K, about 280 kg ha^{-1}, was removed annually from soils given annual dressings of farmyard manure before 1970.

Lucerne removed about one-half as much K as grass from the unmanured soils, although yields of both crops were almost the same (table 11), and recovered about 86 p. 100 of the K applied ; this suggests that lucerne uses soil K less efficiently than grass but recovers more of the K applied to it as fertiliser.

The amounts of N taken up by the grass represent a recovery of about 60 p. 100 of the N applied. Only about 20 kg N ha^{-1} are lost in drainage water from these soils (WILLIAMS, 1976) ; the fate of the remainder is unknown. If the N unaccounted for is lost by denitrification, then this represents a total loss to the farming system. If the N is incorporated into soil organic matter, it may become available again particularly after the grass is ploughed. We shall measure changes in soil organic matter over a number of years to account for gains or losses of soil N in this experiment.

Saxmundham, Rotation II

Manuring, yields and soil analyses.

1899-1964. This experiment was designed to determine how farmers could best use limited amounts of FYM (25 t ha^{-1}) and whether they could profitably use more N and P fertiliser in a four-course rotation, similar to Rotation I. Fertilisers and FYM were applied to different crops in the rotation and not to every crop as in Rotation I. Results were summarized by OLDERSHAW (1941) and BOYD and TRIST (1966); table 12 gives the fertiliser treatments and yields between 1900-52.

Best yields of wheat, mangolds and barley were achieved using treatments 8-10 to which most fertiliser was applied. BOYD and TRIST (1966) commented that this experiment provided clear evidence that superphosphate raised yields of *all* crops in the rotation, not only those to which it was applied. It must, therefore, be numbered among the earliest experiments in England that clearly demonstrate the residual value of phosphate fertilisers.

TABLE 12

Saxmundham, Rotation II : manuring and mean yields, 1900-1952
(BOYD and TRIST, 1966)

Treatment	Winter wheat		Mangolds		Barley		Beans	
	Manuring	Grain (t ha^{-1})	Manuring	Roots (t ha^{-1})	Manuring	Grain (t ha^{-1})	Manuring	Grain (t ha^{-1})
1	—	1.47	—	11.8	—	1.15	—	1.57
2	FYM	2.00	—	28.4	—	1.48	—	2.08
3	FYM	2.22	NP	48.5	—	1.68	—	2.59
4	NP	2.45	FYM	46.2	—	1.76	—	2.77
5	N	2.46	FYM	47.2	—	1.78	P	2.84
6	FYM + N	2.64	P	44.2	—	1.78	—	2.71
7	FYM	2.30	P	44.4	N	2.31	—	2.75
8	FYM	2.36	NP	54.5	1/2 P	1.93	1/2 P	2.86
9	FYM + N	2.67	NP	53.2	N	2.31	—	2.71
10	N	2.45	NP	49.5	N	2.17	FYM	3.06
Mean		2.30		42.8		1.83		2.59

FYM : 25 t ha^{-1} ; N : sodium nitrate, 29 kg N ha^{-1} (19.5 kg N ha^{-1} before 1921) ; P : superphosphate, 60 kg P ha^{-1} (40 kg P ha^{-1} before 1921).

1965-68. Much of the experiment was discontinued after harvest in 1952, but treatments 1-7 were continued unchanged on two of the four blocks until 1964. These 14 plots, together with two plots (treatment 8), which had received extra P until 1952, have been used since 1965 to evaluate the residues of P accumulated since 1899. Each of the 16 plots was divided into two in 1964 and the experiment has been continued since then in four blocks (MATTINGLY, JOHNSTON and CHATER, 1970).

Adequate N and K fertilisers were applied from 1965-68 but no further P was

TABLE 13

Saxmundham, Rotation II : manuring, mean yields, 1965-68 and $NaHCO_3$-soluble P in soils in 1968
(MATTINGLY, JOHNSTON and CHATER, 1970)

Treatment	Manuring [1] (1899-1964)	Barley, 1965		Potatoes, 1966		Sugar beet, 1967		Barley, 1968		$NaHCO_3$-soluble P (mg P kg^{-1})
		Manuring [2]	Grain (t ha^{-1})	Manuring [3]	Tubers (t ha^{-1})	Manuring [4]	Sugar (t ha^{-1})	Manuring [5]	Grain (t ha^{-1})	
1	None	NK	2.00	NK	18.7	NK	3.29	NK	3.04	3
2	FYM	NK	3.93	NK	36.6	NK	5.96	NK	3.73	7
3	FYM + P	NK	4.34	NK	42.3	NK	7.45	NK	4.30	21
4	FYM + P	NK	4.29	NK + FYM	51.4	NK + FYM	8.43	NK	4.02	39
5	FYM + P	NP_1K	4.30	NP_1K + FYM	51.1	NP_1K + FYM	8.45	NK	3.90	54
6	FYM + P	NP_1K	4.28	NP_1K	45.8	NP_1K	7.96	NK	3.94	44
7	FYM + P	NP_2K	4.17	NP_2K	46.7	NP_2K	8.08	NK	4.10	67
8	FYM + 2 P	NK	3.94	NK	40.9	NK	7.54	NK	4.04	28

(1) See table 12 for details of manuring 1899-1964.
N as ammonium nitrate-limestone, P as triple superphosphate, K as potassium chloride.
(2) N : 100 kg N ha^{-1} ; P_1 : 82.5 kg P ha^{-1}, P_2 : 165 kg P ha^{-1} ; K : 104 kg K ha^{-1}.
(3) FYM : 50 t ha^{-1} ; N : 150 kg N ha^{-1} ; P_1 and P_2 as above ; K : 208 kg K ha^{-1}.
(4) FYM : 50 t ha^{-1} ; N : 150 kg N ha^{-1} ; P_1 and P_2 as above ; K : 125 kg K ha^{-1}.
(5) N : 94 kg N ha^{-1} ; K = 50 kg K ha^{-1}.

given in treatments 1, 2, 3 or 8. Table 13 shows how additional FYM totalling 100 t ha^{-1} and supplying about 230 kg P ha^{-1} was given in treatments 4 and 5 and triple superphosphate, supplying a total of about 250 and 500 kg P ha^{-1}, was given in treatments 5, 6 and 7.

Table 13 gives the yields of three crops grown between 1965 and 1968. Yields of barley, given adequate N and K, were almost doubled by the residues from P manuring in 1965 and increased by 30-40 p. 100 in 1968. Fresh applications of superphosphate did not increase them further. Residues of superphosphate (treatment 3) increased yields of potatoes in 1966 by 23.6 t ha^{-1} and of sugar in 1967 by 4.16 t ha^{-1}. Yields of both crops were slightly larger where fresh FYM was also given.

1969-74. At the end of 1968 the experiment consisted of eight treatments arranged in 32 plots. The amounts of P in the soils had been increased in treatments 4, 5, 6 and 7 by FYM and superphosphate applied between 1965-67 and $NaHCO_3$-soluble P in the soils in 1968 ranged from 3-67 mg P kg^{-1} (table 13). From 1969-74 the experiment was cropped in a rotation of potatoes-barley-sugar beet-barley; all crops were present each year, one per block. The 32 plots were divided into five micro-plots; no P was given to two micro-plots and three rates of superphosphate, supplying 27.5, 55 and 83 kg P ha^{-1}, were applied to potatoes or sugar beet on the other micro-plots. No phosphate was given between 1970-73 to barley, which measured residues of the P dressings given to the roots.

Mean yields of potatoes (total tubers) and of sugar from plots without fresh P are given in fig. 1, plotted against the mean $NaHCO_3$-soluble P measured each spring before planting. Potatoes yielded about 39 t ha^{-1} on plots containing 25 mg P kg^{-1} $NaHCO_3$-soluble P and about 43.5 t ha^{-1} on the most enriched soils (39-47 mg P kg^{-1} $NaHCO_3$-soluble P), an increase of about 0.2 t ha^{-1} for each one mg kg^{-1} increase in $NaHCO_3$-soluble P in the soil. Results with sugar beet were different and mean yields of sugar were almost constant (6.54-6.70 t ha^{-1}) on soils containing more than 25 mg P kg^{-1} $NaHCO_3$-soluble P. Yields of barley increased only slightly (4.87 to 5.12 t ha^{-1}) when grown on soils containing more than 25 mg P kg^{-1} $NaHCO_3$-soluble P.

TABLE 14

Saxmundham, Rotation II: increases in yields of potatoes and sugar (1969-74) from P applied as superphosphate (55 kg P ha^{-1}) *and of barley grain* (1970-73) *from the residues of superphosphate*

Treatment	Mean $NaHCO_3$-soluble P in soil (mg P kg^{-1})	Increase (t ha^{-1}) in yield of		
		Potatoes	Sugar	Barley
1	4	+ 12.5	+ 3.59	+ 1.92
2	7	+ 8.2	+ 1.39	+ 0.48
3	16	+ 4.3	+ 0.66	— 0.18
8	25	+ 4.2	— 0.38	+ 0.04
4	30	+ 4.3	— 0.14	+ 0.04
6	34	+ 0.2	+ 0.23	+ 0.08
5	40	+ 1.3	— 0.09	— 0.14
7	48	+ 2.5	+ 0.40	— 0.11

Table 14 gives the mean responses to fresh superphosphate applied at an average dressing of 55 kg P ha^{-1} for potatoes and sugar beet and the residual effects of this phosphate for the following barley crop. For potatoes, the responses decreased as the soluble P in the soil increased from 4 to 47 mg P kg^{-1} but were always positive. The mean increase on soils containing more than 25 mg P kg^{-1} $NaHCO_3$-soluble P was 2.5 t/ha^{-1} of tubers. For sugar beet, however, the extra sugar produced by fresh superphosphate decreased rapidly and, on soils containing more than 25 mg P kg^{-1} $NaHCO_3$-soluble P the mean response was negligible. For barley, residues of phosphate applied to the root crops increased yields on the impoverished soils (treatments 1 and 2) but not on soils containing more than 17 mg P kg^{-1} $NaHCO_3$-soluble P.

DISCUSSION AND CONCLUSIONS

Soil analysis and exchangeable and non-exchangeable P and K in soils

The accounts of the three rotation experiments described here have been largely restricted to summaries of the yields obtained since they started together with some indications, especially for the Agdell rotation, of how and why these experiments have been successively modified. This section discusses briefly the purpose of the soil analysis and its relevance to crop growth on the soils at Rothamsted, Saxmundham and Woburn.

Changes in the nutrient concentrations in soils from all the old rotation experiments have been influenced not only by the net gains and losses from the amounts of fertiliser supplied or removed by crops but also by the depth of ploughing and soil sampling which was increased from about 20 cm to 25 cm in both Rotations I and II at Saxmundham in 1964-65. This decreased the nutrient concentrations in all soils by 10 p. 100 or more ; reliable balance sheets could still be obtained, however, by converting nutrient concentrations (in mg kg^{-1}) to the amounts present in kg nutrient ha^{-1} (MATTINGLY, JOHNSTON and CHATER, 1970). Residues of FYM and superphosphate applied to treatments 4, 5, 6 and 7 on Rotation II from 1965-67 (table 13) did not increase the total P content of the soil, because they were distributed throughout more soil in 1968 than in 1964. However, the gains in total P in the soil to 25 cm (calculated in kg ha^{-1}) agreed closely with the amounts of the residues remaining in the soil. Increases in $NaHCO_3$-soluble P were about 10 p. 100 of the increases in total P for residues accumulated between 1899-1964 and 25 p. 100 for residues of recent (1965-67) applications of superphosphate (MATTINGLY, JOHNSTON and CHATER, 1970).

The results of soil analyses from the Agdell rotation show clearly that residues of PK fertilisers accumulated in the soils between 1848 and 1951 and were available to subsequent crops (e. g. table 2). In this experiment the increase in $NaHCO_3$-soluble P was about 6 p. 100 of the increase in total P in the soil and the increase in exchangeable K about 14 p. 100 of the estimated amount of the residues remaining from K manuring. Cropping with grass from 1958-69 (table 4) removed about 56 kg P ha^{-1} from the unmanured soils which hardly changed the amounts of $NaHCO_3$-soluble P they contained. Grass grown on soils containing PK residues from fertilisers applied between 1848 and 1951 removed about 148 kg P ha^{-1}. The mean $NaHCO_3$-soluble P decreased between 1958 and 1969 by 6.4 mg P kg^{-1}, equivalent to only 16.8 kg P ha^{-1} or 11 p. 100 of the total P used by the grass.

Results with K were similar ; grass removed about 810 kg K ha^{-1} in 12 years from the unmanured soils but exchangeable K in the soils changed very little. Grass removed 1 430 kg K ha^{-1} from soils containing residues ; the mean exchangeable K in the soils decreased by 34 mg K kg^{-1}, equivalent to a removal of 89 kg K ha^{-1} or 6 p. 100 of the total K removed. Much non-exchangeable K and non-bicarbonate soluble P was used by grass between 1958 and 1969.

The modifications to the Agdell rotation and Saxmundham Rotation II experiments have both produced soils containing a range of soluble P which were used to test : *a*) the response of potatoes, sugar beet and barley to increasing levels of soluble P and *b*) the response of each crop (except barley at Saxmundham) to fresh superphosphate broadcast before planting or sowing (fig. 1 ; table 5 and 14). Other evidence (JOHNSTON, MATTINGLY and POULTON, 1976) shows that in experiments at Woburn crop yields and responses to applied P depend on the amount of soil organic matter in the soils. We have, therefore, restricted comparisons between results from Saxmundham and the Agdell rotation to soils containing about the same total carbon (1.4 p. 100 C). Both soils behaved similarly (fig. 1) and, at both sites, potatoes benefited from freshly-applied superphosphate even on soils containing more than 40 mg P kg^{-1} $NaHCO_3$-soluble P (tables 5 and 14). Neither sugar beet nor barley, however, gave consistently larger yields when fresh superphosphate was applied on soils containing more than 25 mg P kg^{-1} $NaHCO_3$-soluble P. The monocalcium phosphate potential ($1/2$ pCa + pH_2PO_4), suggested by SCHOFIELD (1955) as 'the function most likely to give a numerical index of the condition in the soil which mainly controls the availability of phosphate', is closely correlated with $NaHCO_3$-soluble P in both Agdell and Saxmundham soils and is linearly related to the amounts of P applied to Rotation II (MATTINGLY, JOHNSTON and CHATER, 1970).

Much of the data from the P and K analyses of soils from the Agdell rotation, Rotation I at Saxmundham (WILLIAMS and COOKE, 1971) and the Broadbalk and Continuous Wheat and Barley experiments at Woburn (JOHNSTON and MATTINGLY, this Conference) is related to net gains by or losses from the soils (fig. 2). This shows that soils at Rothamsted and Saxmundham will contain between 7 and 10 mg $NaHCO_3$-soluble P kg^{-1} soil when removals in the crops are just balanced by additions of fertiliser-P. The corresponding value for the soils at Woburn is much higher ($\approx$ 17 mg P kg^{-1}).

When K removed in crops is just balanced by K added as fertiliser, the three soils from Agdell, Saxmundham and Broadbalk all contain about 150 mg exchangeable K kg^{-1}. The lighter soils at Woburn, for which the relationship is less well-defined, contain much less exchangeable K ($\approx$ 80 mg K kg^{-1}).

Relationships of this kind, which are readily obtained from long-continued field experiments, provide a simple means of using the net gains of P or K from manuring to estimate approximately the amounts of $NaHCO_3$-soluble P or exchangeable K that will accumulate in different soils. *They do not, however, give any clear indications of the non-exchangeable reserves of P or K in the soils.* There is now an important need to devise simple tests that will estimate quantitatively reserves of P and K which are available to crops but are not measured as $NaHCO_3$-soluble P or exchangeable K in soils.

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RÉSUMÉ

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

Ce mémoire décrit les résultats de trois expériences de fertilisation sur assolement dans le sud de l'Angleterre, ainsi que les modifications qui y ont été introduites au cours de la période récente.

L'expérience la plus ancienne, celle de l'assolement sur le champ désigné par 'Agdell', a été mise en place à la *Station Experimentale de Rothamsted* en 1848 et a continué, presque sans modifications, jusqu'en 1951. Elle comparaît deux rotations quadriennales : *a*) rutabagas, orge, trèfle (ou fèves) et blé d'hiver, et *b*) rutabagas, orge, jachère et blé d'hiver. Les traitements fertilisants étaient les suivants : sans engrais, engrais PKNaMg et engrais NPKNaMg appliqués une fois tous les quatre ans aux rutabagas. Il n'y avait que six parcelles et une seule culture était présente chaque année. De 1952 à 1957 le champ a été mis soit en jachère soit sous culture uniforme, et les sols acides ont été chaulés. L'effet résiduel des engrais appliqués précédemment a augmenté le rendement des fèves, cultivées sans engrais, de 1,76 t de grains/ha^{-1} en 1956, et celui des pommes de terre, ayant reçu un traitement uniforme d'azote en 1957, de 23,8 t/ha^{-1}. En 1958 chaque parcelle a été divisée en deux ; sur l'une des deux moitiés, la valeur des engrais P et K résiduels a été évaluée sur prairie de 1958 à 1970. Sur l'autre moitié, de 1959 à 1962, on a mesuré les effets résiduels de P sur les rendements de l'orge, des pommes de terre et de la betterave sucrière. Les engrais P résiduels ont plus que doublé les rendements de l'orge et des pommes de terre et ont augmenté le rendement en sucre de 70 p. 100.

Entre 1964 et 1970 on a modifié le plan de l'expérience en appliquant des doses de P de 220, 440 et 880 kg de P ha^{-1}, et des doses de K de 260, 520 et 1 040 kg de K/ha^{-1}. Les rendements sur les parcelles sans engrais et sur les parcelles PK de l'assolement original ont été limités plus par le manque de P que par celui de K. Les plus basses doses des nouvelles applications de P et K ont, dans les deux cas, produit une importante augmentation des rendements, s'étalant de 0,9 à 4,8 t/ha^{-1} pour P et de 1,2 à 2,7 t/ha^{-1} pour K. Aux plus fortes doses de P et K, les rendements des prairies sur les anciennes parcelles sans engrais et sur les anciennes parcelles PK ont été presque identiques. De 1970 à 1972, les sols contenaient 3 à 70 mg de P (soluble dans $NaHCO_3$) par kg de sol. On a mis en évidence une relation bien définie entre les rendements de l'orge, de la betterave sucrière et des pommes de terre d'une part, et le contenu en P soluble des sols d'autre part. Les rendements ont augmenté avec l'accroissement en P soluble des sols jusqu'à 20-25 mg P/kg^{-1} ; au-dessus de cette valeur, les rendements de l'orge et de la betterave sucrière ont à peine augmenté, tandis que ceux des pommes de terre ont continué à croître légèrement.

Deux expériences d'assolement ont été mises en place à la *Station Expérimentale de Saxmundham* dans le comté du Suffolk en 1899.

La première (*Rotation I*) consistait en une rotation quadriennale blé, betterave fourragère, orge et une légumineuse (fèves, pois ou trèfle). La fumure, appliquée tous les ans, comprenait le fumier de ferme, les cendres d'os et toutes les combinaisons de N, P et K. Il y avait quatre répétitions de dix traitements et chaque culture était présente tous les ans. L'expérience a continué sans modifications jusqu'en 1965. Les parcelles ayant reçu NPK ont produit légèrement plus de blé, d'orge et de betteraves fourragères que les parcelles avec fumier à dose à peu près égale en éléments fertilisants, mais légèrement moins de fèves et moins de trèfle (2 t ha^{-1}). Les cendres d'os, qui apportaient environ deux fois plus de P que le superphosphate, en même temps que 4-16 kg N ha^{-1}, ont produit des rendements semblables à ceux obtenus avec le superphosphate. L'expérience a démontré l'importance des engrais phosphatés sur sol calcaire carencés en P ainsi que la valeur des engrais azotés pour les céréales. En l'absence de P, l'azote a eu une influence négligeable sur les rendements des navets et de la betterave sucrière. Sur ce sol, les céréales et la betterave sucrière ont peu bénéficié des applications de K, mais celles-ci ont augmenté les rendements des betteraves fourragères, des fèves, des pois et du trèfle.

En 1965-1966, on a modifié le plan de l'expérience en doublant la dose de fumier et en introduisant des doses plus élevées de N, P et K. Entre 1966 et 1969, les nouveaux traitements ont élevé les rendements du blé, de l'orge et de la betterave sucrière au niveau ou au-dessus de la moyenne nationale. Les bénéfices étaient dus, en grande partie, aux doses plus élevées de N et P. Le K additionnel a produit peu d'effet sur le rendement des céréales mais a légèrement augmenté celui des fèves. De 1970 à 1974, des demi-parcelles ont été consacrées à la culture de prairies (mélange de fétuque et de fléole des prés) recevant 100 kg N/ha^{-1} par coupe, ou de la luzerne avec le même traitement PK qu'en 1966-1969. Les rendements moyens ont varié de 8,6 à 12,1 t ha^{-1} pour les prairies et de 8,5 à 13,0 t ha^{-1} pour la luzerne. Les engrais potassiques ont augmenté les rendements de la prairie de 0,64 t ha^{-1} et ceux de la luzerne de 0,86 t ha^{-1}. Le superphosphate n'a exercé qu'une influence insignifiante.

Dans la *Rotation II*, l'expérience a porté sur le même assolement quadriennal que dans la Rotation I mais la fumure a varié avec la culture. L'expérience avait pour but de déterminer comment des doses restreintes de fumier et d'engrais N et P pourraient être le plus profitablement utilisées par les quatre cultures. Elle a continué sans modifications jusqu'en 1952 et, sur certaines parcelles, on a poursuivi le même plan de fumure jusqu'en 1964. De 1965 à 1974, ce champ d'expérience a servi à étudier l'effet résiduel du fumier et des engrais P appliqués : *a*) entre 1899 et 1964, et *b*) entre 1965 et 1967. L'effet résiduel de la fumure appliquée de 1899 à 1964 s'est traduit par un doublement des rendements de l'orge en 1965 (N et K étant fournis en dose suffisante) et par une augmentation de ceux-ci de 30 à 40 p. 100, en 1968. L'effet résiduel du superphosphate a conduit à un supplément de rendement de 23,6 t ha^{-1} des pommes de terre en 1966 et de 4,16 t ha^{-1} de sucre en 1967. De 1969 à 1974, le champ d'essai a été soumis à une rotation de pommes de terre, orge, betterave sucrière et orge ; en 1968, le P des sols soluble dans $NaHCO_3$ variait de 3 à 67 mg P kg^{-1}. En 1969, les parcelles principales ont été divisées en micro-parcelles ; deux de ces dernières n'ont reçu aucune application de P, tandis que trois doses de superphosphate ont été appliquées aux pommes de terre ou à la betterave sucrière sur les autres. Entre 1969 et 1974, le rendement des pommes de terre a été d'environ 39 t ha^{-1} sur les parcelles contenant 25 mg P kg^{-1} (soluble dans $NaHCO_3$), et d'à peu près 43,5 t ha^{-1} sur les parcelles les plus enrichies. Les rendements moyens en sucre (6,54 à 6,70 t ha^{-1}) et de l'orge (4,87 à 5,12 t de grains ha^{-1}) ont peu varié sur les sols contenant plus de 25 mg de P soluble dans $NaHCO_3$ par kg de sol.

L'accumulation ou les pertes nettes de P et K dans les sols ont varié dans le même sens que la teneur des sols en P soluble et en K échangeable. Et pourtant, en culture d'épuisement, une grande partie du K non-échangeable et du P non-soluble dans le bicarbonate a été prélevée par les plantes.

ZUSAMMENFASSUNG

LANGFRISTIGE FRUCHTFOLGEVERSUCHE IN DEN VERSUCHSZENTREN VON ROTHAMSTED UND SAXMUNDHAM : WIRKUNGEN DER BEHANDLUNGEN AUF DIE KULTURERTRÄGE UND BODENANALYSEN UND NEUE VERÄNDERUNGEN AN ZIEL UND PLAN

In dieser Mitteilung werden die Ergebnisse und die neuen Veränderungen bezügliche dreier Fruchtfolgeversuche Südenglands beschrieben. Der früheste Versuch, die Agdellsehe Fruchtfolge, fing in dem Versuchszentrum von Rothamsted im Jahre 1848 an und ging fast unverändert

bis zu 1951 weiter. Er bestand in der Vergleichung zweier vierjährigen Fruchtfolgen *a)* Kohlrübe, Gerste, Klee (oder Pferdebohne) und Winterweizen *b)* Kohlrübe, Gerste, Brache und Winterweizen. Die Behandlungen waren folgende : ungedüngt, PKNaMg Düngung und NPKNaMg Düngung der Kohlrüben alle vier Jahre. Es gab nur sechs Parzellen und eine Ernte im Jahr. Zischen 1952 und 1957 wurde der Ort entweder brachliegend gelassen oder gleichförmig geerntet während sauere Böden Kalkdünger erhielten. Seit 1958 sind die Parzellen unterteilt worden, um in Mikroparzellenversuchen den Wert der P und K Rückstände im Boden zu bestimmen.

Zwei Fruchtfolgeversuche wurden im Jahre 1899 in dem Versuchszentrum von Saxmundham (Suffolk) angefangen. Der erste (Fruchtfolge I) bestand in einer vierjährigen Fruchtfolge : Weizen, Mangold, Gerste und Hülsenfrüchte (Pferdebohne, Erbse oder Klee). Die jährlich zugeführten Dünger umfassten Stallmist, Knochemmehl und alle möglichen Kombinationen von N, P und K Düngern. Es gab vier Wiederholungen von zehn Behandlungen und jede Kultur fand alle Jahre statt. Der Versuch, der bis zu 1965 unverändert weiterging, wurde zwischen 1966 und 1969 geändert, um den Vorteil höherer Stallmist- und N, P und K Gaben für die vier selben bestellbaren Kulturen zu bestimmen. Er wurde noch ab 1970 verändert, um den Gras- und Luzerneertrag und die Aufnahmesätze von N und K aus dem Boden zu vergleichen.

Der Fruchtfolgeversuch II in Saxmundham betraf dieselbe vierjährige Fruchtfolge als der Versuch I, aber die Behandlungen änderten sich gemäss der ausgeführten Kultur. Es wurde gezlelt zu bestimmen wie beschränkte Mengen von Stallmist und N und P Düngern durch die vier bestellbaren Kulturen best ausgenutzt sein könnten. Der Versuch ging bis 1952 unverändert weiter und einige Parzellen wurden bis 1964 mit der Anfangsdüngung geerntet. Zwischen 1964 und 1974 wurden diese Parzellen für Versuche benutzt, welche die Bedeutung der Phosphatdüngerrückstände für Gerste, Kartoffel und Zuckerrübe betrafen und welche kurz beschrieben sind.

РЕЗЮМЕ

Долгосрочные опыты с севооборотами на экспериментальных станциях в Ротхемштете и Саксмундхеме. Действие разных обработок на продуктивность культур и анализы почв. Недавние изменения целей и организации опытов.

Г. Е. Г. МЕТТИНГЛИ, А. Е. ДЖОНСТОН.

В данной работе описываются результаты полученные в трех опытах с севооборотами, проведенных на юге Англии, и недавно внесенные в них изменения. Самый старый из этих опытов (ротация Асделль) начат был в 1848-м году на экспериментальной станции в Ротхемштете, продолжался почти без изменений до 1951-го года и служил для сравнительного изучения двух четырехпольных севооборотов : а. брюква, ячмень, клевер (или фасоль) и озимая пшеница; б. брюква, ячмень, черный пар и озимая пшеница. Обработки в этом опыте были следующие : а. без удобрений (контроль); б. удобрение PK Na Mg; в. удобрение NPK Na Mg, внесенное полностью под брюкву. Каждый вариант насчитывал 6 повторностей (делянок) и одна из культур отсутствовала из севооборота каждый год. За исключением периода 1952-1957, почва одного из опытов периодически занималась черным, или занятым паром, и также периодически проводилось известкование кислых почв. Начиная с 1958-го года каждая делянка делилась на микро-делянки, для определения на этих последних процента остаточных фосфора и калия в почве.

Два других опыта с севооборотами начались в 1899-м году на экспериментальной станции в Саксмундхеме (Суффольк). Первый из них (ротация 1) представлял четырехпольный севооборот : пшеница, свекла, ячмень и бобовое (фасоль, горох, или клевер). Ежегодное внесение удобрений состояло из навоза, муки из костей и всевозможных комбинаций

питательных элементов NPK. Всего применялось 10 разных обработок в четырех повторностях, и каждая культура фигурировала в севообороте каждый год.

Этот опыт, продолжавшийся без перемен и перерывов до 1965-го года, был изменен между 1966-м и 1969-м годом для изучения действия более крупных доз навоза и минерального удобрения NPK на те-же 4 временные культуры. Позже, начиная с 1970-го года, были введены новые изменения, для сравнения продукции травы и люцерны, и определения процента почвенных N и K, вынесенных культурами из почвы.

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