THE IONIC EXCHANGE BETWEEN PLANT AND SOIL WITH SPECIAL REFERENCE TO HYDROGEN, CALCIUM AND SULPHUR.

by

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GENERAL INTRODUCTION.

Some recent investigations carried out at the Edinburgh and East of Scotland College of Agriculture have dealt with the variation in acidity of soils. It was shown (100) that there was a regular seasonal variation, modified both by fluctuations due to rainfall and temperature, and by the effects of plant growth. For example, during the growing season the pH value of the soil fell more or less steadily to the time of maximum growth about July - August and then gradually rose to the original value; in the absence of plants these changes were much greater but the original and final values were almost identical. The effect of the growing plant in modifying the pH changes was also studied in pot and dish experiments and it was found that the plant considerably reduced the changes in the pH value of the soil. Since many investigators had shown that a seasonal variation in the concentration of soil electrolytes existed, it was deduced that a close relationship probably existed between the pH of the soil and the concentration of electrolytes/

electrolytes in the soil solution. The measurement of the pH value of a soil suspension would naturally be influenced by the electrolytes present in the fresh soil on account of the existence of exchange acidity; the recommendation of the International Commission for Soil Research (92) to carry out pH determinations in KCl solutions as well as in water are presumably designed to get over the difficulty of varying amounts of salts present in soils at different times.

Another point which seemed to merit further attention was the possibility of change in reaction taking place due to the evolution of carbon dioxide in the soil atmosphere as a result of either biological activity or plant root excretion. It was suggested that possibly the formation of bicarbonates might influence to a considerable extent the pH value of the soil.

The object of the present investigation was to study in detail some of the changes in plant and soil accompanying the change in pH value of the soil. The subject is of course a wide one and it was decided to confine attention to such matters as the concentration of the soil solution as determined by conductivity measurements, the absorption of sulphur and calcium by the plant under different conditions, the effect of carbon dioxide, sulphur and calcium hydroxide on the pH value of the soil and to see whether these/

these factors might be correlated sufficiently closely to support previous hypothesis and justify further developments along this line of research.

The work falls naturally into four divisions and it will be more convenient to submit the results of each in turn and to conclude with a general statement embracing the relationships of the data as a whole.

The first section is concerned with the effect of the growing plant on the variation in acidity of the soil. These effects were observed by means of dish experiments conducted under carefully controlled conditions in the laboratory. The influence of carbon dioxide in changing the soil acidity is also recorded. Section 1. pp. 6-18.

The second section deals with the seasonal variation in the pH value of the soil and to what extent the plant alters this variation both in pot and field experiments. The relationships found to exist between the soil acidity and the conductivity and calcium content of the water extract of the soil are also described. Section 2. pp 19-32.

The effects of liming a soil on its acidity and on the growth and composition of plants are dealt with in the third section: both pot and field experiments are used in this section and also in section four which is concerned with the change in acidity of/ Section 3. pp. 33-46. Section 4. pp. 47-56.

of the soil and the effect on the growth and composition of plants brought about by the addition of sulphur to the soil.

It is realised that dish experiments are essentially artificial and do not represent exactly what takes place in the field. On the other hand, errors incurred in sampling the soil are at a minimum and results obtained from these experiments can be used as an indication of what probably takes place under more natural conditions.

Pot experiments, although an improvement on dish experiments, have a number of disadvantages. The small depth of soil and want of the subsoil restrict the full development of the plant in addition to disturbing the natural conditions of water movement with the result that in periods of dry weather the soil dries out very quickly. This entails watering and this fact along with the others mentioned must be taken into account in examining the results.
The chief factor in favour of dish and pot experiments, apart from the ease in control of climatic conditions, is the great accuracy in sampling which is obtained and this is the greatest difficulty experienced under field conditions. In all the experiments undertaken an attempt has therefore been made to support dish with pot experiments and these again by field experiments. Two of the soils, B and W, which have been used/

used for most of the work carried out, are probably rather extreme cases. Soil B is a heavy fertile loam while W is a very infertile sandy soil which has been subjected to continuous leaching for over sixty years. It might be expected, then, that there would be a considerable difference in results obtained with these two soils.

SECTION 1.

(a) The Effect of the Plant on the Variation in Acidity of the Soil and (b) the Influence of Carbon Dioxide in changing the Soil Acidity.

(a) Introduction.

As has already been stated, the plant appears to exert a considerable influence on the pH value of the soil (100). In order to observe these changes in soil acidity a number of dish experiments were undertaken.

Experimental.

The soils used were the following:-

Soil B:- a heavy clay loam from the College Experiment Farm, Boghall. The mechanical analysis of this soil by the International Pipette method gave the following percentage composition:- coarse sand 20, fine sand 26, silt 24, clay 25, air dry moisture 3.7 and loss on ignition 7.4.

Soil G:- A sandy soil, from an uncultivated raised beach close to the south shore of the Firth of Forth, having 68 per cent coarse sand, 10 per cent fine sand and 8.5 per cent loss on ignition.

Soil P:- An uncultivated peaty soil overlying well-weathered basic andesite. The loss on ignition of the oven dry material was 48 per cent.

Soil W:- A light sandy soil taken from a mound of glacial sand, which had not been cultivated for at least 60 years and very infertile. The loss on ignition, due largely to partly decayed organic matter was 9 per cent, with coarse sand 50 per cent, and fine sand 20 per cent. A study of the chemical properties of the soil has already been published (99) soil number 196.

The material used in the dishes consisted of the following:-

Material.	% moisture.
1. Soil B.	16
2. Soil B + 0.025% sulphur as Sulphuric acid.	16
3. Soil B + 0.125% Calcium hydroxide	16
4. Soil P.	59
5. Soil P + 1% calcium hydroxide	59
6. Soil P + 2% calcium hydroxide	59
7. Soil W.	15
8. Soil G.	15

Fifteen gr. of soil were placed in each dish in the B series, 25 g. in the P series, 18 g. for soil W and 20 g. for soil G. Two peas, previously germinated in distilled water, were planted in each dish.

The/

Fig (2)

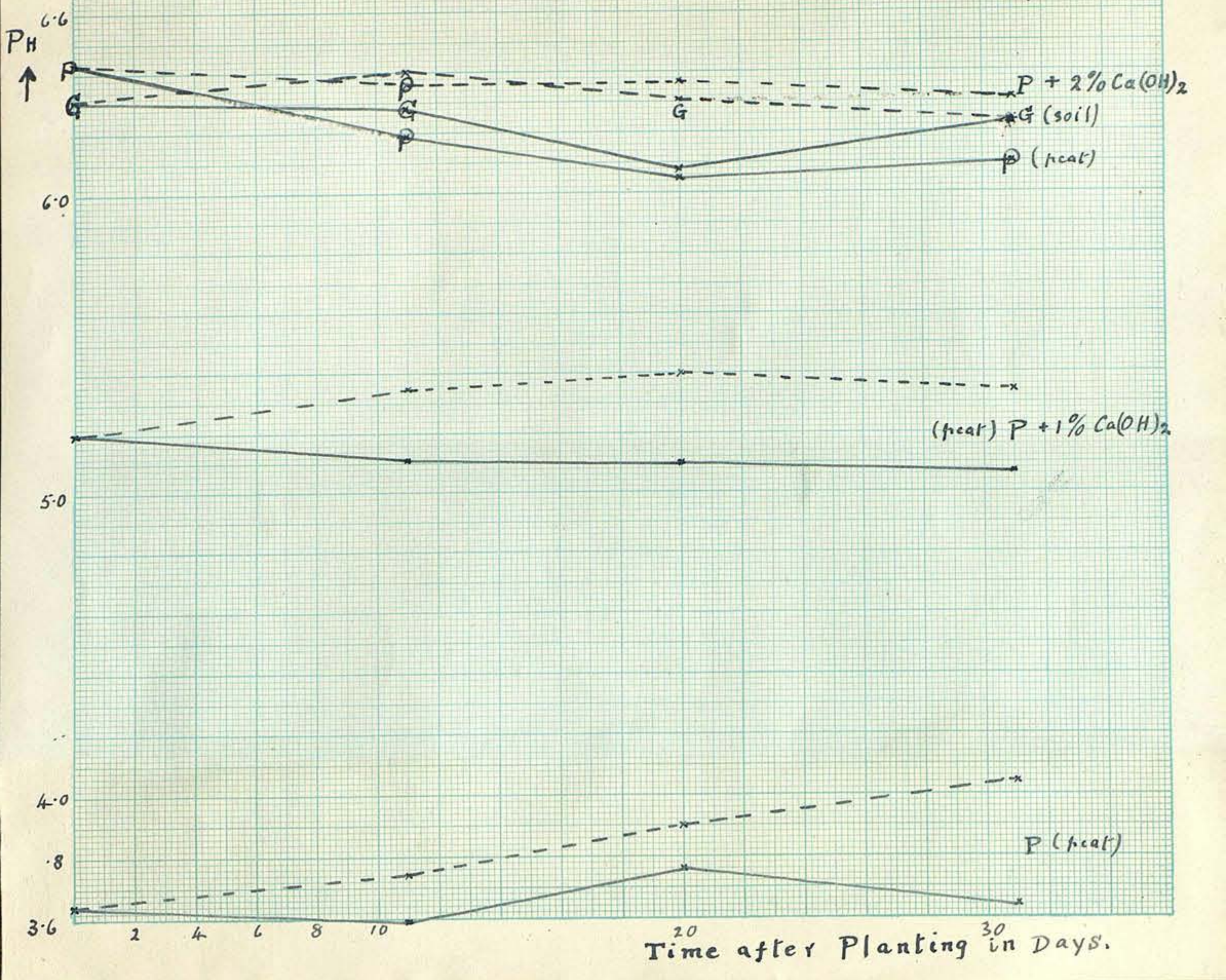
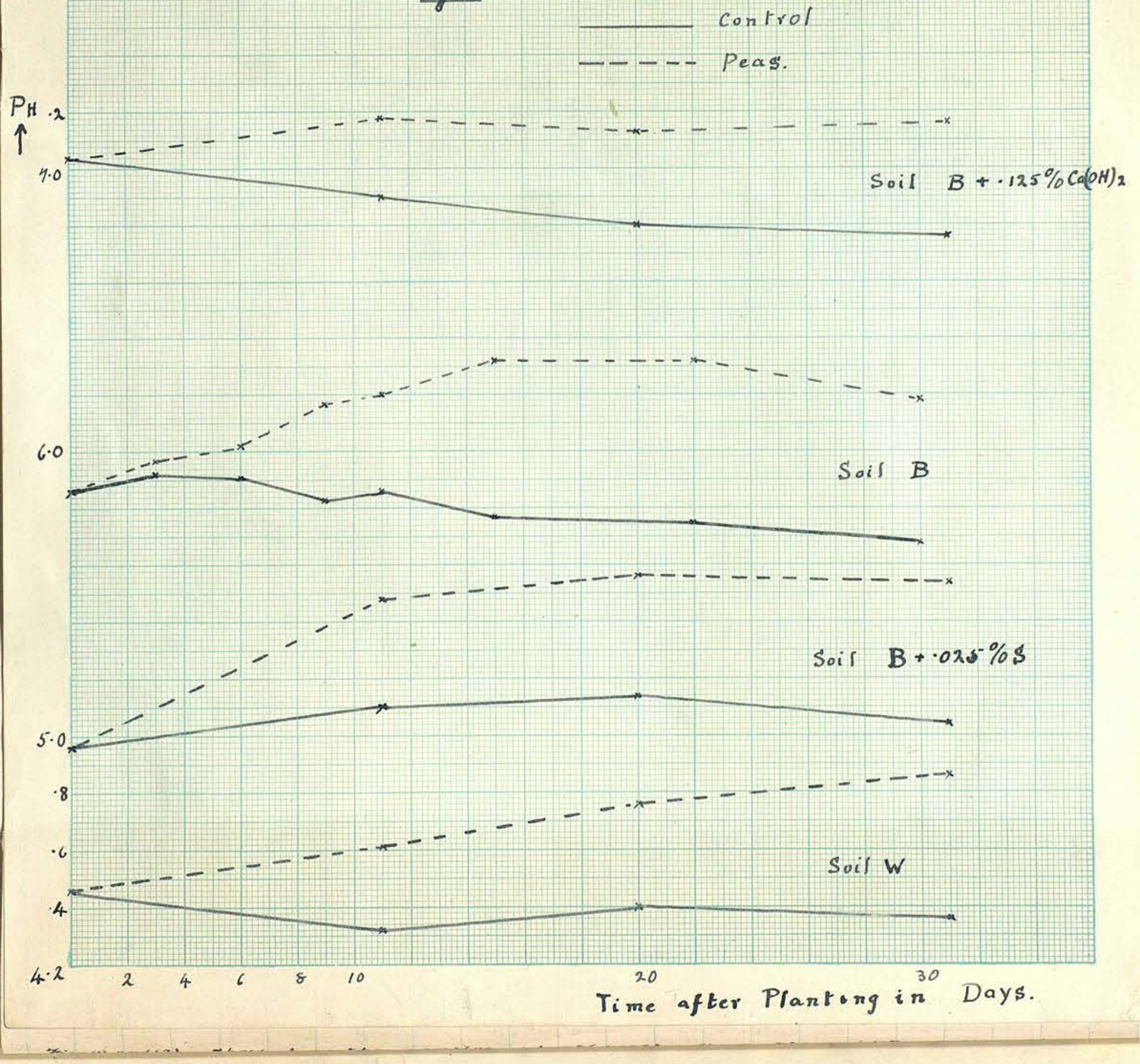

Control
peas.
PH
6·6
6·0
5·0
4·0
·8
3·6
P + 2% Ca(OH)2
G (soil)
P (peat)
(peat) P + 1% Ca(OH)2
P (peat)
2
4
6
8
10
20
30
Time after Planting in Days.

Fig (1)


Control
Peas.
PH ·2
4·0
6·0
5·0
·8
·6
·4
4·2
Soil B + ·125% Ca(OH)2
Soil B
Soil B + ·025% S
Soil W
2
4
6
8
10
20
30
Time after Planting in Days.

The dishes were incubated in an electrically controlled germinating frame at from 18-20°C. and the soils were moistened with distilled water as required. At regular intervals of a few days, dishes were removed from the frame and the pH values of the soil were determined. A complete dishful of soil was used for each determination. Where there was a plant, it was carefully removed from the dish and the soil washed from the roots with CO_2 free distilled water into the reaction vessel along with the remainder of the soil from that particular dish. All the pH determinations were carried out in duplicate shortly after sampling and according to the recommendations put forward in the Report of the 2nd Commission, 1. S. S. S. (92). The average results are shown graphically in figs. (1) and (2) opposite.

Results:

The results obtained (figs. 1 and 2) substantiate those found with potatoes (100), namely, that whereas the pH value of the incubated soil tends to decrease when there is no plant growing, it rises in presence of a growing plant. In other words the effect of the actively growing plant is to raise the pH value of the soil. This may be due/

due to a combination of factors. For example the plant will tend to reduce the concentration of electrolytes present in the soil and so reduce the acidity of the suspension of soil in water; but the possible excretion of carbon dioxide from the plant roots may be responsible for the formation of bicarbonates which may effect considerable change in the acidity of the soil suspension. In order to test the latter idea the series of experiments described in (b) was carried out.

(b) The Influence of carbon dioxide in changing the Soil Acidity.

Introduction.

A great amount of work has been done on the part played by carbon dioxide in Agriculture beginning with the experiments of de Saussure in 1804 (97) showing the necessity of carbon dioxide for plant life. Liebig's theory that the plant obtained all the carbon in its composition from carbon dioxide absorbed through the leaves followed in 1840.

Within the last few years the advantage of increasing/

increasing the concentration of carbon dioxide in the air of greenhouses has been appreciated and become a commercial proposition. (42) (98). Both the yield and the percentage dry matter of such fruits as tomatoes are increased by these additions of CO_2 to the air, while with young wheat plants (46) it has been found that CO_2 absorption under constant illumination is a direct function of the temperature. As the temperature rises so does the carbon assimilation for these artificial additions of CO_2 to the air (59).

Increasing the CO_2 of the soil air, however, has been found to have a detrimental effect on the plant (105) (60) and with water cultures it is very marked. Free (28) passed nitrogen, oxygen and air through water cultures and the plants matured equally well. On blowing carbon dioxide through the cultures the plants wilted and died in a few days. Similar results have been obtained by Hall (37).

The addition of carbon dioxide to the soil has been found to increase and its removal to decrease, the silica content of oats (79) and seedlings can utilize larger quantities of rock phosphate when the soil is saturated with carbon dioxide (13). The latter effect is probably due to the small quantities of/

of carbon dioxide given off by the roots of young plants. It has even been found (7) that young plants will absorb CO_2 through the roots and put on leaves although all but the roots are kept free from carbon dioxide.

When organic matter has been added to the soil, the carbon dioxide content may be increased to such an extent as to be harmful to young plants, (4) but as soon as the excess has been removed by cultivation the plants grow vigorously. It would appear that the effect on the plant of additions of carbon dioxide to the soil depends upon the CO_2/O_2 ratio in the soil. This is supported by work done by Ochler (76) who found that forced ventilation of the soil increased the evolution of carbon dioxide and was accompanied by increased plant growth.

The carbon dioxide found in the soil air has been stated by some authors (104) (101) to be due almost entirely to bacterial action. More bacteria have been found on cropped than on uncropped land and Starkey (102) (101) has found the numbers of bacteria, carbon dioxide and the production of nitrate to be greatest near the roots of plants. Many other workers have found the increase in numbers of fungi, bacteria and actinomycetes in the soil to vary with the crop grown (94) (95) (67) (102) (39) (41).

It/

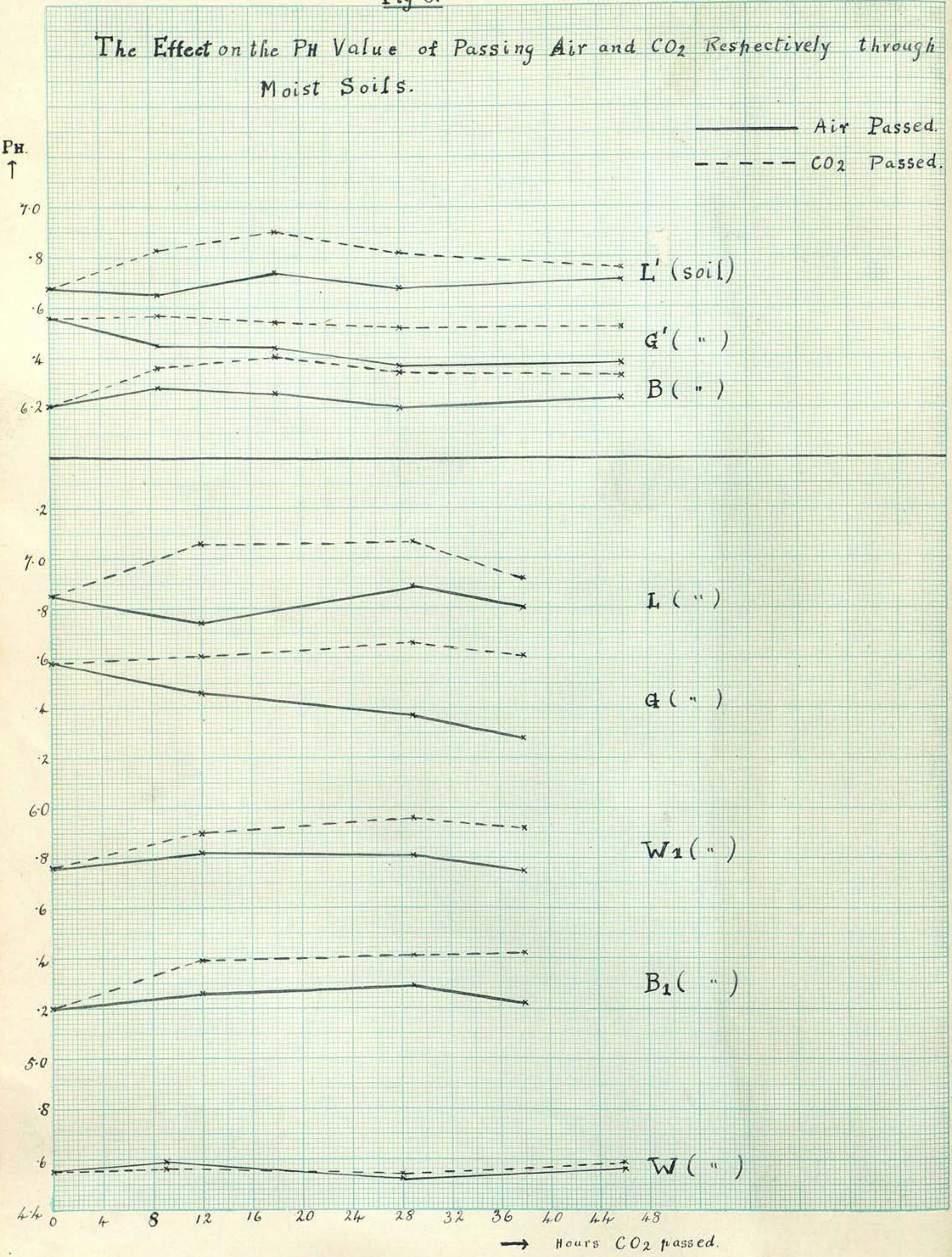
It has been shown conclusively, however, from the mass of evidence put forward (39) (110) (41) that the growing plant, especially at its maximum growth is the most important agent in carbon dioxide production.

Experimental.

The four soils W_1 which consisted of W + 2% $Ca(OH)_2$, G, B_1 or B to which 1200 lb. S per acre had been added in the field, and L were made up to 20% moisture content with distilled water and left for 36 hours. Soil L is a heavily manured garden soil from the College Gardens and contains free lime.

Two sets of 100 gm. of each moist soil were lightly packed into long glass tubes of ¾" cross section. Each set of tubes was connected in the same order, viz. W_1 to G to B_1 to L. One set was connected to a carbon dioxide cylinder through a washing flask of distilled water, and the other was left open to the outside air. Flasks with distilled water were interposed between the tubes to keep the gases moist during passage through the soils. Air and carbon dioxide, respectively, were then drawn slowly through the tubes with the aid of a water pump regulated to allow the same volume of gas to pass through each set. Samples were taken at intervals from both ends/

Fig 3.


The Effect on the PH Value of Passing Air and CO2 Respectively through Moist Soils.
Air Passed.
CO2 Passed.
PH.
7.0
·8
·6
·4
6·2
·2
7.0
·8
·6
·4
·2
6·0
·8
·6
·4
·2
5·0
·8
·6
4·4
L' (soil)
G' (")
B (")
L (")
G (")
W1 (")
B1 (")
W (")
0
4
8
12
16
20
24
28
32
36
40
44
48
Hours CO2 passed.

ends of each tube and the pH determined. The results are shown graphically in Fig. 3. In order to test whether the change effected by the CO_2 was permanent, the experiment was repeated with the soils W, G^1, B and L^1 and samples of soil from the "carbon dioxide tubes" taken at the same time as the other samples, were shaken up with distilled water (ratio of soil: water = 1: 2.5) and aerated with a rapid stream of air. The pH values of the suspensions were then measured and as can be seen in table I in the appendix, the effect of aeration was negligible.

Carbon dioxide and air, respectively, were also passed through 1:2½ suspensions of these soils in water. The acidity rose to a constant value when the suspension was saturated xxx with carbon dioxide. As might have been expected the time taken and the final value reached depended on the buffer capacity of the soil. When these carbon dioxide saturated suspensions were rapidly aspirated with air the pH value rose again to approximately the original. (See tables II and III appendix)

200 g. of soils B, W, and G with 20%, 16% and 16% moisture, respectively, were packed in separate glass tubes and water saturated with carbon dioxide allowed to drip from fine jets and percolate through the soils. The lower ends of the tubes were plugged with/

with glass wool previously treated with HCl and well washed. The top half inch of soil after leaching became more acid with all three soils while the second half inch became more alkaline with B and W: with G the acid effect went much deeper (table IV, appendix). Percolation became very difficult after a time with all the soils.

Results.

The results presented graphically in Fig. 3 show quite definitely that the passage of carbon dioxide through the moist soil raises its pH value. This surprising result, although to a certain extent anticipated on the basis of the hypothesis mentioned (page 9) does not seem to have been previously observed and is probably contrary to the usual assumptions made with regard to the effects of carbon dioxide on the soil. It is further of great interest to find that these curves showing the change in pH values with the passage of air and carbon dioxide respectively are very similar to those obtained for plant growth (Figs. 1 and 2). In the dish experiments, however, the temperature was maintained at 18-20°C while the tubes were generally at temperatures from 12 to 14°C and this difference must be taken into account in any comparison of the results.

It/

It would appear that the changes in acidity in the soil brought about by the passage of carbon dioxide are permanent. At least aspirating the treated soil in a water suspension with a rapid flow of air had practically no effect on the pH value.

Passing carbon dioxide through a water suspension of the soils lowers the pH value until the solution is saturated: the final value depending on the buffer capacity of the soil and the degree of saturation of the solution.

Leaching the soils with a saturated solution of carbon dioxide amounts essentially to a dilute acid extraction of the soil with displacement of exchangeable bases by hydrogen and a fall in pH value. The displaced bases mentioned appear to accumulate further down the column of soil, the depth depending on the ease of percolation and is accompanied by a rise in pH value of the soil.

Discussion of Results.

The effects of carbon dioxide seem therefore to be dependent upon the amount of water present in the soil and the amount of carbon dioxide which can be brought into the reaction. Experiments designed to resemble the evolution of carbon dioxide by the plant growing in soil were not completely satisfactory and consequently/

consequently it was not possible to draw definite conclusions regarding the relative importance of this factor in modifying soil acidity. Hoagland and Sharpe (45) have found that the pH of an acid soil suspension was not markedly altered by additions of carbon dioxide even up to 10 per cent but with alkaline soils the pH rose considerably. In addition Hoagland (44) found that increasing the concentration of carbon dioxide in the soil air increased the concentration of the soil solution especially as regards calcium. He is of the opinion that the effect of carbon dioxide on the soil will depend upon the acidity of the soil. The more alkaline the soil the more will it be affected by carbon dioxide.

There has been a great controversy as to the part played by carbon dioxide in the feeding power of plants. Davis, Hoagland and Lipman (19) ascribe all differences in absorption of calcium and phosphate to the different amounts of carbon dioxide given off by the plant roots and to the extent of the root system. This is supported by some results of Newton (74) growing peas and barley in sand cultures to compare the carbon dioxide production with the intake of calcium. He found no significant difference in calcium content of barley, peas and vetch when grown in the same or similar solution cultures with either high/

high or low calcium content. When peas and barley were grown in the same soil cultures the peas took up much more calcium than the barley. These differences are ascribed to be due to the effect of the greater evolution of carbon dioxide from the pea roots bringing salts into solution in the soil.

The above idea is not borne out by work done by Parker (78). He grew velvet beans, buckwheat, sorghum, cowpeas and soybeans in pots in a slightly acid, moderately fertile sandy soil. The amounts of carbon dioxide excreted by the plant roots were in the order:- cowpeas > velvet beans > sorghum > soybeans > buckwheat while calcium was absorbed in the order:- buckwheat > cowpeas > velvet beans > soybeans > sorghum.

Truog (109) on the other hand considers the feeding power of plants to be a function of the acidity of the cell sap following its effect on the equilibrium of carbonic acid and calcium phosphate with the formation of their products of interaction -

$$Ca_3 (PO_4)_2 + 2H_2CO_3 \rightleftharpoons Ca_2 H_2 (PO_4)_2 + Ca H_2 (CO_3)_2$$

Plants with a high sap acidity, e.g. buckwheat are supposed to absorb both the products to the right of the equation. Plants with a low sap acidity, however, absorb calcium bicarbonate much slower than dicalcium phosphate. This will give an excess of the former, forcing the reaction back and preventing the further/

further solution of rock-phosphate. Truog represents this class by corn and oats. This idea has been supported by some workers (5) (6) (36) but has been vigorously refuted by others (19).

It can be seen, therefore, that there exists great diversity of opinion as to the general function and effects of CO_2 in the soil towards plant growth. The fact, however, that the influence of carbon dioxide and the influence of the growing plant in modifying the acidity of the soil are so similar that they would seem to indicate that the evolution of carbon dioxide by the plant roots plays an important part in determining the acidity of the soil and so indirectly in the availability of plant nutrients.

SECTION 2.

The Seasonal Variation in Soil Acidity and the Effect of Plant Growth as revealed by Pot and Plot Experiments; The Relationship between Soil Acidity and Composition of the soil water as shown by measurements of Conductivity and Concentration of Calcium.

Introduction.

The pH value of a soil, as such, and its effect on the plant has probably been rather over-stressed. It has been shown that plants do not grow very well on very acid or very alkaline soils but it has been shown that a particular plant may be grown throughout a considerable range of acidity. A great diversity of opinion, however, is evident from a perusal of the work done in connection with the subject.

The effects of acidity and alkalinity on plants have been observed by a large number of workers. For example, Hoagland (43) has studied the growth of plants in solutions over a wide range in acidity. He found that barley seedlings grew quite well at a pH of 5.16 but below this they did not thrive so well and finally died when the pH had fallen to 2.16. The same plants could not withstand the same degree/

degree of alkalinity, however, a pH value of 8.26 for the solution was harmful and with 9.40 it was fatal. Many others have found slightly acid conditions best for a number of plants, such as Salter and McIlvaine (96) who obtained the best growth for wheat, soybeans, and lucerne under slightly acid conditions. A pH value of 5.94 gave them their best results for these crops, while for maize they found that it grew best with the pH value at 5.16 but when it had dropped to 2.96 the plants were injured and at 2.16 killed. Similar results were also obtained by Powers (82).

In this connection Bryan (18) has found cereals to be much less sensitive to acids than to alkalies and less sensitive to acids than most legumes. He found differences even amongst the cereals. The maximum growth of oats was obtained with a pH of 6 while with wheat it was higher and lay between 6 and 7 and he found that oats generally were much less affected by acidity than wheat. Under field conditions with alfalfa the best results were obtained with the soil approximately neutral or free calcium carbonate present.

A number of others have stated causes for the injury done to the plant at a particular pH value. For example, McCall and Haag (64) have shown that between/

between the range of pH values from 4 to 7 the injury was due to iron starvation. While at higher pH values ranging from 8 to 9 Reid and Haas (91) found that plants suffered from a lack of calcium and when it was added the plant proceeded to grow normally.

Then again there are the results of Gilbert and Pember (31) obtained with lettuce grown in water cultures. When the plants were grown in solutions of pH value from 3.2 to 7.5 they suffered practically no ill effects but even very small additions of aluminium salts were toxic. They also found a better correlation between the yields of barley obtained under different climatic conditions and the amounts of free aluminium in the soils than with their pH values. On the other hand, Prianishnikov (83) correlated the injury sustained by plants at various pH values with the buffer capacity of the soil. He used a number of different soils with their pH values adjusted to range from 4.5 to 8.0 and grew peas, mustard and beet in them. He found that soils with a high buffer capacity could support plants at a low pH and also that these highly buffered acid soils contained considerable amounts of Calcium.

Pot/

TABLE NO. 1.

POT EXPERIMENTS - SOIL B.

The Crops Grown and the Treatment of the Soil in the Various Pots for the Seasons 1930-31 (1931) and 1931-32 (1932).

Pots.	12.4.30	14.4.30	1.4.31	9.4.31	15.3.32	25.3.32
1, 2,	.02% S	Fallow	.015% S	Fallow	.015% S.	Fallow
3 - 6	.02% S	Epicure	"	Barley	"	Peas
7 - 10	.02% S	Golden Wonder	"	Peas	"	Beans
11, 12	-	Fallow	-	Fallow	-	Fallow
13 - 16	-	Epicure	-	Barley	-	Peas
17 - 20	-	Golden Wonder	-	Peas	-	Beans
21, 22	.1% $Ca(OH)_2$ *	Fallow	-	Fallow	-	Fallow
23 - 26	"	Epicure	-	Barley	-	Peas
27 - 30	"	Golden Wonder	-	Peas	-	Beans

* Approximately ½ the "lime requirement" as determined by the Hutchieson and McLennan method.

TABLE NO. 2.

POT EXPERIMENTS - SOIL W.

The Crops Grown and the Treatment of the Soil in the Various Pots for the Seasons 1931 and 1932.

Set.	Pots.	7.4.31	8.4.31	25.3.32.
1	1,2	-	Fallow	Fallow
2	3 - 6	-	Oats	Peas
3	7 - 10	-	Peas	Beans
4	11, 12	.2% $Ca(OH)_2$ *	Fallow	Fallow
5	13 -16	"	Oats	Peas
6	17 - 20	"	Peas	Beans
7	21, 22	.45% $Ca(OH)_2$ *	Fallow	Fallow
8	23 - 26	"	Oats	Peas
9	27 - 30	"	Peas	Beans
10	31, 32	1% $Ca(OH)_2$ *	Fallow	Fallow
11	33 - 36	"	Oats	Peas
12	37 - 40	"	Peas	Beans

* These treatments were calculated from a buffer capacity curve to raise the pH value by approximately 1, 2, and 3 units i.e. to give a range of values 4.6, 5.6, 6.6 and 7.6. The actual figures at the commencement of the experiment were 4.66, 5.63, 6.70 and 8.12.

Pot Experiments.

The soils B and W (pages 6 & 7) were used for the pot experiments. The former was placed in ordinary earthenware pots - 12" diameter - and the latter in Mitscherlich pots. The treatments and crops grown are described in the accompanying tables. (Nos. 1 and 2).

It will be observed that throughout each series of experiments the fallow pots were in duplicate and the planted pots in quadruplicate. The pots were sampled at intervals throughout the season by means of a small auger and the samples conveyed to the laboratory in small glass tubes for pH determination. The agreement between replicate pots was invariably good and the average results for soils B and W are shown graphically in figs. 1, 2, 3 and 4, 5 respectively in the appendix.

The drainage water from each set of Mitscherlich pots was collected at various times and combined for determination of the calcium content which was estimated by evaporating the solution to dryness, igniting at dull red heat and extracting the ash with hydrochloric acid. Iron and aluminium present were removed by ammonia and the calcium precipitated as oxalate. The calcium then estimated by titration with potassium permanganate/

- (see appendix for the results, figs 6, 7, 8, 9).

Results.

The pH values, for both soils B and W, show a considerable seasonal variation, with differences of as much as 0.6 pH unit in a month. The maximum pH value of the soil occurs after heavy rainfall i.e. leaching, while the minimum is found after a period of warm dry weather i.e. at a time of maximum evaporation.

The effect of the growing plant on the acidity of the soil is to raise the pH value throughout the growing season. After the removal of the plant in autumn the pH value of the planted soil falls and drops below that of the unplanted soil. The one exception to this is the heavily limed W_4 series. Here the pH of the planted soil remained below the fallow except for a short period at maximum plant growth when the pH of the former rose above that of the control.

The calcium leached from the Mitscherlich pots varied but on the average the increases were in a similar order to the applications to the soil (figs 6, 7, 8, 9). The organic matter in the drainage also increased with the increase in additions of lime to the/

TABLE NO. 3.

BOGHALL REACTION PLOTS - SOIL B.

The Crops Grown and the Treatment of the soil in the 10 plots for the Seasons 1930, 1931 and 1932.

Plot	27.11.29	3.4.30	April-May 1930	31.3.31	April-May 1931	18.3.32	March-April 1932
A 1	-	6 lb. S	Barley + seed mixture.	-	Hay	4 lb. S	Beans
A 2	-	2 lb. S	"	-	"	2 lb. S	"
A 3	-	-	"	-	"	-	"
A 4	12 lb $Ca(OH)_2$ *	-	"	-	"	-	"
A 5	36 lb $Ca(OH)_2$ *	-	"	-	"	-	"
B 1	-	6 lb. S.	Potatoes, Golden Wonder & Epicure.	4 lb. S.	Barley + grass mixture.	2 lb. S.	Hay
B 2	-	2 lb. S.	"	2 lb. S.	"	1 lb. S.	"
B 3	-	-	"	-	"	-	"
B 4	7 lb $Ca(OH)_2$ *	-	"	-	"	-	"
B 5	21 lb $Ca(OH)_2$ *	-	"	-	"	-	"

* The amounts of $Ca(OH)_2$ added to plots 4 and 5 were equivalent respectively to approximately $\frac{1}{2}$ and $1\frac{1}{2}$ times the lime requirement as estimated by the Hutchieson and McLennan method.

the soil. The water from the untreated soil was colourless while that from the pots which had received the greatest addition of lime was a deep brown.

It was also found that more calcium was leached from the unplanted than from the planted pots until plant growth was greatest; then there was a considerable increase in soluble calcium from the pots planted with peas. In some cases the calcium leached out exceeded that from the controls to a considerable extent. This may be due to the large quantities of CO_2 said to be given off by the roots of legumes. (94, 95, 102). The maximum accumulation of calcium in the drainage occurred at the period of greatest rainfall in August and probably there was left a minimum concentration of soluble calcium in the soil. The pH values of the soil for the corresponding period were very high, showing the tendency for the pH value of the soil to rise as the concentration of soluble salts falls.

Plot experiments.

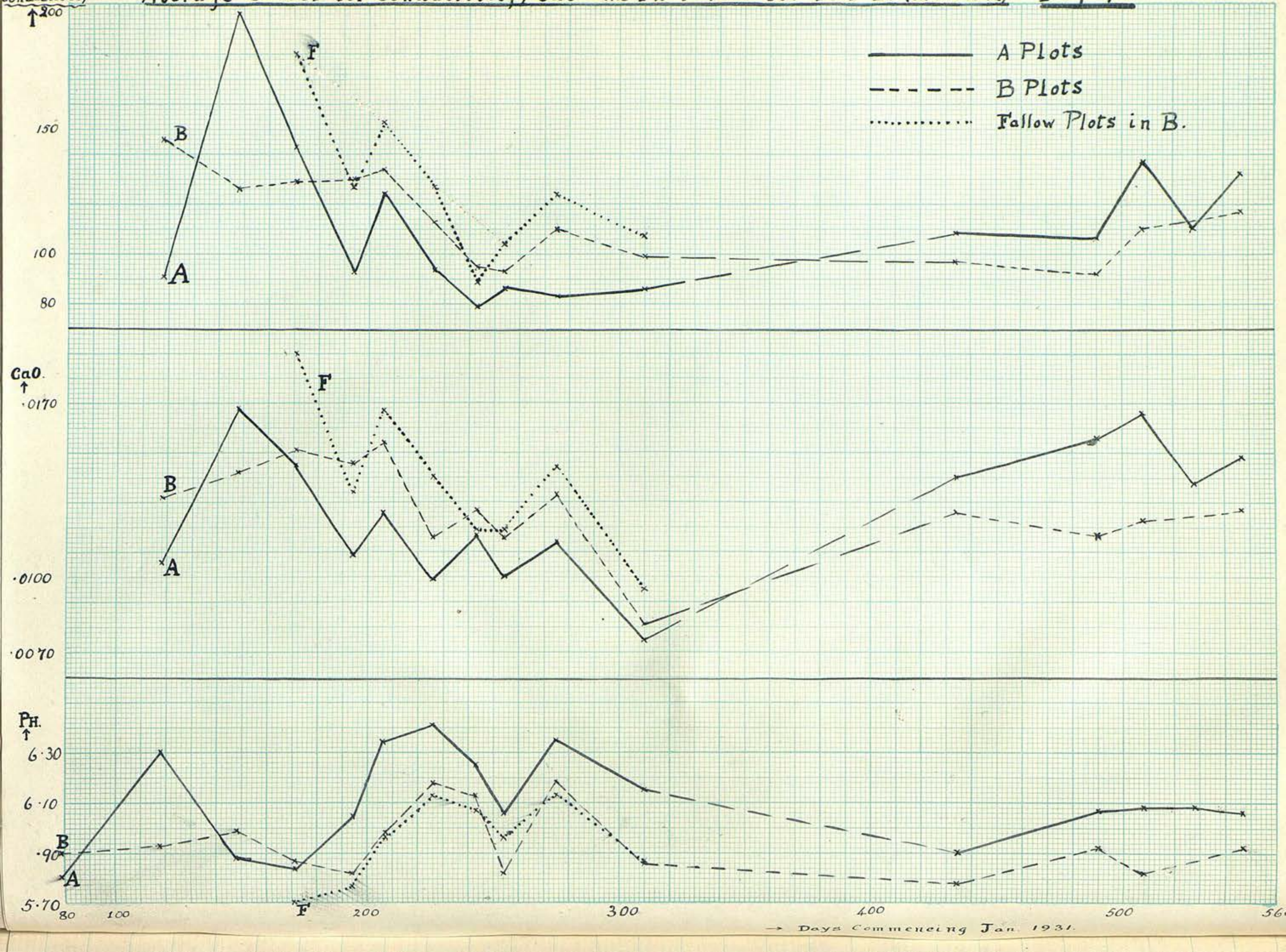
The plot experiments were carried out at the College Experiment farm, Boghall (Soil B, page 6). The plots were laid out and treated as shown in the accompanying table No.3. Soil samples were taken at intervals throughout the seasons 1931-32. Six borings/

borings of soil were taken with a large auger to a depth of 6 inches from each plot and combined to give a representative sample. The pH of each sample was determined and in addition a water extract was made by mixing 100 gms. of the air dry soil with 500 cc. of distilled water, shaking for twenty-four hours and filtering. The conductivity of the filtrate and its calcium content were then determined. Conductivity measurements were made by means of Evershed's Conductivity Meter. This instrument may not give quite accurate measurements but the aim of the experiment was to obtain comparative rather than absolute figures. The calcium content of the solution was estimated by precipitating the iron and aluminium by ammonia, filtering and precipitating the calcium as oxalate in the filtrate. The calcium oxalate was estimated by titration with potassium permanganate.

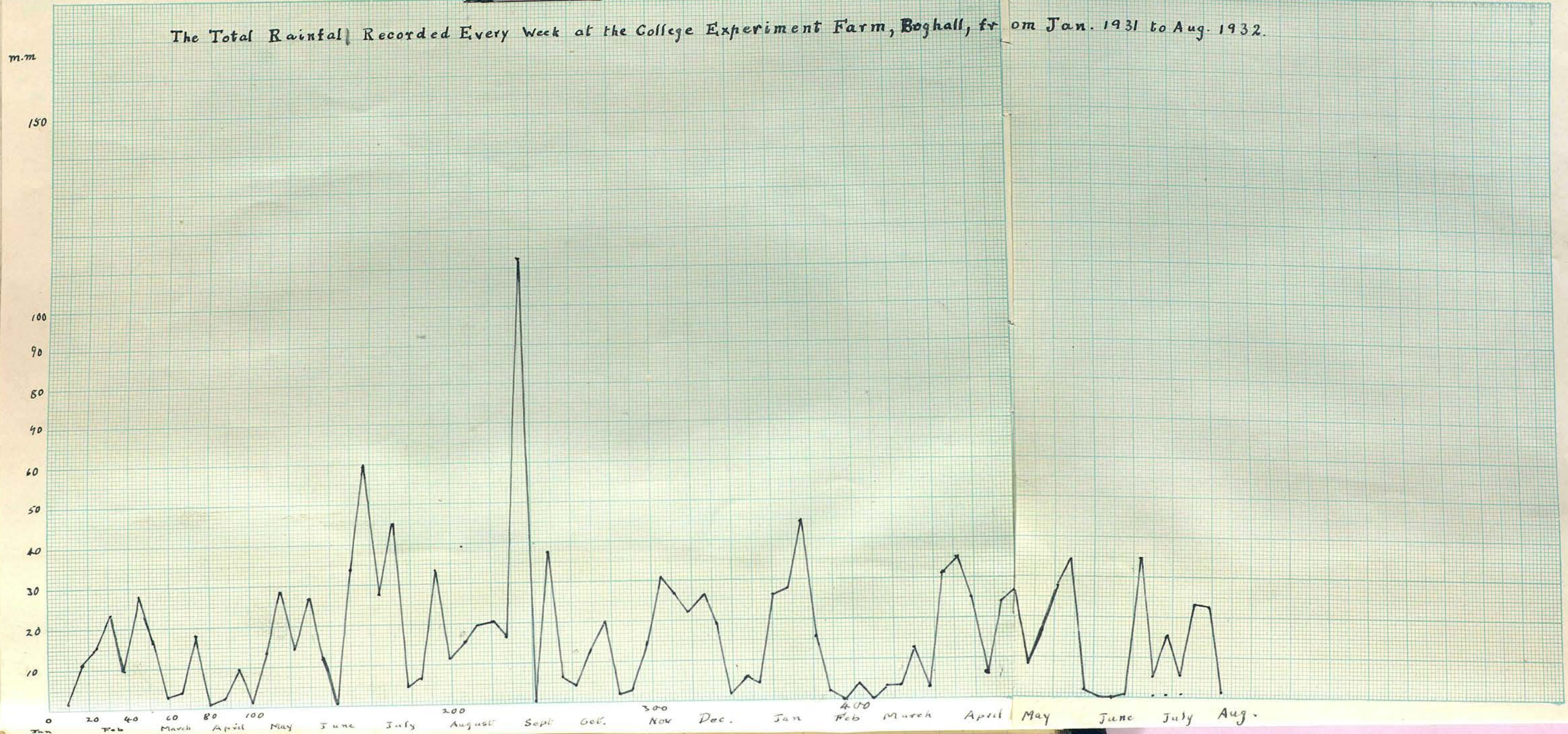
Results.

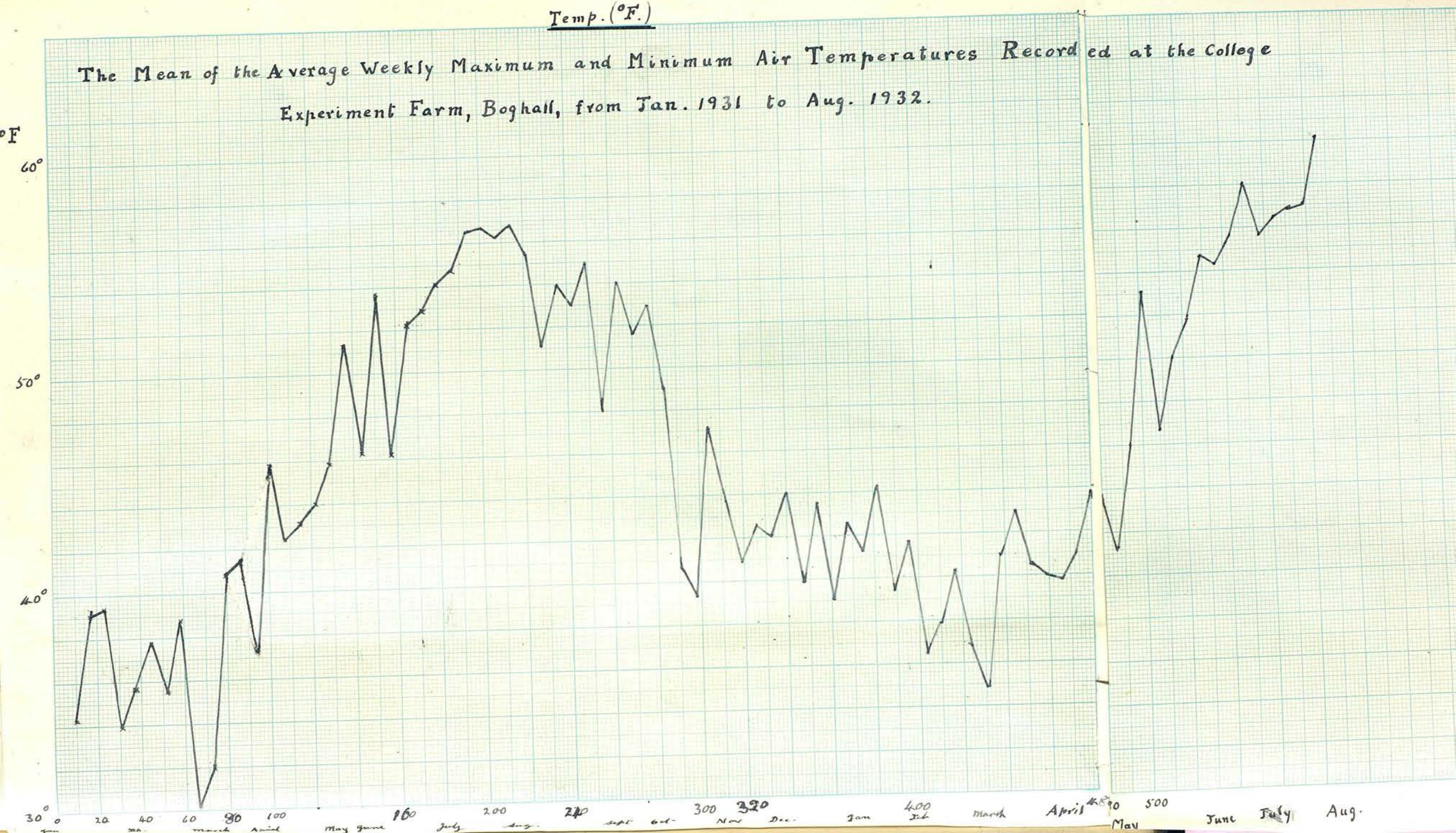
Under the different treatments, fluctuations in the pH values of the soil during the period of observation were almost identical. That is shown clearly in the pH curves for each plot. (Appendix curves 10-14). The same thing occurs in the various curves for conductivity and calcium content of the soil extract (Appendix curves 15-24). For convenience in/

Average Curves for Conductivity, CaO and PH Values for Soil B. (in the field) Fig 4.



Rainfall (in mm)




Temp. (°F.)
The Mean of the Average Weekly Maximum and Minimum Air Temperatures Recorded at the College Experiment Farm, Boghall, from Jan. 1931 to Aug. 1932.
°F
60°
50°
40°
30
0
20
40
60
80
100
160
200
240
300
320
400
May June
July
Sept
Nov
Dec.
Jan
March
April
500
May
June
July
Aug.

in comparison, average curves have been prepared by plotting the average values of pH, conductivity and calcium respectively of the different plots for each series (fig 4). Curves showing the variation in temperature and rainfall over the same period are also included.

The close parallelism of the curves for conductivity and calcium values of the water extract are shown very well. The inverse nature of the curves for pH and conductivity values is also brought out clearly. At about 120 days from the beginning of 1931 the pH was high, there was a moderate rainfall after a dry spell, a medium temperature and the conductivity and calcium values very low. It would be assumed, then, from the latter results that the concentration of electrolytes present in the soil solution, at this period, would also be low. The conductivity then rises to its maximum, the pH falls to a minimum, and the temperature is high offsetting the effect of rainfall. A high concentration of electrolytes should be present in the soil at this period. The conductivity falls away again throughout the rest of the season with a minimum at the period of excessive rainfall in August. The pH values, on the other hand rise again and are at a maximum during these heavy August rains. At this later period the concentration of electrolytes in the soil must be very low/

low. These results bring out very clearly the inverse nature of the relationship which exists between the pH value of the soil and its concentration of electrolytes.

When the individual curves (appendix figs 10-14) are examined it can be seen that, as in the case of the pot experiments, there was a considerable variation in acidity of the soil throughout the year. Fluctuations of as much as 0.8 pH unit took place within short periods during the growing season.

The results obtained from the pots were similar but not so consistent as those obtained in the field and this was probably due to the watering the pots received during periods of dry weather. These results show that, generally speaking, the pH value of the soil was at a maximum when the rainfall and leaching were greatest and that the minimum pH value occurs during dry warm weather.

The individual curves for conductivity of the water extracts from the various plots run exactly parallel to those for calcium content. The A series with a hay crop in 1931 had a maximum conductivity at the end of May when the corresponding pH values reach a minimum and then a steady fall except for the limed plot A 5. The conductivity rises again in this case but this is probably due to free lime present in the/

the soil as shown by the much greater rise in the corresponding calcium values. During the period of this fall in conductivity and calcium content in the soil solution the pH values rise and reach their maximum value, showing definitely the inverse relationship of pH and concentration of salts in the soil solution. One notable feature of the results is the fact that whilst the pH of the fallow soil is generally lower than that of the planted soil during the growing season the conductivity and calcium content of the aqueous extract is almost invariably greater in the case of the fallow soil.

Discussion of Results.

It may be seen from these results, obtained both by pot and field experiments, that there was a considerable seasonal variation in the acidity of the soil accompanied by a similar variation in the concentration of electrolytes in the soil solution.

The acidity was at a minimum at these periods of high rainfall when it may be assumed that a large proportion of the salts present in the soil solution were washed out. On the other hand the maximum figures for acidity were usually found at periods of dry weather when evaporation is likely to exceed percolation and give rise to an increase in salt concentration/

concentration of the soil solution. The usual measurement of the pH value of the soil in a water suspension is then considerably affected by exchange acidity.

The effect of the plant on the soil acidity, as shown by the results obtained from the pot and plot experiments, was to raise the pH value throughout the growing season. After the removal of the plant, the acidity increased and generally became greater than that of the unplanted soil for a short period during the cold weather. The pH rose again above that for the unplanted soil with the commencement of plant growth in spring. The effect of the plant may be due to one or more causes. The plant absorbs ions from the soil and, as indicated by the results, keeps the salt content of the soil at a lower level than exists in the fallow soil. The presence of foliage will exert a moderating influence on the effects of temperature and rainfall. Carbon dioxide is excreted from the plant roots and probably increases the concentration of alkaline salts such as calcium bicarbonate etc. in the soil. All these factors will tend to modify changes in soil acidity due to accumulation or leaching of soluble salts.

The statement by various writers that certain plants grow best with the soil having a definite pH value (page 20) is not borne out by the experiments described in this section. It has been stated that cereals/

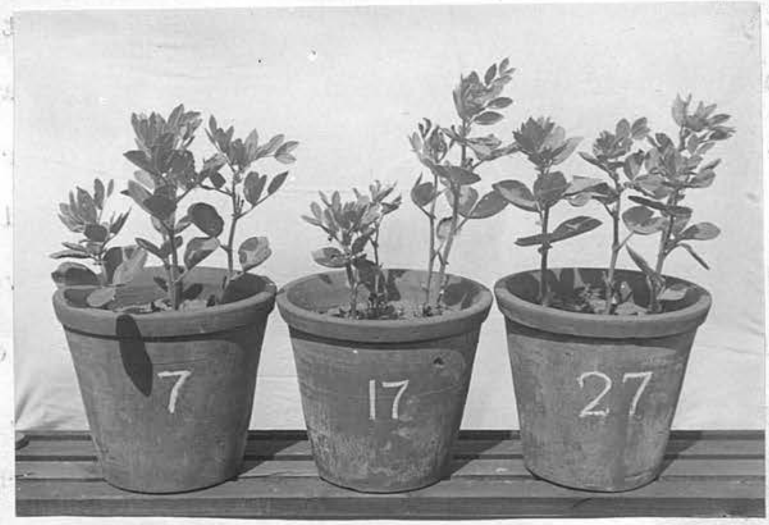


Photo. 1. Beans Growing in Soil B – Taken on the 30th May, 1932. The Plants Were Practically Identical. The PH Values of Pots 7, 17 and 27 Were 5·23, 5·94 and 6·92 respectively.

cereals are better suited to acid conditions than legumes and various pH values have been given at which a particular plant will give best growth. This was not obtained with soil B in the field, when the plots were planted with such crops as barley, beans, hay and potatoes. Each crop was grown with the pH of the soil ranging from approximately 5.5 to 7.5 and the difference in growth and yield were negligible. Similarly with soil B in pots. There was no appreciable difference in yield with barley, beans and peas although the pH value of the soil varied from approximately 5.2 to 6.8. The accompanying photograph taken on the 30th May, 1932 illustrates this point quite distinctly. There was no noticeable difference in the general appearance of the plants grown under the different conditions. It must be borne in mind, however, that the range of acidity in soil B was brought about by artificial means. The conditions existing in the soil as a result of applications of sulphur, would not be the same as those in a soil naturally acid. It is therefore not legitimate to draw any conclusion regarding the behaviour of plants on soils of different acidity from the observations made here. The most that can be said is that, as far as the fertile loam B is concerned, alteration of its pH value by artificial means/

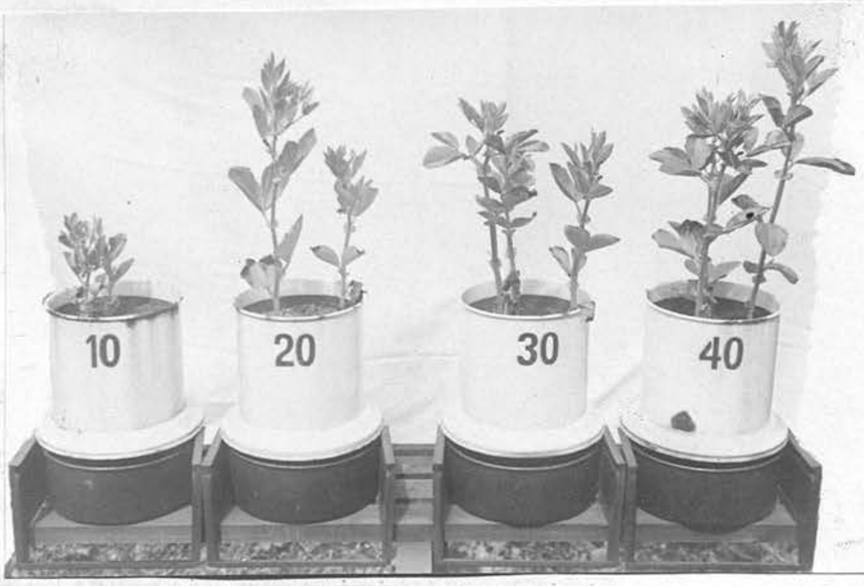


Photo 2. Beans Growing in Soil W – Taken on the 30th May, 1932. Pots 10, 20, 30 and 40 Had Received 0, ·20, ·45 and 1% $Ca(OH)_2$ and Had PH Values of 4·78, 5·55, 6·46 and 7·90 Respectively.

Photo 3. Beans Growing in Soil W in the Field (at Boghall) – Taken on the 21st July, 1932. All Plots Received Compound Fertilizer (8% N, 16% P_2O_5, 16% K_2O) at the Rate of 400 lb per Acre. Alternate Plots (Starting from Front Left) also Received ·38% $Ca(OH)_2$ (See Page 43.)

means do not appear to have any considerable effect on the growth and yield of any of the common crops. That the composition of the crop is affected, however, will be shown later.

The results obtained in the pot experiments using soil W were totally different. In the untreated soil with a pH value of 4.5, plant growth of such crops as beans, oats and peas was barely supported and none of the plants ever reached maturity. In the limed pots the best growth of the oats and peas was obtained with the pH value of the soil approximately 6.5 while with beans the best results were obtained with a pH value of 8.0. The accompanying photograph taken on the 30th May, 1932, will serve to show clearly how beans responded to treatment of the soil with lime. The same thing was very well demonstrated in the field and the photograph taken on the 21st July, 1932 shows the difference in the growth of beans on the limed and unlimed plots on Soil W, described on page 43 . Soil W, of course, differs markedly from B in being comparatively open in texture and extremely infertile. From experience one would have confidently predicted that it would respond to a dressing of lime. It is evident, however, that the pH figures alone for the two soils would give little indication of the real difference between them in respect of their cropping capacity. The tendency in various quarters to give undue importance to pH /

pH measurements in the assessment of soil properties is therefore to be deprecated.

SECTION 3.

The Effect of Lime on the Acidity of Certain Soils and on the Growth and Composition of Plants as shown by Pot and Plot Experiments.

Introduction.

Calcium is one of the most important elements for plant growth. A deficiency of this element is shown by brown spotting and death of the leaves of plants. This was observed by Von Raumer and Kellermann (86) in the first important study of calcium effects. The plants are also very stunted and either do not mature or mature much later than usual.

When peas are grown in distilled water the root development stops after the third day (63) (62) but the addition of even a trace of calcium sulphate causes renewed growth. This has also been noticed with young orange trees (88) (89) (91), potatoes (75) and soy beans (32).

It was originally thought (86) that calcium was used in the formation of cell wall material and also of proteins. A later theory (80) was that the main use of calcium was in the precipitation of acids, chiefly oxalic, formed as by-products by the plant in/

in the synthesis of proteins. This is supported by the fact that plants rich in protein, such as peas, beans, etc. are also very rich in calcium. Newton (74) put forward as an argument against this the fact that peas and barley did not absorb calcium and nitrogen in proportionate amounts when grown in water cultures. Then again, Davis, Hoagland and Lipman (19) ascribed all differences in absorption of calcium to the different amounts of carbon dioxide given off by the roots. This has been shown to be incorrect by Parker (78). There is further evidence in favour of calcium being used by the plant to neutralize organic acids, in the study of calcium starved citrus trees by Kelley and Cummins (53). The mottled leaves contained much less calcium than the normal healthy ones. Part of the calcium was found to be present in the form of calcium oxalate and part as calcium pectate cementing the walls together.

When plants are suffering from over nutrition, calcium is a very good antidote. Further when plants are under fed as with cultures of single salts or distilled water calcium salts have a more beneficial effect than any other.

The effect of calcium on the soil with respect to its intake by plants would appear to depend upon a number of factors, chief amongst these being the 'lime requirement' /

requirement' of the particular soil. When a soil is deficient in lime and has an acid reaction then the addition of lime will improve the growth of most plants and increase the yield. An important exception is the potato plant which generally gives the best results when grown within the range of pH from 4.8 to 5.4 units. (114) Even light applications of lime to the soil may cause scab with this crop.

Gedroiz (29) has studied some of the relationships between the calcium in the soil and the growing plant. He found the same yield with oats on the natural soil as with the same soil saturated with calcium. As a result of his work he came to the conclusion that plants can use soil calcium only in the exchangeable form while they can utilize the non-exchangeable potassium and magnesium. He showed this by obtaining a normal crop after removing the exchangeable potassium and magnesium from the soil and still obtained a normal crop. When the exchangeable calcium had been removed, however, there was no growth at all.

Lipman records some increases in crop obtained by liming accompanied by an increase in the nitrogen recovered in the crop, especially with legumes. This fact he attributed to their large demand on the calcium of the soil becoming satisfied and allowing free formation of protein. This effect of increased nitrogen/

nitrogen content with liming has also been explained by the favourable effect of lime on the legume bacteria as it has been shown that most species of legume bacteria grow best under neutral or slightly alkaline conditions. (70) (27) (10).

Blair (11) finds a quicker maturity with slightly increased grain yield with maize grown on limed soil.

A considerable amount of work has been done on the effects of liming on the absorption of potassium and phosphate and very different results obtained. These results have been obtained by the Neubauer method and were (1) $CaCO_3$ lowered the absorption of P_2O_5, (2) P_2O_5 absorption increased by $CaCO_3$ but K_2O unchanged, (3) neither K_2O nor P_2O_5 increased by $CaCO_3$, (4) $CaCO_3$ lowered the absorption of both K_2O and P_2O_5, (5) $CaCO_3$ increased the absorption of K_2O but lowered that of P_2O_5.

Gracanin and Němec (34) in a comparison of the above results obtained by different writers with their own came to the conclusions that the effect of liming depended on the pH and calcium content of the soil. On liming soils with pH values of from 4.40 to 6.90 the root soluble phosphate and potash was increased. While with a range of pH values from 7.40 - 8.35 and a sufficiency of lime on the soil they found that liming increased the absorption of PO_4 by the plant. Yet/

Yet with increasing phosphate content of the soil liming depressed its absorption by the plant. The results were similar with potassium. As the potassium content of the soil increased so did liming decrease its availability to the plant.

Mooers (70) also found that liming generally decreased the availability of Potash to the plant. That is to say its outgo in the free soil water was decreased greatly and liming can be used for the greater retention of potassium from green manuring in soils (68) (69).

Lagatu and Maume (54) growing potatoes in soils rich in (1) calcium and (2) potassium, found that the distribution of the two elements in the leaves was proportional to the amount in the soil. Fonder (25) found that calcium and potassium were interchangeable in the plant although not with the same physiological effect, when alfalfa plants were grown on different soils with different calcium and potassium contents. If the calcium content in the plant was low then the potassium content was high and vice versa. It would appear that the potassium content depends on the calcium content, which in turn depends on the available calcium in the soil.

Liming has also been found to decrease the solubility of Manganese in the soil (61) while that of iron/

iron was increased by small additions of lime, while heavier applications decreased it again. It would appear from this work, that with heavily limed soils, the chlorosis of plants was due to a manganese shortage as the absorption of this element by the plant closely followed its solubility in the soil.

The moisture content of the soil appears to be little affected by liming (30) although the surface layer became more permeable to water with an improvement in texture. The condition of the subsoil however was the reverse of the surface soil after the addition of lime.

EXPERIMENTAL.

The soils B and W (pages 6 & 7) were used in the pot experiments as already described in tables 1 and 2 respectively. The plot experiments were those laid out at the College Experimental farm, Boghall (soil B table 3, page 24).

The samples for pH determination were taken as detailed in page 25 and the conductivity and calcium content of the water extract determined (page 25). For the above results see figs. 1-24 appendix.

The plants in the pots were sampled at maturity in 1931 by cutting the plants close to the soil level. The plants for each crop were combined from the similarly treated pots in each section. The same procedure was followed in 1932 and in addition samples of the crops were taken before flowering. In the case of the field experiments samples were taken from each plot at a number of points and combined to give a representative sample of the crop. With the hay crop in 1931, rye grass and clover were sampled and analysed separately.

All crop samples were conveyed to the laboratory and the plants washed free from any adhering soil particles and oven-dried. The dry material was then finely ground and bottled, and the calcium and sulphur contents estimated in the various samples. The

moisture/

moisture content was obtained for all samples by drying at 100°C. and the calcium and sulphur contents are expressed as percentages SO_4 and CaO respectively in the oven dry material.

The calcium content in the dry material was estimated as follows:- a quantity of the material was ashed at dull red heat in an electric muffle, the ash evaporated with HCl to render silica insoluble and extracted with HCl and filtered. Phosphate, iron and aluminium were removed from the filtrate by the addition of ferric chloride and sodium acetate. The calcium was precipitated from the solution as oxalate and estimated by titration with potassium permanganate.

The sulphur in the dry material was estimated by fusion with sodium peroxide and sodium carbonate. The fused mass was extracted with water, filtered and the sulphate precipitated in the filtrate as barium sulphate with barium chloride. The precipitate of barium sulphate was ignited and weighed as barium sulphate and the percentage sulphate calculated in the dry weight.

Results.

The rise in pH value for the particular applications of lime depended naturally on the buffer capacity of the soil. The actual pH values obtained and their fluctuations throughout the year are shown in/

in the appendix (figs. 1-5 and 10-14). Liming soil B in the field increased the conductivity and calcium content of the water extract. The increases were small with the smaller application of lime and at some periods the values were less than for the untreated soil. The increases for the higher applications were more pronounced.

The calcium in the drainage water collected from the pots containing soil W (appendix figs. 6-9) increased with the increasing applications of lime.

The effect on the growth of the plant due to liming the soil was apparent only with soil W. This soil has been uncultivated for about seventy years and is very acid with a very low content of exchangeable calcium (99). As would be expected liming made a very great difference to the growth and yield of plants. The plants in the unlimed pots hardly exceeded three inches in height and never matured. The plant generally had a sickly yellow appearance as has been observed (86) with shortage of lime. When lime was added to soil W a normal healthy plant was obtained. The same soil also shows some of the ill-effects which follow from over-liming. The size and growth of the plants were retarded with the greatest application accompanied by later maturity for the first year. After the heavy leaching which took place during the first year along with carbona-

tion/

TABLE NO. 4.

POT EXPERIMENTS - SOIL W.

The Effect of $Ca(OH)_2$ on the Calcium and Sulphur Content of the Crop.

Year	Crop	Ca in Crop as % CaO.†				S in Crop as % SO_4.†			
		Set 1.	Set 2.	Set 3.	Set 4.	Set 1.	Set 2.	Set 3.	Set 4.
1931	Oat (Straw)	.082	.092	.157	.228	.398	.480	.286	.126
"	Oat (Grain)	.111	.058	.057	.067	.109	.029	.024	.036
"	Peas	-	1.076	1.185	1.801	-	.564	.426	.540
1932	Peas (1)x	.233	1.216	1.287	1.714	.257	.486	.248	.231
"	Peas (2)x	.228	1.021	1.148	1.374	.433	.511	.345	.284
"	Beans (1)x	.133	.658	.761	.928	.210	.299	.226	.207
"	Beans (2)x	.164	.667	.820	1.000	.393	.367	.277	.242

x (1) = Cut before flowering.

x (2) = Cut after flowering.

† All percentages calculated in terms of the oven-dried material.

carbonation of the $Ca(OH)_2$, the next year's crops were not affected to the same extent. The yield of beans for this set was even greatest as is shown in the accompanying table which also brings out very well the advantages acquired by adequate liming and its effect on the fertility of the soil.

Pot Experiments with Soil W. Crop Yields under Different Treatments.

	1931 (dry weight)		1932 (actual plants)	
Set	Oats (gms.)	Peas (gms)	Peas(gms)	Beans (gms)
1	4.05	2.00	11.8	53.8
2	12.11	11.60	118.2	304.5
3	26.84	15.93	182.8	404.6
4	24.67	5.70	169.8	528.1

The yields obtained from soil B, both in pot and plot experiments were practically identical for the limed and unlimed soil.

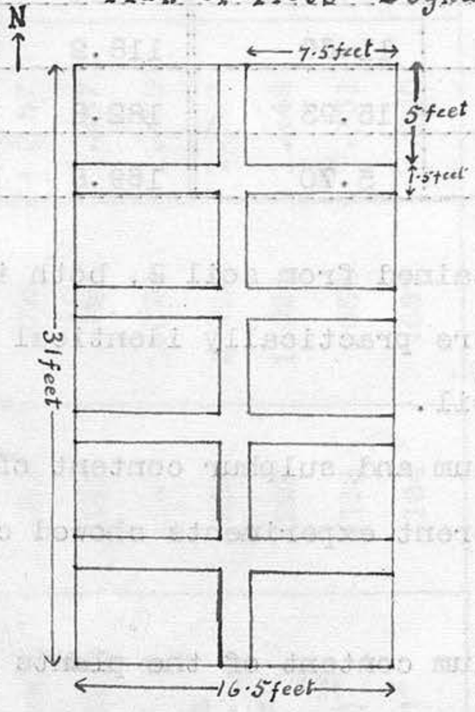
The calcium and sulphur content of the plants from the different experiments showed considerable variation.

The calcium content of the plants grown on soil W in the pots (table 4) increased with the increased applications of lime to the soil. The largest increase being as much as eight-fold. The sulphur content/

content of the plants generally rose for the first small application of lime, dropped back to the original value with the second addition and for the third it decreased further. This is a good example of the antagonism of ions in the soil and how an excess of one affects the absorption of another by the plant. It is possible that the smallest addition of lime made good the deficiency of calcium compared with sulphur in the soil and resulted in a fairly normal growth with increased absorption of both ions. It may be that further additions of lime upset the balance again.

The effect of liming soil W in the field was also studied. A small area (50 - 60 sq. yds.) of soil W at Boghall was taken into cultivation in 1931. The turf was stripped and buried and the soil dug over. Potatoes were grown the first year in order to get the ground thoroughly cleared. In November 1931 the area was divided into 10 plots (see sketch opposite) and the even numbers treated with .38% $Ca(OH)_2$ which was carefully mixed to a depth of 9 inches. This was the treatment which gave the best results with soil W in pots. In April 1932 each plot received compound fertilizer (8 % N, 16 % P_2O_5, 16% K_2O) at the rate of 400 lbs. per acre and beans were sown in all the plots. In June the beans in the limed plots/

Plan of Plots – Boghall, Soil W.



plots were growing vigorously while in the unlimed plots they were barely showing. In July the beans in the limed soil had reached a height of about 3 feet and were forming pods quite well. On the other hand those on the unlimed soil were only 6 inches high and were going back. They had the same yellow spotted appearance noted for the same soil in the pots. The difference in growth for the two treatments is shown clearly in the ~~accompanying~~ photograph taken on the 21st July (see page 31). Samples of the beans were taken on the same day for analysis. About five plants were taken at random from each plot and it is interesting to observe that the average weight of each plant from the limed plots was approximately ten times that of the plants grown on the unlimed plots, because the ratio of calcium in the limed to unlimed plants was also approximately ten : one.

Treatment of plot.	Ca Content as % CaO	S Content as % SO_4	Average Wt. of Plant.
Unlimed (manured)	.183	.235	6.7 gms.
limed (")	1.839	.178	68.8 gms.

These results also show that when a soil is very deficient in lime, manuring may have little or no effect until the calcium deficiency has been made good. This conclusion was supported by the results obtained in a series of pot experiments with the same soil.

Beans/

TABLE NO. 5.

POT EXPERIMENTS - SOIL B.

The Effect of $Ca(OH)_2$ on the Calcium and Sulphur Content of the Crop.

Year	Crop	Ca Content of Crop as % CaO †		S Content of Crop as % SO_4 †	
		Set 2.	Set 3	Set 2.	Set 3
1931	Barley X	.113	.126	.343	.347
"	Peas	.638 fruit	.939	.285	.305
1932	Peas (1) x	1.116	1.113	.188	.167
"	Peas (2) x	.880	.844	.147	.182
"	Beans (1) x	.872	.877	.205	.227
"	Beans (2) x	.903	.886	.230	.155

X Practically all the grain was lost in high winds and the above refers to straw.

x (1) = cut before flowering.

x (2) = cut after flowering.

† All percentages calculated in terms of the oven-dried material.

<u>TABLE NO. 6.</u>

<u>PLOT EXPERIMENTS. (BOGHALL - SOIL B.)</u>

The Effect of $Ca(OH)_2$ on the Calcium and Sulphur Content of the Crop.

A PLOTS.

		Ca Content of Crop as % CaO †			S Content of Crop as % SO_4 †		
Year	Crop	A 3	A 4	A 5	A 3	A 4	A 5
1930	Barley	.041	.040	.029	.086	.079	.069
1931	Hay (Rye Grass	.132	.129	.117	.190	.182	.197
"	Hay (Clover	1.088	1.311	1.273	.129	.130	.132
"	Hay (Rye Grass	.116	.165	.159	.336	.309	.298
"	2nd Crop Hay (Clover	1.268	1.231	1.240	.162	.161	.164
1932	Beans	1.230	1.257	1.282	.384	.347	.336

B PLOTS.

		Ca Content of Crop as % CaO †			S Content of Crop as % SO_4 †		
Year	Crop	B 3	B 4	B 5	B 3	B 4	B 5
1930	Potatoes						
"	Epicure	.039	.034	.034	.096	.084	.073
"	Golden Wonder	.040	.044	.044	.080	.077	.081
1931	Barley	.041	.035	.035	.056	.053	.052

† All percentages calculated in terms of the oven-dried material.

Beans did not appear to respond to the application of fertiliser on the unlimed soil and there was not a striking difference in plant growth between the limed, and limed and fertilised, soils.

It is obvious that the results obtained by liming this soil are exceptional. The continuous leaching to which this sandy soil has been subjected for over 60 years while lying uncultivated has reduced the content of exchangeable bases to a very low value. As a matter of fact it contains only about 1 m. equiv. of exchangeable calcium per 100 gms. soil. (99).

Although this soil is exceptional in its low calcium content, yet the difference between it and any other inadequately limed soil is only one of degree. The infertility of the soil appears to be due mainly to calcium deficiency and demonstrates the low level for plant growth which a soil may reach if liming practices are not maintained.

The fertile soil B did not exert such a marked influence on the composition of the plant. In 1931 there was an increase in calcium content of the crops but in 1932 there was practically no change with liming in the pot experiments. (see table 5). In the field there was about the same number of increases and decreases in calcium content of the plants grown on the limed, as against those on the unlimed, soil. (table 6).

The

The sulphate content of the plants in the pot experiments tended to show a slight increase with liming, while in the field the tendency was towards a decrease.

Conclusion.

These results show that the effect on the composition of the plant of liming a soil depended both on the amount added and the composition of the soil. When the soil was deficient in lime and strongly acid, then liming improved the yield considerably and increased the percentage calcium in the plant. Excessive liming tended to decrease yields and also the sulphur content of the plants. The shortage of sulphur in the soil may be a limiting factor here. On the other hand liming a slightly acid fertile soil was only sometimes responsible for an increased calcium content of the plant. This generally occurred with legumes, while the tendency with cereals was towards a decreased calcium content with liming. The effect on yield, due to liming this fertile soil, however, was practically negligible.

SECTION 4.

The Effect of Sulphur on the Acidity of the Soil and on the Growth and Composition of plants by means of Pot and Plot Experiments.

Introduction.

The fact that sulphur is an essential element for plant growth has been recognised for a considerable period. Sulphur is contained to a greater extent in the leaves than in the stems of plants (21) (8) and the leaves should thus give the first indication of sulphur deficiency. This has been found to be the case in practice. The leaves turned yellow and brown spots appeared on the roots with soy beans in culture solutions without sulphates (32). Tobacco plants also became chlorotic. This effect on the plant due to sulphur starvation appears to be different from that caused by lack of magnesium or potassium. With fruit trees sulphur deficiency was similar in effect to nitrogen shortage but less severe. (112) (113).

When sulphur is added to a soil it is oxidised to sulphuric acid. This is partly a chemical and partly a bacterial action. The sulphur bacteria can live under extremely acid conditions and can be obtained/

obtained pure at a pH value of about 1. All other forms of life, moulds, etc., having died off. (85)

Sulphur is contained in various plant constituents, being essential for protein formation (9) (23), and reappears in the soil as sulphate when these decompose. The sulphate is the only form in which plants can obtain sulphur for their various requirements.

The early work done on the oxidation of elemental sulphur to sulphate was observed and studied in France and Germany (35) (12) (20) (14) (52). Since then the oxidation of sulphur has been studied intensively in the United States (52) (58) (3) (93) (49) (111) (15) (73) especially with regard to bacterial action and properties. One of these organisms (111) can live in a purely inorganic solution obtaining its carbon from CO_2. Another, Thiobacillus thio-oxidans, can exist and grow even when the pH of the mixture has fallen to 0.58. This was also found by Jensen (47) in a very acid sandy soil (pH 2.2) existing in Denmark. This soil contained free sulphuric acid and soluble iron compounds. The inoculation of the soil with sulphur bacteria has caused a quicker formation of sulphates from sulphur in some cases (40) (77) but it is generally agreed that there are sufficient sulphur oxidising micro-organisms in any soil for rapid and efficient oxidation of added elemental sulphur.

The/

The sulphuric acid formed by sulphur oxidation interacts with bases present in the soil, such as phosphates, and increases their availability to the plant. This is shown by the following experiment.(58) Three soils, sea sand, a loam and a heavily manured greenhouse soil were composted with sulphur and rock phosphate. The production of acidity and available phosphate in the three differed only in degree, showing that bacterial action was restricted by the medium. The increase in acidity of the greenhouse soil was much greater than in the sand, and the increase in acidity for sulphur much greater than for sulphur plus rock phosphate. As much as 85 per cent of the phosphate, however, was rendered available as the acid from sulphur oxidation had reacted with the tricalcium phosphate. The water soluble phosphate also increased in all the mixtures receiving sulphur and phosphate. The tricalcic phosphate would seem to aid the oxidation of sulphur by furnishing phosphate for the life activities of the organisms, while removing excess acid which might tend to become toxic. This has been followed up with a view to forming a good fertilizer. When sulphur, manure and rock phosphate were composted and well aerated, the availability of the phosphate was greatly increased. Fine grinding, i.e. increasing the surface area of the/

the components along with good aeration gave the greatest efficiency. (81) Certain salts, e.g. sodium nitrate and potassium iodide reduced while ferrous sulphate and aluminium sulphate increased the availability of the phosphate. (17)

In sand cultures with millet, the best results were found with equal amounts of sulphur and rock phosphate, in which case the utilization coefficient of the P_2O_5 of the rock phosphate is the same as calcium mono-hydrogen phosphate. (51) McCall and Smith (65) have increased the water soluble potassium of greensand to as much as 41 per cent by a mixture of greensand, morl, manure and sulphur, after several months composting.

The ability of a soil to oxidise sulphur to sulphate has been termed its "sulfofying" power by American writers. Oxidation takes place only where there is good aeration. When air is excluded the opposite takes place and sulphates are reduced to sulphides. Various treatments affect the rate of oxidation or "sulfofying" power of the soil. Manganous sulphate and colloidal iron decrease bacterial action but increase chemical oxidation. (77) Green manuring, farmyard manure and organic matter in general, tend to increase oxidation (115). The moisture and aeration also have a marked effect.

A/

A moisture content of approximately fifty per cent saturation and a mixture of fifty per cent soil and sand were best for oxidation. (51)

The oxidation of sulphur has been found by some to have a depressing effect on nitrification with soils deficient in bases (93). On the other hand, other investigators with Oregon and Idaho soils have shown increases in the nitrogen content of the crop, chiefly with alfalfa where the protein content was much increased. (72) (73) (81)

Another very important effect of sulphur is in its action on alkaline soils. In this connection it has been used with very beneficial results: chiefly with soils reclaimed from the sea or where soils tend to run together under irrigation. (40) (50) Sulphur exerts a very marked flocculating action on soils. (1) (40) (50) It causes the soil to remain more open as well as to increase its acidity as compared with untreated soils over extended percolation trials. Calcium also becomes active under sulphur treatment of the soil and displaces the sodium on the ultra clay complex forming a calcium clay which is not only very fertile but can be tilled with success. Lime and manure or gypsum supplements to the sulphur treatment also help. Leaching with fresh water then removes the sodium sulphate formed and quickens the process.

Frapps/

Frapps (26) in a series of pot experiments found that sulphur alone, when added to some Texas soils did not increase yields, but did so when accompanied by a complete fertilizer. McGibbon (66) found increases in yield with sulphur and rock phosphate and many others (2) (21) have found increases in yield following the application of sulphur as such to the soil or in the form of gypsum and also when accompanied by phosphates. (38)

Glynne in Victoria (33) with a plot down to wheat for fourteen years was obtaining very poor yields. These increased greatly with additions of sulphur. Adding sulphur and rock phosphate together increased the ratio of weight of grain to the total weight of the plant. (51) Doak (21) working with Lucerne in New Zealand found increases in yield and sulphur content for various sulphur treatments. He had lucerne planted on a stony loam for six years and four sets of three plots each, marked out. Three sets were treated with finely divided sulphur, superphosphates and sulphur, and sulphur respectively with one set as a control. Another similar experiment was conducted at the same time with the difference that all the plots were limed. All the treatments gave an increase in yield over the control but the return was greatest with gypsum both on the limed and unlimed soil. The/

The yield being greatest on the limed plot shows that it was the sulphur and not the calcium that was having the beneficial effect with the gypsum. He suggested that the greater solubility of gypsum in the soil solution was the cause of its efficiency. The sulphur treatment reduced the dry matter content of the lucerne with these experiments. This was also noticed by Alway (2)

Some results were also given by Doak (21) from plots established in Central Otago. Large increases in yield up to 100 per cent were recorded for treatments with sulphur plus superphosphates. All the treatments gave an increase in sulphur content of the plant. The nitrogen, calcium and potassium contents in the plant were also increased but not the phosphate, showing that it was the sulphur and not the phosphate of the manure, where the latter was added, which had been beneficial.

Experimental.

Soil B (page 6) was used for the pot and field experiments - pages 22 and 24 , respectively, - in the determination of the effects of sulphur on the soil and plant. The pots were sampled for pH determination (page 22) and the results appear in figs 1-5, appendix. The plants were sampled and analysed for sulphur/

TABLE NO. 8.

PLOT EXPERIMENTS. (SOIL B - BOGHALL)

The Effect of Sulphur on the Calcium and Sulphur Content of the Crop.

		A PLOTS.					
		Ca Content of Crop as % CaO †			S Content of Crop as % SO_4 †		
Year	Crop	A 1	A 2	A 3	A 1	A 2	A 3
1930	Barley	.052	.050	.041	.108	.095	.089
1931	Hay (Rye Grass	.154	.143	.132	.225	.211	.190
"	Hay (Clover	1.345	1.318	1.086	.148	.136	.129
"	Hay (Rye Grass	.183	.177	.116	.422	.386	.336
" 2nd crop	Hay (Clover	1.343	1.305	1.268	.185	.175	.162
1932	Beans	1.456	1.357	1.230	.562	.518	.384

		B PLOTS.					
		Ca Content of Crop as % CaO †			S Content of Crop as % SO_4 †		
Year	Crop	B 1	B 2	B 3	B 1	B 2	B 3
1930	Potatoes						
"	Epicure	.059	.040	.040	.122	.105	.096
"	Golden Wonder	.053	.057	.040	.104	.089	.080
1931	Barley	.049	.046	.041	.061	.058	.056

† All percentages calculated in terms of the oven-dried material

TABLE NO. 7.

POT EXPERIMENTS - SOIL B.

The Effect of Sulphur on the Calcium and Sulphur Content of the Crop.

Year	Crop	Ca Content of Crop as % CaO †		S Content of Crop as % SO_4 †	
		Set 1.	Set 2.	Set 1.	Set 2.
1931	Barley X	.129	.113	.458	.343
"	Peas	.906	.638	.362	.285
1932	Peas (1) x	1.153	1.116	.290	.188
"	Peas (2) x	.934	.880	.239	.147
"	Beans (1) x	.940	.872	.374	.205
"	Beans (2) x	.967	.903	.361	.230

X Practically all the grain was lost in high winds and the above refers to barley straw.

x (1) = cut before flowering.

x (II) = cut after flowering.

† All percentages calculated in terms of the oven-dried material.

sulphur and calcium as described in the last section (page 40) The results are tabulated opposite (table 7).

The field plots were sampled (page 25) for pH determination and the calcium content and conductivity of a water extract determined (page 25). The pH values are shown graphically in appendix, figs. 10-14, the conductivity measurements figs 15-19 and the calcium values figs 20-24. The crops were sampled (page 39) and analysed for calcium and sulphur. The results are tabulated on the opposite page. (table 8)

Results.

The addition of sulphur to soil B decreased the pH value according to the amount of sulphur added, both in the pots and in the field.

In the case of soil B in the field, a very considerable increase in conductivity and calcium content of the water extract was brought about by the sulphur treatment. In some cases the value for the untreated soil was doubled and tripled for the first and second applications, respectively. This shows to what extent sulphur increases the content of electrolytes in the soil. (Figs 15-19)

There was practically no change in yield, either in the plots or pots, with sulphur as compared with the untreated soil. This was to be expected with such/

such a heavy fertile soil which probably contains sufficient sulphur for all plant requirements.

The composition of the plant was affected to a much greater extent than the growth and yield. The amounts of calcium and sulphur contained in the various crops grown, both in the pots and on the plots, increased in a manner similar to the conductivity values for the corresponding soil. The increases, both for sulphur and calcium contents of the crops, were of the order of fifteen per cent for each addition of sulphur. This was found, as shown in the tables (7 and 8), to be the case with such varied crops as barley, beans, hay, peas and potatoes.

Conclusions.

The above results, showing that both the calcium and conductivity values for the soil solution were increased by additions of sulphur to the soil, confirm the results obtained by many other workers. In fact, it has generally been found that the addition of sulphur as such, or in the form of gypsum or superphosphates, caused an increase in the content of sulphates, calcium and potassium and generally a decrease in phosphate, in the soil solution.

The increased sulphur content of the plant due to additions of sulphur to the soil has also been found by many workers, (2) (21) (26) (66) accompanied by increased yields. Only a small percentage of the total/

total sulphates present in the soil is taken up by the plant, the remainder being washed out. It is evident, then, that unless sulphur is added in some form to the soil it will become a limiting factor for plant growth, especially with such crops as alfalfa whose content of sulphur exceeds that of phosphorus. In this plant a sulphur deficiency would become injurious before phosphorus.

In general, when sulphur is added to a soil its future effect depends on the nature of the particular soil. Sulphuric acid is first formed, both by bacterial and chemical action, which interacts immediately with the bases present bringing them to a form more easily utilized by the plant. It is not surprising, then, that no increase in yield was obtained in the experiments described with soil B. Soil B is a moderately fertile loam and probably has a sufficient supply of sulphur and other ions for all plant requirements. It is very probable, however, that the addition of sulphur to a lighter soil, which has not been supplied for some time with manures containing sulphur, will increase the yield as well as the sulphur content of plants.

CONCLUSIONS.

The results, obtained from the various dish and pot experiments using soils of a very varied nature, show convincingly that the growing plant has the effect of raising the pH value of the soil. In the dish experiments, where the root system is considerable compared with the quantity of soil, the removal of electrolytes must be comparatively great and when this happens the acidity falls. When the plant has developed somewhat, the additional factor of excretion of carbon dioxide by the plant roots must be taken into consideration. At this stage, when root development is large and the roots are in contact with such a large proportion of the soil, carbon dioxide excretion must account for a considerable part of the increased pH value by the formation of alkaline salts, such as calcium bicarbonate, etc. The effect of carbon dioxide in raising the pH value of the soil has been demonstrated by its passage through moist soil. The resulting rise in pH value is very similar to that caused by the growing plant. It is therefore probable that a close relationship exists between the carbon dioxide excreted by the plant roots and the alteration caused by plant growth in the pH value of the soil. The rise in pH value of the soil effected by the plant in the dish experiments/

experiments was also found in the pot experiments and it is generally found that the growing plant raises the pH value of the soil throughout the growing season. After the removal of the plant in autumn, the acidity of the soil rises and may exceed that of the unplanted soil before the next seasons growth commences.

The results, obtained from the pot and field experiments, show the large seasonal fluctuations in acidity which take place. The fluctuations appear to be very closely connected with the concentration of electrolytes in the soil solution. The pH value of the soil is high during periods of very heavy rainfall when considerable leaching is taking place and when it would naturally be assumed that salt concentration would be at a minimum. This is supported by the large quantities of soluble calcium found in the drainage water at those periods of maximum rainfall. On the other hand, during a period of dry weather or when evaporation is the predominating factor and salt concentration is at a maximum, the pH values are low.

It was thought that measurements of the conductivity and calcium content of a water extract of the soil would give an indication of the concentration of salts present in the soil solution and determinations of these and the pH values were made at the same time. The results obtained show that high concentrations/

concentrations of electrolytes in the water extract were accompanied by low pH values and vice versa. This lends support to the theory put forward above that the pH value of the soil bears an inverse relationship to the concentration of salts in the soil solution.

Another fact brought out in these experiments on the effects produced by acidity on the soil and crop grown ~~show~~ is, as might be expected, that the results depend on the nature of the soil. The very acid, infertile soil W (pH 4.5) barely supports plant growth and a normal crop results only when the soil has been limed. The addition of fertilizers containing nitrogen, phosphorus and potassium shows no improvement over the untreated soil; yet even a small addition of lime gives rise to normal growth. When the fertile soil B is limed, however, there is practically no visible change in growth or yield of the crop. The changes in composition vary with the crop and are small. The calcium content of clover, beans and peas tends to increase while with barley and potatoes the tendency is towards a decrease. The sulphur content shows little variation.

When soil W was limed both the yield and the composition of the various crops grown were greatly altered. In 1931 the best yields for oats and peas in the pots were obtained with the addition of ·45% of/

of calcium hydroxide to the soil and a pH value of approximately 6.5. In 1932 with beans the best yield was obtained from the addition of 1% calcium hydroxide and a pH value of approximately 8.0. The greatest increase in yield over the untreated soil was nearly eight-fold as also was the increase in calcium content of the crop. When beans were grown in soil W, in the field, fertilized with nitrogen, phosphorus and potassium, the addition of .35% $Ca(OH)_2$ brought about a ten-fold increase in both yield and calcium content with a decrease in sulphur content of the plant. In the pot experiments the sulphur content of the plants rose for the 0.2 per cent addition of lime, which permitted a normal growth and absorption of nutrients by the plant. With increasing lime additions the sulphur content of the plant decreased as the calcium content increased.

The drainage experiments carried out in connection with the lime treatments of soil W in pots showed an increase in calcium in the drainage water, with increased additions of lime to the soil and rise in pH value. The amounts of calcium leached from the planted pots were generally less than for the controls except for the pots containing peas at the period of maximum growth. Then the calcium obtained from these pots increased and in some cases rose considerably above the unplanted. This is probably due/

due to the large quantities of carbon dioxide given off by the roots.

The additions of sulphur to soil B, both in the pots and in the field, had practically no effect on the growth or yield of the various crops grown. The composition of the crops as well as the water soluble salts in the soil were considerably increased. The values for conductivity and calcium content of the soil extract were approximately doubled and tripled, respectively, for additions of approximately 400 and 1200 pounds of sulphur per acre, to soil B in the field.

The calcium and sulphur contents in the plant were also greatly increased by the additions of sulphur to the soil. Although, in this case, using a fertile soil with a high reserve of plant nutrients, there is no change in growth and yield of the crop with the sulphur treatment, yet it can readily be seen that for a poor soil low in sulphur content the shortage of this ion would become a limiting factor for plant growth; especially with continued liming and the addition of fertilizers not containing sulphur in some form.

Another point brought out throughout these experiments is the relative insignificance of the effect on plant growth of the pH value alone. Cereals have been stated to grow best under acid conditions and legumes/

legumes with the soil nearly neutral. Yet in the field no difference in yield has been obtained in yield with such crops as barley, beans, hay and potatoes with the pH value of the soil ranging from approximately 5.5 to 7.5. In pots, equally good growth was obtained with barley, beans and beas in soil B with a range of 5.2 to 6.8 pH units. In soil W beans gave best results with a soil pH of 8 , while with oats and peas the best results were obtained with the soil at a pH value of 6.5. In other words, varying the pH value of the fertile soil B has very little effect on plant growth, while with the poor sandy soil W, very low in exchangeable calcium, the calcium deficiency must be made good first for healthy plant growth. When this has been attained altering the pH value of the soil has little effect on the plant. The pH value of a soil should therefore be used only as an indication of the nature of the soil and in conjunction with other data.

SUMMARY.

1. The effect of the growing plant on the acidity of the soil has been studied by means of dish and pot experiments.

2. The growing plant had the effect of raising the pH of the soil in all cases.

3. The various effects of carbon dioxide on a number of soils have been studied.

4. The passage of carbon dioxide through the moist soils raised their pH values in a manner similar to that of the growing plant.

5. The passage of carbon dioxide through suspensions of various soils in water increased the acidity. The extent of the change depended on the degree of saturation and the buffer capacity of the soil.

6. Leaching three soils with a saturated carbonic acid solution increased the acidity of approximately the first half inch, and lowered that of the second half inch, of soil.

7. Measurements of the seasonal variation of pH value, and conductivity and calcium content of a water extract of the fertile soil B were made.

8./

8. The pH value of the soil was at a maximum after heavy rainfall and at the time of minimum conductivity and calcium content in the soil extract i.e. with a minimum concentration of electrolytes in the soil solution, and vice versa.

9. The effect of lime on the soil and on the plant was observed.

10. The pH value, conductivity and calcium content of the water extract increased with liming soil B.

11. The changes in yield, calcium and sulphur content of the crops grown on the limed soil were insignificant.

12. Liming the infertile soil W in pots increased the pH value of the soil and the crop yield. The yield increased up to 8 times that for the untreated soil as also did the calcium content. The sulphur content of the plants rose slightly with the smallest addition and then fell with larger applications of lime to the soil.

13. Liming soil W in the field caused a ten-fold increase in both yield and calcium content with a decrease in sulphur content of the crop.

14./

14. The effect of sulphur on the soil and plant was observed.

15. The conductivity and calcium content of the soil extract were more than doubled by the addition of sulphur.

16. The calcium and sulphur contents of the growing plants were increased considerably by the sulphur treatment of the soil.

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TABLE NO.I.

ACTION OF CO_2 ON THE PH OF MOIST SOIL.

Hours air passed	0	9	18	28	46
Soil W (pH)	4.55	4.59	4.55	4.52	4.56
" G^1 "	6.55	6.45	6.43	6.37	6.37
" B "	6.22	6.28	6.26	6.20	6.24
" L^1 "	6.68	6.64	6.74	6.68	6.71
Hours CO_2 passed	0	9	18	28	46
Soil W (pH)	4.55	4.58	4.55	4.54	4.59
" G^1 "	6.55	6.57	6.54	6.52	6.52
" B "	6.22	6.36	6.44	6.35	6.33
" L^1 "	6.68	6.83	6.91	6.82	6.76
Hours CO_2 passed followed by air.	0	9	18	28	46
Soil W (pH)	4.55	4.56	4.55	4.58	4.59
" G^1 "	6.55	6.54	6.54	6.50	6.52
" B "	6.22	6.35	6.43	6.40	6.33
" L^1 "	6.68	6.84	6.89	6.84	6.76

TABLE NO.II.

ACTION OF CO_2 ON THE PH OF THE SOIL SUSPENSION.

	Hours air passed					Hours CO_2 passed.			
	0	6	13	20	27	6	13	20	27
Soil W (pH)	4.32	4.51	4.48	4.51	4.42	4.43	4.32	4.35	4.29
" G "	6.36	6.58	6.53	6.59	6.47	5.64	5.41	5.39	5.34
" B "	6.22	6.40	6.33	6.39	6.25	5.70	5.53	5.43	5.40
" L "	6.60	6.87	6.74	6.75	6.68	5.88	5.84	5.66	5.53

TABLE NO. III.

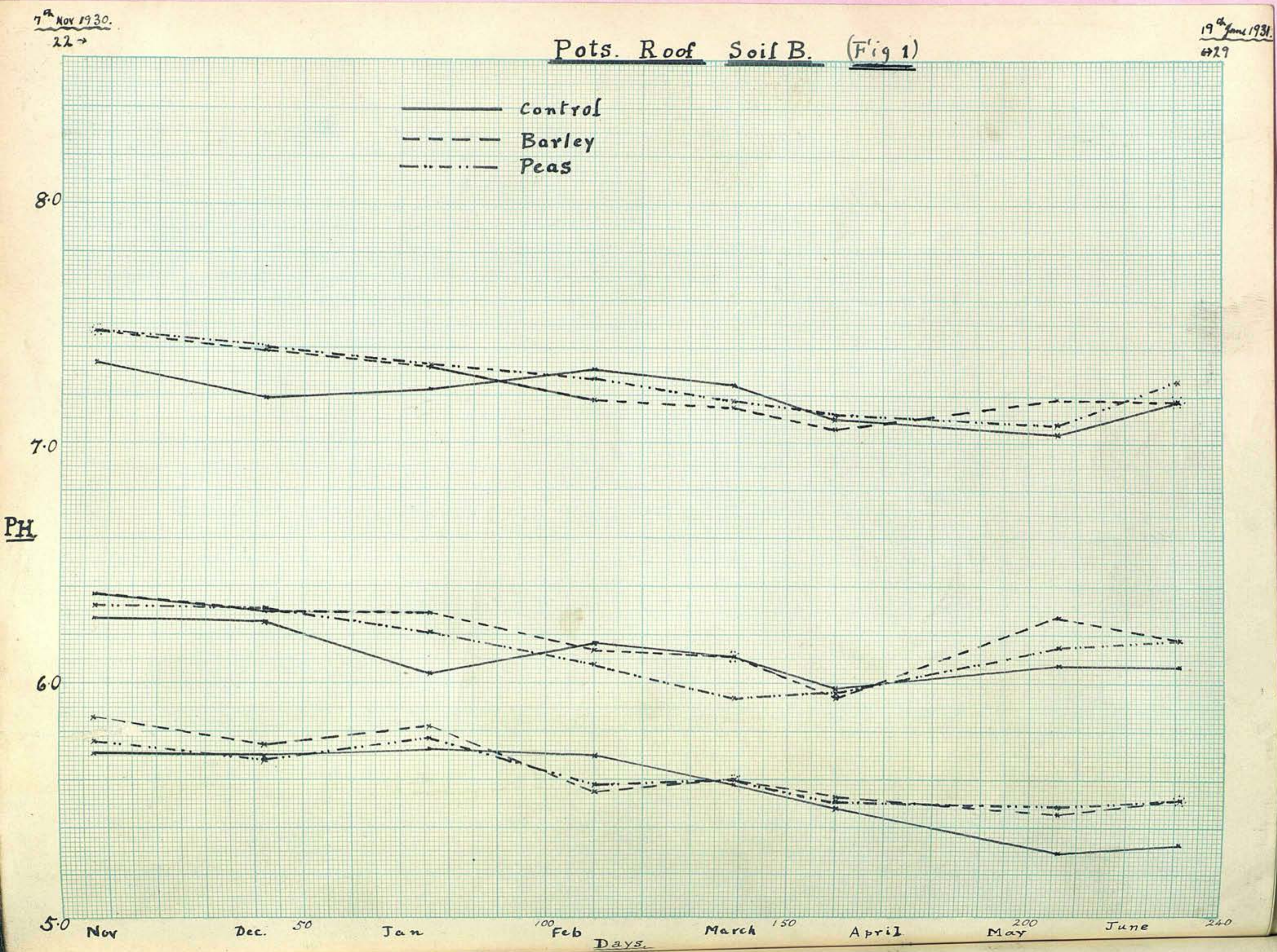
ACTION OF CO_2 ON THE PH OF THE SOIL SUSPENSION.

Soil	Hours air passed.			Hours CO_2 passed		Hours CO_2 passed and aerated.	
	0	8	16	8	16	8	16
Soil B (pH)	6.29	6.35	6.34	5.77	5.69	6.35	6.54
Soil G (pH)	6.57	6.58	6.59	5.60	5.40	6.53	6.44

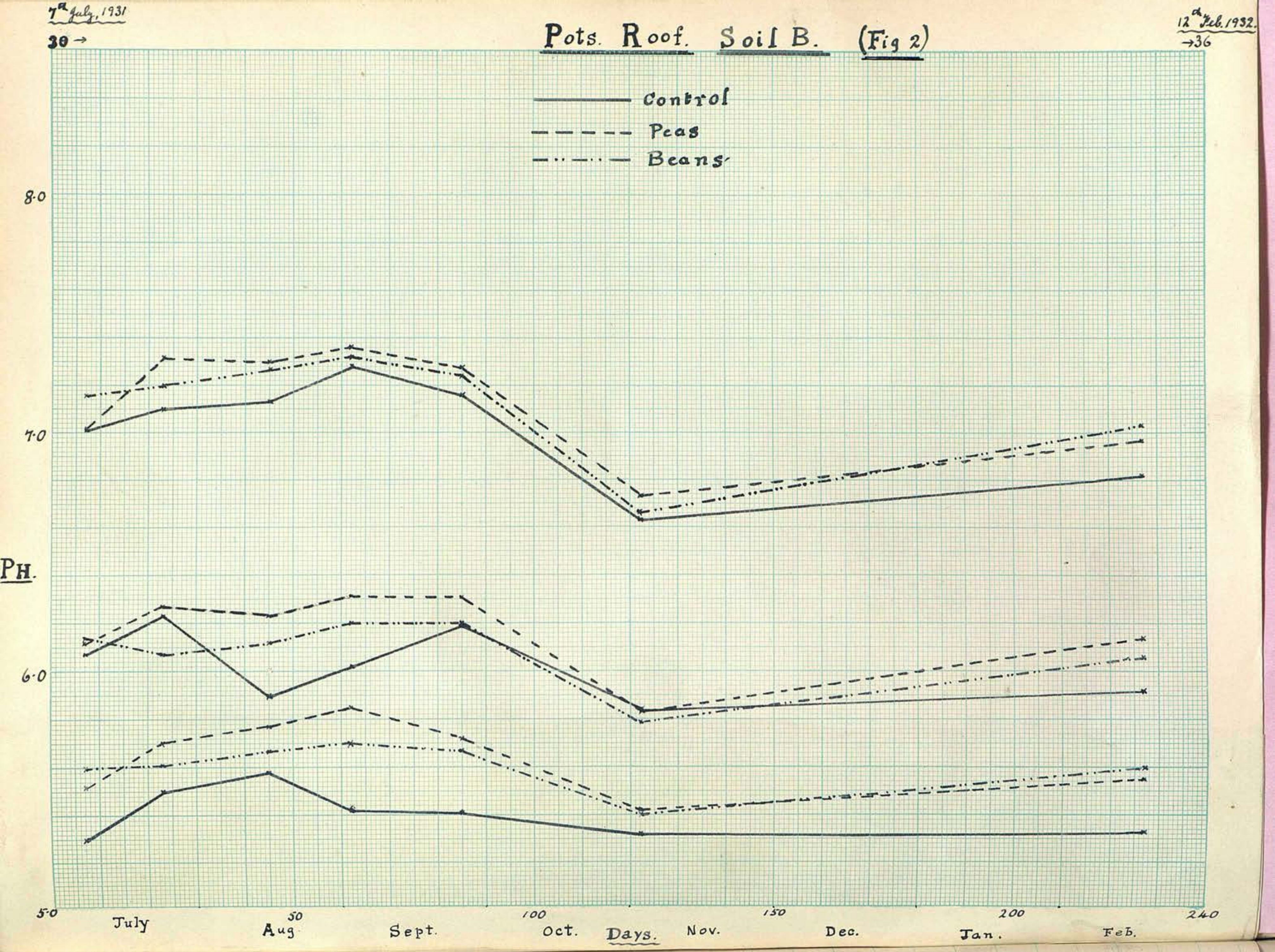
TABLE NO. IV.

EFFECT ON PH OF LEACHING SOIL WITH A SATURATED SOLUTION OF H_2CO_3

	Orig. pH	Vol. H_2CO_3 passed	pH	Vol. H_2CO_3 passed	pH
Soil B					
1st ½" of soil	5.95	150 cc.	5.85	150 cc.	5.90
2nd " " "			5.97		5.97
Soil W					
1st ½" of soil	4.64	500 cc.	4.67	240 cc.	4.54
2nd " " "			4.71		4.76
Soil G					
1st ½" of soil	6.51	450 cc.	5.35	200 cc.	5.46
2nd " " "			5.62		6.04

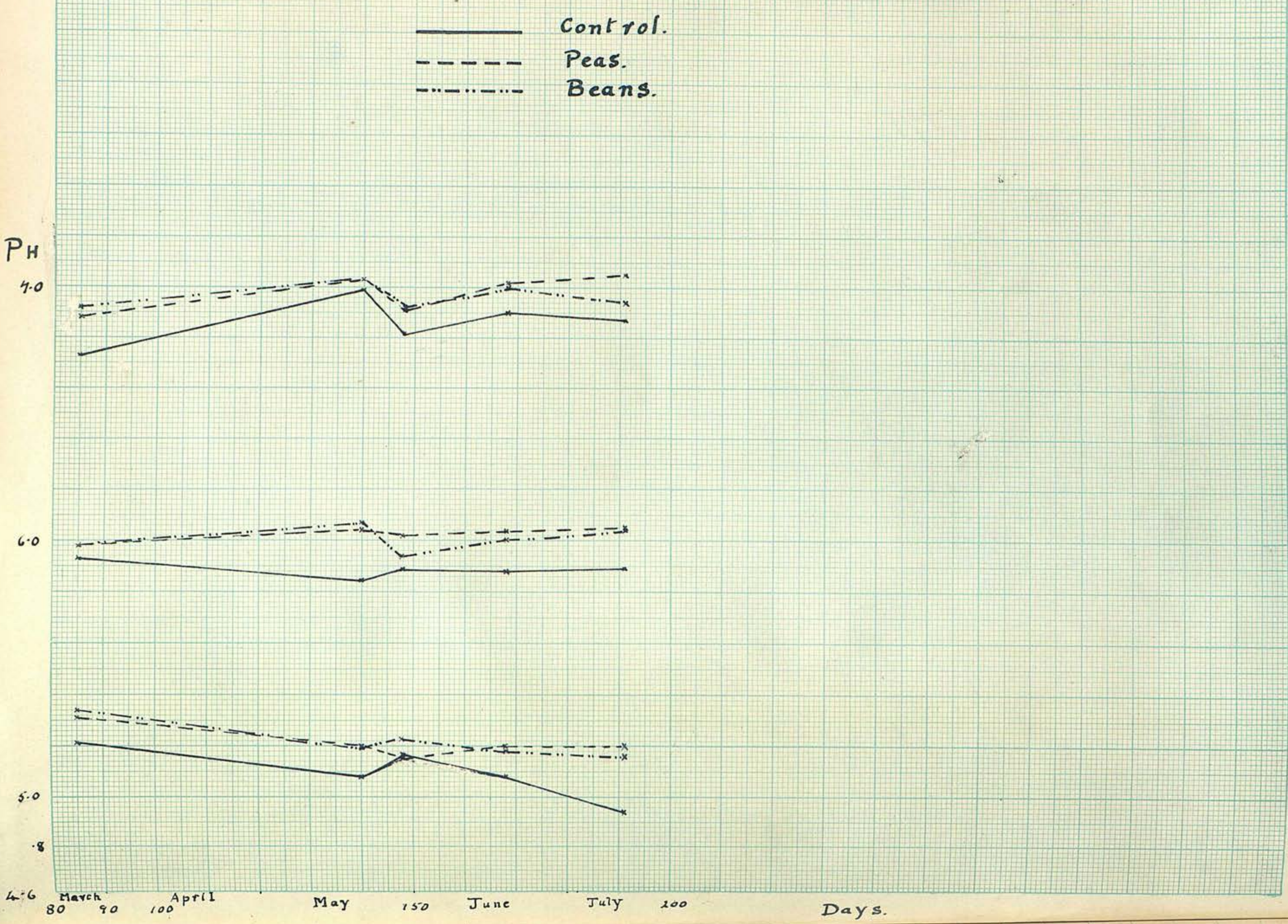

7th Nov 1930.
22 →
Pots. Roof Soil B. (Fig 1)
19th June 1931.
229
Control
Barley
Peas
8.0
7.0
PH.
6.0
5.0
Nov
Dec.
50
Jan
100
Feb
March
150
April
200
May
June
240
Days.

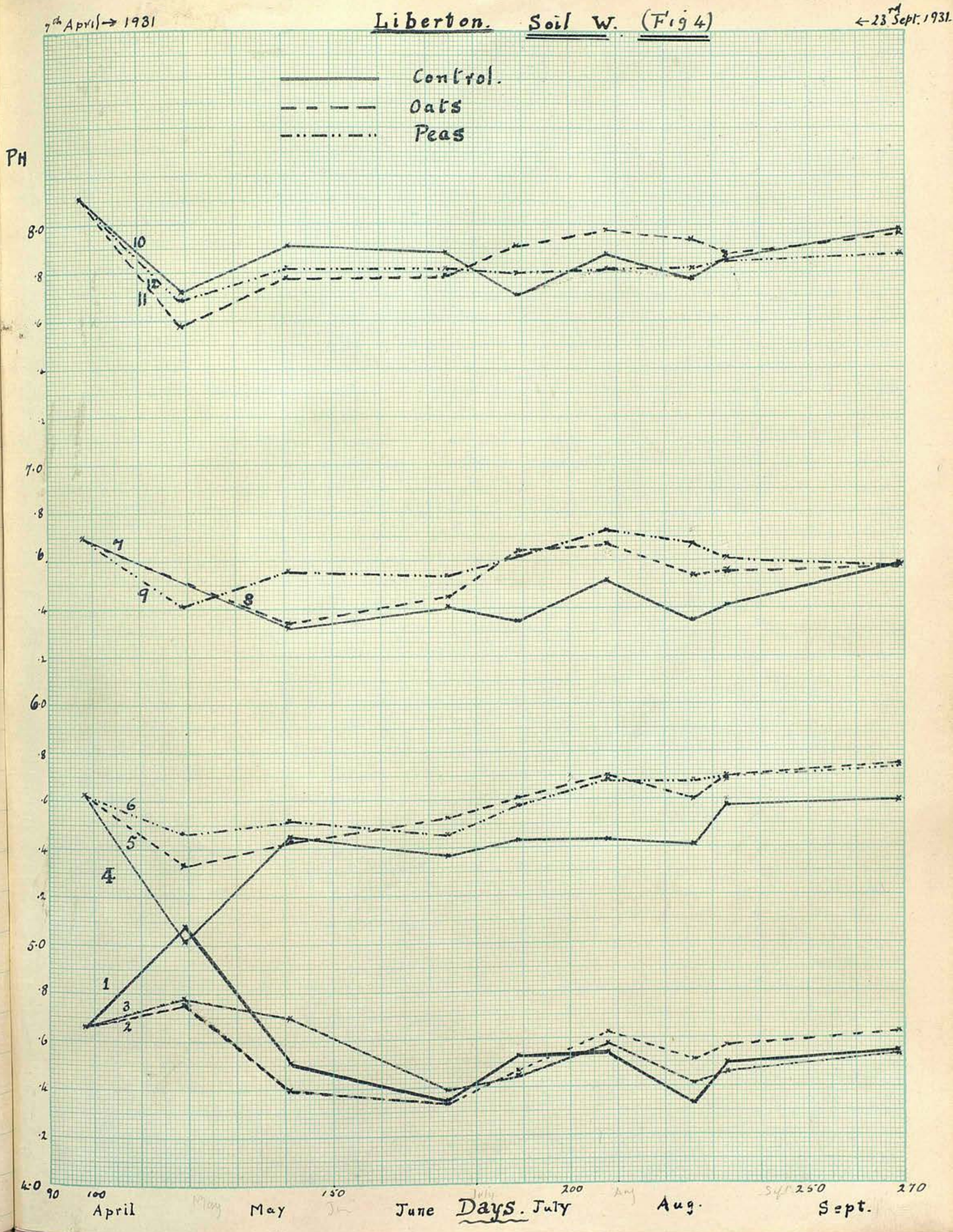
Pots. Roof. Soil B. (Fig 2)



(Fig 3)

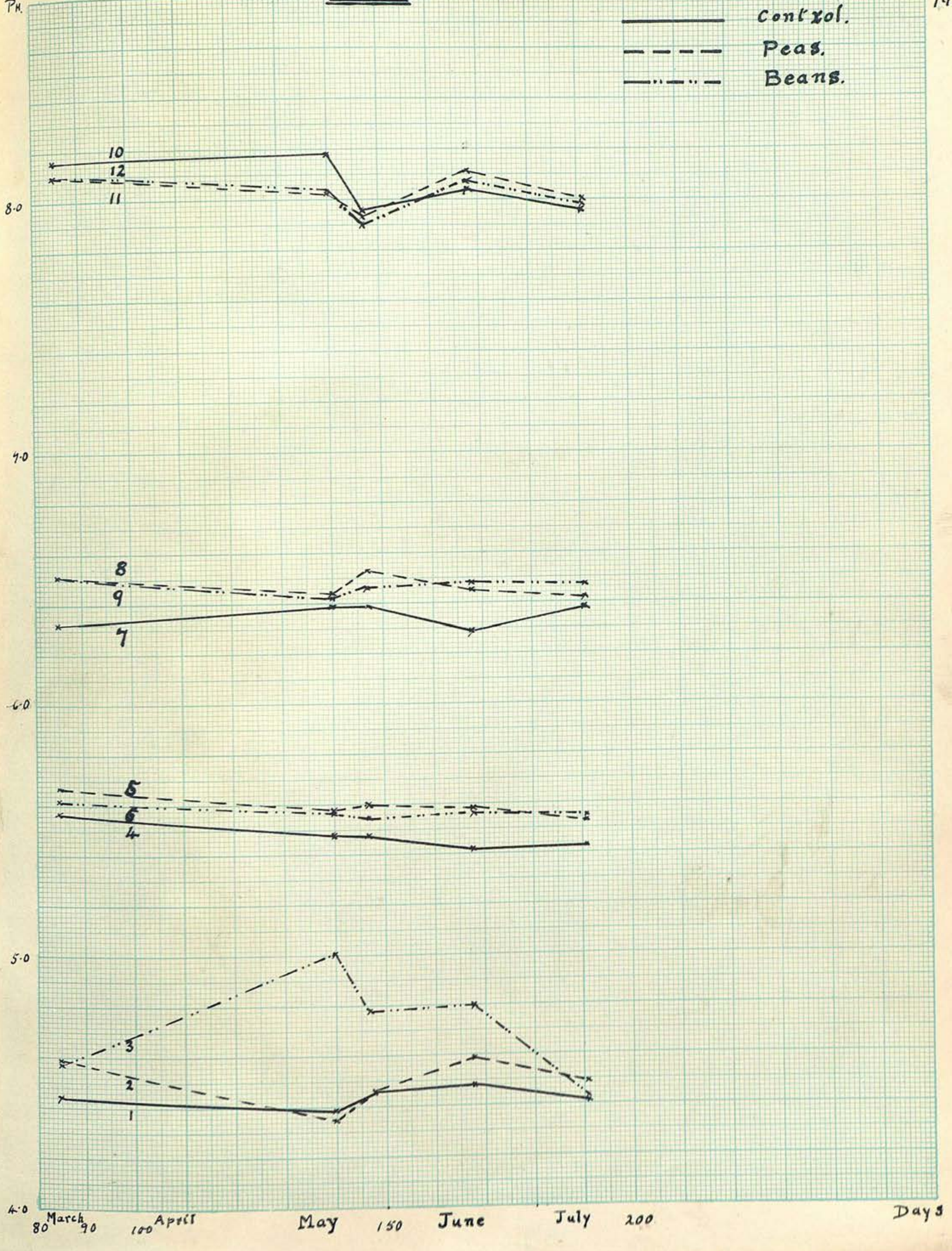
Pots: Soil B. 25th March - 9th July, 1932.



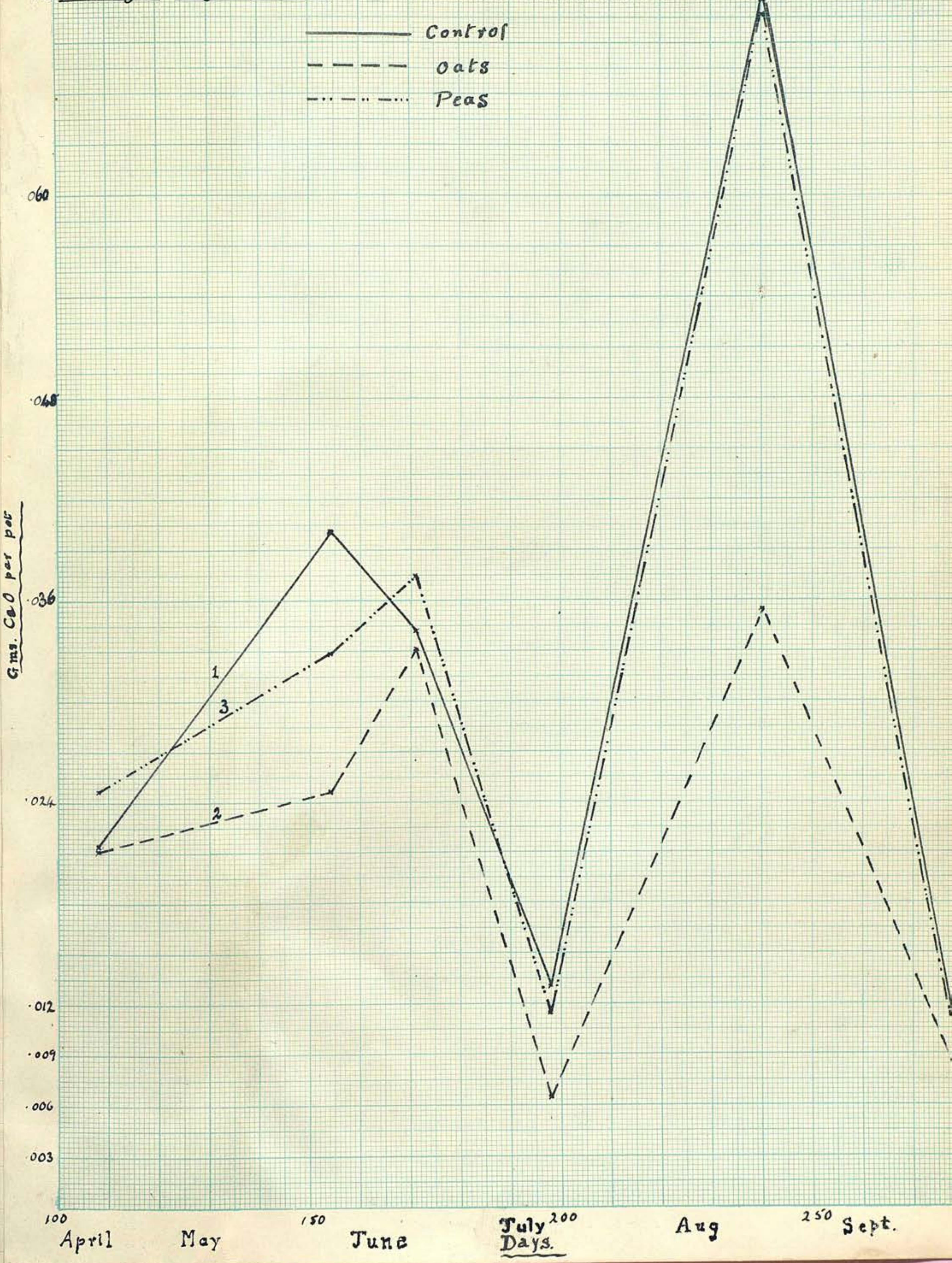

7th April → 1931
Liberton. Soil W. (Fig 4)
← 23rd Sept. 1931.
Control.
Oats
Peas
PH
8.0
7.0
6.0
5.0
4.0
10
11
12
7
8
9
6
5
4
1
2
3
90
100
150
200
250
270
April
May
June
Days.
July
Aug.
Sept.

(Fig 5)

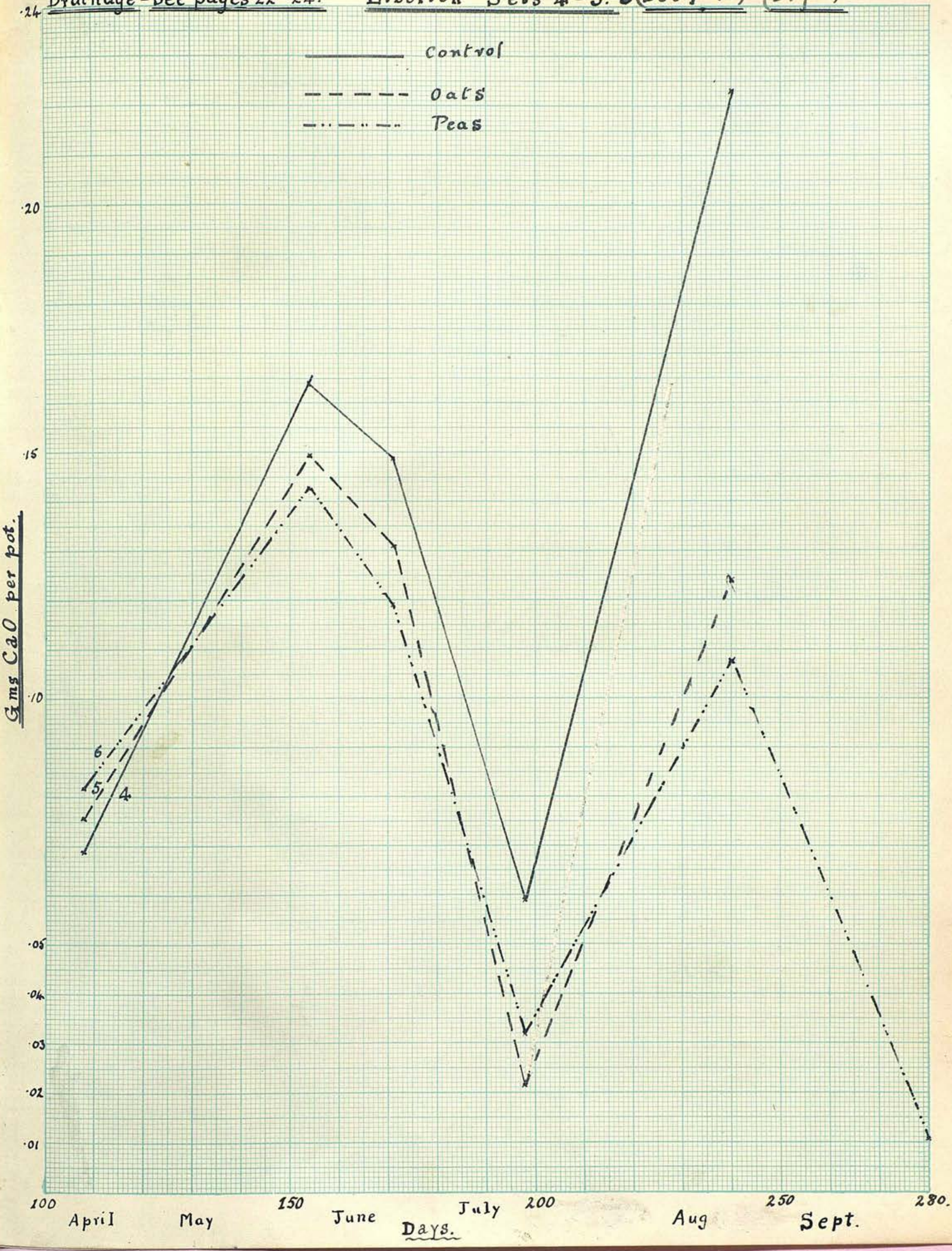
Pots: Soil W. 25th March - 9th Ju[illegible] 193[illegible]



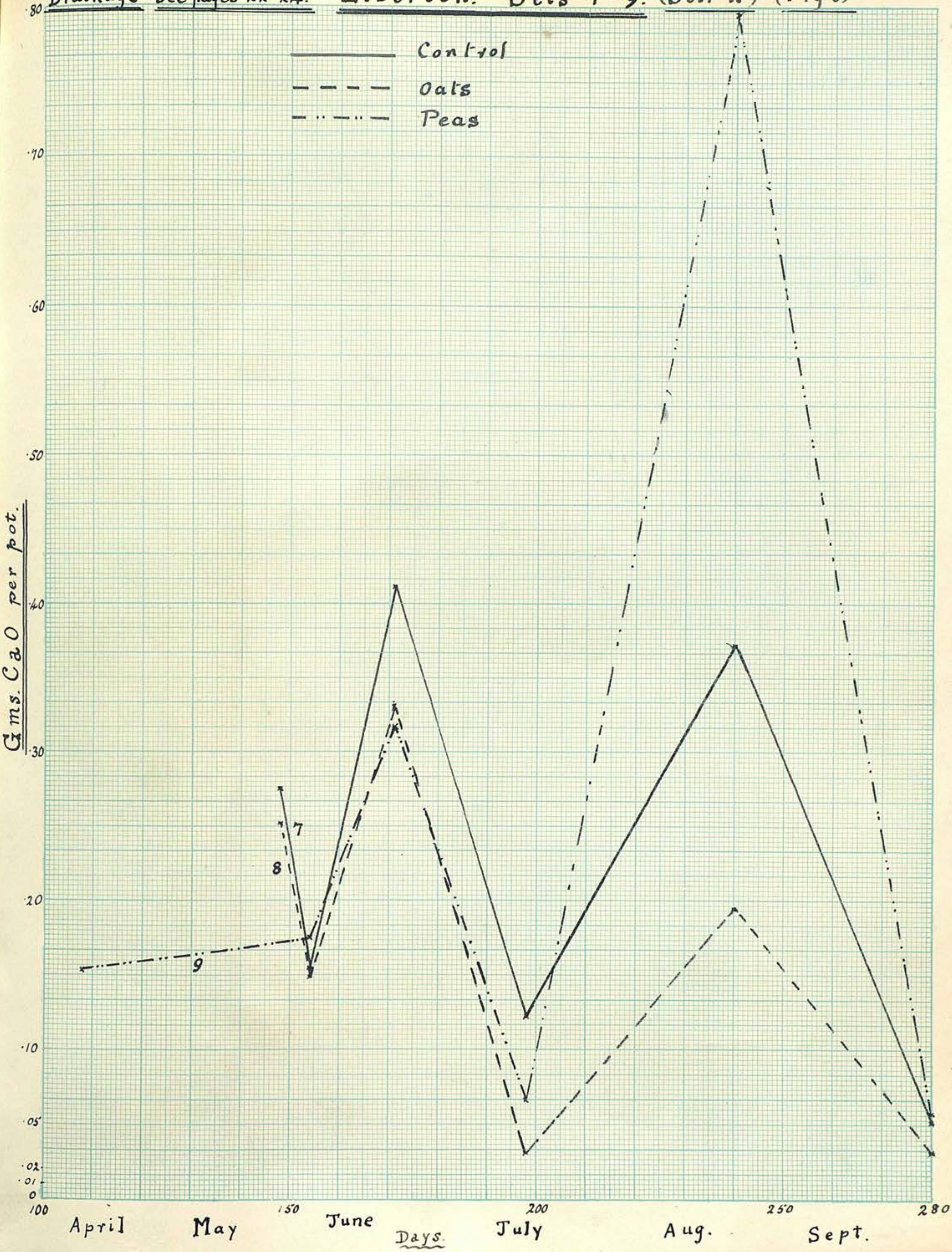
Drainage – pages 22-24. Liberton Sets 1-3. Soil W. (Fig 6)



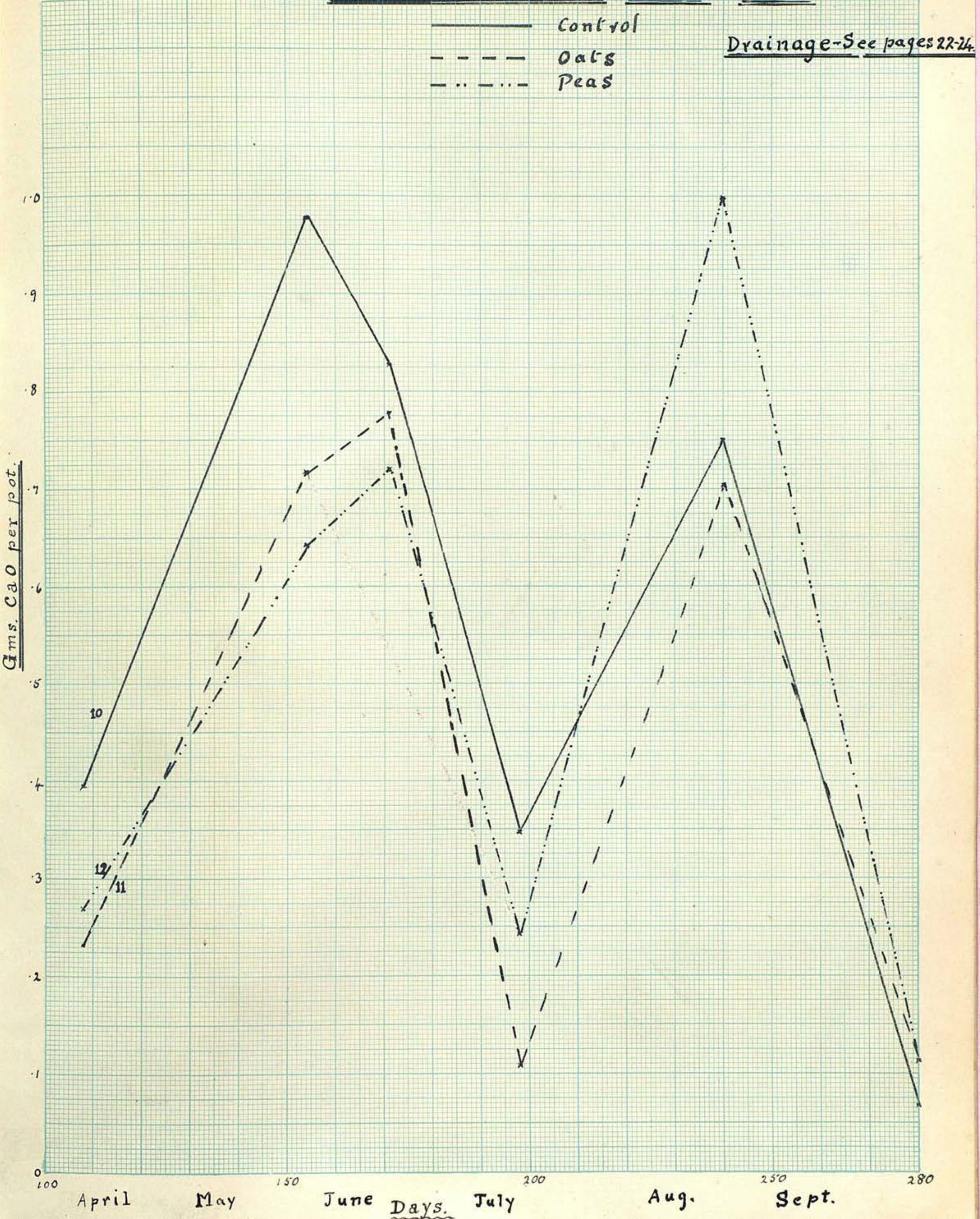
Drainage - See pages 22-24. Liberton Sets 4-5-6 (Soil W) (Fig 4)



Drainage - See pages 22-24. **Liberton. Sets 7-9. (Soil W) (Fig 8)**

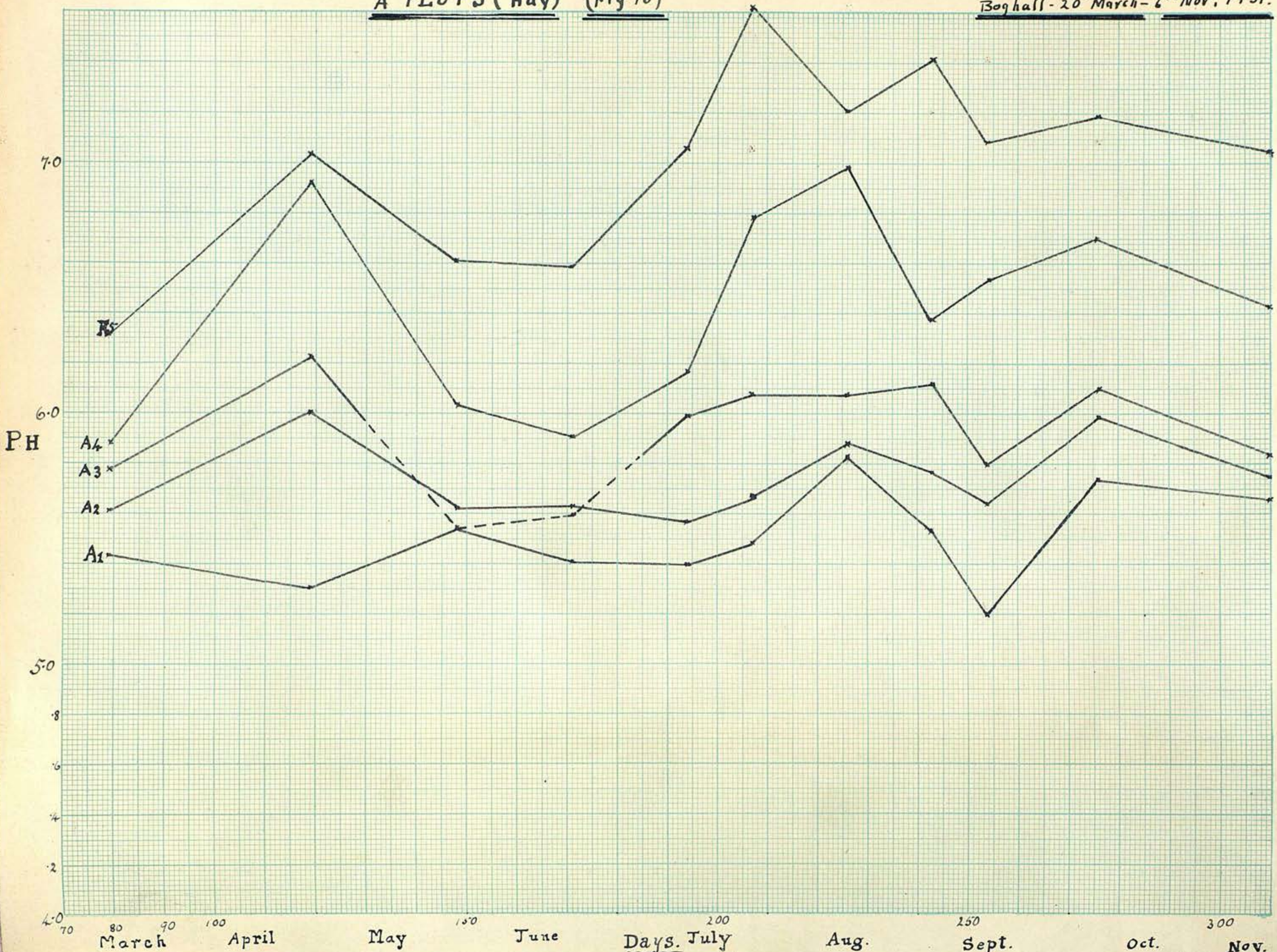


Liberton. Sets 10-12 Soil W. (Fig 9)



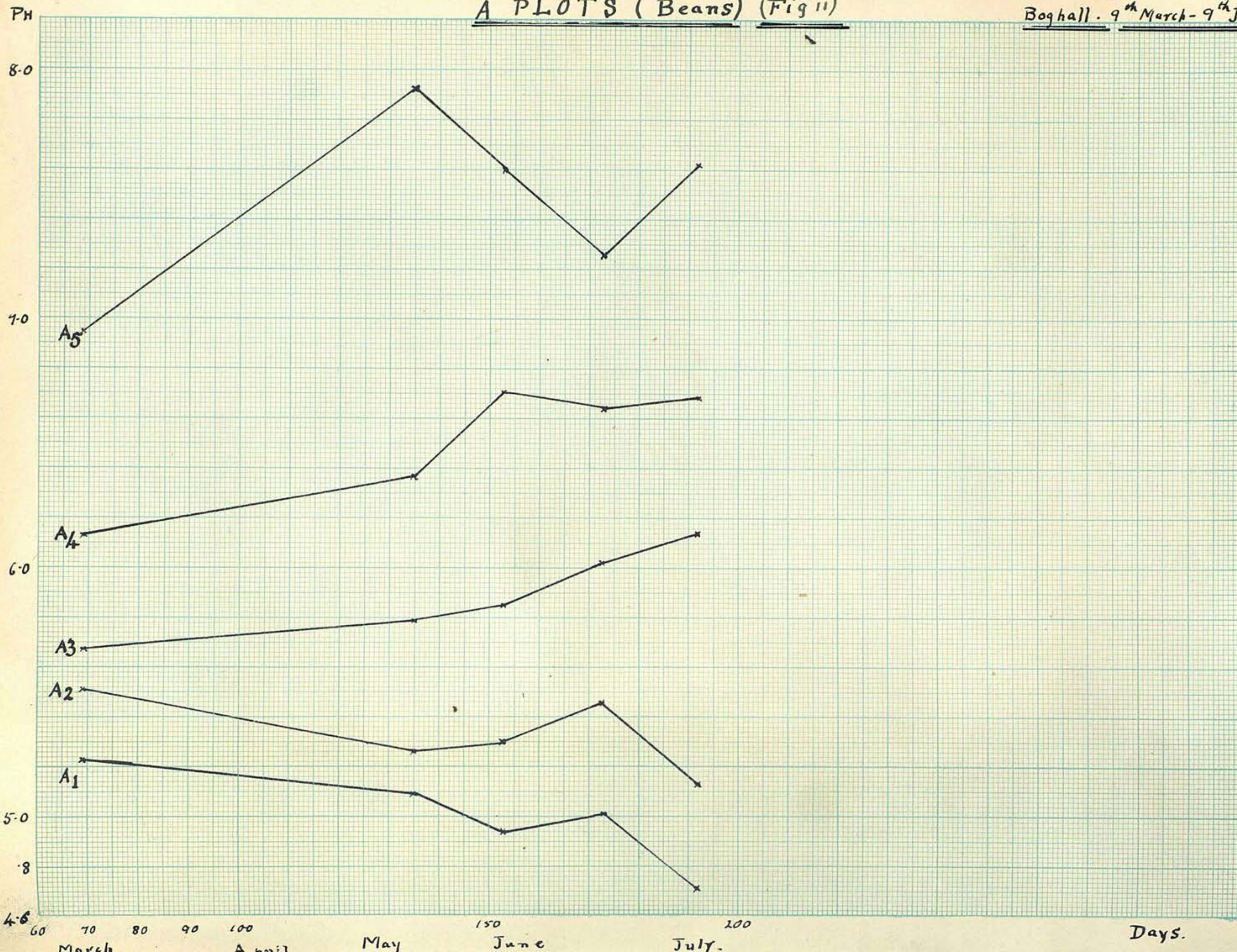
A PLOTS (Hay) (Fig 10)

Boghall - 20th March - 6th Nov, 1931.



A PLOTS (Beans) (Fig 11)

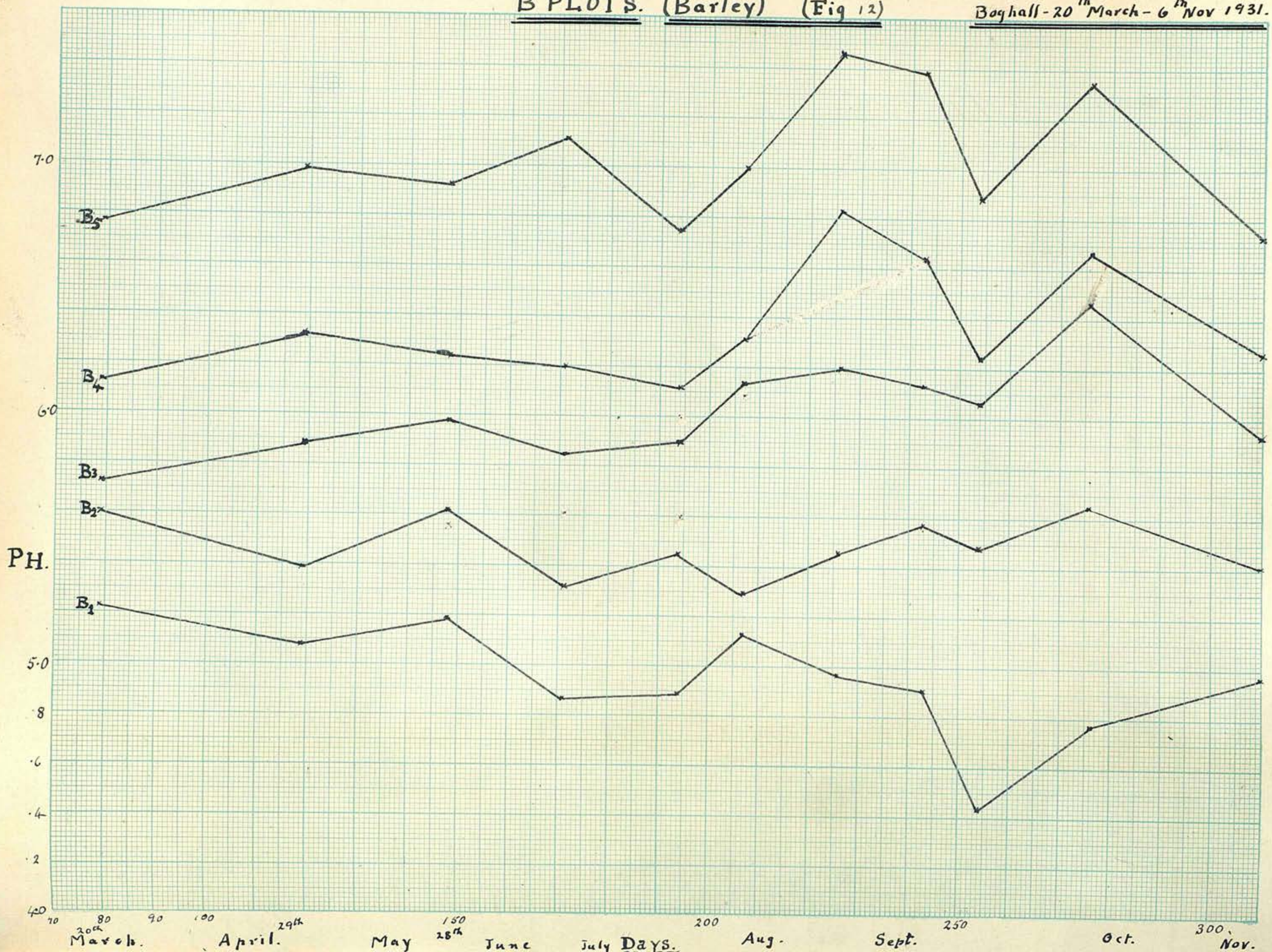
Boghall. 9th March - 9th July 1932



PH B.

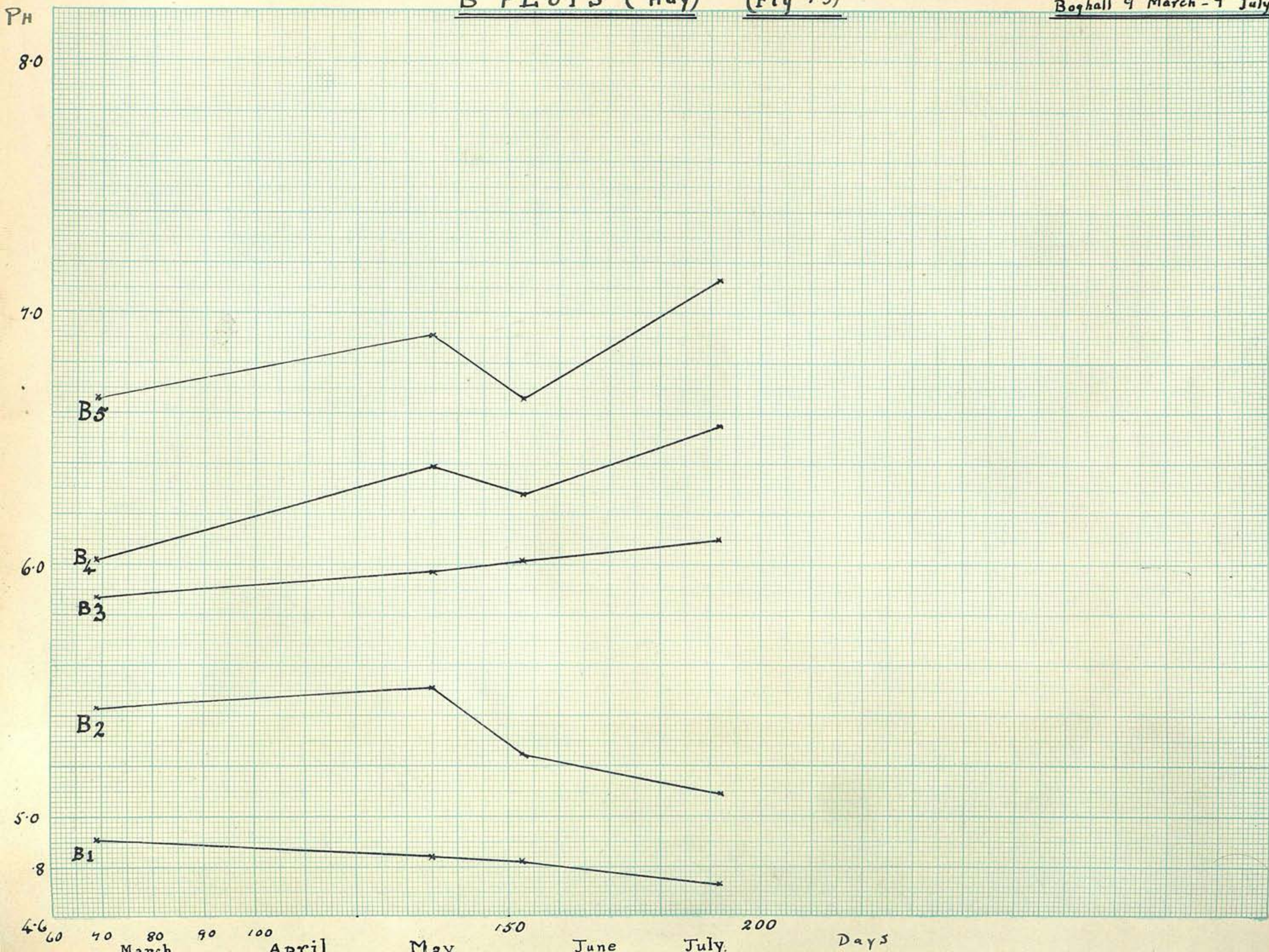
B PLOTS. (Barley) (Fig 12)

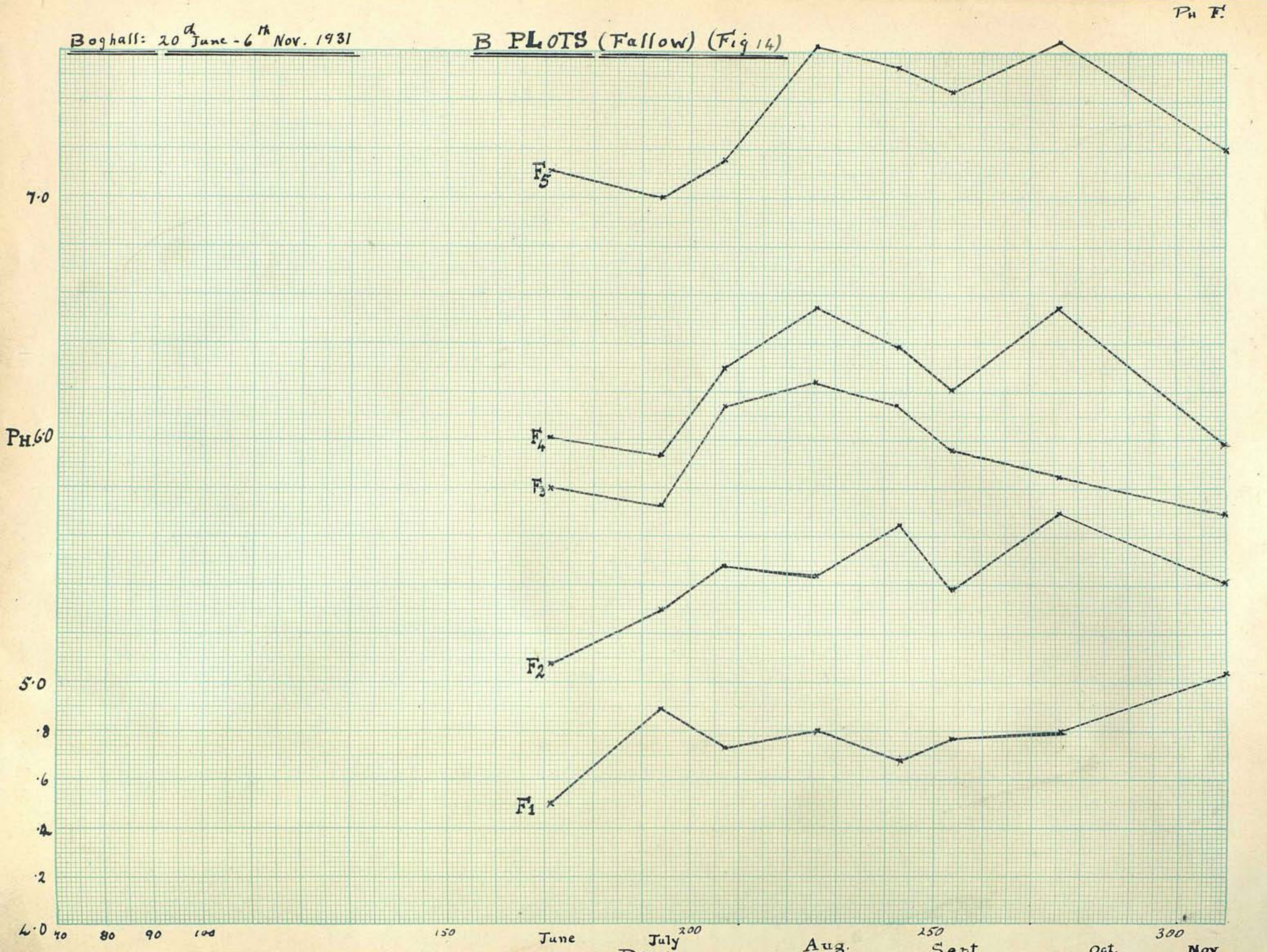
Boghall - 20th March - 6th Nov 1931.



B PLOTS (Hay) (Fig 13)

Boghall 9th March - 9th July, 1932.

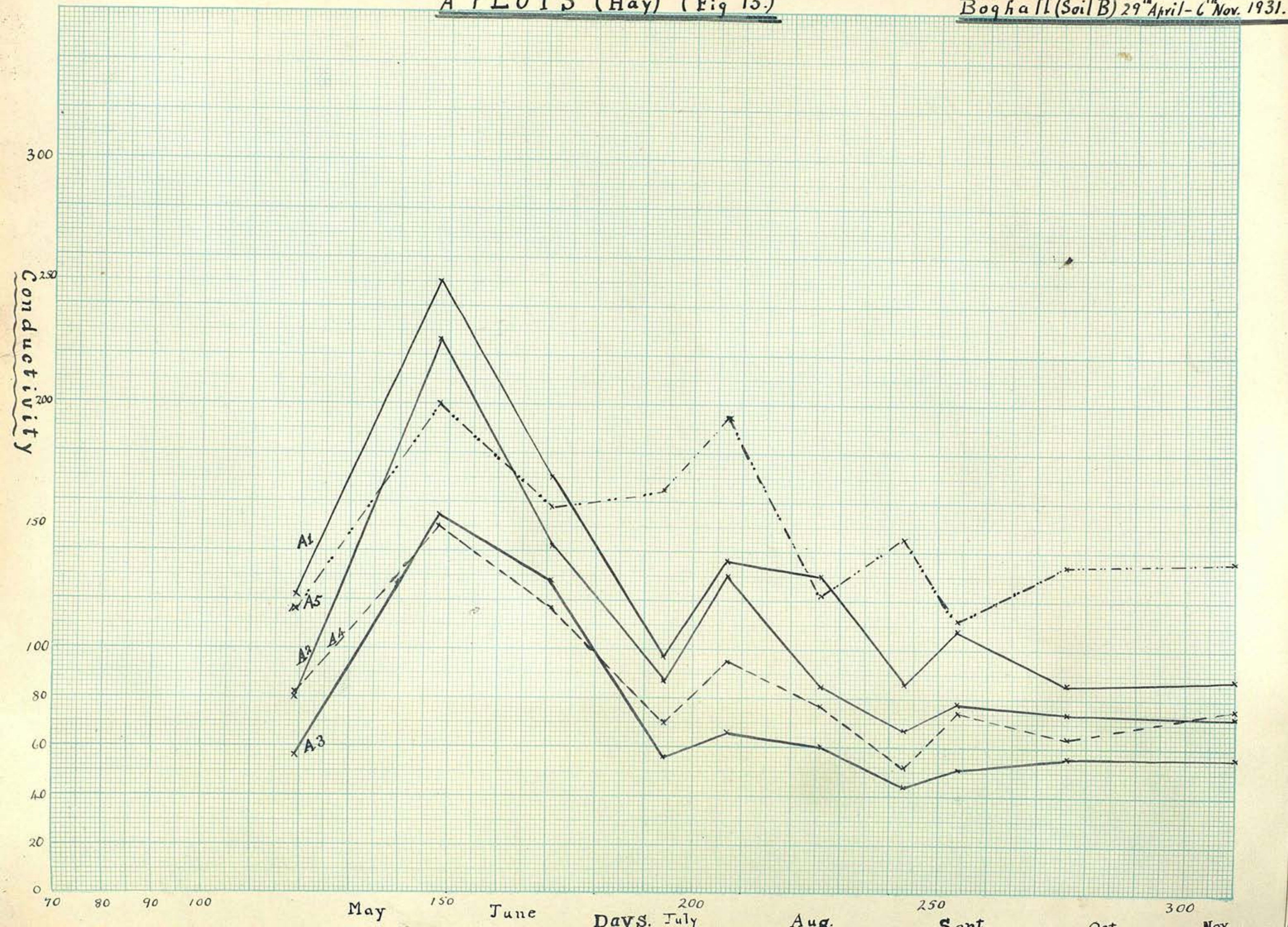




PH F.
Boghall: 20th June - 6th Nov. 1931
B PLOTS (Fallow) (Fig 14)
PH 6.0
7.0
5.0
·8
·6
·4
·2
4.0
70
80
90
100
150
200
250
300
June
July
Aug.
Sept.
Oct.
Nov.
F1
F2
F3
F4
F5

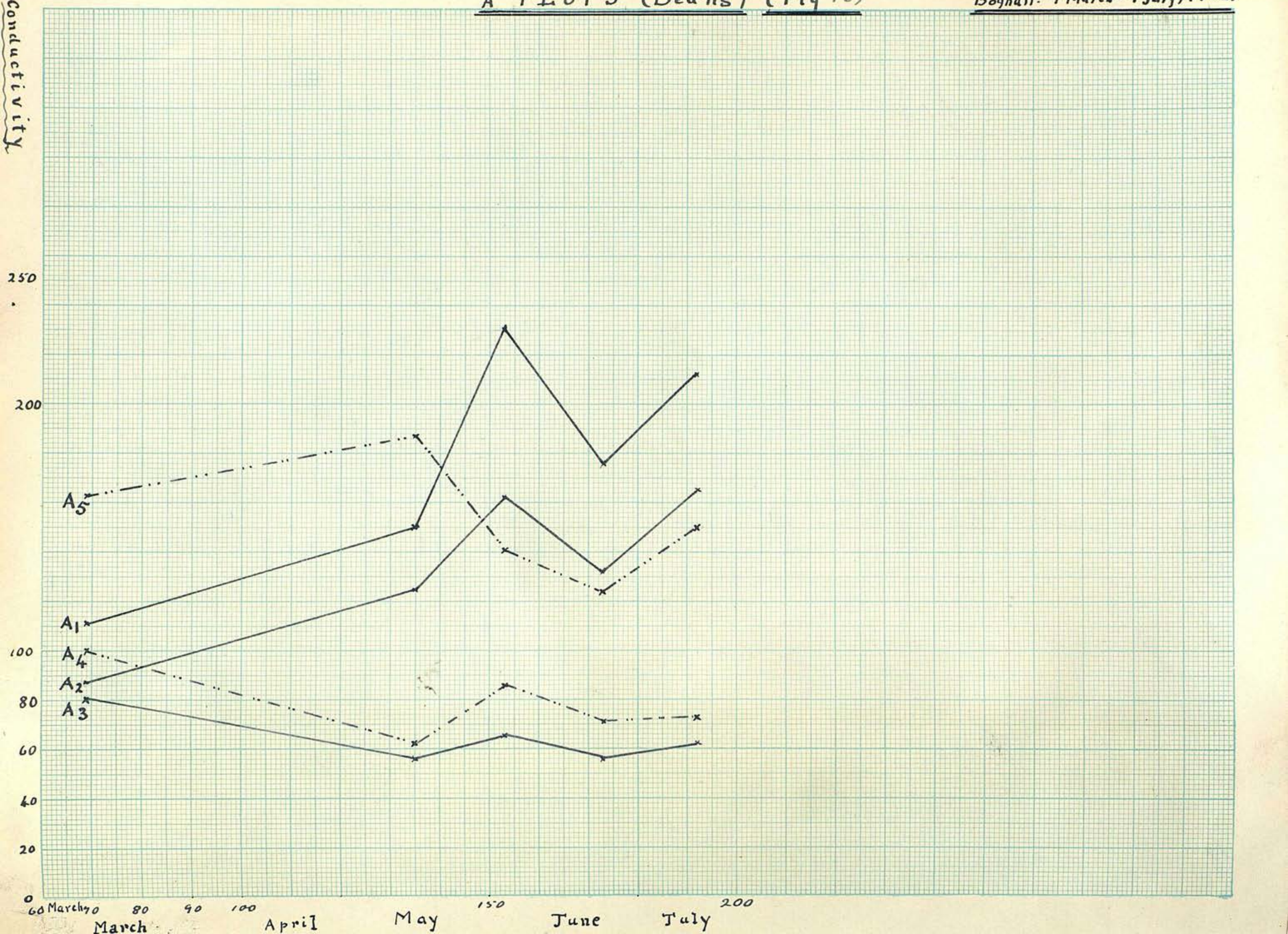
A PLOTS (Hay) (Fig 15.)

Boghall (Soil B) 29th April - 6th Nov. 1931.

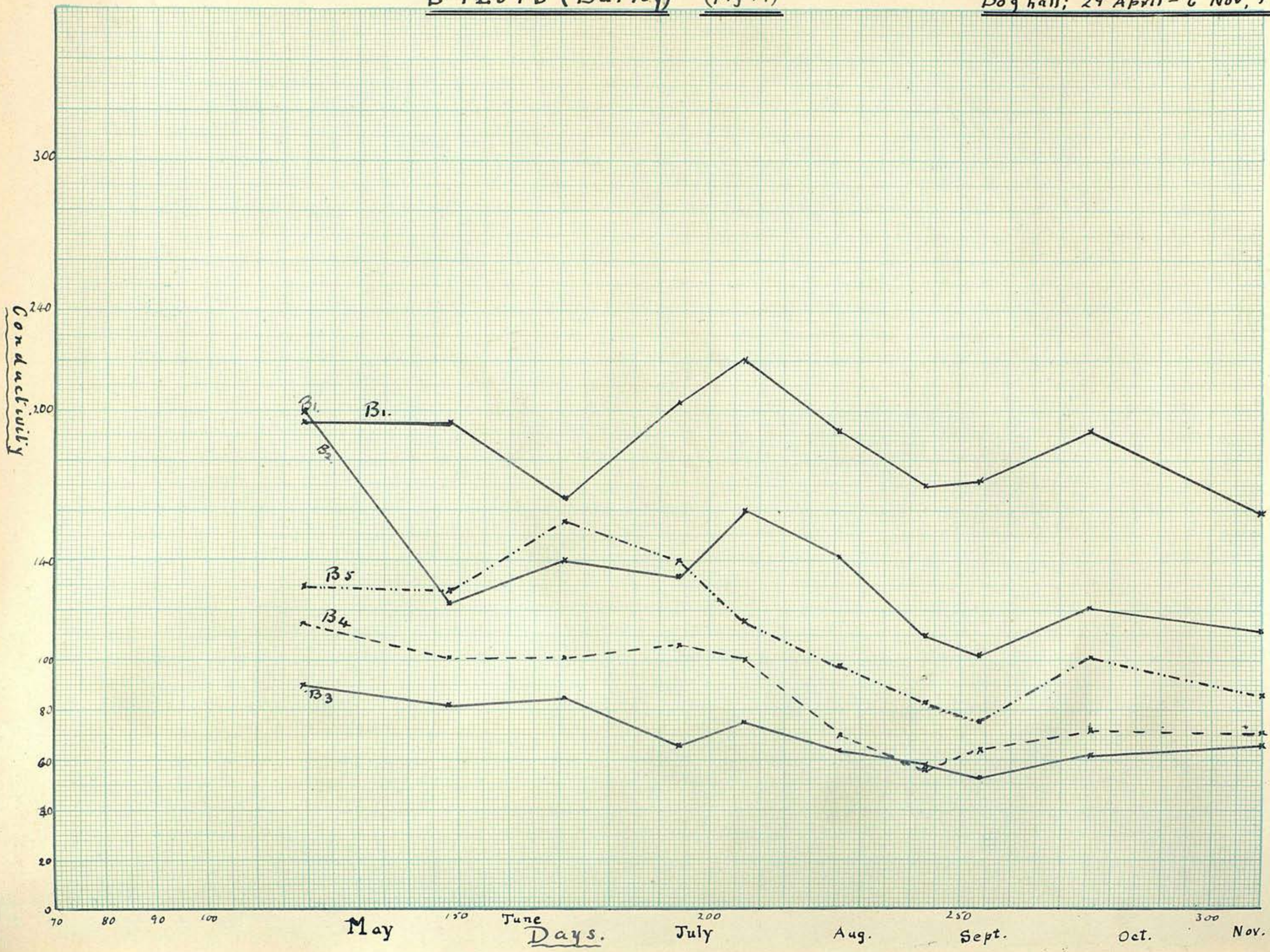


Cond. A

A PLOTS (Beans) (Fig 16) Boghall: 9th March - 9th July, 1932.

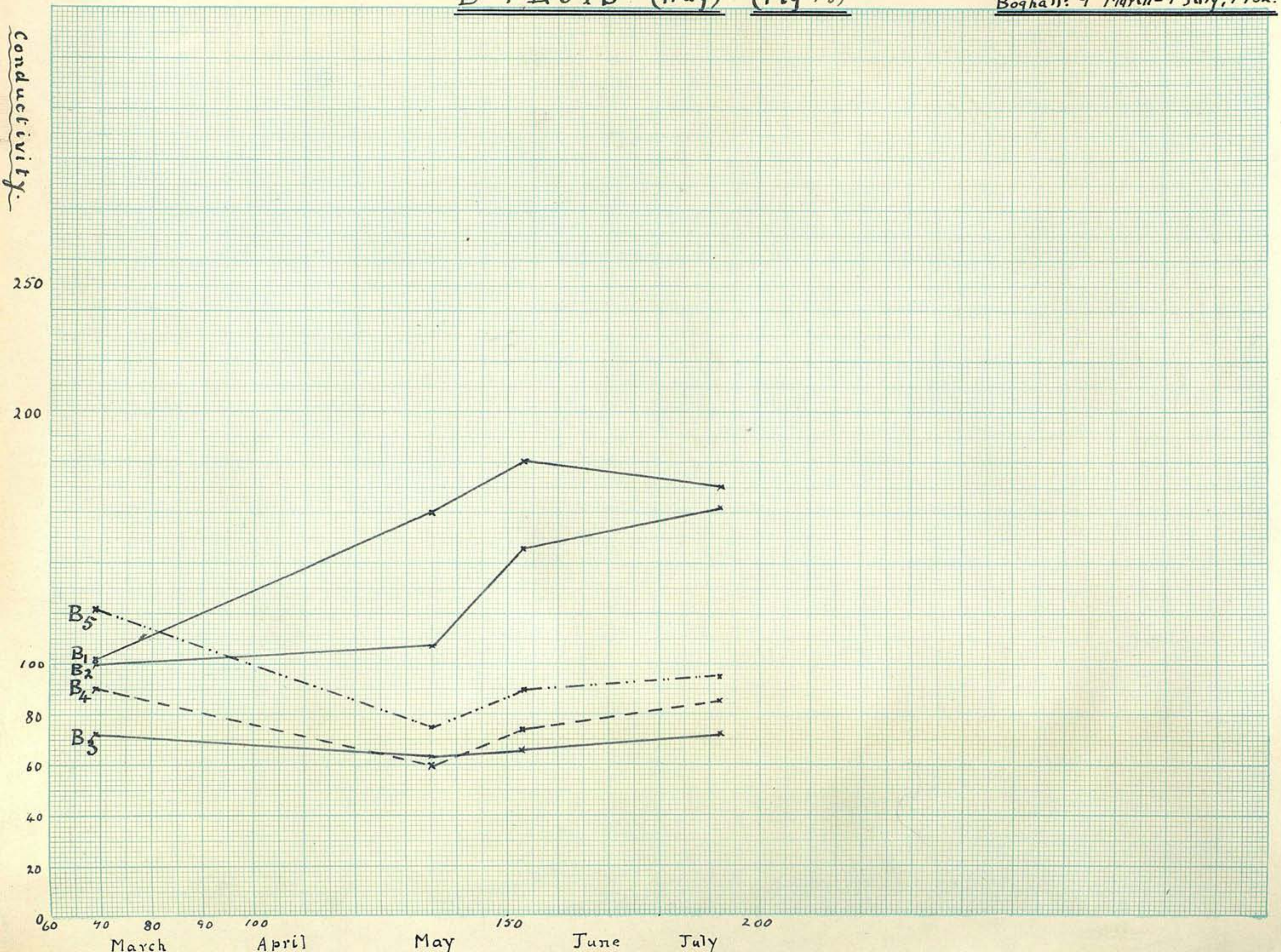


B PLOTS (Barley) (Fig 14) Bog hall; 29th April – 6th Nov, 1931



B PLOTS (Hay) (Fig 18)

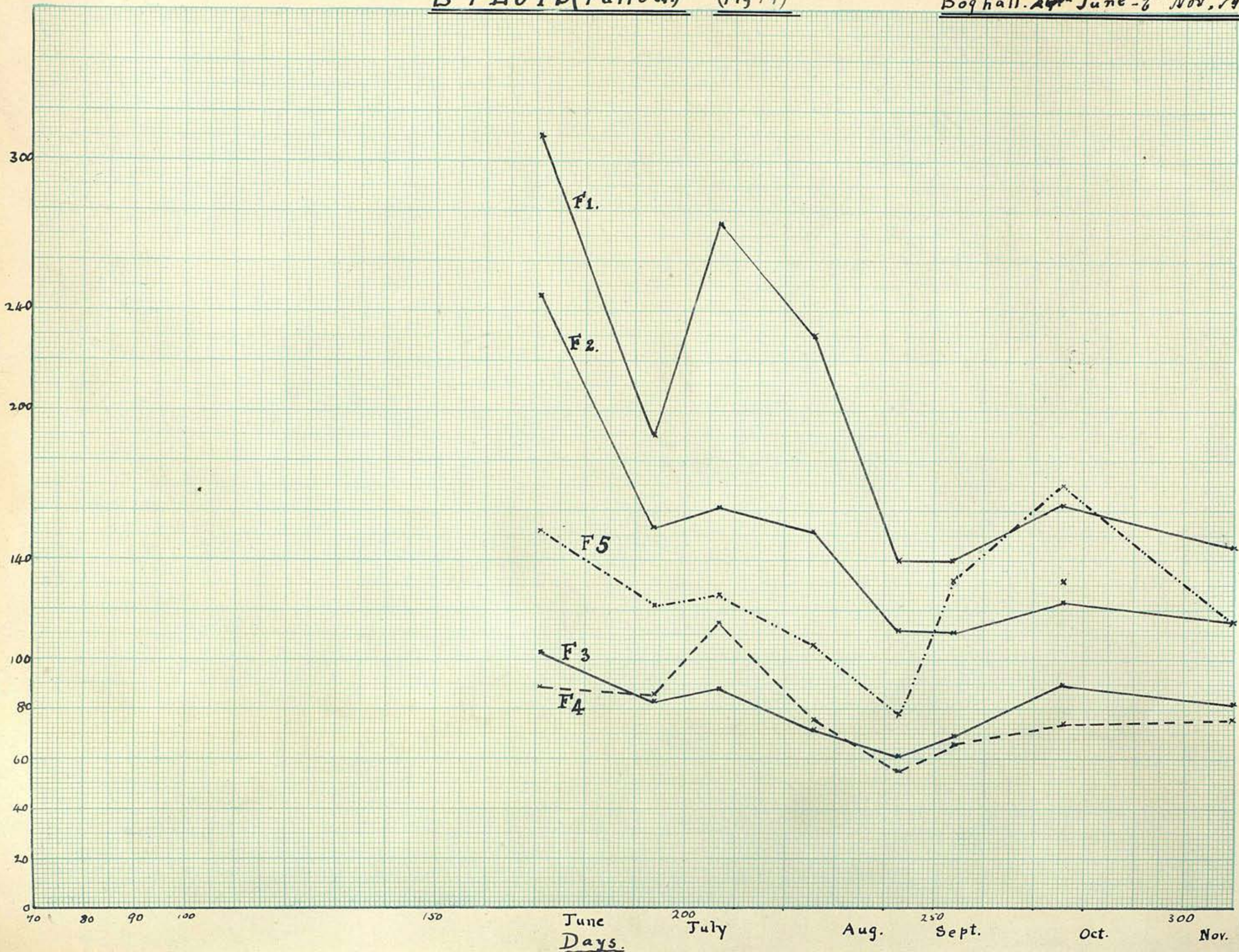
Boghall: 9th March – 9th July, 1932.



Cond. F

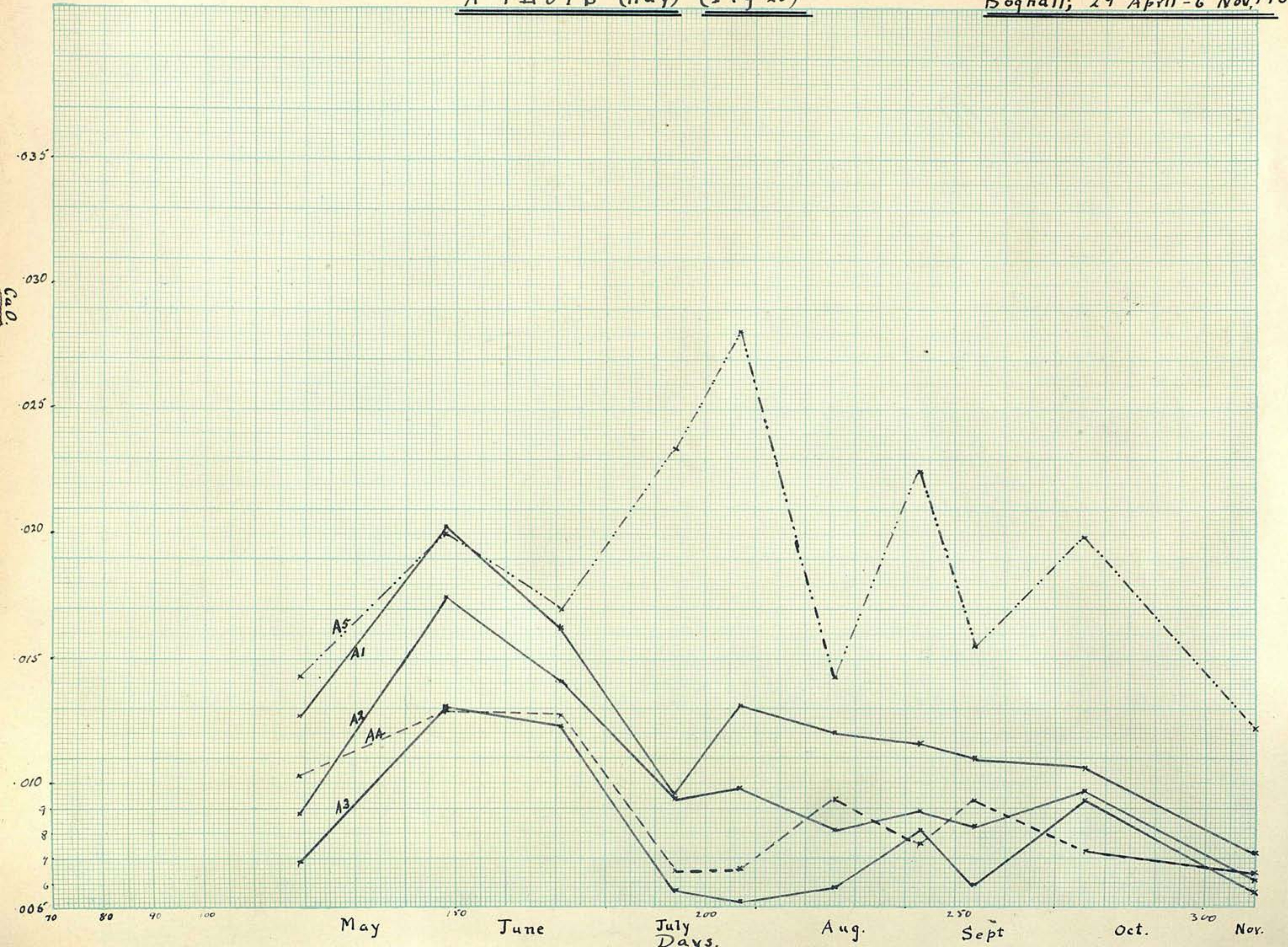
B PLOTS (Fallow.) (Fig 19)

Boghall. 20th June - 6th Nov, 193



A PLOTS (Hay) (Fig 20)

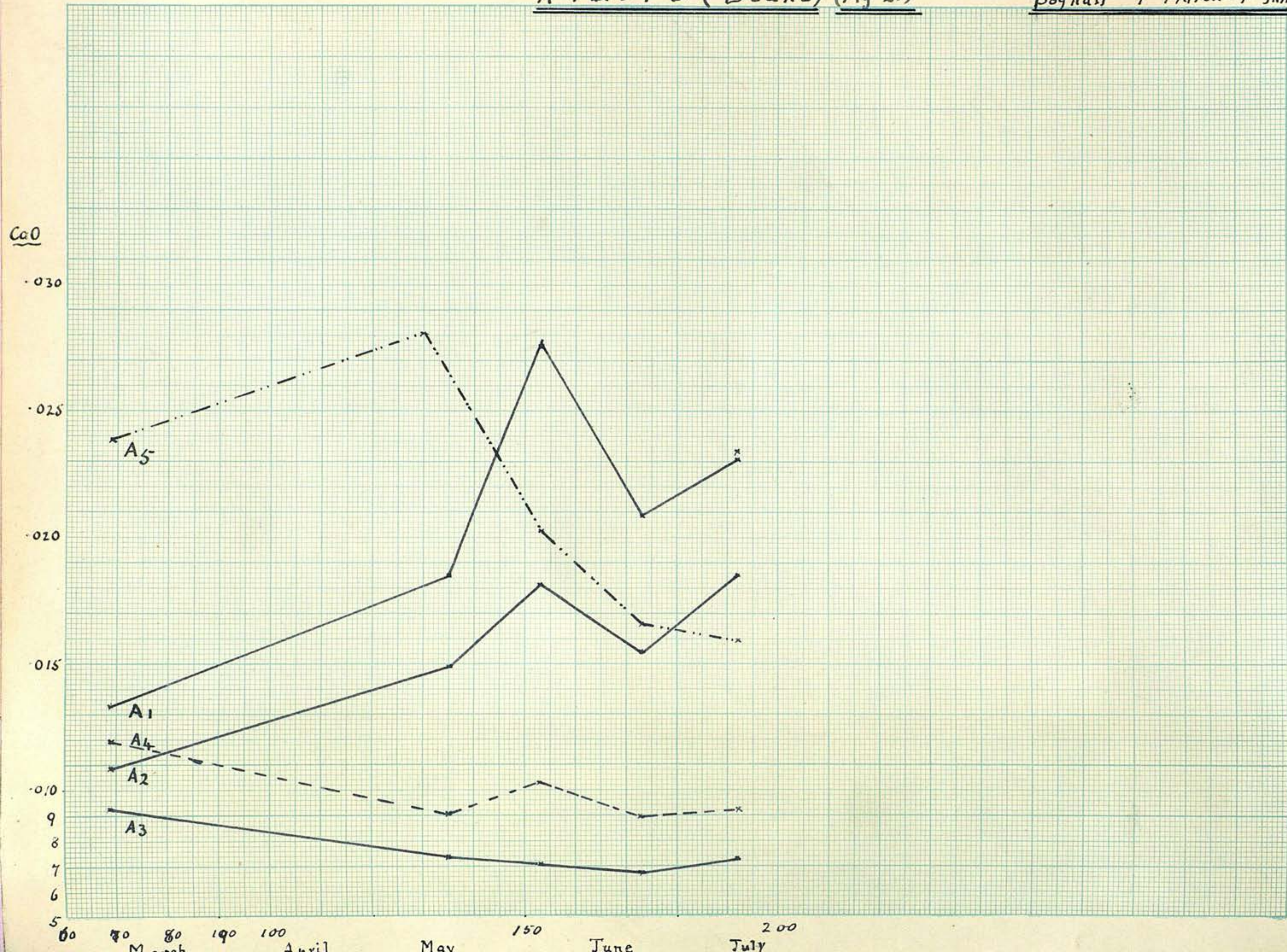
Boghall; 29th April - 6th Nov, 1931.



CaO - A.

A PLOTS (Beans) (Fig 21)

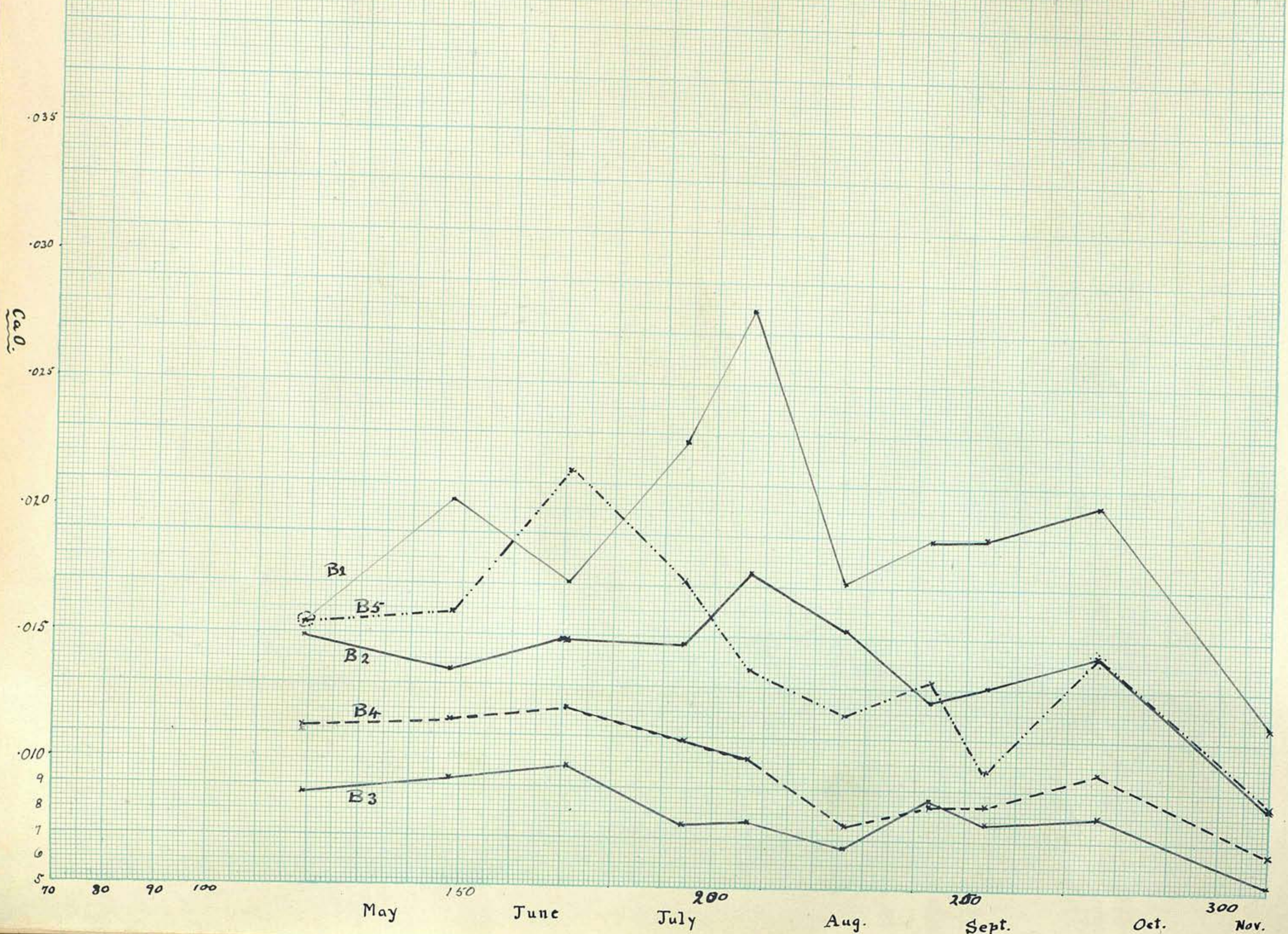
Boghall 9th March - 9th July 193



CaO B

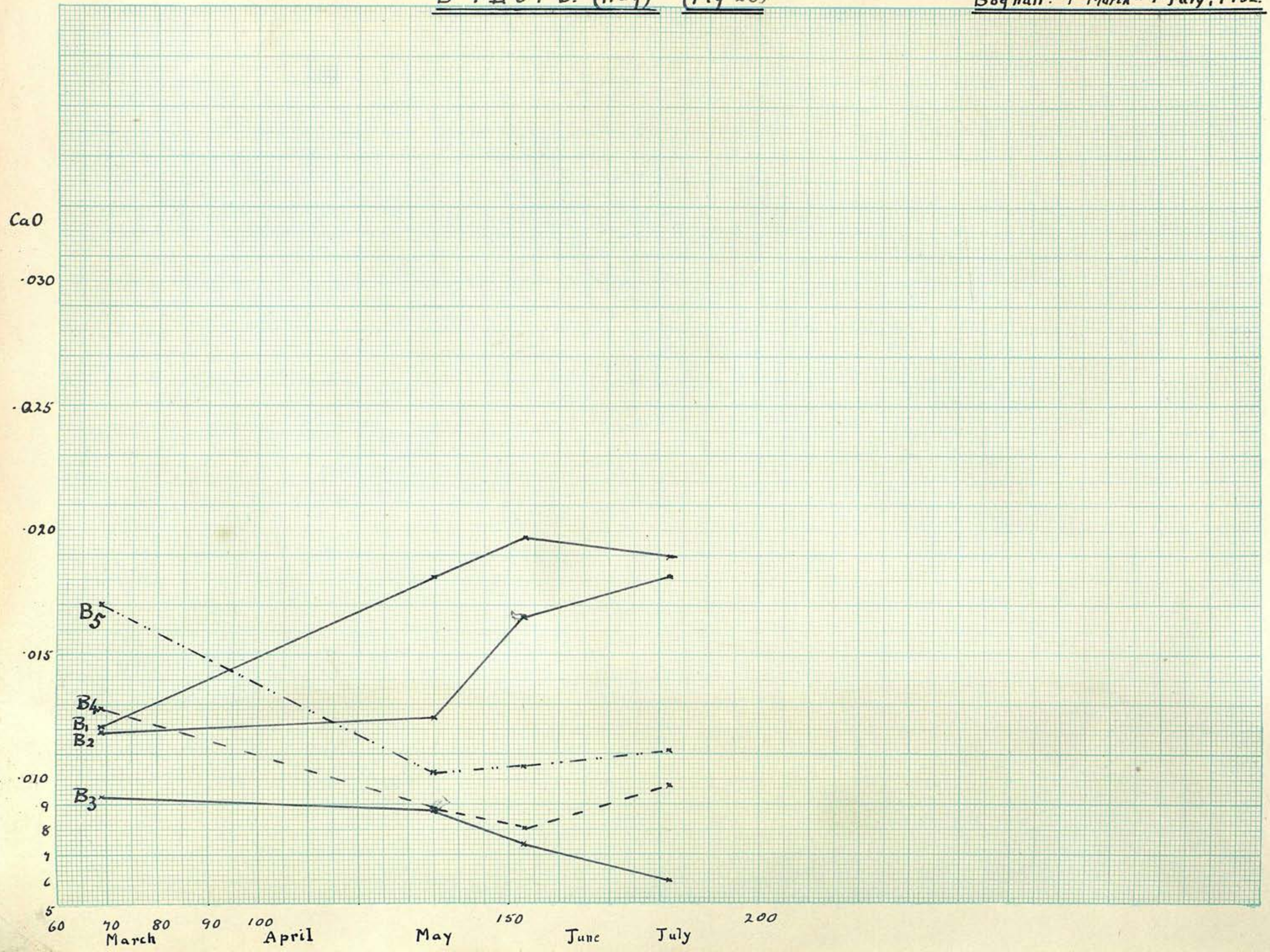
B PLOTS (Barley) (Fig 22.)

Boghall. 29th April - 6th Nov, 1931.



B PLOTS. (Hay) (Fig 23)

Boghall: 9th March – 9th July, 1932.



CaO F

B PLOTS (Fallow) (Fig 24)

Boghall; 20th June - 6th Nov, 1931