On the Function of Silica in the Nutrition of Cereals.—Part I.

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1. *Introduction.*

The presence of silica in plants was first demonstrated by the analyses of De Saussure,* who pointed out that the Gramineæ were particularly distinguished by the large proportion of this constituent present in their ash. Liebig, who classified plants as "silica plants," "lime plants," and "potash plants" according to the predominance of one or other of these constituents in their ash, in accordance with his "mineral theory," regarded the silica as a necessary element in plant nutrition. This view led Way† to introduce as a cereal manure a rocky material derived from the Upper Greensand near Farnham, which contained a considerable proportion of silicate easily soluble in acids. But when Sachs‡ succeeded in maturing maize plants in water cultures containing no silica, whereby the proportion of silica in the ash of the mature plant was reduced from the normal 20 per cent. or so to as little as 0·7 per cent., it became evident that silica could no longer be placed in the same category as phosphoric acid and potash as essential elements of plant nutrition, and Jodin§ raised four successive generations of maize in water cultures without any supply of silica beyond that contained in the original seed.

Other investigators again showed that the stiffness of cereal straw, which had been attributed to the presence of silica, depends on the development of the internodes under the influence of such factors as illumination and exposure.

Henceforward little or no importance seems to have been attached to the presence of silica, yet, as the following ash analyses show, it forms a constant and considerable proportion in the ashes of certain plants, though it is almost absent from the majority.

* 'Recherches sur la Végétation,' Paris, 1804.

† 'Roy. Agric. Soc. Journ.,' vol. 14, 1853, p. 225.

‡ 'Flora,' 1862, p. 52.

§ 'Ann. Agron.,' vol. 9, 1883, p. 385.

Table I.—Percentage of Silica in Ash.

	SiO_2, per cent.		SiO_2, per cent.
Wheat straw (Rothamsted mean)...	62·1	Hops, leaves (Wolff, mean)...........	21·1
„ grain „ ...	0·7	„ cones „	17·2
Barley straw „ ...	46·0	Beech leaves „	31·0
„ grain „ ...	18·3	Larch needles „	22·5
Oat straw (Wolff, mean)...	46·1	*Calamus Rotang* (Wolff, 1 anal.)...	68·0
„ grain „ ...	36·3	*Bambusa arundinacea* „ ...	28·3
Rye grass (*Lolium perenne*) „ ...	26·7	*Sphagnum palustre* „ ...	61·8
Maize (whole plant) „ ...	43·0	*Pteris aquilina* „ ...	43·7
Sugar cane „ ...	56·4	*Equisetum arvense* „ ...	41·7
		Erica Tetralix „ ...	48·4

Owing to the inevitable presence of external dust and dirt upon plant material before analysis, it is almost impossible to say whether the small amounts of silica found in the ashes of many other plants are accidental or inherent.

But while it has been demonstrated that silica is not essential to the nutrition even of the cereals, it is hardly likely that a material present to the extent of 60 per cent. of the mineral constituents, as in the ash of wheat-straw, can be wholly without use in the economy of the plant. The only experiments, however, which throw any light on its function appear to be those of Wolff and Kreutzhage.* These investigators grew oats in culture solutions of the type usually described as complete, but further divided into three series, receiving soluble silica in considerable quantity, in a small quantity, and not at all. They observed that while the total growth was not much increased by the presence of silica, the proportion of grain formed was considerably raised, a precisely similar effect to that brought about by an addition of phosphoric acid to culture solutions deficient in that element. Hence they concluded that the action of silica and of phosphoric acid were in some way related, the former acting, however, indirectly on grain formation by promoting the migration of the food materials.

With this exception the possibility that silica plays any part in plant nutrition appears to have been ignored, just as its practical use in the manuring of cereals has been discontinued. Observation, however, of some of the plots at the Rothamsted Experimental Station, which have long been subjected to a manuring with soluble silicates, seemed to show that the question of the function of silica required further consideration, and an

* 'Land. Versuchsstationen,' vol. 30, 1884, p. 161.

examination of the records indicated at once that the appearances noticed were not accidental, but had persisted from year to year.

2. *Field Experiments at Rothamsted with Soluble Silicates.*

At Rothamsted sodium silicate has been applied as a manure to certain of the experimental plots over long periods of time, and shows regular and well-marked effects.

On the permanent grass plots in the Park, which is cut for hay every year, there are two plots receiving similar heavy applications of ammonium salts, phosphates, and potassium, sodium, and magnesium sulphates. One of these, which receives sodium silicate also, yields a crop exceeding by about 10 per cent. the crop of the parallel plot without sodium silicate, taking an average over the last 42 years. It is possible, however, that the weakly-held sodium base has some part in this action, by neutralising the acidity produced in the soil by the continued use of ammonium salts. This difficulty of interpretation does not, however, apply to the barley plots.

In Hoos field, on which barley has grown every year since 1852, one series of plots receives sodium nitrate with various combinations of mineral manures, so as to provide plots receiving (1) nitrogen alone; (2) nitrogen and phosphoric acid without potash; (3) nitrogen and potash without phosphoric acid; and (4) a complete manure.

Since 1864 one-half of each of these plots has been cross-dressed with sodium silicate; hence the effect of the silicate is seen in conjunction with each of the elements of a complete manure. The average results obtained are set out in Table II.

Table II.

Plot.	Manures per acre.					Average over 41 years, 1864—1904.			
						Grain.		Straw.	
	Sodium nitrate.	Super-phos-phate.	Potas-sium sulphate.	Sodium sulphate.	Magne-sium sulphate.	Without silicate.	With silicate.	Without silicate.	With silicate.
	lb.	cwt.	lb.	lb.	lb.	Bushels.	Bushels.	cwt.	cwt.
1	275	—	—	—	—	27·3	33·8	16·2	19·8
2	275	3·5	—	—	—	42·2	43·5	24·6	25·8
3	275	—	200	100	100	28·6	36·4	17·9	21·7
4	275	3·5	200	100	100	41·2	44·5	25·3	27·6

In this case only a normal amount of nitrogen is supplied in the form of sodium nitrate, a neutral salt, so that there is no acid to be neutralised

by the soda of the sodium silicate. The beneficial effect of the sodium silicate is chiefly shown on Plots 1 and 3, and there is little gained by its use on Plots 2 and 4. Now Plot 3 is abundantly supplied with alkaline salts in the shape of sodium nitrate and sulphates of sodium, potassium, and magnesium, so the addition of a further supply of sodium in sodium silicate would not be likely to produce any effect. Rather, if the sodium were the active constituent, would its effect be seen on Plot 2, which receives no alkaline salts beyond the sodium in the sodium nitrate common to all the plots. The notable fact is that the effect of the sodium silicate is seen only on the two Plots 1 and 3 suffering from phosphoric acid starvation, because they have been cropped for so many years without the application of any phosphates. The silica, in fact, would seem to partially replace or to do the work of the superphosphate supplied to Plots 2 and 4.

Such an opinion, derived from the yield, may be confirmed by an examination of the plots when approaching ripeness. The most striking feature at that time is the deferred maturity of the barley on the plots without phosphoric acid; they remain of a greener colour, and are still erect at a time when the barley on the normal plots has turned down and begun to yellow for harvest. This ripening effect of phosphoric acid finds a parallel, though to a smaller degree, on the half plots receiving sodium silicate. On Plots 1 and 3, which are without phosphoric acid, the portions receiving sodium silicate are always riper by a few days than the other halves which get neither phosphoric acid nor silica.

A series of analyses of the ash of the barley grown on these plots in 1903, a wet and sunless year, and 1904, a normally warm season, also serve to strengthen the idea that the action of the silica is in some way bound up with that of the phosphoric acid in the plant. Table III shows the percentages of phosphoric acid and silica in both grain and straw on the four plots, each of which is subdivided so as to be with and without silica.

It will be seen that the lack of phosphoric acid in the manure applied to Plots 1 and 3 is reflected in the diminished proportion of phosphoric acid in the ash of the grain, and still more in the low percentage present in the ash of the straw. When sodium silicate is added to the plots without phosphoric acid the proportion of phosphoric acid in the grain ash rises, but simultaneously it falls in the straw ash.

On the plots receiving phosphoric acid the silicate does not always cause an increase in the percentage of phosphoric acid in the grain ash, though as before it generally diminishes that in the straw ash.

On all the plots the sodium silicate causes an increase of silica in the ash

of the grain, and particularly in that of the straw, indicating that under the ordinary soil conditions the barley plant does not obtain all the soluble silica it would otherwise appropriate.

Table III.—Hoos Field Barley.

Nitrogen and Pure Ash per cent. in Dry Matter, and Phosphoric Acid and Silica in Pure Ash.

	Nitrogen.		Nitrogen and phosphate.		Nitrogen and potash.		Nitrogen, potash, and phosphate.	
	Only.	With silica.	Only.	With silica.	Only.	With silica.	Only.	With silica.
	1.	1 S.	2.	2 S.	3.	3 S.	4.	4 S.
Grain.								
1903—								
Nitrogen in dry matter...	1·63	1·57	1·50	1·50	1·59	1·61	1·53	1·54
Pure ash ,, ...	1·74	1·98	2·27	2·37	1·78	1·96	2·36	2·36
Phosphoric acid in pure ash	35·80	37·74	42·27	42·64	35·54	36·11	41·83	44·31
Silica in pure ash	14·19	18·67	16·43	20·60	15·81	18·00	16·95	19·71
Ratio, P_2O_5 to N	0·38	0·48	0·64	0·67	0·40	0·44	0·64	0·68
1904—								
Nitrogen in dry matter...	1·79	1·72	1·52	1·46	1·58	1·73	1·46	1·45
Pure ash ,, ...	1·94	2·09	2·34	2·41	1·97	2·15	2·33	2·32
Phosphoric acid in pure ash	32·19	35·29	40·16	36·40	30·96	34·16	38·82	38·46
Silica in pure ash	16·76	20·13	19·62	20·75	16·45	17·47	16·34	19·08
Ratio, P_2O_5 to N	0·35	0·43	0·62	0·60	0·39	0·42	0·62	0·62
Straw.								
1903—								
Nitrogen in dry matter...	0·53	0·43	0·43	0·41	0·56	0·50	0·42	0·44
Pure ash ,, ...	3·66	4·80	3·71	4·86	4·24	4·82	3·98	4·73
Phosphoric acid in pure ash	2·34	2·40	4·18	3·62	2·41	2·19	4·02	4·38
Silica in pure ash	51·98	63·88	56·67	64·00	46·22	55·37	48·14	57·30
Ratio, P_2O_5 to N	0·16	0·27	0·36	0·43	0·18	0·22	0·38	0·48
1904—								
Nitrogen in dry matter...	0·49	0·48	0·40	0·42	0·50	0·48	0·43	0·45
Pure ash ,, ...	4·07	5·00	4·36	5·09	4·61	5·29	4·19	5·01
Phosphoric acid in pure ash	2·66	2·13	4·47	4·17	2·48	2·02	4·78	3·96
Silica in pure ash	44·00	52·54	47·19	51·28	35·91	44·07	37·43	44·13
Ratio, P_2O_5 to N	0·21	0·23	0·49	0·51	0·23	0·22	0·47	0·44

As the application of a soluble silicate lowers the proportion of phosphoric acid in the straw while raising it in the grain, it would seem at first sight to

act by facilitating the migration and utilisation in the grain of the initially small store of phosphoric acid derived from the soil.

But such an interpretation of the function of silica is not borne out if the whole amount of phosphoric acid removed by the crop from the soil on each plot be considered, instead of the proportion of phosphoric acid in the ash. It has already been shown that the use of sodium silicate on the no phosphoric acid plots, 1 and 3, results in a considerable increase of crop, and as the grain of this increased crop is somewhat richer and the straw only a trifle poorer in phosphoric acid than the grain and straw from the non-silicated portions of the plots, it follows that the whole crop manured with silica contains a greater total amount of phosphoric acid derived from the reserves of phosphoric acid in the soil. This extra phosphoric acid derived from the soil is itself sufficient to explain the greater yield brought about by the silicate without attributing to the silica within the plant any specific action in economising the phosphoric acid there present. If the function of the silica were to replace the phosphoric acid within the plant and enable it to be moved off to the active tissues and used over and over again, the larger crop due to manuring with silicates would not contain any greater amount of phosphoric acid, but the general growth of the plant, *e.g.*, the dry matter produced and the nitrogen assimilated, would be increased. Hence the ratio of the phosphoric acid to the dry matter and to the nitrogen would be lowered in proportion to the increased growth, conditions which are not realised in the cases under examination, where indeed the ratio of phosphoric acid to nitrogen is generally slightly raised by the applications of silicate.

The results on the other hand indicate that the silicate gives the plant such a stimulus as enables it to develop more vigorously and obtain more phosphoric acid from the soil, and that all the consequences observed follow from the increase of phosphoric acid thus brought about.

Wolff and Kreutzhage held that the function of the silica was to enable the plant to make fuller use of whatever phosphoric acid it had obtained from the soil, the Rothamsted results indicate that its action takes place earlier, in stimulating the plant to draw more efficiently upon the vast but dormant reserves of phosphoric acid in the soil.

3. *Effect of Silica on the Development of Barley in* 1904.

In order to study the question more closely it was decided in 1904 to trace the effect of phosphoric acid and silica upon the development of the barley on these plots at regular intervals from the time of flowering onwards. As the effect of phosphoric acid had been most evident in forwarding the maturation of the crop, it was considered that the later period of the growth

of the crop need only be investigated, *i.e.*, the period during which the nutrition of the plant from the soil has largely ceased and assimilation is coming to a standstill, while the materials previously accumulated in the stem and leaf are migrating into the seed.

The method adopted was to take a certain number of rows of barley in the middle of each plot and remove the whole plant, as far as possible with the roots intact, for two yards up these rows, at weekly intervals from June 13 until harvest on August 8, or nine times in all. The plants were then air-dried after washing the roots free from soil, the grain when formed was separated from the straw, and both were finally dried in the steam oven, so as to obtain the weight of dry matter; although dealing with such small areas it is impossible to make more than a very approximate estimate of the yield per unit area. The dried material was ground, and after determinations of the nitrogen in one portion, the rest was burnt for ash, in which the pure ash, free from sand and charcoal, and the phosphoric acid and silica were determined.

The analytical results are set out in Appendix Tables VII to X, from which are derived the various curves of development now to be considered (figs. 1 to 11). Before however proceeding to a consideration of particular cases it will be convenient to trace by means of an average result for all the plots the general course of development in the later stages of the growth of the barley plant.

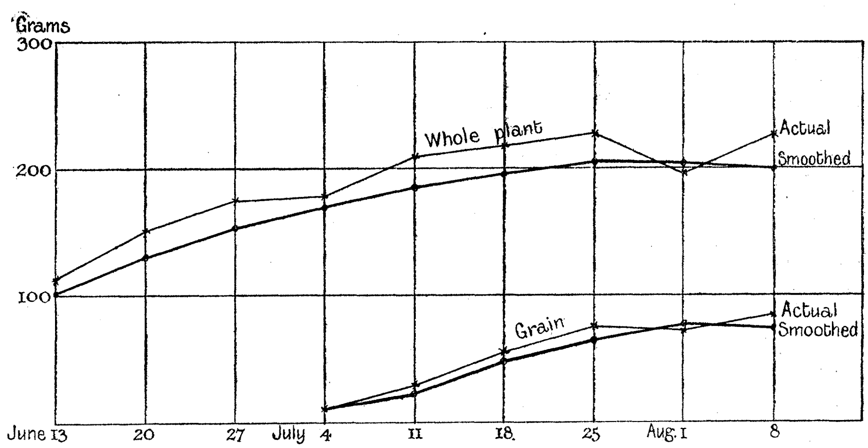

FIG. 1.—Dry Weights. Mean of all plots. Whole Plant and Grain.

Fig. 1 shows the mean dry weight of all the eight plots on each date, both of the whole plant and of the grain. The crop attained its maximum weight about July 18—25, after which it remained stationary and probably indeed declined slightly. The result shown for August 1 is clearly exceptional; on

that date several of the plots happened to yield an exceptionally small number of stems on the area harvested.

For the better calculation of mean results the smoothed curve also shown in fig. 1 was drawn; by combining the smoothed dry weights read off this curve with the true mean percentages at each date were obtained the data contained in Table IV and expressed graphically in fig. 2.

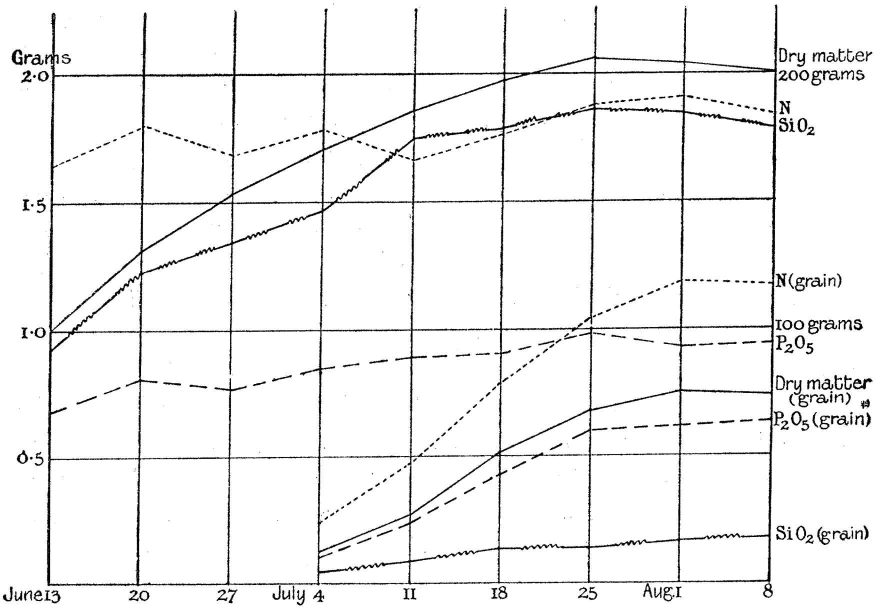

FIG. 2.—Dry Matter, Nitrogen, Phosphoric Acid, and Silica in Whole Plant and Grain. Means calculated on smoothed weights of whole Plant. (SiO_2 on $\frac{1}{2}$ scale of N and P_2O_5.)

From these curves it will be seen that the dry matter of the crop goes on increasing until about a fortnight before cutting, but the whole of the nitrogen would appear to have entered by July 11, a fortnight before there was any sensible grain. The phosphoric acid seems to reach its maximum at a slightly later date, and the figures for the silica, though subject to greater errors of determination, show that the assimilation of silica continues still later, until the grain has progressed somewhat. Of the nitrogen within the plant, about 63 per cent. is eventually moved into the grain and rather less than 70 per cent. of the phosphoric acid; the migration of the phosphoric acid does not, however, take place exactly *pari passu* with that of the nitrogen, but follows it somewhat. Of the silica but a small proportion, 9 per cent. at the maximum, reaches the grain, and nearly the whole of this is transferred in the earlier stages of grain formation, being doubtless present in the adherent pales and glumes and not in the seed proper.

Table IV.—Hoos Field Barley. Season 1904.

Mean Weight and Composition of Barley (all Plots taken together).

	June 13.	June 20.	June 27.	July 4.	July 11.	July 18.	July 25.	Aug. 1.	Aug. 8.
Percentage (true means) in Dry Matter.									
Grain — Nitrogen	—	—	—	2·224	1·808	1·550	1·538	1·590	1·576
Grain — Phosphoric acid	—	—	—	0·976	0·911	0·845	0·883	0·821	0·866
Grain — Silica	—	—	—	0·919	0·722	0·540	0·412	0·428	0·443
Straw and roots — Nitrogen	1·642	1·372	1·101	0·963	0·745	0·664	0·605	0·552	0·530
Straw and roots — Phosphoric acid	0·675	0·609	0·492	0·464	0·407	0·314	0·281	0·235	0·234
Straw and roots — Silica	1·832	1·873	1·743	1·765	2·072	2·223	2·483	2·618	2·572
Weights calculated on Smoothed Weights of Dry Matter.									
Total dry matter (smoothed weights adopted)	100	131	153	170	185	197	205	203	200
Dry grain	—	—	—	10·9	26·1	50·0	67·2	74·5	73·6
Dry straw and roots	100	131	153	159·1	158·9	147·0	137·8	128·5	126·4
Grain — Actual nitrogen	—	—	—	0·242	0·472	0·775	1·034	1·185	1·160
Grain — ,, P_2O_5	—	—	—	0·106	0·238	0·423	0·594	0·612	0·637
Grain — ,, SiO_2	—	—	—	0·100	0·188	0·270	0·277	0·319	0·326
Straw and roots — Actual nitrogen	1·642	1·797	1·685	1·532	1·184	0·976	0·834	0·709	0·670
Straw and roots — ,, P_2O_5	0·675	0·798	0·753	0·738	0·647	0·462	0·387	0·302	0·296
Straw and roots — ,, SiO_2	1·832	2·453	2·667	2·808	3·292	3·268	3·422	3·363	3·250
Whole plant — Actual nitrogen	1·642	1·797	1·685	1·774	1·656	1·751	1·868	1·894	1·830
Whole plant — ,, P_2O_5	0·675	0·798	0·753	0·844	0·885	0·885	0·981	0·914	0·933
Whole plant — ,, SiO_2	1·832	2·453	2·667	2·908	3·480	3·538	3·699	3·682	3·576

Perhaps the most important point brought out is that the grain establishes a particular composition at an early stage in its development, after which, although it continues to grow and increase in weight, it does not sensibly alter its composition. From July 18 onwards the percentage of nitrogen and the percentage of phosphoric acid in the grain remain approximately constant, though the grain gains a further 50 per cent. of its weight during the same period. Whatever chemical changes take place during the latter stages of ripening, they consist in the rearrangement of the minerals within the grain rather than in any progressive change in the character of the intake.

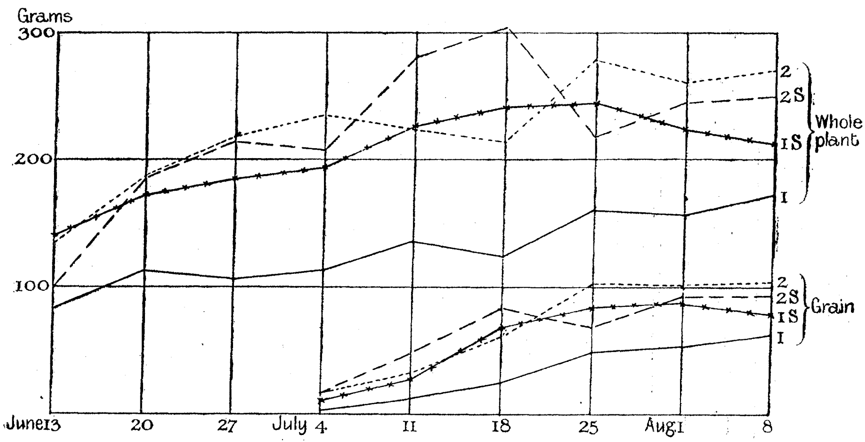

FIG. 3.—Dry Weights of plots without Potash.

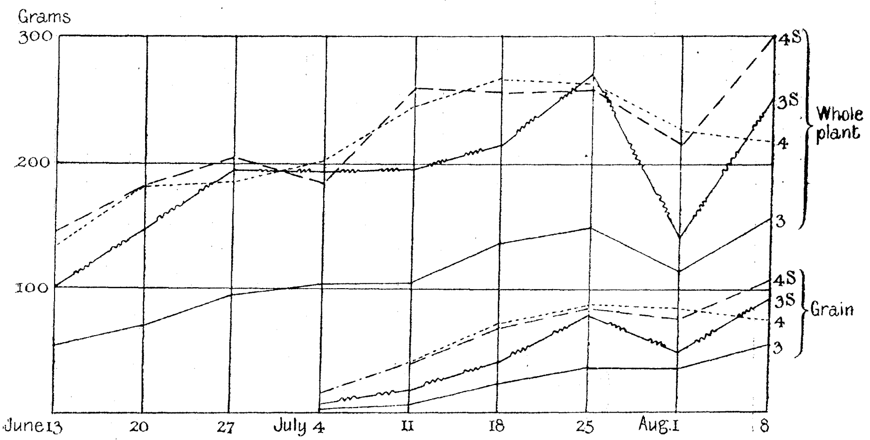

FIG. 4.—Dry weights of plots with Potash.

Taking these mean figures as indicating the normal course of development it will now be possible to review the results yielded by individual plots and

trace the effect of silica on the assimilation of carbon (dry matter yield), nitrogen, and phosphoric acid, and particularly on the movement of these materials into the grain. Figs. 3 and 4 show in graphic form the yield from individual plots, fig. 3 deals only with Plots 1 and 2, where no potash is supplied in the manure, while fig. 4 deals with Plots 3 and 4, each of which receives equal amounts of sulphates of potassium, sodium and magnesium. In each figure curves are drawn separately for the silicated and non-silicated portions of the plot.

The accidental fluctuations in yield from week to week are too violent to admit of smoothing, but the general character of the curves shows that Plots 1 and 3, which receive neither phosphoric acid nor silica, give consistently a much lower yield than the others. The curves representing Plot 2 (with phosphoric acid), Plot 1 S (with silica), and Plot 2 S (with both phosphoric acid and silica), do not differ from one another by more than the extent of the accidental fluctuations from week to week of any one of them, but all indicate a yield about half as large again as that of Plot 1. Similarly where potash is used: Plot 3, without silica or phosphoric acid, never yields much more than half the crop on the Plots 3 S, 4, and 4 S, receiving either silica or phosphoric acid, or both together. As judged then by the dry matter produced, the silicate manuring is able to do the same work for the plant as the phosphatic manuring on Plots 3 and 4.

Despite the magnitude of the accidental fluctuations some differences in the character of the curves may be discerned; both Plots 1 and 3 (without silica or phosphoric acid) reach their maximum only on August 8, whereas in five of the other six cases where silica and phosphoric acid form part of the manure the maximum is reached by July 18 or 25. This would confirm the appearance in the field of deferred maturity in the absence of either phosphoric acid or silica.

Fig. 5 shows the proportion the grain bears to the whole plant at weekly intervals for the four plots which receive no potash, together with the smoothed mean of all the plots for comparison. It will at once be seen that on Plot 1, receiving neither phosphoric acid nor silica, the proportion of grain is below the normal, and also that the grain is later in forming. The 3 per cent. or so indicated on July 4, the earliest date when any separation of grain was possible, would be wholly made up of the adherent pales. It is only in the following week that the weight of grain has become sensible on Plot 1. On Plot 2, receiving phosphoric acid, the formation of grain precedes, and also is finally somewhat above the normal.

Plot 1 S, receiving silica but not phosphoric acid, occupies an intermediate position; though starting a little later than Plot 2, it eventually becomes

almost identical with it. In other words, the free supply of silica without phosphoric acid to Plot 1 S has enabled the plant to mature as high a proportion of grain, and almost as rapidly, as does the supply of phosphoric acid to Plot 2. The further addition of silica to phosphoric acid as on Plot 2 S does not effect any change in the character of the development of the grain.

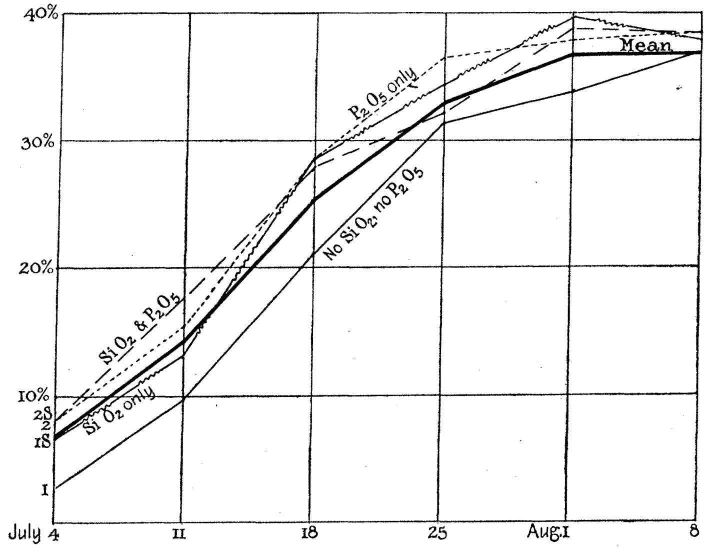

FIG. 5.—Percentage of Grain in Plant. Plots without Potash.

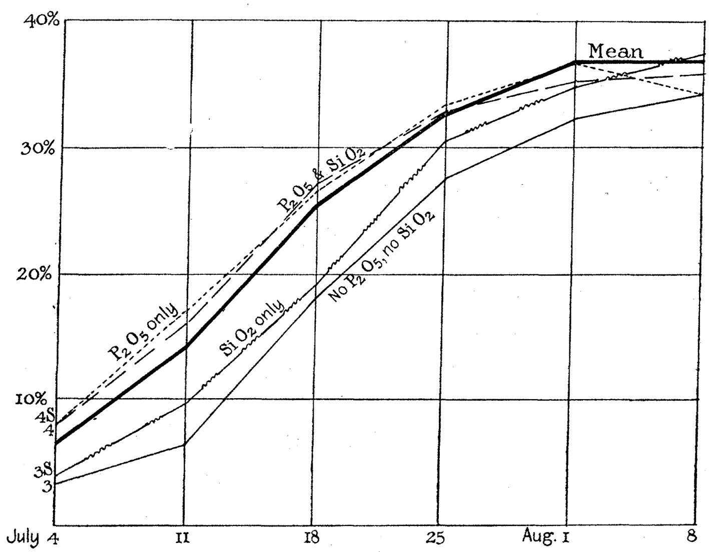

FIG. 6.—Dry Grain in 100 Total Dry. Plots with Potash.

In fig. 6 curves are seen representing the same succession of plots, this time however they all receive potassic manure. Again, the proportion of grain on the plot without either phosphoric acid or silica, 3, is low, and its formation is retarded as compared with the normal. Plots 4 and 4 S, the two plots receiving phosphoric acid, are practically identical and agree closely with the normal, while the curve representing Plot 3 S, where silica but no phosphoric acid is used, occupies an intermediate position. The development of grain on these plots receiving potash is later than is normal, though ultimately as high a proportion of grain to straw is produced.

As regards the formation of grain, the curves show that phosphoric acid hastens the formation of grain, and eventually causes a higher proportion of the material in the plant to pass over into that state, while silica acts in the same direction, though not to so large an extent.

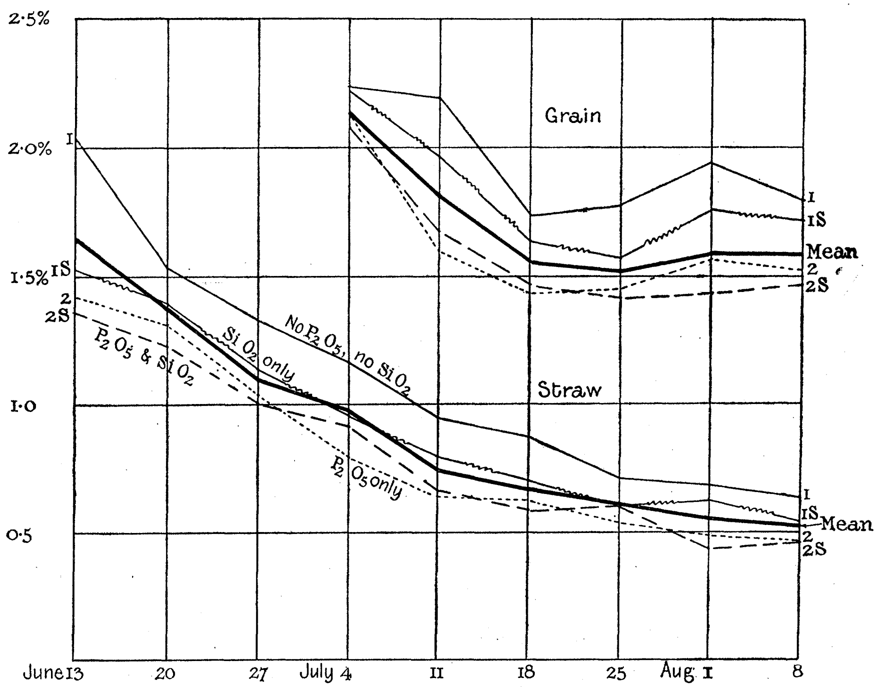

FIG. 7.—Percentages of Nitrogen in Dry Matter.

Turning to the entry of the nitrogen, fig. 7 shows the percentage of nitrogen in the grain and straw at the successive dates and for the four plots receiving no potash, the mean results being also plotted for purposes of comparison. Plot 1, receiving neither phosphoric acid nor silica, yields the highest proportion of nitrogen in both grain and straw at each stage of the

growth. The use of phosphoric acid on Plot 2 reduces the percentage of nitrogen in both grain and straw to a little lower than normal level, and this reduction is most marked in the grain. Again, silica without phosphoric acid on Plot 1 S gives rise to an intermediate curve of development, nearer to the normal than to the curve representing the plot without either phosphoric acid or silica. Silica added to phosphoric acid (Plot 2 S compared with 2) makes practically no difference in the curve.

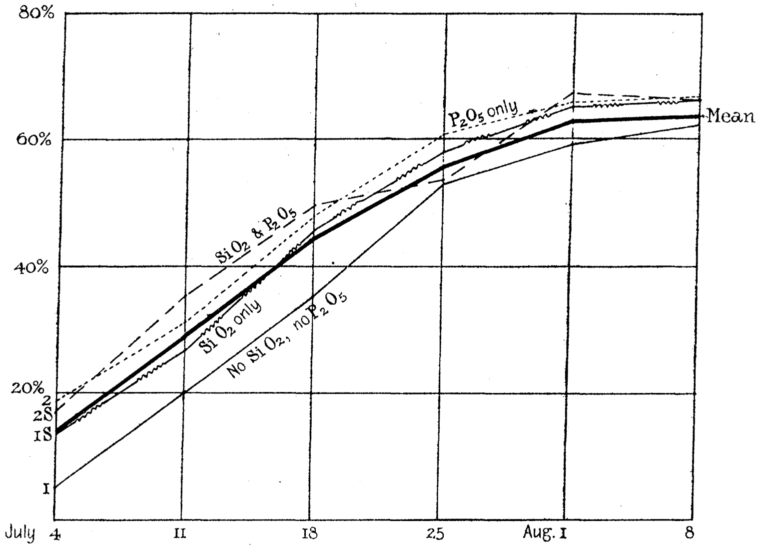

FIG. 8.—Nitrogen. Percentage of whole content present in the Grain. Plots without Potash.

Fig. 8 shows the movement of the nitrogen into the grain; although both the grain and straw of Plot 1, without phosphoric acid or silica, contain the highest percentages of nitrogen, yet the proportion of the nitrogen within the plant which passes over to the grain is lower on this plot than on the normal; the transfer again begins at a somewhat later date. The phosphoric acid alone on Plot 2 induces both an earlier and a greater proportionate transfer of nitrogen to the grain than the normal. Silica on Plot 1 S induces an earlier and more complete transfer of nitrogen, though not to the extent caused by the phosphoric acid. On the corresponding plots with potash (fig. 9) very similar results obtain; without phosphoric acid or silica (Plot 3) the transfer of nitrogen to the grain lags behind the normal, while the use of phosphoric acid (Plot 4) accelerates this process beyond the normal, silica (Plot 3 S) acts in the same direction though not to the same extent.

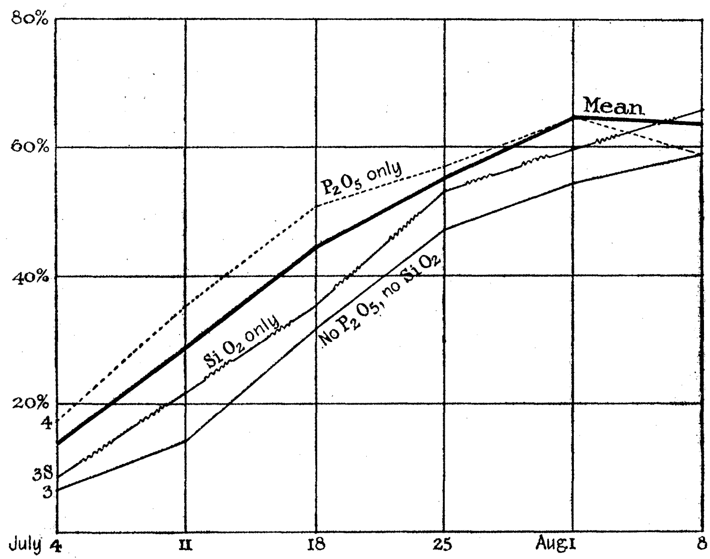

FIG. 9.—Nitrogen. Percentage of whole content present in Grain. Plots with Potash.]

As regards the phosphoric acid, the proportion of phosphoric acid in the dry matter of the grain is increased by the use of phosphatic manure, as it is also by the use of silica, especially where no phosphatic manuring takes place. The removal of the phosphoric acid to the grain is naturally more complete in the cases of phosphoric acid starvation; and when silica without phosphoric acid has been supplied, almost the whole of the extra

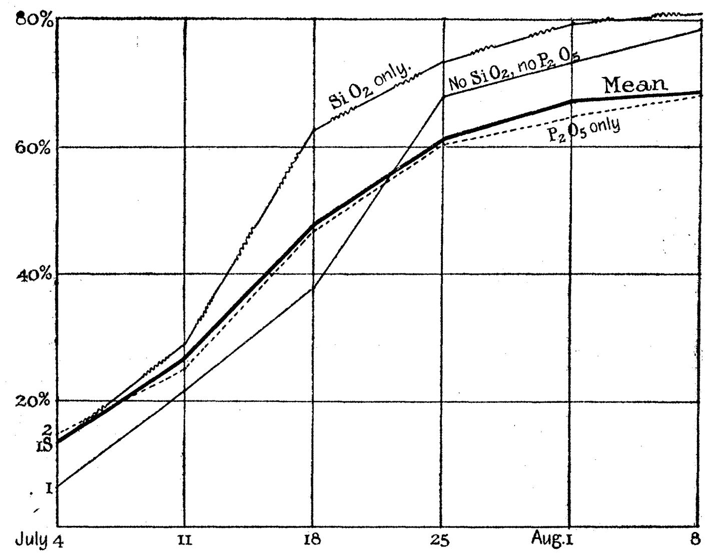

FIG. 10.—Phosphoric Acid. Percentage of whole content present in Grain. Plots without Potash.

phosphoric acid which the plant had thus been able to acquire is moved off into the grain. This may be seen more clearly in fig. 10, which shows what proportion of the plant's phosphoric acid is to be found in the grain on the successive dates. On Plot 1, without phosphoric acid or silica, the movement of phosphoric acid to the grain begins much later, but is ultimately more complete than on the normal or on the plots receiving phosphoric acid. With silica but no phosphoric acid (Plot 1 S) the migration of phosphoric acid begins at an earlier date and the proportion transferred is much increased, in spite of the fact that the actual amount of phosphoric acid in the plant is also much greater than on the first plot. Exactly the same conclusions are derived from an examination of the curves yielded by the parallel plots receiving potash (fig. 11); the use of silica both accelerates the migration of phosphoric acid to the grain and makes it more complete, although a greater proportion is initially present.

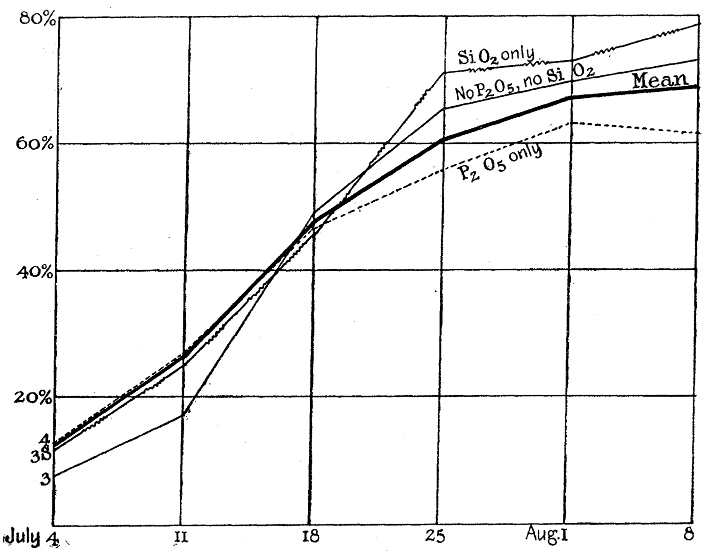

FIG. 11.—Phosphoric Acid. Percentage of whole content present in Grain. Plots with Potash.

The fact that a greater proportion of the phosphoric acid present in the plant is utilised in the grain on the silica plots, seems for the first time to indicate some specific action of the silica in facilitating the migration of phosphoric acid, so that it is not left unused as waste material in parts of the plant no longer active. But it will be found that the actual percentage of phosphoric acid finally left in the dry matter of the straw is no lower where silica has been used, on Plots 1 S and 3 S, than on the corresponding Plots 1 and 3 without either phosphoric acid or silica. If something like

0·11 per cent. of phosphoric acid be taken as the lower limit of phosphoric acid in the straw, that limit is just as much attained in the absence as in the presence of silica. The greater share of the plant's phosphoric acid transferred to the grain in the latter case comes from the fact that the amount of phosphoric acid assimilated, though increased by the silica, is still not sufficient for the requirements of the plant in the formation of grain, hence the straw continues to be depleted of its phosphoric acid to the lowest limit possible.

The consideration then of each of the factors submitted to detailed examination—the formation of grain and the migration of nitrogen and phosphoric acid into the grain—leads to the same general conclusion, that an abundant supply of soluble silica renders the barley plant more able to obtain a stock of phosphoric acid from the soil. On the plots therefore which are suffering from phosphoric acid starvation the manuring with sodium silicate acts like a supply of phosphoric acid; indeed, the plant does actually thereby obtain a larger amount of phosphoric acid.

Further evidence that the silica acts by stimulating the plant to take up phosphoric acid is derived from water cultures grown in 1904. Three plants of barley were grown in each of four jars, holding about 3 litres of solution, containing the following nutrient salts per litre:—

Calcium nitrate	1·64 gram.
Di-hydrogen potassium phosphate ...	0·29 „
Magnesium sulphate (crystallised)...	0·62 „
Potassium chlorate	0·71 „

with a trace of ferric chloride.

Growth was vigorous from the first; the barley plants tillered freely and made a large number of shoots from each grain. On June 7 the nutrient solution was replaced by distilled water, which was changed again on the 8th, and replaced on the 9th by a fresh solution. The new solution contained calcium nitrate, magnesium sulphate, and potassium chloride as before in all the jars; the phosphoric acid, however, was varied as follows:—

No. 1. No phosphoric acid.
No. 2. No phosphoric acid, but 0·146 gramme silica in solution.
No. 3. 0·355 gramme phosphoric acid, no silica.
No. 4. 0·355 gramme phosphoric acid, and 0·146 gramme silica in solution.

It soon became evident that the phosphoric acid and silica, both separately and together, had a ripening effect, which was indicated by an earlier and an increased formation of ears.

On August 5, although the plants were by no means fully mature, it was necessary to harvest them because of an attack of aphis. When dried they gave the following results :—

Table V.—Barley in Water Cultures. Yield on August 5, 1904.

Plot.	Number of ears.	Number of grains.	Dry matter.		
			Grain.	Straw and roots.	Total.
			grammes.	grammes.	grammes.
1	4	0	0	35·17	35·17
2	7	5	0	31·87	31·87
3	18	177	5·26	50·79	56·05
4	27	272	9·63	56·26	65·89

Assuming that on June 9, when the treatment was varied, all of the plants were approximately equal, it will be seen that the extra phosphoric acid added to Nos. 3 and 4 allowed them to double their weight during the remaining period of growth. The silica alone added to No. 2 did little to enable the plant to make better use of the restricted amount of phosphoric acid already in the plant, for although the formation of ears seems to have been a little forwarded, the few grains that were produced possessed no sensible weight. When, however, silica is provided in the presence of phosphoric acid, No. 4 compared with No. 3, it brings about a considerable increase of growth and an accelerated formation of grain—just such a change, in fact, as would be brought about by an increased assimilation of phosphoric acid. In fact, these cultures demonstrate that although silica cannot replace phosphoric acid, nor even economise and make more effective a restricted supply already within the plant, it will stimulate the plant to assimilate a greater amount of phosphoric acid should that be obtainable from the medium in which the plant is growing. Hence, when applied to a silica plant on a soil impoverished in phosphoric acid, it has the same effect in increasing and accelerating the formation of fruit as would result from a direct application of phosphoric acid.

It might be supposed that the action takes place within the soil itself, that the sodium silicate in some way attacks the insoluble phosphates of the soil so as to render them more available for the plant, much as an application of lime or gypsum will liberate an increased supply of potash from the soil. On chemical grounds it is difficult to see how such an action should occur, nor do the results with water cultures bear out such a view. To obtain further evidence on this point, samples of soil from the eight plots in question were

extracted (1) with strong hydrochloric acid and (2) with a 1 per cent. solution of citric acid. While there is no method of determining the real amount of plant food in the soil which is at the service of the crop, the latter method* gives comparative estimates which are of value when dealing with soils of the same type.

Table VI shows a series of determinations of the total phosphoric acid and of the phosphoric acid soluble in 1 per cent. citric acid solution.

Table VI.

	Total phosphoric acid.		Phosphoric acid soluble in 1 per cent. citric acid.	
	No silica.	With silica.	No silica.	With silica.
1	0·097	0·096	0·0086	0·0067
2	0·194	0·199	0·0495	0·0721
3	0·092	0·089	0·0075	0·0094
4	0·179	0·183	0·0674	0·0743

Comparing the soils with and without silica, the use of silica has not affected the amount of total phosphoric acid; the greater draft it occasions year by year from the soil of Plots 1 and 3, which are not supplied with phosphoric acid, is barely visible as yet in the analyses.

The silica has also little or no effect on the phosphoric acid soluble in citric acid on the four Plots 1, 1 S, 3, and 3 S; but the amount going into solution is distinctly higher on Plots 2 S and 4 S than on Plots 2 and 4, all plots receiving phosphoric acid in the manure. It is not, however, on these plots, but on Plots 1 and 3 that the silica shows any effect on the crop, hence these determinations support the conclusion that the sodium silicate has no action upon the soil phosphates.

Though the seat of the action is thus transferred from the soil to the plant, it is by no means settled whether the stimulus which the silica gives to the plant to enable it to take up more phosphoric acid from the soil reserves is a general stimulus or a specific one confined to the phosphoric acid. In other words, does the presence of a free supply of soluble silica so invigorate the plant that it is enabled to repair any weak link in the chain of nutrition and get as need be more nitrogen, phosphoric acid, or potash from the soil, or is the beneficial effect confined to the phosphoric acid alone? It is chiefly towards the settlement of this point that the further experiments both with silica and non-silica plants are now being directed.

* Dyer, 'Chem. Soc. Trans.,' vol. 65, 1894, p. 115.

The further question of the intimate mechanism by which the silica acts within the plant, and the nature of the chemical changes into which it enters to bring about the observed effects, cannot yet be raised. In the first place little is known of how the phosphoric acid itself acts; it is evident that it induces seed-formation and hastens maturity, but in what way it takes part in the cell processes is still doubtful. Some of the data accumulated in the present investigation may profitably bear discussion in this connection—it is evident, for example, that there is little or no interdependence between the phosphoric acid and the assimilation or migration of nitrogen, as has often been suggested. Again, the results would seem to indicate that a distinction must be drawn between physiological maturity and ripeness. The grains of a phosphoric acid starved Plot like No. 1 go through a ripening process, but they never approach to the composition, or even attain the appearance, of the truly mature grain on more normal Plots like 2 and 4. The grain from Plots 1 and 3, though ripe, has still many of the characters of immature grain. If the progress of the grain be judged by such factors as the percentage of nitrogen or the ratio of phosphoric acid to nitrogen, the grain early in its formation settles down to a standard composition correlated with the original supply of nutriment, and after this point has been reached it does not change its gross composition, though it is continually increasing in size and weight. For example, the grain of Plot 1, with its high percentage of nitrogen and low ratio of phosphoric acid to nitrogen, which might be taken as indicative of its generally immature character, shows no tendency as its grows and ripens to approximate in composition to the thoroughly mature grain of Plot 2. The later stages of ripening are without doubt attended by changes in the nature of both the carbohydrate and the proteid contents of the grain, which however are not apparent in the elementary analysis of the grain.

Conclusions.

The following general conclusions have been reached in the course of this investigation:—

(1) Silica, though not an essential constituent of plant food, does play a part in the nutrition of cereal plants, like barley, which contain normally a considerable proportion of silica in their ash.

(2) The effect of a free supply of soluble silica manifests itself in an increased and earlier formation of grain, and is thus similar to the effect of phosphoric acid.

(3) The silica acts by causing an increased assimilation of phosphoric

acid by the plant, to which phosphoric acid the observed effects are due. There is no evidence that the silica within the plant causes a more thorough utilisation of the phosphoric acid that has already been assimilated, or itself promotes the migration of food materials from the straw to the grain.

(4) The seat of the action is within the plant and not in the soil.

Appendix.

Table VII.—Hoos Field Barley, 1904.

Actual Dry Weights of Grain and Total Plant.

Date of sample.	No silica.				With silica.				Mean of all plots.
	Plot 1. Nitrogen only.	Plot 2. No potash.	Plot 3. No phosphate.	Plot 4. Complete.	Plot 1 S. Nitrogen only.	Plot 2 S. No potash.	Plot 3 S. No phosphate.	Plot 4 S. Complete.	
				Whole Plant.					
	grammes.	grammes.	grammes.	grammes.	grammes.	grammes.	grammes.	grammes.	grammes.
June 13...	84·5	134·5	53·1	135·3	140·4	101·5	109·4	146·7	113·2
„ 20...	112·0	187·5	70·1	180·6	163·0	186·3	146·9	164·9	151·4
„ 27...	107·9	218·5	96·5	186·3	184·7	216·4	195·1	202·0	175·9
July 4...	116·5	236·5	103·0	201·1	194·0	203·8	193·7	184·7	179·2
„ 11...	138·9	225·0	104·0	244·5	226·6	280·7	194·9	258·0	209·1
„ 18...	124·2	215·1	134·7	266·9	241·4	304·0	212·2	255·6	219·3
„ 25...	161·4	279·2	139·3	263·1	245·1	219·5	260·2	260·0	228·5
Aug. 1...	158·9	260·9	111·1	226·5	223·0	244·8	139·4	214·3	197·4
„ 8...	173·3	270·2	154·4	217·1	211·4	249·9	248·7	301·1	228·3
				Grain.					
July 4...	3·2	18·8	3·3	15·8	12·5	16·4	7·6	14·6	11·5
„ 11...	13·5	34·9	6·8	41·7	29·5	49·6	18·9	41·4	29·5
„ 18...	26·2	61·0	24·5	71·0	67·9	85·0	40·3	69·1	55·6
„ 25...	50·4	102·0	38·6	87·7	84·0	70·6	80·5	85·4	74·9
Aug. 1...	53·8	99·0	35·8	83·3	88·3	94·9	48·7	75·5	72·4
„ 8...	63·8	103·6	52·7	74·2	80·4	95·6	92·7	108·0	83·9

Table VIII.—Hoos Field Barley. Season 1904.
Percentage of Nitrogen in the Dry Matter.

Date of sample.	No silica.				With silica.			
	Plot 1. Nitrogen only.	Plot 2. No potash.	Plot 3. No phosphate.	Plot 4. Complete.	Plot 1 S. Nitrogen only.	Plot 2 S. No potash.	Plot 3 S. No phosphate.	Plot 4 S. Complete.
				In Grain.				
July 4...	2·245	2·133	2·358	2·228	2·225	2·193	2·547	2·165
„ 11...	2·198	1·604	2·009	1·742	1·963	1·670	2·242	1·743
„ 18...	1·735	1·431	1·715	1·516	1·637	1·460	1·739	1·480
„ 25...	1·769	1·451	1·687	1·420	1·566	1·416	1·677	1·504
Aug. 1...	1·944	1·561	1·560	1·467	1·762	1·430	1·747	1·424
„ 8...	1·791	1·517	1·578	1·461	1·716	1·463	1·733	1·448
				In Straw and Roots.				
June 13...	2·039	1·421	2·404	1·627	1·524	1·604	1·524	1·579
„ 20...	1·541	1·309	1·551	1·268	1·398	1·234	1·465	1·413
„ 27...	1·330	1·031	1·261	1·016	1·133	1·012	1·165	1·063
July 4...	1·162	0·797	1·151	0·977	0·957	0·909	1·121	0·812
„ 11...	0·943	0·646	0·863	0·658	0·796	0·655	0·862	0·703
„ 18...	0·868	0·617	0·824	0·535	0·704	0·580	0·747	0·624
„ 25...	0·709	0·544	0·736	0·542	0·599	0·591	0·661	0·546
Aug. 1...	0·687	0·498	0·626	0·476	0·626	0·444	0·640	0·537
„ 8...	0·633	0·472	0·573	0·528	0·538	0·467	0·542	0·533

Table IX.—Hoos Field Barley. Season 1904.
Percentage of Phosphoric Acid in Dry Matter.

Date of sample.	No silica.				With silica.			
	Plot 1. Nitrogen only.	Plot 2. No potash.	Plot 3. No phosphate.	Plot 4. Complete.	Plot 1 S. Nitrogen only.	Plot 2 S. No potash.	Plot 3 S. No phosphate.	Plot 4 S. Complete.
				In Grain.				
July 4...	0·591	1·064	0·746	0·869	0·861	1·092	1·116	1·007
„ 11...	—	0·908	0·787	0·872	0·946	0·932	0·932	0·911
„ 18...	0·403	0·889	0·736	0·857	0·814	0·937	0·889	0·893
„ 25...	0·572	0·923	0·693	0·962	0·845	1·007	0·879	0·959
Aug. 1...	0·631	0·945	0·591	0·898	0·669	0·872	0·827	0·928
„ 8...	0·650	0·972	0·638	0·990	0·776	0·961	0·820	0·942
				In Straw and Roots.				
June 13...	0·394	0·700	0·369	0·776	0·613	0·887	0·555	0·835
„ 20...	0·362	0·667	0·386	0·713	0·576	0·692	0·490	0·739
„ 27...	0·306	0·586	0·308	0·553	0·442	0·603	0·383	0·556
July 4...	0·256	0·543	0·294	0·511	0·401	0·654	0·342	0·545
„ 11...	0·230	0·497	0·261	0·483	0·356	0·483	0·301	0·474
„ 18...	0·180	0·404	0·173	0·364	0·193	0·416	0·249	0·392
„ 25...	0·123	0·352	0·140	0·379	0·163	0·416	0·161	0·408
Aug. 1...	0·120	0·317	0·121	0·308	0·112	0·294	0·165	0·317
„ 8...	0·105	0·283	0·122	0·322	0·116	0·301	0·134	0·364

Table X.—Hoos Field Barley. Season 1904.

Percentage of Silica in Dry Matter.

Date of sample.	No silica.				With silica.			
	Plot 1. Nitrogen only.	Plot 2. No potash.	Plot 3. No phosphate.	Plot 4. Complete.	Plot 1 S. Nitrogen only.	Plot 2 S. No potash.	Plot 3 S. No phosphate.	Plot 4 S. Complete.
				In Grain.				
July 4...	0·331	0·920	0·344	0·730	0·876	1·216	0·657	1·236
„ 11...	—	0·680	1·016	0·620	0·800	0·712	0·696	0·777
„ 18...	0·335	0·442	0·501	0·621	0·466	0·631	0·486	0·630
„ 25...	0·294	0·329	0·448	0·336	0·484	0·536	0·384	0·493
Aug. 1...	0·301	0·403	0·382	0·388	0·433	0·521	0·337	0·558
„ 8...	0·339	0·475	0·339	0·417	0·443	0·548	0·419	0·468
				In Straw and Roots.				
June 13...	1·541	1·523	1·619	1·516	1·850	2·686	1·937	1·969
„ 20...	1·506	1·515	1·764	1·596	2·161	2·487	1·932	1·843
„ 27...	1·242	1·502	1·299	1·259	1·762	2·391	1·881	2·084
July 4...	1·191	1·528	1·368	0·907	1·988	2·784	1·767	2·257
„ 11...	1·415	1·974	1·604	1·578	2·516	2·527	2·124	2·280
„ 18...	1·643	1·966	1·404	1·569	2·656	2·905	2·388	2·558
„ 25...	1·809	2·214	2·085	1·954	2·678	3·069	2·462	3·291
Aug. 1...	2·210	2·203	1·858	1·915	2·985	3·550	2·644	3·171
„ 8...	1·572	1·690	2·356	2·033	3·028	3·874	2·748	2·923