UNIVERSITY OF CALIFORNIA PUBLICATIONS
IN
AGRICULTURAL SCIENCES
Vol. 1, No. 13, pp. 495-587 March 26, 1917

EXPERIMENTS ON THE EFFECTS OF CONSTITUENTS OF SOLID SMELTER WASTES ON BARLEY GROWTH IN POT CULTURES

BY
C. B. LIPMAN AND W. F. GERICKE

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INTRODUCTION

In 1913[1] the senior author and F. H. Wilson reported briefly the results of some preliminary investigations on the effects of $CuSO_4$, $MnSO_4$, $ZnSO_4$, and H_2SO_4 on the growth of wheat and of vetch in a humus sand in pots, under greenhouse conditions. One year prior to the appearance of the report just cited, the present authors instituted new and more complete experiments with the objects noted below. These experiments, covering a period of three years, are now complete in several significant phases and we are therefore proceeding to a discussion of them.

The importance of a study of this subject is attested by the recent appearance of monographic works devoted to it, by the significance of the practical bearings of the physiological studies involved and, in view of these, by the conflicting nature of the results thus far obtained, and the evident non-consideration, by investigators, of the nature of the medium of plant growth as a vital determinant of the results. Some of the outstanding early work on the inorganic poisons, particularly copper, as affecting plant growth is either reviewed or cited in the communication above referred to. In this paper no historical sketch will be given, but important investigations which may be relevant to our findings will be discussed in connection with the results and meaning of our experiments.

OBJECTS OF THE EXPERIMENTS

The objects of our experiments were as follows: (1) To ascertain whether metals like copper, zinc, lead, iron, and manganese used in the sulfate form in the soil as a medium are toxic in any quantity to barley. (2) To ascertain whether the substances named can be toxic in soils if found in quantities which

[1] Bot. Gaz., vol. 55, no. 6, p. 409, June, 1913.

would be possible in the vicinity of smelters. (3) To ascertain whether the same substances would be a menace to lands more remote from smelters if carried down to them in solution in irrigation water of streams polluted by solid smelter wastes. (4) To ascertain whether the compounds named may exercise a stimulating effect on plants grown in soil as a medium and, if so, whether the effect noted is ephemeral or permanent in one way or another. (5) To ascertain whether potassium aluminum sulfate can have any value as a source of potash or as a plant stimulant.

METHODS OF THE EXPERIMENTS

The experiments were carried out in the greenhouse, the successive crops being grown at different seasons of the year so as to allow a study of the effects of a variety of climatic conditions. The plants were not artificially shaded during the period of growth. The soil used in most of the experiments was a clay adobe containing a very good supply of organic matter to start with, and was made up by adding barnyard manure to our hillside clay adobe soil. The other soils employed in a number of the experiments which served as checks on the heavier soils were a blow sand from Oakley, California, and the clay adobe soil above named unmixed with manure. Evidence is thus obtained of the effects on barley of at least one of the salts mentioned, in four types of soils, since a humus sand was, as explained above, employed in the preliminary experiments. The chemical analysis by the Hilgard strong acid digestion method of the humus clay adobe, of the blow sand, and of the clay adobe yielded the results shown in table 1 (p. 498).

The containers for the soils just described were ordinary earthenware pots nine inches in diameter at the top. These pots were paraffined to preclude the possibility of the absorption of salts by the porous walls. From ten to twelve pounds of soil were used per pot, depending upon the kind of soil employed. The salts were applied in solution in all cases except in that of the lead sulfate, which, owing to its insolubility, was mixed, in the form of powder, with the soil. The mixing was done as

TABLE I

CHEMICAL ANALYSES OF SOILS USED

	Greenhouse humus clay adobe	Clay adobe	Oakley sand
Insoluble residue	74.03	85.50	92.04
Soluble silica	9.18	7.40	3.14
Lime (CaO)	2.26	1.05	.66
Iron Oxide ($FeSO_3$)	4.59	3.61	3.60
Aluminum oxide (Al_2O_3)	5.80	3.85	1.24
Sulfuric acid (SO_3)	.....	.....	.....
Manganese sesqui-oxide (Mn_3O_4)	.13	.13	Trace
Magnesium oxide (MgO)	.72	.54	.22
Potash (K_2O)	.62	.25	.30
Soda (Na_2O)	.43	.21	.17
Phosphoric acid (P_2O_5)	.48	.20	.16
Moisture and volatile matter	11.68	4.70	1.72
Total	100.78	100.44	100.32
Nitrogen	.31	.12	.03
Humus	3.20	1.85	.30
Nitrogen in humus	6.75	8.00	11.80

thoroughly as possible to approach closely a uniform distribution of the salt. Obviously such thorough mixing as could be desired was not attained with the $PbSO_4$; hence one reason for the irregularity of some of the results obtained therewith. In the case of the copper, lead, manganese and zinc sulfates the treatments were made as parts per million of the dry weight of the soil, whereas the ferrous sulfate was supplied in much larger quantities on the percentage basis. The precise quantities of the salts employed are shown in the tables submitted below, but it is added here, in explanation, that the treatments as indicated there represent aggregate amounts in the case of the copper, zinc, iron, and potash alum series of two separate applications, *one prior to planting the first and the other prior to planting the second crop* of barley in the humus clay adobe soil. It will further be noted that all the salts were added in the form of sulfates of the metals studied, except as otherwise stated.

Water was applied to the surface of the soil in irrigating. As a rule, that operation was carried out twice a week, or as needed, and 400 c.c. of tap water was the amount used at every irrigation. From earlier tests it appeared that this quantity of irrigation water and the mode of its application were most desirable under the circumstances and were such as to preclude losses of water and salts by percolation and drainage.

Barley (*Hordeum vulgare*) was the crop grown throughout all series of experiments. The variety employed was a selected and vigorous strain of Beldi. Three crops were grown in succession on the humus clay adobe soil, the first and third crops being produced in the period between September and January of the years 1912–1913 and 1913–1914 respectively, and the second crop between March and June, 1913. Only two crops were grown on the non-humus clay adobe soil, in periods corresponding to the last two for the humus clay adobe soil. One crop only was grown on the blow-sand soil.

At the time of harvest, which was carried out when the grain was thoroughly mature, the plants were cut as close as possible to the ground. The total crop thus obtained was placed in paper bags and dried until the weight was constant. Then the weights, separately, of grain and straw were determined. At the same time the soil in the pots was thoroughly worked over to obtain the roots produced in every case. In some instances nitrification studies on the soil were made, and also determinations of the amounts of salts remaining behind in the soils after harvest, and the amounts taken up by the crop. Enough of these analyses, as well as of nitrogen determinations in the grain, were accomplished to ascertain the tendency of these conditions in the plants and soils studied.

RESULTS OF THE EXPERIMENTS

It will undoubtedly be of interest to our readers to learn first, from the results of our experiments, something of the appearance, height, tillering, color, and similar observations on the growth of the barley, and later the yields obtained, composition of the grain, and changes in the soil. The following general statements may therefore be made at this point with respect to the first class of data obtained through the experiments. The different features will be considered separately.

Color of Leaves

In the first crop on the greenhouse soil the color of the blade was a much deeper green in the treated pots, no matter what salt was used, than in the untreated ones. This was true despite the fact that the leaves were dark green in the plants of the control pots, which had a plentiful supply of available nitrogen at their disposal. The plants of the pots treated with copper sulfate showed, however, a darker green color than those in the pots treated with other salts. That excessive nitrogen feeding was probably the cause of the very deep green color of the leaves referred to was further indicated by the tendency to lodge manifested by the plants in the copper and lead series and to some extent in the other series. In the second crop, prior to the planting of which the salt content of all series in the greenhouse soil, except the lead and the manganese, was doubled, manifestations as to color similar to those above described were observed. These were not so marked, however, even though the contrast between the plants on the treated and those on the untreated soils was easily discernible. As a result of the smaller amount of stimulation in the crop under consideration, no tendency to lodging was noted, and the plants were erect and rigid. In the third crop on the same soil without further salt treatment, there was only a slightly deeper green color in the leaves of plants on the treated than in those on the untreated soil. Again, the plants were erect and vigorous in appearance throughout.

On the Oakley blow-sand soil, in which only copper was tested, was discerned a similarly striking effect on the color of the barley blade exercised by the salt treatment of the soil. In the clay adobe soil similar observations were made. We are therefore led to believe that the effect of the salts in question seems to be general in at least one direction for all soils, namely, for the production of a deeper green color in the leaves of plants growing on the treated soil. The stimulating effect in that direction shows a tendency to diminish at first rapidly, then slowly, in the succeeding crops. The probable causes of this manifestation, as briefly referred to above, will be mentioned later in connection with the studies of the treated soils themselves. As further evidence of the general nature of the effects of the salts in question in soils on the color of the leaves of plants, we may cite again the observations on that point made by both Pammel [2] and Van Slyke.[3] Those investigators reported marked deepening of the color of the leaves of tomatoes and other plants due to treatment of the culture soil with $CuSO_4$. Other kinds of plants, therefore, as well as other soil types than those employed by us seem to be similarly influenced by $CuSO_4$ with reference to color production in leaves.

Tillering

During the first two crops grown, the amount of tillering occurring in the plants on the greenhouse soil was studied. This was done with the idea of noting if any close correlation existed between the amount of growth and dry matter produced by the treatment and the number of tillers formed. Our observations give a negative reply to this query. Thus in the first crop of the copper series the number of tillers per pot of four plants varied from thirteen to thirty-one over the whole range of concentrations of copper sulfate employed. This in itself would of course be of little significance in connection with the question under consideration if there was a decrease or an increase in the number of tillers with a change in concentration of $CuSO_4$. This was not strictly the case, however, and to illustrate we may say that the largest number of tillers in the first crop of the $CuSO_4$ series was in one of the pots receiving 1500 p. p. m. $CuSO_4$; the smallest number of tillers was produced in the pots remaining untreated. Moreover, there was but little agreement in that respect between duplicate pots receiving $CuSO_4$. Thus the duplicate of the pot above mentioned as producing the largest number of tillers (thirty-one) produced only twenty-one, and such large discrepancies between duplicate pots were common. The fact remains, nevertheless, that while small concentrations and large concentrations of $CuSO_4$ do not differ in their effects on the number of tillers, some $CuSO_4$ as against no $CuSO_4$ appears to be of definite effect in the first crop. Thus in the large

[2] Iowa Agr. Exp. Sta. Bull. no. 16, 1892.
[3] N. Y. (Geneva) Agr. Exp. Sta. Bull. no. 41, 1892.

range of concentrations employed in the copper series, there was no pot receiving $CuSO_4$ in any quantity which did not produce more tillers than any of the control pots, which showed from thirteen to fourteen tillers in each of three pots employed as untreated controls. In general, therefore, it seems that in the first crop, copper sulfate does stimulate tillering, but it does so irregularly and small amounts of the salt appear to be as effective in that direction as large amounts. In the second crop of the $CuSO_4$ series the number of tillers was decreased throughout because of climate and other obvious effects accompanying the conditions of the experiment which are above described. Nevertheless, the treated pots were, with very few exceptions, decidedly superior in tiller production to the untreated pots, which, again, agreed well among themselves. Otherwise, the tillering of the second crop in the $CuSO_4$ series was not significantly different from that of the first crop.

In the first crop of the zinc sulfate series the number of tillers was very markedly larger than in the first crop of the copper sulfate series. Thus the largest number of tillers produced in the first crop of the copper series is about equivalent to the smallest number of tillers in the first crop of the zinc sulfate series. In one pot of the zinc series sixty-five tillers were produced by four plants, a number more than twice as great as the maximum in the first crop of the copper series. Moreover, the agreement between duplicate pots was on the whole much better in this regard in the zinc than in the copper series, despite the fact that several large discrepancies were noted. In the first crop, therefore, the zinc sulfate, like copper sulfate, has not only stimulated tiller production, but has done so to a much more marked degree than the last-named substance. In the second crop, however, conditions and results are considerably changed. Thus, whereas the stimulating effects of $CuSO_4$ on tiller production are clearly manifest throughout the series, even after the salt concentration is doubled in the same soil, only one case of stimulation in that respect (at the lowest concentration) is noted in the $ZnSO_4$ series under similar conditions. Moreover, in the $CuSO_4$ series we find scarcely one undoubted case of depression in tillering even in the second crop, due to the treatment of the soil, but such depression obtains almost without exception in the second crop of the $ZnSO_4$ series. In other words, a very marked decrease in the number of tillers results from the second $ZnSO_4$ application to the greenhouse soil, both absolutely and relatively speaking, in comparison with either the untreated control pots or with the treated pots of the copper series. Much better agreement between duplicate pots with reference to tillering is noted in the second crop of the $ZnSO_4$ series than in the other series above described.

In the case of the potash alum series, in the first crop the results were very similar to those obtained in the corresponding copper series except that tillering was not so markedly stimulated as in the latter. In the second crop, also, the results of the potash alum series were not strikingly different as regards tillering from those in the copper series.

In the first crop of the $FeSO_4$ and $PbSO_4$ series no observations were made on tillering owing to the poor development of plants and their prostrate mode of growth, which was especially marked in the lead series. Observations on the amount of tillering produced in the second crop of the $FeSO_4$ series indicated that the stimulating effect of the $FeSO_4$ on tillering was not so great as that of either copper or potash alum, but greater than that of zinc.

In the third crops of all series scarcely any tillering was observed, the plants producing for the most part single upright stalks. It appears, therefore, that the stimulating effects of the salts tested with respect to tillering are ephemeral in their nature, but are more distinctly so with some salts than with others.

Height of Plants

In the second crop only, observations and measurements were made of the average and total heights of plants produced in the $CuSO_4$, $ZnSO_4$, $FeSO_4$, and potash alum series. These indicated definite increases in height of plants produced by certain concentrations of all the salts named, over those attained by the plants in the untreated pots. The superior height of the plants was, however, variously distributed through the series. Thus it was apparent in the first five lowest concentrations of the $CuSO_4$ series. It did not show in the first two concentrations of $ZnSO_4$, but in all others, and was clearly manifest almost throughout the potash alum series. In the $FeSO_4$ series the heights followed the general observations just recorded for the $ZnSO_4$ series so far as comparison with controls is concerned. As regards absolute heights of plants the $ZnSO_4$ series showed the highest, and the potash alum series was a close second, with the others considerably behind.

It appears, therefore, that with regard to stimulation both of tillering and of tallness, $ZnSO_4$ is superior to the other salts. The agreement between duplicate pots in respect to the height of plants was far more satisfactory than that for tillering. None of the actual data are given here because of the necessity for brevity in such papers and because of the decidedly minor significance of the results in connection with the main issue under examination.

Germination of Seeds

In all of the series under discussion, the germination of seeds was more rapid in the salt-treated soils than in those untreated, at least up to certain very considerable concentrations of the salts. Exceptions to this rule were of course found in certain concentrations of the salts which entirely inhibited growth and in those which almost did so; but in all pots in which the salt concentrations were not of that order, germination was much more rapid than in those which remained untreated. The stimulation in respect to germination was about of the same degree in all concentrations of every salt which would at all stimulate germination, larger amounts of salts not differing from the smaller ones. Certain definite differences, however, existed in that regard among the different salts. Thus $CuSO_4$ stimulated germination most, $ZnSO_4$ was second in order, $FeSO_4$ third, and the other salts exerted only a slight influence. Our findings in this respect, therefore, are again in accord with those of Pammel [4] and Van Slyke,[5] which are above cited, and also with

[4] Iowa Agr. Exp. Sta. Bull. no. 16, 1892.

[5] N. Y. (Geneva) Agr. Exp. Sta. Bull. no. 41, 1892.

those of many other investigators, among whom may be mentioned Effront.[6] It may be added here that the stimulating effects of the salts studied with respect to germination of seed were noted in the first and second crops. In the third crop there was little, if any, superiority in germination of the seeds in the treated as against the untreated pots. In other words, we have noted that in regard to germination, as well as in respect to tillering and other superficial characters, the salts employed stimulated the barley for one or two seasons at certain concentrations and after that showed no marked effect in either direction. It should also be observed that in cases in which such salts as $CuSO_4$ at higher concentrations retarded germination in the first crop, the retarding effect disappeared in the second and third crops.

YIELDS OBTAINED

In studying the yields of barley in all the series, the weights of straw, of grain, and of roots were determined in every case after drying at 100° C and bringing to constant weight. All such determinations are given in the tables which follow, together with other necessary data. It will be noted that the yields of the single pots in every duplicate pair are given, as well as the averages. This is for the purpose of pointing out the large variations in yield frequently obtained in duplicate pots of soil cultures and for that of allowing our colleagues to study our data at first hand and reach their own conclusions. The different salts will be considered separately below, with one type of soil at a time.

Copper Sulfate—Greenhouse Soil

Tables II*a*, II*b*, and II*c* give the results obtained with $CuSO_4$ in three successive crops on the greenhouse soil. Through an error, as was stated above, a second application of $CuSO_4$ equivalent to the first was made to the soil prior to planting the second crop, so that for the second and third crops, amounts of $CuSO_4$ were present in the soil which were far larger than those intended for the study. While, therefore, we have obtained

[6] Effront, J., Comptes Rendus Acad. Sci. (Paris), vol. 141, p. 625, 1905.

three successive crops on the same soil, only one of them, the third, was influenced purely by the residual effects of the $CuSO_4$ application remaining after the production of one crop. With these observations in mind, let us now consider the results of the $CuSO_4$ applications in the three crops harvested on the greenhouse soil.

First Crop

The growth of the plants in the first crop was very rank in the controls as well as in the treated pots, with the result that high yields of dry matter were obtained. This was doubtless due to a large supply of available plant food in the fresh greenhouse soil and especially to the high nitrate content and high nitrifying power of the soil. The deep green color of the leaves, above referred to and the tendency shown by the plants to lodge seem to confirm this view, and it is further supported by nitrification studies which we carried out and which are reported below. Because of the conditions for rank growth, however, the growing season was lengthened and scarcely any grain was produced. The data of the first section of table II therefore give only the yields of straw and roots. Despite considerable discrepancy among the yields of duplicate pots, there can be no question after an examination of the data for the first crop that $CuSO_4$, in the concentrations and under the conditions employed, has caused the barley to produce more dry matter than was produced in the control pots. Such stimulated growth is apparent throughout the whole series of copper concentrations varying from 50 p. p. m. to 1500 p. p. m. Concentrations above 1000 p. p. m. seem to be definitely more toxic, or at least less stimulating, to the barley plants than lower concentrations if average yields are adopted as criteria. Such procedure may, however, be unjustifiable because of the large discrepancies among the yields of duplicate pots. That the increases in yields of dry matter of barley are real and not accidental is evidenced not only by their manifestation in the whole series, but also by the magnitude of the increases involved. Thus in the concentration of 600 p. p. m. $CuSO_4$ an increase in yield over that of the control pot was obtained which was equivalent to nearly 50 per cent of the total yield of the latter, and in several other cases such increases amounted to 30 per cent or 35 per cent.

Giving brief consideration now to the yields of roots alone, we find that they, too, like the total dry matter in general, are definitely affected by the $CuSO_4$ treatment. Increased root production over that in the control pots is found in all the pots having concentrations from 50 p. p. m. to 600 p. p. m. $CuSO_4$, inclusive. Beyond that point, however, unlike the case of the total dry matter considered, the increased concentrations of $CuSO_4$ appear to depress root development very definitely. The decreases continue steadily more significant as the concentration of $CuSO_4$ increases from 600 p. p. m. to 1100 p. p. m., when the toxic effect seems to reach a stationary point and no further decreases occur, even though more $CuSO_4$ is added up to concentrations of 1500 p. p. m.

Taking into consideration the effects of $CuSO_4$ on the first crop of barley in the greenhouse soil in regard to both tops and roots produced, it appears that we must consider the point of stimulation to cease at 600 p. p. m. $CuSO_4$. It is possible in addition that even the 700 and 800 p. p. m. concentrations may be looked upon as still stimulating to both tops and roots of the barley plant in the soil in question. Beyond those points, however, $CuSO_4$ is stimulating, in the first crop, to the production of tops only, not to the production of roots.

Second Crop

The very large decrease in yield of the second crop in the same pots, so far as total dry matter is concerned, is clearly indicated in table II*b*. This is evidently not due to the doubling of the percentage of $CuSO_4$ in pots receiving treatment, since the decrease in the second as compared with the first crop is just as clearly marked in the control pots. On the other hand, whereas the first crop produced practically no grain, probably for reasons above discussed, the second crop produced a large yield of grain, amounting not infrequently to 25 per cent or considerably more of the total dry matter. Again, we see in the figures for the second crop the disparity between yields of duplicates, but again also the consistently large yields of dry matter in the treated as against those of the untreated pots. This is strikingly so for both the straw and the grain yield, but is most consistently and undeniably apparent in the latter. The root yields in most of the treated pots are also superior to those obtained in the untreated pots, and duplicate cultures show better agreement in that respect than do the straw and the grain yields. The grain produced was in all cases well filled and normal in appearance. In brief, we find that the second crop on the soil treated with $CuSO_4$, despite the doubling of the $CuSO_4$ application, shows as markedly, and perhaps even more markedly, the stimulating effect of the salt under consideration to barley grown on greenhouse soil. While in detail the results of the second crop differ from those of the first crop, they appear to confirm the latter in general. The average yields of dry matter are greater with all treatments than they are in the untreated pots. This strikingly stimulating effect of $CuSO_4$ on barley under the conditions named in concentrations reaching a maximum of 0.3 per cent $CuSO_4$, based on the dry weight of the soil, is as astounding as it is interesting, and it would appear to lend little support to the idea of the toxicity of $CuSO_4$ in relatively small amounts to crops grown on field soils. This phase of the subject will, however, receive more attention below.

Third Crop

Grown under more propitious weather conditions, as explained above, the third crop in the $CuSO_4$ series on the greenhouse soil yielded throughout much larger amounts of dry matter than the second crop, though not such large amounts as the first crop. Again, we note the general stimulating effect of $CuSO_4$ to the production of dry matter in barley plants. This time, it should be observed, the stimulating effect was not manifest throughout the treated portion of the series, as it was in the first two crops. Thus four of the $CuSO_4$ concentrations employed, namely, 600 p. p. m., 1600 p. p. m., 2400 p. p. m., and 2600 p. p. m., depressed the yield of barley if average yields of duplicate pots are considered. In most cases, however, such depression of yield is easily within the experimental error and therefore may be without significance. This is especially so since there is no regularity in the inhibiting power of $CuSO_4$ referred to; but small as well as large concentrations at isolated points in the series depressed the yields as above pointed out, whereas the rest of the concentrations, also small and large, stimulated the yields.

While the total dry matter produced in the third crop, as shown above, is greater than that yielded in the second crop, the yield of grain in the latter is far superior to that in the third crop. Thus the highest grain yield in the third crop is scarcely more than one-third that of the second crop, and the lowest yield of the third crop is about one-sixth that of the second crop. Nevertheless these facts are of no significance in connection with the effects of $CuSO_4$, since the control pots manifest the same depression in grain yields which is characteristic of the treated pots in the third crop. Likewise, in most cases the treated pots produced more grain than the untreated pots.

The point of maximum stimulation of $CuSO_4$ to the production of dry matter by the barley plant on the greenhouse soil is very difficult to discern. While apparently it occurs at the concentration of from 0.18 per cent to 0.2 per cent $CuSO_4$ of the dry weight of the soil, the irregularity and non-agreement of many of the duplicate pots render decisions in such matters unsafe, if not valueless. In general, however, the figures in table II*c* leave little room to doubt the non-injurious nature and perhaps the stimulating effect of $CuSO_4$, at considerable concentrations, for barley in the greenhouse soil under the conditions described.

Copper Sulfate—Adobe Soil

Tables III*a* and *b* give the results obtained with $CuSO_4$ treatment in the case of the adobe soil in the first and second crops respectively. It will be noted at the outset that the yields on the adobe soil are much lighter than those on the greenhouse soil. The reasons for this circumstance are of course not far to seek, in the light of the origin and descriptions of the soils used in these experiments which are given above. Only two crops were grown on the adobe soil, because we did not decide to start it for comparison with the greenhouse soil until one crop had been obtained with the latter.

First Crop

We find in the case of the adobe soil the same unfortunate disparity among the yields of duplicate pots which was noted with the greenhouse soil. This disparity is of course the more noticeable when much smaller absolute amounts are involved, as in the present case. Despite all that, however, there appears to be justification for the conclusion, based on the data in table III*a*, that $CuSO_4$ does exercise a stimulating action on the growth of barley in adobe soil. Such stimulation is not apparent throughout the whole series, as it is in the case of the greenhouse soil, but it appears to exist in all concentrations of $CuSO_4$ employed up to 900 p. p. m. Concentrations in excess of the latter seem to depress, definitely, the yield on the adobe soil. But whether or not we admit the existence of a stimulating effect by $CuSO_4$ on the barley, based on the figures here studied, it can scarcely be denied that $CuSO_4$ is not toxic to barley in the first crop grown on adobe soil until nearly 0.1 per cent $CuSO_4$ is present in the soil. Amounts of $CuSO_4$ slightly less than 0.1 per cent stimulate the growth of the barley significantly. At concentrations of 0.15 per cent and 0.2 per cent $CuSO_4$ no growth is obtained at all, showing of course marked toxicity.

Some interesting facts are brought to light in table III*a* with respect to the relationships among straw, grain, and root yields which obtain between treated and untreated soils and among themselves in the case of the different concentrations of the latter. In the first place, it will be noted that the grain yields form an even larger percentage of the total dry matter of the first crop on the adobe soil than they do in the second crop on the greenhouse soil. In some cases, indeed, the average yield of grain in duplicate pots exceeded the average yield of straw. In nearly half the treatments, the grain yields were larger than those of the control pots so that the stimulating effect of the $CuSO_4$ application, if allowed, applies to the grain yields as well as to those of total dry matter. The root yields are proportionately smaller on the adobe than on the greenhouse soil, as are the yields of the barley as to tops. Nevertheless, the average yields of roots also show the stimulating effects of $CuSO_4$, since they are greater in all concentrations than those of the control pots until a concentration of 1000 p. p. m. $CuSO_4$, or 0.1 per cent based on the dry weight of the soil, is reached. In excess of that concentration, $CuSO_4$ is toxic to roots and appears to inhibit their development.

Second Crop

Much better agreement among the yields of straw in duplicate pots of the second crop on the adobe soil was obtained than in any of the series with $CuSO_4$ above described. In fact, the agreement between the duplicates in nearly all cases was as good as could possibly be hoped for when one allows for the ever-present idiosyncrasies of plant protoplasm. Up to and including concentrations of 400 p. p. m., $CuSO_4$ seemed to depress barley growth except in one concentration, namely, at 300 p. p. m. Such depression is probably not significant, except at the concentration of 100 p. p. m. However that may be, $CuSO_4$ did not stimulate the development of barley at the lower concentrations in the second crop on the adobe soil as it did, with one exception, in the first crop. On the contrary, conditions reversed themselves in the second crop, and the most marked and consistent stimulation occurred in the higher concentrations of $CuSO_4$, only the very highest concentration—namely, 2000 p. p. m.—showing a more or less definitely toxic effect. Thus, while no growth was obtained in the first crop on the adobe soil containing 1500 p. p. m. of $CuSO_4$, the same soil on the second planting stimulated the growth of barley so that in both pots, taken separately and by averages, the yield was superior to that of the control pots. Irregularities of course crept into this series as into the others, for instance, depressed growth or no stimulation at a concentration of 1200 p. p. m., when stimulated growth is obtained at 100 p. p. m. $CuSO_4$ on the one hand and at 1500 p. p. m. on the other, is a circumstance which is very difficult of explanation.

Again, unlike the first crop on the adobe soil, the second crop yielded no grain. This of course cannot be attributed in any way to the effects of $CuSO_4$, since the control pots behaved in the respect noted like the treated ones. Presumably, unfavorable climatic conditions and the heavy nature of the soil may have produced and influenced the result obtained. The root yields, however, were very considerably larger in the second than in the first crop, and fairly good agreement between duplicate determinations was obtained. Considering the small total yield of dry matter in roots, it is perhaps a very significant stimulation to their development which $CuSO_4$ exerts.

Regarded then from the standpoint of the total dry matter produced, there appears to be no question from the data in table III*b* that $CuSO_4$ can stimulate growth in the barley plant on a clay adobe soil even when present at very considerable concentrations. If only the dry matter of the above-ground parts is considered, three exceptions to this rule in the whole series can be found. In a general way, the results with $CuSO_4$ on the adobe soil confirm those obtained on the greenhouse soil using the same salt. It may be repeated with advantage here that even if such stimulating properties of $CuSO_4$, which in our opinion we have shown above to exist, are not allowed, our data do not offer any support to the idea that in the ordinary quantities in which copper may be introduced in agricultural soils it is even likely to be toxic to grain plants.

Copper Sulfate—Oakley Soil

Only one crop of barley was grown on the Oakley soil in the tests with $CuSO_4$. Since closing the experiment we have regretted the fact that the Oakley soil was not cropped successively for two or three seasons after treatment, but at the time of the experiment this was not deemed necessary. Table IV gives the results obtained with the one crop in question. The figures really do not tell the whole story, since the appearance of the barley plants was far superior on the treated soils on which they developed at all than it was on the untreated soil. Nevertheless, the figures are striking enough to be used alone as a criterion to determine the effects of $CuSO_4$ on the growth of barley in the Oakley sand. Our data show very clearly the stimulating effect of $CuSO_4$ for barley in the first crop on the Oakley sand. They also show, more clearly than any series above described, the toxic effect exercised by $CuSO_4$ at the higher concentrations. The stimulating effects further do not occur at such high concentrations of $CuSO_4$ in the case of the Oakley sand as in that of the greenhouse soil or even in that of the adobe soil. To be specific, we find that at concentrations of 100, 200, and 300 p. p. m., $CuSO_4$ is definitely stimulating to barley production on the Oakley soil under the conditions of our experiment. The most marked results of the stimulation in question are not manifest in the production of straw or even in that of roots when it is at all perceptible, but is very marked in nearly all cases so far as grain production is concerned. It is a curious fact that at a concentration of 600 p. p. m. $CuSO_4$ in the Oakley soil, we obtain the largest grain production of the whole series, and yet the straw production is depressed through the $CuSO_4$ treatment at that concentration and the root development almost entirely inhibited. This fact is very difficult to explain, but exhibits parallelism to similar facts observed by both Pammel and Van Slyke in the experiments above cited. When the dry matter produced is considered as a whole, and straw, grain, and roots are considered together, stimulation is noted only in the case of the first two concentrations of $CuSO_4$ employed, and the stimulation is not very marked. In other words, one is obliged to state definitely the criterion employed when forming a judgment as to the existence or non-existence of a stimulating effect of $CuSO_4$ on barley grown on the Oakley sand. It will be necessary in the future, for a more decided judgment of the question in hand, to grow several successive crops of barley on the soil named, once treated with $CuSO_4$, as shown in the table, and possibly also to supply available nitrogen, which is a serious limiting factor in the growth of barley on that soil. Without making any final statements in the premises, however, the data given by us in table IV seem to point strongly to the existence of a stimulating action of $CuSO_4$ to barley growth, even on the Oakley sand.

Zinc Sulfate—Greenhouse Soil

Only the greenhouse soil was employed to test the effect of $ZnSO_4$ on barley plants. As was the case with $CuSO_4$ on the same soil, three successive crops were grown, two treatments of $ZnSO_4$ being given. The results obtained, together with the treatments given, are indicated in tables V*a*, V*b*, and V*c*.

First Crop

A study of table V*a* reveals the fact that $ZnSO_4$ in the case of the first crop of barley is not unlike $CuSO_4$ in its action. In other words, while the latter salt exercises a greater and more definite stimulating action in the first crop, $ZnSO_4$ also manifests a definite though smaller stimulating effect on the barley plants. This seems to be supported by the fact that only eight pots out of thirty treated with varying amounts of $ZnSO_4$ give a smaller yield than the highest yield of the control pots. In general, the stimulation seems to be greatest at concentrations of $ZnSO_4$ varying from 500 p. p. m. to 1200 p. p. m. inclusive. This statement has reference only to the total yield of dry matter and not to any parts, like roots or tops, taken separately. On the same bases, also, no definitely toxic effect of $ZnSO_4$ was observed, though, as above intimated, some apparent effects of that nature were noted. Again, in accord with the results obtained with $CuSO_4$ no grain worth weighing was produced in the first crop, and the weights of the straw given in the table therefore include such partially formed heads as were developed. In still further agreement with the results of the first crop of the $CuSO_4$ series, $ZnSO_4$ stimulated the growth and development of roots practically throughout the whole series. The stimulation to root development alone was, however, greater in the $ZnSO_4$ series than in the $CuSO_4$ series, just as the opposite was true for the tops. The greatest stimulation to root development appears to have been attained at the higher rather than at the lower concentrations of $ZnSO_4$, the difference being most marked in that respect between the first three concentrations employed and the rest. This circumstance, as will be seen by a comparison of table V*a* with table II*a*, is the reverse of that noted in the first crop of the $CuSO_4$ series, in which the first four concentrations gave the largest increases of dry matter of roots over the controls. All in all, the effect of $ZnSO_4$ in the case of the first crop on the greenhouse soil must be regarded as one definitely stimulating to the production of dry matter in the barley plant.

Second Crop

While in the first crop the $CuSO_4$ and $ZnSO_4$ series are in general similar so far as the effects of the salts on the barley plants are concerned, they differ markedly in the second crop. To illustrate, it may first be noted in table V*b* herewith, on the basis of the total dry matter produced, that $ZnSO_4$ beyond concentrations of 600 p. p. m. is distinctly toxic to barley in the greenhouse soil. With similar concentrations of $CuSO_4$ in the second crop, the latter salt was not only not toxic beyond 600 p. p. m., but was actually more stimulating at most of the higher than at the lower concentrations. It would therefore seem that so far as the yields of the total dry matter are concerned, $ZnSO_4$ is either more toxic than $CuSO_4$ or the latter is more readily adsorbed by the greenhouse soil and thus removed from the active solution which bathes the feeding roots. It must, nevertheless, be added that while $ZnSO_4$ appears to be definitely more toxic to barley than $CuSO_4$ in the greenhouse soil, it cannot be considered very toxic since 0.06 per cent $ZnSO_4$ of the dry weight of the soil is not only not toxic, but actually stimulating. We may now consider for a moment the different components of the total dry matter produced in the second crop of the $ZnSO_4$ series. So far as the straw alone is concerned, only a concentration of 200 p. p. m. $ZnSO_4$ gave stimulating effects. That concentration produced a very marked stimulation, and good agreement is evident in the duplicate pots. Concentrations in excess of 200 p. p. m. depress straw production. Such depression, however, is in some instances not very great, and considerable disagreement between duplicates here, as in the copper series, renders it difficult to pass final judgment in the matter. In general, there is little difference in the depressing effects on straw production of concentrations of $ZnSO_4$ varying between 600 p. p. m. and 3000 p. p. m. Beyond 3000 p. p. m. a more definite depressing effect on the production of straw in the second crop becomes apparent. The fact that the wide range of concentrations just referred to is productive of similar effects seems to indicate that most of $ZnSO_4$ is adsorbed by the soil and but little of it is free to affect the plant in the soil solution.

With the exception of one or two doubtful cases, grain production is somewhat depressed throughout the second crop of the $ZnSO_4$ series. This appears to be even more true for the first concentration of $ZnSO_4$, which stimulates straw production, than for the higher concentrations, which depress straw production. All of these judgments, however, are based on averages of duplicate pots which do not agree very well, and hence considerable caution is employed in stating them. Again, the effect of $ZnSO_4$ on grain production seems to be about the same whether small or large quantities of the salt are employed.

So far as root production is concerned, however, the data of the second crop in the $ZnSO_4$ series are very different from those bearing on the yields of grain and straw. With three exceptions, two of them at the highest concentrations of $ZnSO_4$ employed, the latter induced the production in all pots of more roots than were produced in the control pots. While in many cases the stimulation in the direction noted was not great, it was definite, and in many other cases it was very considerable. Moreover, there was good agreement between the duplicate determinations. The greatest stimulation to root production occurred between 200 and 2600 p. p. m. $ZnSO_4$. While, therefore, the second crop of the $ZnSO_4$ series differed from that of the $CuSO_4$ series with respect to grain production, there was great similarity in action between the two as regards root yields.

Third Crop

In the third crop of the $ZnSO_4$ series, the toxicity of $ZnSO_4$ appears to have become augmented even over that of the second crop. There seems to be no case of stimulation even in the lowest concentration (200 p. p. m.). This applies to straw, grain, and roots equally well. On the other hand, the toxicity of $ZnSO_4$ for root and grain production by barley in the third crop is certainly not very marked, although uniform. For straw production, $ZnSO_4$ becomes suddenly very much more toxic than at the lower concentrations when more than 2400 p. p. m. is employed in the culture medium here used. At 200 p. p. m. neither the straw and grain on the one hand, nor the roots on the other, are seriously affected in one direction or another by the $ZnSO_4$ in the third crop. Beyond these remarks no discussion of table V*c* is necessary. The figures given in that table speak plainly enough for themselves. In contrast with the $CuSO_4$ series of the third crop, however, table V*c* shows $ZnSO_4$ to be again totally different in its effect on the barley plant in the greenhouse soil. Thus the $CuSO_4$ exercises a stimulating effect on total dry-matter production in the third crop at almost all concentrations, while $ZnSO_4$, far from doing so in any case, is actually toxic in all concentrations in the third crop on the same soil. This points clearly to sharp differences in the specific physiological effects of the copper and zinc ions, since they were the only apparent variables in question in this experiment.

Ferrous Sulfate—Greenhouse Soil

Owing to the rapidity with which ferrous salts are rendered insoluble in well-aerated soils, it was deemed advisable to depart from the procedure followed in the other series so far as quantity of $FeSO_4$ used is concerned. Applications of the salt were therefore made at intervals of 0.1 per cent between two succeeding cultures in the series, the lowest concentration used in the first crop being 0.1 per cent, and the highest 1 per cent. As in the other series above described on the greenhouse soil (the only one used in the $FeSO_4$ series), the amounts of salts were doubled prior to planting the second crop. The results of the yields are given in tables VI*a*, VI*b*, and VI*c*.

First Crop

Even though the amounts of $FeSO_4$ used were very large, we see clearly from table VI*a* that the salt stimulated, in the first crop, the production of dry matter in barley. Considering averages of duplicate pots, we find that there is no concentration of $FeSO_4$ which did not yield increased growth of barley. This constitutes the most striking set of stimulations noted in the series thus far discussed. Moreover, we find again an evident lack of relationship between the amount of $FeSO_4$ employed and the degree of stimulation induced thereby. In agreement with the results obtained in the $CuSO_4$ and $ZnSO_4$ series, the $FeSO_4$ series yielded no grain worthy the name in the first crop. Again in agreement with the results of the other series, considerable discrepancy was found in duplicate pots so far as yields are concerned. In the case of the root yields, we have also large discrepancies between duplicate pots. However this may be, the straw yields in the treated pots of the first crop surpass those of the untreated pots in almost all cases, even if the higher figure for straw yields of the control pots be employed as a criterion. This is not so for the yields of roots; and while average yields show definite stimulation by $FeSO_4$ for root production of barley plants on the greenhouse soil, single values from duplicate pots do not justify any conclusions of that nature. Despite all this, there is certainly no reliable evidence of definite toxic effects on the part of $FeSO_4$ to barley plants under the conditions of this experiment. In general, therefore, the results of the $FeSO_4$ series are not unlike those of the $CuSO_4$ series, and the $ZnSO_4$ series on the greenhouse soil so far, at least, as the first crop is concerned.

Second Crop

It will be remembered again that the amounts of $FeSO_4$ employed for the first crop were doubled before planting the second crop. On studying the yields of the latter, one is at once struck by the strong parallelism in effect exerted on the barley plants by $ZnSO_4$ and $FeSO_4$ in the second crop. Both stimulate total dry-matter production in the very low concentrations and yet the discrepancies between the actual amounts of salts used in the two cases are of course very large. Besides, both seem to stimulate root development and, very slightly, the production of straw, at certain concentrations. Again, there appears to be indirect evidence that most of the salt applied is not only rendered insoluble, as is probably the case with $FeSO_4$, but that much of the salt remaining is adsorbed by the soil and becomes inactive so far as the barley roots are concerned.

Third Crop

In table VI*c*, which sets forth the yields of dry matter obtained in the third crop of the $FeSO_4$ series, we find some data of unusual interest. Despite discrepancies in the weights of dry matter obtained in duplicate pots, there can be little question that the higher concentrations of $FeSO_4$, beginning with 1.4 per cent, definitely stimulate straw production, while the lower concentrations employed, less definitely but probably without doubt, depress it. Grain production, on the other hand, seems to have been stimulated in the third crop by all concentrations of $FeSO_4$ employed, and the yields are high enough and agree well enough in the duplicates to justify that conclusion. In the case of the roots, still another effect was probably induced by $FeSO_4$. No stimulation can be definitely noted, yet the toxic effect, if any, is small and apparent in very few instances. In the case of the total dry matter produced, marked stimulation seems to have been obtained at concentrations of $FeSO_4$ respectively of 1.4 per cent, 1.6 per cent, and 2 per cent. When compared with the third crop of the $CuSO_4$ and $ZnSO_4$ series, the third crop of the $FeSO_4$ series stands out sharply. It gives stimulation only at the higher concentrations, the $ZnSO_4$ gives no stimulation and almost positive toxicity throughout, and the $CuSO_4$ gives stimulation almost throughout the whole series in the third crop. While all three of the salts may be quite harmless and even stimulating in relatively small quantities, they manifest very definite and specific characters when employed in higher concentrations and when results are obtained on the same soil for more than one season.

Lead Sulfate—Greenhouse Soil

Entirely unlike the three salts thus far discussed, $PbSO_4$ exercises what appears to us to be a definitely toxic effect throughout the first crop. This observation must be considered separately for every crop. It should be noted that unlike the copper, zinc, and iron salts, $PbSO_4$ was applied once only prior to planting the first crop.

First Crop

Like $ZnSO_4$ and $FeSO_4$, the $PbSO_4$ was tested in the greenhouse soil only. The yields obtained in the $PbSO_4$ series are given in table VII*a*, VII*b*, and VII*c*. They will be discussed in conjunction with the comment already made with reference to the aspect of the plants in the $PbSO_4$ series. It will be noted there that the plants possessed little rigidity, were deep green in color, and in general assumed a sprawling or prostrate, instead of an erect, habit of growth. This was a result of some specific reaction of $PbSO_4$ and was exerted even though only small quantities of the salt could have existed in the soil solution, owing to the insolubility of the salt. It should also be observed in this series, as it has been in the others, that the quantity of $PbSO_4$ employed seemed to have little relation to its toxic effects on the yields of straw. The lack of grain production has already been explained in other discussions above and is connected not with any salt treatment, but with the condition of the greenhouse soil itself, of which more detailed discussion has been given.

Root production was particularly affected in a deleterious manner by $PbSO_4$ in the first crop. Roughly speaking, it was reduced in the $PbSO_4$ treated pots by more than 60 per cent of the yield obtained on the untreated or control pots. In other words, in this series, as in many others, root production and straw production run almost parallel. This is further evidenced by the uniformly depressing effect of $PbSO_4$ regardless of the quantity in which it was employed. We find therefore in $PbSO_4$ (and in Pb, because all the sulfates used have a common anion) a substance which in the first crop on the greenhouse soil exhibits characteristics totally different from those of copper, zinc, and iron under similar circumstances. Thus while the three salts last named show definite powers of stimulating barley growth in the first crop on the greenhouse soil, lead very markedly depresses the growth of that plant under the same conditions.

Second Crop

In the second crop quite different conditions obtain with respect to the effects of $PbSO_4$. While nearly all of the higher concentrations of the series are still toxic to barley, three of the lower concentrations, including 600 p. p. m., are distinctly stimulating to that plant. If it were not for injury to the plants by mice, the concentrations of 200 p. p. m. and 400 p. p. m. $PbSO_4$ would doubtless have shown as much stimulation as the others just mentioned. In other words, taking the total dry matter produced, it seems true beyond cavil that in the second crop on the greenhouse soil, $PbSO_4$ in very considerable concentrations acts as a stimulant to barley growth.

With reference to the separate fractions of the total dry matter produced in the second crop of the $PbSO_4$ series, we note some interesting facts. In the first place, no grain was produced in the second crop of the lead series. This is very difficult to explain, since the control pots and the treated ones behaved similarly in that regard. In view of our statements in the introductory portion of this paper, we can scarcely believe that the mere location of the plants of this series in a somewhat shaded part of the greenhouse can account for the discrepancy. The root yields were nearly all depressed by the action of $PbSO_4$ in the second crop. The exceptions to this rule were in isolated pots with no duplicates to confirm them. It would therefore seem that $PbSO_4$ is toxic to the root development of the barley plant even in the second crop, in spite of its stimulating effect on the straw yield at certain concentrations. Such effect of $PbSO_4$ is unlike that of any of the other salts, which, at least at a number of concentrations, stimulate root development, particularly so in the case of $CuSO_4$ and $ZnSO_4$.

Third Crop

A progressive improvement may be seen in the soil treated with $PbSO_4$ as crop follows crop. Just as the second crop gave very much better results than the first, so the third crop gave very much better results than the second. In the third crop the stimulation to the growth of barley exerted by $PbSO_4$ is, however, the most striking, since it obtains particularly at the higher concentrations of $PbSO_4$. As was the case with some of the other salts in other crops, $PbSO_4$ seems to be toxic in the third crop at the low concentrations at which it stimulated growth in the second crop. On the other hand, it stimulates growth as above stated in the third crop at some of the higher concentrations at which it was toxic in the second crop.

However, most of the stimulating influence of $PbSO_4$, and perhaps all of it, in the third crop affected the straw production and not the root yields. This is again at variance with the results obtained in many of the other series above described, in which the usual condition was a parallelism between the effects exerted by a salt on the different fractions of the total dry-matter yields. Thus very good straw yields were obtained in most of the pots of the series in the third crop and instances of increases over those of the control pots were numerous, but no definite evidence of such stimulation in the case of the roots could be noted. In the case of the grain, on the other hand, the higher concentrations of $PbSO_4$ seemed to be as definitely stimulating as they did in the case of the straw yields. This is in almost entire harmony with $FeSO_4$ in the third crop, but has little resemblance to the corresponding $CuSO_4$ and $ZnSO_4$ series.

Potash Alum—Greenhouse Soil

This salt was tested in these experiments because it had been proposed that if it was not detrimental to soils and crops, it could be employed as a source of potash for fertilizers. It could be cheaply obtained in all probability by treating granitic rock containing adequate percentages of potash, with H_2SO_4, which can be manufactured in large quantity by the important smelter plants through the oxidation of SO_2 fumes. In view of the foregoing, potash alum was applied, as indicated in tables VIII*a*, VIII*b*, and VIII*c*, which are given below, on the basis of a certain number of pounds per acre, beginning with 300 pounds K_2O per acre in the form of $KAl(SO_4)_2.12H_2O$ and going up to 2000 pounds K_2O per acre in the same form.

First Crop

Table VIII*a* shows clearly that the application of potash alum in the first crop was distinctly stimulating to the barley plant so far as the production of total dry matter is concerned. The degree of stimulation is not unlike that of $CuSO_4$, $ZnSO_4$, and $FeSO_4$ in the first crop and, again, seems to be about the same with the lower as with the higher concentrations. When we consider the root yields separately from the straw yields we find, however, that the former were not increased by the potash alum treatment, though they were scarcely depressed with any concentration of the salt.

Second Crop

With the concentration of potash alum doubled in the second crop, the marked evidences of its stimulating effect on barley growth are still manifestly present. The entire series of treated pots, when averages of total dry matter produced are taken as the criterion, gives results far superior to those of the control pots, even though there is variation among the latter and among the treated pots in duplicate cultures. So far as the production of the total dry matter of barley is concerned, there appears to be no evidence in the second crop and very little, if any, in the first, of any toxic properties of potash alum.

We may now consider briefly the separate parts of the total dry matter as affected by the potash alum. The yield of straw is without exception greater in the treated than in the untreated pots of the second crop of the potash alum series. That part of the total dry matter has therefore been very materially increased by the potash alum application. The grain yields in the absolute were of very great magnitude and amounted in many cases to as much by weight as the dry matter of the straw. In some cases they even excelled the latter. This is analogous to the condition of the second barley crop in the $CuSO_4$ series, which was the only one of the other series manifesting as high a grain production. Not only, however, were the grain yields large in the absolute, but they indicated clearly the stimulating effect of potash alum on their production, since all the treated pots yielded much more grain than the control pots.

In the second crop, on the other hand, as in the first, the larger amounts of potash alum were neither inferior nor superior to the smaller amounts in increased production of straw and grain, but were of about the same influence throughout. Consistent with the effect of potash alum on the straw and grain yields was that on the root yields. The latter were, throughout the whole series in the second crop, increased by the potash alum applications and, as in the cases of straw and grain, independently of the amounts of potash alum employed. We have, therefore, another phase of analogy between the potash alum and the $CuSO_4$ series in the second crop which seems only to make the resemblance stand out in greater relief. The production of every part of the plant in the second crop was stimulated by both potash alum and by $CuSO_4$, but not by the other sulfates employed.

Third Crop

Wholly at variance with the effects just noted are those observed in the third crop of the potash alum series. So far from stimulating the growth of barley in all respects, as it did in the first and second crops, and particularly in the latter, potash alum in any and all concentrations depresses the growth of barley when the yields of total dry matter are used as a basis of comparison. This is true also for the straw and root yields taken separately, with the possible exception of the straw yield with the lowest concentration of potash alum. In the case of the grain yields, however, no indubitable evidence of a depressing effect by the potash alum is at hand. It is indeed not impossible that definite though small effects of potash alum stimulating to grain production in the third crop might be allowed in some of the concentrations of the salt employed. The explanation of this striking change in the effects of potash alum in two successive crops is obviously not simple, though several possible explanations immediately suggest themselves. It is probable that the most favorable explanation would be over-stimulation of plant growth in the first two crops and the removal of most of the easily available bases in the soil, leaving an impoverished soil condition and perhaps a so-called "physiological acidity," which would of course react deleteriously on the development of the barley plant. Again, the washing out of the salt by irrigation may have caused physical conditions in the soil which are inimical to the proper air and water supply for both plants and the soil bacteria. The first conception is the one employed to a considerable extent by the "old-line soil chemist" to explain the depressing effects on soil fertility of the large and continued use of gypsum. The second is a condition demonstrated in this laboratory recently[7] to be of considerable importance. Further discussion will be accorded this subject in a general comparison given below of our results with those of others. In general it may be added that the results of the third crop in the potash alum series are more in keeping with those of the $ZnSO_4$ series than with those of any other series discussed.

Manganese Sulfate

After our work on the effects of the compounds mentioned on barley plants had been under way for one season, it was deemed advisable to inaugurate some new experiments, using manganese salts. The latter it will be remembered were represented by $MnSO_4$ in preliminary experiments by F. H. Wilson and the senior author, which are cited above. Owing to the fact that the preliminary experiments with manganese had shown the latter to be comparatively innocuous, and even stimulating at considerable concentrations, for barley and vetch, larger amounts of manganese than of copper and zinc were employed. Both $MnSO_4$ and $MnCl_2$ were tested. Each of these salts will be considered separately, and tables IX*a*, IX*b*, and IX*c*, which follow, give the plan and the results of the experiments with $MnSO_4$. In the case of both manganese salts, only one application was made, and that was prior to the first crop.

First Crop

It becomes at once clear from an examination of table IX*a* that we can find in the first crop no indubitable evidence of

[7] Univ. Calif. Publ. Agri. Sci., vol. 1, no. 10, p. 291.

toxicity for barley of $MnSO_4$ even when amounts of that salt equivalent to 0.6 per cent of the dry weight of the soil were used. On the other hand, the stimulating effect of $MnSO_4$ for barley in the first crop on the greenhouse soil appears to be clearly evident. This is particularly true for the first three concentrations, amounting respectively to 500, 1000, and 1500 p. p. m. At concentrations exceeding 1500 p. p. m. $MnSO_4$, the stimulation is only slight, and three concentrations—namely, 3500 p. p. m., 4000 p. p. m., and 5500 p. p. m. $MnSO_4$—possibly depress barley growth to some extent. The latter effect can scarcely be taken as indicating definite toxicity, however, since, as above pointed out, even the highest concentration employed (6000 p. p. m. $MnSO_4$) appeared to stimulate barley growth slightly, and the toxic evidences referred to are noted at concentrations which lie between slightly stimulating concentrations on both sides. At any rate, we have no evidence of the toxicity of $MnSO_4$ in the first crop until concentrations equivalent to 3500 p. p. m. of $MnSO_4$ are reached.

When the root and straw yields are considered separately in the first crop, some interesting observations may be made which are not possible when the dry matter is considered as a whole. For example, stimulation to root development in the first crop of the $MnSO_4$ series is apparent only in the first three concentrations above noted as giving the largest yields of dry matter. Moreover, the straw yields are also distinctly higher at those same concentrations. But whereas $MnSO_4$ gives evidence of toxicity to root development, either slightly or definitely, at all concentrations tried above 1500 p. p. m., it continues beyond that concentration to be slightly stimulating to straw production.

In comparison with the other salts above described, $MnSO_4$ is distinctly superior in the magnitude of its stimulating effects. The only other salt which manifests some resemblance to $MnSO_4$ in that respect is $CuSO_4$. Since the concentrations of these two salts here employed, however, are very different from each other in the two cases, no more detailed comparison would be wholly justified.

Second Crop

When the total dry matter of the second crop in the $MnSO_4$ series is considered (table IX*b*), we find that not only has the stimulation noted in the first crop disappeared, but that an actually definite toxicity has supplanted it. Moreover, such toxicity is as marked with the lowest as it is with the highest concentrations of $MnSO_4$, and it is even possible that the former definitely surpass the latter in that respect. Again, as in some preceding cases with other salts, the total dry-matter yields do not give a complete picture of the effects of $MnSO_4$ on barley growth. Thus if we consider the straw, grain, and root yields separately, we find data leading to conclusions slightly different from those above. For example, whereas both the grain and root production are definitely depressed at all concentrations of $MnSO_4$ in the second crop, this is not so for the straw yields. The latter are in many instances, including the cultures of the highest concentrations of $MnSO_4$, increased by the effects of the salt. Were it not for the lack of agreement in some of the duplicates, we might add more emphatically that straw yields are markedly stimulated by $MnSO_4$ in the second as in the first crop on the greenhouse soil. This seems particularly true at the higher concentrations of the latter salt, but is also apparent at some lower concentrations. Since, therefore, no grain was produced in the first crop, and since only three of the lowest concentrations of $MnSO_4$ in it gave stimulation to root development, it seems not unreasonable to consider that the results of the second crop in the $MnSO_4$ series are, in the large, not essentially different from those of the first crop. The outstanding result is the stimulation to straw production which is noted, and that is different in degree only, not in kind, in the two crops here considered. Despite all this, however, we do not attempt to disregard the differences which characterize the effects of $MnSO_4$ in the first and second crops as above pointed out, but we regard them as of minor significance.

When we compare $MnSO_4$ in the second crop with other salts under similar circumstances in the greenhouse soil, we find that it has but little in common with them. It approaches perhaps most closely the behavior of $PbSO_4$ in the second crop, but is different from it in several important particulars. As a general thing, the other salts still give more stimulating effects in the second crop so far as the total dry-matter production is concerned, but this is not true in any instance of the second crop of the $MnSO_4$ series. It should be borne in mind, however, that the manganese series is not comparable with the others except possibly with the lead series, because only one treatment, prior to the first crop, was given.

Third Crop

The depressing effect exerted by $MnSO_4$ in the second crop of barley, at least so far as the grain and straw yields are concerned, appears to have been merely an ephemeral one. There was not only a total disappearance thereof in the third crop, but an actually stimulating effect seems to have replaced it; and to have extended to straw, grain, and root production and was not confined, as in the second crop, merely to straw production in part of the series. Moreover, the stimulating effect of the $MnSO_4$ appears to have extended throughout all concentrations and would seem to have been greatest at the medium high concentrations, as is indicated in table IX*c*. While much better agreement between duplicate determinations could have been desired, the clear superiority in yield of the majority of treated pots, when compared with the controls, leaves scarcely any room for doubt that we are here confronted with real cases of stimulating effects. The results are the more interesting and striking since large concentrations of $MnSO_4$ are involved. The results call for further observations on the apparent reversal of results between the second and third crops and between the second and first crops. Unfortunately, no definite leads are in our possession which would aid us in answering this question. Theoretically, however, it would seem possible to explain the facts as follows: In the first crop the large quantity of organic matter present in the soil brings about the adsorption of the $MnSO_4$ and leaves the active soil solution relatively dilute in that salt. This low concentration acts as a stimulant to both the higher plants and the soil flora and induces an increased yield. After one season of exposure to sun and cultivation, the soil loses a considerable portion of its organic-matter supply and therefore possesses a much smaller surface for adsorption of $MnSO_4$ Hence the usable portion of the soil solution would tend to become more concentrated with respect to that salt and induce depressions in yield of roots and grain. By the time the third crop is planted, thorough oxidation of the $MnSO_4$ has occurred and most of the manganese is rendered insoluble, thus leaving again only a small quantity of the salt in the soil solution. This acts as a stimulant, as it did in the first crop, and induces an increased yield again. This explanation, while open to question in one or two important respects, may prove of some assistance in the ultimate clearing up of the somewhat perplexing facts which are here considered. Other explanations, involving the relationship of $MnSO_4$ to the soil colloids and to other phases of the soil solution besides that above mentioned, offer themselves at this time, but they must all await the further study of fundamental principles of plant physiology before they can be considered to advantage. Irrespective of the theoretical arguments which may account for the results obtained in the $MnSO_4$ series, the striking facts relating to the changes in effect on three successive crops of a given salt application made prior to the first planting are of great practical moment. Not only do they render of doubtful value for practical purposes one season's results on the effects of salts on crops, but they cause one to wonder if anything less than five successive crops should ever constitute sufficient evidence upon which to base a judgment. Taking all of our results together, it may be said in general that $MnSO_4$ is to be regarded, for a limited period at least, as definitely stimulating to barley growth in soils.

Manganese Chloride

As pointed out above, $MnCl_2$ was tested along with $MnSO_4$, so that manganese in different compounds might be studied for itself as well as in comparison with other elements. The experiment was arranged similarly to that of the $MnSO_4$ series, and details with respect to it, together with the results obtained, are set forth in tables X*a*, X*b*, and X*c* for the three crops grown.

First Crop

Table *Xa* shows the striking effects of concentrations of $MnCl_2$ on barley growth in the greenhouse soil during the first crop. Whereas the first three concentrations of that salt, namely 500 p. p. m., 1000 p. p. m., and 1500 p. p. m., give very marked stimulation to barley growth (far more indeed than that given by similar concentrations of $MnSO_4$), amounts in excess of 1500 p. p. m. $MnCl_2$ are very markedly toxic. This toxicity increases strikingly with the increase in concentration in $MnCl_2$ beyond 2500 p. p. m., until at a concentration of 6000 p. p. m. almost no growth is obtained. Even the difference between 1500 p. p. m. and 2000 p. p. m. in the soil means a change from a high degree of stimulation for barley production to a marked toxicity and a decrease of about 50 per cent in the yield. No series of salt concentrations studied by us and reviewed above gave anything like the sharpness of manifestation of toxicity that is noted in the first crop of the $MnCl_2$ series. We are evidently dealing again with the acute toxicity of chlorine for living cells which we have on other occasions pointed out in various connections. This is true, if we may repeat again, despite the fact that at the lower concentrations, chlorine may, as is strikingly exemplified in table *Xa*, give astounding evidences of stimulation to barley which surpasses any noted above with other and more uniformly stimulating substances.

When we study straw and root yields separately we find that, in general, the effects of $MnCl_2$ are similar with respect to both in the first crop. The roots are, to be sure, only slightly stimulated in growth in the first three concentrations employed, whereas the tops are enormously stimulated. When, however, the toxicity of $MnCl_2$ becomes apparent, it is equally striking in the roots and tops, as the figures in the table clearly show. While in some respects, therefore, and particularly as regards stimulation, the $MnCl_2$ behaves like the $MnSO_4$ in the first crop and the first three concentrations, it is totally different from the latter salt in giving marked evidences of toxicity at concentrations in excess of 1500 p. p. m. Nevertheless $MnSO_4$ still continues to stimulate growth, even though it does so very slightly throughout the series. On the other hand, although the resemblance between the behavior of $MnSO_4$ and $MnCl_2$ in the first crop is limited in extent, $MnCl_2$ resembles $MnSO_4$ much more in its effects on barley growth in the first crop than it does any of the other salts under similar circumstances. Again, we are obliged to stop with this general comparison owing to the high concentrations of $MnCl_2$ employed, as compared with the relatively much lower or much higher concentrations of the other salts employed.

Second Crop

When the total dry matter is considered (see table X*b*), the second crop of the $MnCl_2$ series gives the latter salt a reversal of form. At the first three concentrations at which it notably stimulated the production of dry matter in the first crop, it becomes decidedly toxic in the second crop. On the other hand, at the concentrations above 1500 p. p. m., at which it was acutely toxic in the first crop, $MnCl_2$ is stimulating when the total yields of the treated as against those of the untreated pots are considered. Such marked reversal of effects of $MnCl_2$ between two succeeding crops on the same soil needs further attention under the general discussion below. Following the procedure employed in the case of the other series, we may now study separately the yields of straw, grain, and roots as given in table X*b*. Taking the straw yields first, we find that they were, in all cases but one or possibly two in the series, much larger than those of the control pots, and that at concentrations in excess of 1500 p. p. m. the average yield of straw was nearly twice as great as that of the control pots. While different in degree, therefore, this effect of $MnCl_2$ in the second crop is very similar in kind to that exerted by $MnSO_4$ in the second crop with respect to the yield of straw.

In the case of the grain, however, we find totally different conditions, for here only one case of stimulation is noted and that, owing to the great discrepancy in the duplicates, is an unsafe one to accept. In excess of 3000 p. p. m., $MnCl_2$ manifests a very marked toxicity so far as grain production is concerned, until at 6000 p. p. m. very little or no grain is produced. This result is again different only in degree, not in kind, from that of the corresponding one in the $MnSO_4$ series. Respecting root yields, the toxic effects of $MnCl_2$ in the second crop are apparent throughout the whole series. While the decreases are not quite so great at the lower concentrations of $MnCl_2$ as they are at the higher concentrations, they are not far different, and in general amount to from 40 to 60 per cent of the amount yielded by the control pots. We see in the root yields, therefore, a further analogy between the second crop of the $MnCl_2$ series and that of the $MnSO_4$ series. In brief, it should be observed that while wide discrepancies in total yields of dry matter are noted between the second crops of the $MnCl_2$ and $MnSO_4$ series, the discrepancies are superseded by striking resemblances when the straw, grain, and root yields are compared separately in the two series. Since the differences seem to be those of degree only, is it not possible that we have here the dominant manifestations of the effects of manganese, which are only slightly modified by the element or elements combined therewith? If this were not the case, would we not expect to find much larger discrepancies between the two series in question, based on the specifically different effects of the $-Cl$ and the $-SO_4$ ions on barley growth?

Third Crop

The stimulating powers of manganese, as exemplified in the effects of $MnSO_4$ ions on the third crop of barley, are again manifest but very much more strikingly in the third crop of the $MnCl_2$ series. While the yields of duplicate pots still fail to agree closely in a number of the salt concentrations tested, they show a much better agreement than those of the $MnSO_4$ series. At any rate, there can be no doubt of the stimulating effects of manganese chloride for barley grown in the greenhouse soil even in the third crop. Again, as was the case in the $MnSO_4$ series, the $MnCl_2$ stimulates the production of all parts of the plant and not merely of any one portion of the dry matter thereof. Thus, for example, whereas there was practically no stimulation to grain production in the second crop of the $MnCl_2$ series, the third crop shows such stimulation markedly throughout the series. In no case, further, so far as the total dry weight produced is concerned, did any of the treated pots produce so low a yield as the control pots, when averages are considered. The great immunity to chlorine which the plants in the third crop of this series manifest is very difficult to explain. In general, however, the changes in the effects of $MnCl_2$ from one crop to another are much the same in nature as those of the $MnSO_4$ series which have been discussed more in detail above. It looks obvious that we are dealing primarily in both manganese series with the effects of the kation rather than with those of the anions, though, to be sure, specific effects of the latter do not seem to be wanting. The balance of the data presented in table X*c* speaks for itself.

COMPARISON OF OUR RESULTS WITH THOSE OF PREVIOUS INVESTIGATORS

It is quite unnecessary to review in detail the results of the numerous investigations which bear on the subject in hand, particularly those relating to copper and its influence on living organisms. Although, therefore, we are herewith citing a very extensive bibliography, we shall make no attempt at reviewing all of the investigations which have been carried out. It does seem desirable, however, to compare in general the results of our investigations with those of other researches in the hope that we may thereby arrive at some definite understanding, now that so much experimental work has been accomplished, as to the real status of the salts in question in the realm of plant physiology. In order to simplify such discussion, we shall take up the different so-called toxic metals separately.

Copper Sulfate

As pointed out above, the bibliography on the subject of copper and its effects on plants is very extensive. One needs but to turn to the complete reviews of it by Czapek,[8] Pfeffer,[9]

[8] Biochemie der Pflanzen, vol. 2, p. 910, Jena, 1905.

[9] Pflanzenphysiologie, vols. 1 and 2, Leipzig, 1897 and 1901.

and Brenchley[10] to be confirmed in that opinion. The general impression given by the reviewers is that so far as plants are concerned, copper is to be regarded as a distinctly toxic substance. To quote Brenchley from the work above cited, for example: "Altogether, after looking at the question from many points of view, one is forced to the conclusion that under most typical circumstances, copper compounds act as poisons to the higher plants, and that it is only under particular and peculiar conditions and in very great dilutions that any stimulative action on their part can be clearly demonstrated." This statement is not qualified with respect to the kind of medium employed for testing the effects of copper on plants. But whether it be applied to solution or to soil cultures, it would scarcely seem to be adequately supported by experimental evidence, and particularly is this true regarding soil cultures. In solution cultures, copper in various compounds was found to be toxic to the higher plants by Otto,[11] Haselhoff,[12] Coupin,[13] Kanda,[14] True and Gies,[15] True and Oglevee,[16] Jensen,[17] Brenchley,[18] Heald,[19] Harter,[20] and Haywood.[21] While exceedingly high dilutions of copper salts were employed by some of these investigators, the possibility still exists in their work that the merest traces of copper may have acted as stimulants. Moreover, in the case of Jensen's work the evidence on the toxicity of very dilute solutions of copper salts is really negative, since he emphasizes principally the fact that no stimulation was observed with $CuSO_4$ in solution cultures.

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[10] Inorganic plant poisons and stimulants, Cambridge, 1914.

[11] Ztschr. Pflanzenkrank., vol. 3, no. 6; Bot. Cent., 56, p. 340; E. S. R., 5, p. 649.

[12] Landw. Jahrb., 21, p. 263; E. S. R., 3, p. 499.

[13] Comptes Rendus Acad. Sci., Paris, 127, p. 400; E. S. R., 10, p. 611.

[14] Jour. Col. Sci. Imp. Univ. Tokyo, 19, p. 47; Bot. Cent. 95, p. 538; E. S. R., 16, p. 228.

[15] Bull. Torr. Bot. Club, 30, p. 390.

[16] Bot. Gaz., 39, p. 1; Science, 19, p. 421.

[17] Bot. Gaz., 43, p. 11.

[18] Inorganic plant poisons and stimulants, Cambridge, 1914.

[19] Bot. Gaz., 22, p. 125.

[20] U. S. Dept. Agr., Bur. Pl. Ind., Bull. 79, p. 40.

[21] U. S. Dept. Agr., Bur. Chem., Bulls. nos. 89, 113, and 113, revised.

Opposed to the findings of the investigators just named were those which showed evidence of stimulating effects of copper salts to plants in solution cultures. Among these investigators were Tschirch,[22] Montemartini,[23] and Forbes.[24] So far as germination of seeds is concerned, Effront[25] also noted the stimulating effect of copper. Owing to conflicts in the results obtained by different investigators working with copper in solution cultures, one seems scarcely justified in subscribing to the statement above quoted from Brenchley, even if it were made to apply only to solution cultures. As Dr. Brenchley herself admits, there is no absolutely satisfactory method for determining whether or not a certain substance is toxic or stimulating to plants. But from the theoretical standpoint of ascertaining how the protoplasm of the plant is affected by a given substance, if at all, the solution-culture method is the only one involved, since the other methods are confessedly not intended to show anything more than effects of substances on plants under conditions closely approximating the natural. If, then, the solution culture method is the only one among those at present known that is suitable for studying the effects of different chemicals on plant growth in a more or less intimate way, why do we obtain the conflicting results above noted with respect to the effects of copper on plants? The answer to this question is to be found in a number of circumstances surrounding the manipulation of the solution-culture method. Some investigators use distilled water, others use tap water, still others physiologically balanced solutions of a large variety. For reasons well known to plant physiologists, the results of such different media among the solution cultures must show wide discrepancies. If, however, the claim is made that all media but pure distilled water be discarded in such work, owing to the factors of salt antagonisms which enter into salt solutions to vitiate results, a very strong counter-claim can be made. The protoplasm of plant cells is not in a natural medium when it is placed in distilled water, and

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22 Abstract in Chem. Ztg., 18, p. 320; E. S. R., 6, p. 872.

23 Staz. Sper. Agr. Ital., 44, p. 564.

24 Results soon to be published, Univ. Calif. Publ. Agri. Sci.

25 Compt. Rend. Acad. Sci. (Paris), 141, p. 626; E. S. R., 18, p. 126.

hence it may manifest distress and weakness which under natural conditions might be quite impossible. Owing to osmotic influences, the plant would lose salts and other substances to the distilled water more quickly and in larger quantity than to tap water or to a balanced solution. It would therefore be more subject to weakening or to the absorption of toxic materials in the former than in the latter medium. In other words, under such circumstances copper, for example, would merely exaggerate the untoward conditions for plant growth, while it might have no power to affect the plant under more favorable conditions. Again, seeds are not usually allowed to germinate in the solution which is to be tested in the cultures, but in a medium of a harmless nature. Does not sudden removal to salt-solution cultures render them less immune to certain substances than if they had been allowed to accustom themselves from the beginning to a given salt?

We do not desire to give the impression from these arguments that we deprecate the use of the solution-culture method. On the contrary, we think it of great value in the study of many fundamental problems and also for obtaining relative data. When, however, one attempts to use it in drawing absolute conclusions for purposes of application to such a subject as that under consideration, it falls as far short of throwing light on the actual effects of a given substance on plant protoplasm (as the latter is situated under natural conditions), as does any other method of study now employed. We believe that the conflicts in the results just reviewed are perhaps explicable on one of the bases above discussed; and since no modification of the solution-culture method is free from serious objection, we must accord equal value to all results of reliable investigators. Consequently we arrive at the conclusion that in the experiments above cited there is no absolute evidence that copper is or is not stimulating to plant protoplasm in solution cultures. While there appears to be more evidence that copper is toxic under the conditions and in the concentrations named than that it is stimulating, we cannot admit that the plant has been tested in any two of the experiments under essentially the conditions of its natural habitat. Since plants are, after all, to be found growing naturally only in soils, it cannot be a matter of indifference to us, in attempting the study of the effect of a certain substance or substances on them, whether they are supplied with normal conditions for their development or not.

Proceeding now to an examination of the results obtained by other investigators on the effects of copper on plants grown in soil or sand instead of solutions we find many interesting observations. Injurious effects of $CuSO_4$ at the rate of about 400, 800, and 1600 pounds per acre to potatoes and beans were noted by Steglich,[26] but he failed to observe such toxic effects on the same soil to strawberries or fruit trees. Haselhoff[27] claims also to have noted injury to grass, beans, and other plants from smelter smoke containing copper. Owing to other conflicting factors concerned in smelter-smoke injury, Haselhoff's results are open to serious criticism. Simon[28] experimented with oats and mustard on garden soil, clay, and sand, and used amounts of $CuSO_4$ varying from 0.01 per cent to 10 per cent. His statements imply that copper was toxic throughout, with the oat plants showing more resistance than the mustard, and that $CuSO_4$ was least toxic in garden soil and most toxic in the sand. Opposed to the three cases just cited are numerous results showing the stimulating effects of copper to plant growth in soils. We find among these the results obtained by Girard,[29] Kanda,[30] Jensen,[31] Voelcker,[32] Forbes,[33] and Sachser.[34] A large number of observations have also been made on the stimulating effects, or lack of any effect, of copper sprays, and in other ways of the effect following direct contact of the copper solution with plant cells, among which may be mentioned those of Frank and

26 Ber. Tat. Landw. Abt. K. Vers. Stat. Pflanzenkult, Dresden, p. 4, 1903; E. S. R., 16, p. 133.

27 Fühling's Landw. Ztg., vol. 57, no. 18, p. 609; E. S. R., 20, p. 831.

28 Landw. Vers. Stat., 71, p. 417; E. S. R., 22, p. 439.

29 C. R. Acad. Sci., Paris, 120, p. 1147; E. S. R., 7, p. 99.

30 Jour. Col. Sci. Tokyo Imp. Univ., 19, p. 47; E. S. R., 16, p. 228.

31 Bot. Gaz., 43, p. 11; E. S. R., 18, p. 625.

32 Jour. Roy. Agr. Society, England, vols. 73, 74, and 75, Report for 1912, 1913, and 1914.

33 Univ. Calif. Publ. Agr. Sci., 1, no. 12, 1917.

34 Cent. Agr. Chem., 33, p. 533; E. S. R., 16, p. 865.

Kruger,[35] MacDougal,[36] Chuard and Porchet,[37] Demoussy,[38] Prandi,[39] Olive,[40] and Molinari and Ligot.[41] In addition to all these results, which show either no toxicity or decidedly stimulating effects on plants from the use of copper (usually $CuSO_4$) in soil, there are extant a number which testify to the high resistance of plants in soil to extremely large amounts of copper (Such, for example, as from 2 per cent to 5 per cent of the dry weight of the soil). Among these may be mentioned the observations of Van Slyke[42] and Pammel.[43]

All of these findings render it extremely improbable that copper in soil, can at any time be considered definitely toxic in relatively small quantities (say, below 0.10 per cent of the dry weight of the soil). On the contrary, the evidence seems very well established that positive stimulation of plants may be induced through the use of small quantities of copper (say, from 0.01 to 0.05 per cent of the dry weight of the soil), in the form of $CuSO_4$ particularly, and possibly also in other forms. Our investigations as discussed would seem to confirm and be confirmed by earlier investigations of the senior author and F. H. Wilson and by numerous other experiments carried out in different parts of the American and European continents and in England. These observations would appear therefore to refute the conclusion of Dr. Brenchley which is above quoted and to point clearly, through the added data which we have submitted, to the conclusion that copper in the form of $CuSO_4$ is to be regarded, at some concentrations, as being decidedly stimulating to some plants grown in soils, and, what is perhaps more important, relatively innocuous in large amounts. The mechanism of the stimulation obtained does not involve one single effect, but probably several. We know, for example, through experi-

35 Ber. deutsch. bot. Gesell., 12, p. 8; E. S. R., 5, p. 926.

36 Bot. Gaz., 27, p. 68; E. S. R., 11, p. 24.

37 Bull. Soc. Vaud. Sci. Nat., 4th series, vol. 36, p. 71; Bull. Murith. Soc., Valais Sci. Nat., no. 33, p. 204.

38 Ann. Agron., 27, p. 257; E. S. R., 13, p. 657.

39 Staz. Sper. Agr. Ital., 40, p. 531; E. S. R., 19, p. 755.

40 S. Dak. Agr. Exp. Sta., Bull. 112; E. S. R., 21, p. 436.

41 Ann. Gembloux, 18, p. 609; E. S. R., 20, p. 873.

42 N. Y. Agr. Exp. Sta., Bull. 41.

43 Iowa Agr. Exp. Sta., Bull. 16.

ments[44] carried out in our laboratory, that copper is markedly effective in increasing the nitrifying activity of soils; we know, from other results which we have obtained, but not yet published, that the minerals of the soil are rendered more easily available through the action of $CuSO_4$; we know from the results of Porchet and Chuard that plant cells may be directly stimulated by $CuSO_4$. It is therefore reasonable to explain any stimulating effects of copper in soil cultures as being of a complex nature and the results of better conditions for plant growth either directly or indirectly induced by copper through influences known to be characteristic of it as just explained.

Zinc Sulfate

We may now review, in a manner similar to that employed for $CuSO_4$, the results obtained by other investigators as compared with our results on the effects of $ZnSO_4$ on plant growth. Data indicating the toxicity of zinc to plants grown in solution cultures have been obtained by Baumann,[45] Jensen,[46] Krauch,[47] Storp,[48] True and Gies,[49] and Brenchley.[50] Most of these toxic effects were obtained with relatively small quantities of zinc salts and usually under conditions antagonistic to their toxic effects owing to the presence of nutrient salts. As opposed to these evidences of the toxicity to plants of zinc, we have at times, in the work of the same investigators, manifestations of the stimulating effects of zinc in solution cultures. For example, Brenchley admits in the monograph cited a slight stimulation of peas by $ZnSO_4$, while showing the latter to be toxic to barley. Jensen, too, whose work is described, while obtaining no stimulation for $ZnSO_4$, likewise showed no toxicity thereof in dilute solution, and expressed the opinion that the possibility exists of

[44] Lipman and Burgess, The Effects of Copper, Zinc, Lead, and Iron on Ammonification and Nitrification in Soils, Univ. Calif. Publ. Agri. Sci., vol. 1, p. 127.

[45] Landw. Versuchs. Stat., 31, p. 1.

[46] Bot. Gaz., 43, p. 11.

[47] Jour. für Landw., 30, p. 271.

[48] Landw. Jahrb., 12, p. 795.

[49] Bull. Torrey Bot. Club, 30, p. 390.

[50] Inorganic plant poisons and stimulants, Cambridge, 1914.

a stimulating power of $ZnSO_4$ at still greater dilutions than those which he employed. More direct evidence of the stimulating effects of $ZnSO_4$ is given by Kanda[51] in solutions free from nutrient salts, and by Javillier[52] in nutrient solutions. So far as solution cultures of all kinds are concerned, therefore, the evidence with respect to the effects of zinc on plants is conflicting, it being as strong on the side of stimulation at great dilutions of $ZnSO_4$ as on that of lack of it or of definite toxicity.

Let us now examine the data available in which a solid substratum such as sand or soil is used instead of the solution. Direct observation of toxicity of zinc to plants in solid media is given by Storp, whose work is above cited, by Noble, Baessler, and Will,[53] Jensch,[54] Ehrenberg,[55] and Haselhoff and Gössel.[56] Evidence of the non-effectiveness of zinc either as a toxic or stimulating agent is given by Phillips,[57] by Holdefleiss,[58] and by Haselhoff and Gössel[59] As against these results, however, we have many others showing definitely stimulating effects of zinc on plants grown in sand or soil. Among them may be mentioned those of Kanda,[60] Jensen,[61] Silberberg,[62] Zaleski and Reinhard,[33] Ehrenberg,[64] Bertrand,[65] Nakamura (with some plants only),[66] Javillier,[67] Roxas,[68] Lipman and Wilson,[69] and the present writers. While, however, the evidence appears to

[51] Jour. Col. Sci., Tokyo Imp. Univ., 19, p. 1.

[52] Compt. Rend., etc., 155, p. 1551.

[53] Landw. Versuchs. Stat., 30, p. 380.

[54] Ztschr. Angew. Chem., 14, p. 5.

[55] Chem. Zeit., 32, p. 937.

[56] Ztschr. Pflanzenkrank., 14, p. 193; E. S. R., 16, p. 952.

[57] Chem. News, 46, p. 224.

[58] Landw. Versuchs. Stat., 28, p. 472.

[59] Ztschr. Pflanzenkrank., 14, p. 193; E. S. R., 16, p. 952.

[60] Jour. Col. Sci., Imp. Univ. Tokyo, 19, p. 47.

[61] Bot. Gaz., 43, p. 11.

[62] Bull. Torrey Bot. Club, 36, p. 480.

[63] Biochem. Ztchr., 23, p. 193.

[54] Landw. Versuchs. Stat., 72, p. 15.

[65] Rev. Sci. (Paris), 49, p. 673.

[66] Bull. Col. Agr., Tokyo Imp. Univ., 6, p. 147.

[67] Ann. Inst. Pasteur, 22, p. 720; also 7th Internat. Cong. Appl. Chem., sec. vii, Agr. Chem., p. 163.

[68] Philippine Agric. and Forester, 1, p. 89.

[69] Bot. Gaz., 55, p. 409.

be overwhelmingly in favor of the stimulating effects of zinc to plant growth in soils, several instances of stimulation are qualified to hold for certain plants only or at very low concentrations of the metal. Therefore the data submitted are not as strong in favor of the stimulating effect of zinc salts to plants as one would suppose from the review above given. Nevertheless, it is strong enough in our opinion to satisfy even the critical that zinc can be a stimulant to plant growth in certain rather considerable concentrations. Besides that, its toxic effects are nowhere to be regarded as very serious if small quantities of the salt are present. Our results indicate, in addition to all this, that $ZnSO_4$, for example, may be stimulating to barley growth at considerable concentrations, but that the after-effects on the soil in the third season or crop may be injurious. Such injury, however, is relatively speaking, not very great unless very high concentrations of $ZnSO_4$ are employed. Even in the third season of cropping in the case of the same soil, it appears that $ZnSO_4$ continues to be stimulating to barley at a concentration of 200 p. p. m. of that salt as referred to the dry weight of the soil in question. Moreover, it is not unlikely that the reversal from a toxic to a stimulating condition occurring in the manganese series between the second and third crop might occur in the zinc series between the third and fourth crop. This possibility would seem to find some support from the fact that the third crop in the zinc series corresponds to the second crop of the manganese series, since two treatments—one before the first, and one before the second crop—were given to the zinc-treated pots.

Iron Sulfate

Results obtained in experimental trials with $FeSO_4$ in cultures of the higher plants have been perhaps more contradictory than those noted in the cases of $CuSO_4$ and $ZnSO_4$ which are reviewed above. This is particularly manifest in the extensive bibliography prepared by Horton[70] dealing with the use of sulfate of iron in agriculture. While the latter emphasizes primarily the results obtained with $FeSO_4$ in combating weeds,

[70] A Contribution to the bibliography of the use of sulfate of iron in agriculture, Chicago, 1906.

a large number of experiments are cited, among which are to be found cases of injury, ineffectiveness, and stimulation by $FeSO_4$ to crop plants. Very few experiments appear to have been reported on the effect on plant growth of $FeSO_4$ or other iron compounds in solution cultures. Those that are given indicate the uniformly toxic nature of iron to the higher plants under the conditions noted. For evidence on this point, the reader is referred to the investigations of Boiret and Paturel,[71] Gile,[72] Ruprecht,[73] Thompson,[74] and Knop.[75] No case has as yet come to our notice of the stimulating effects of iron salts to plants in solution cultures.

In soil cultures the picture is an entirely different one, and it is under those conditions that we observe the contradictory results mentioned above. Distinct cases of injury by $FeSO_4$ to plants in soil cultures have been reported. In illustration of these, may be mentioned statements of Voelcker,[76] Steglich,[77] Nessler,[78] Halsted,[79] and others. As showing $FeSO_4$ to be without effect on plants grown in soils, may be mentioned the experiments of Scovell and Peter,[80] A. Mayer,[81] Boiret and Paturel,[82] Petit,[83] Larbaletrier and Malpeaux,[84] and others. In other words, some of the investigators just mentioned, as well as Coste-Floret,[85] Brooks,[86] Griffiths,[87] Treboux,[88] and a number of others,

[71] Ann. Agron., 18, p. 417; E. S. R., 4, p. 435.

[72] Jour. Agr. Res., 3, no. 3, p.

[73] Mass. Agr. Exp. Sta., Bull. 161.

[74] Jahresber. Agr. Chem. N. F., 36, p. 106.

[75] Landw. Versuchs. Stat., 2, p. 73.

[76] Jour. Roy. Agr. Soc. Eng., 2d ser., 1, p. 113.

[77] Ztschr. Pflanzenkrank, 11, p. 31; see also Jahresber. Agr. Chem., 43, p. 352.

[78] Centbl. Agr. Chem., 2, p. 125.

[79] N. J. Sta., Ann. Rept., p. 321, 1890.

[80] Ky. Agr. Exp. Sta., Bull. 17.

[81] Jour. für Landw., 40, p. 19.

[82] Ann. Agron., 18, p. 417.

[83] Compt. Rend., etc., 117, p. 1105.

[84] Ann. Agron., 22, p. 20.

[85] Prog. Agr. et Vit., 26, pp. 434, 463, 496.

[86] Mass. Agr. Exp. Sta., Ann. Rept., p. 42, 1896.

[87] Chem. News., 50, p. 167.

[88] Flora, 92, p. 59.

have noted very definite stimulation of plants by $FeSO_4$ in soil cultures. In addition to these direct results on the stimulation of plants, moreover, may be mentioned the numerous cases of stimulation of plants induced by spraying the leaves with solutions of $FeSO_4$ either for destroying ever-present weeds in crops or for overcoming certain diseases like chlorosis. These cases are too numerous to mention here, but are well reviewed in the bibliography prepared by Horton, which is referred to above. As the discussion of our results has shown, we are in accord with the idea of the stimulating powers of $FeSO_4$ even if used in relatively large concentrations in soils so far as the first two successive crops on the treated soil are concerned. In the third crop also, marked stimulation is obtained, but only in the higher concentrations, which in the second crop were toxic. This circumstance will be critically considered below.

Lead Sulfate

The literature dealing with the subject of the effect of $PbSO_4$ or lead in any form on plant growth is very meager. That which is extant deals more specifically with the effect of lead sprays on foliage and fruit of trees than on the actual growth of trees, in which we are interested here. In the case of solution cultures we have found but two papers, and both of these testify to the stimulating action of $Pb(NO_3)_2$ in dilute solutions. We refer to the investigations of Jensen[89] and Stoklasa.[90] In greater concentration the $Pb(NO_3)_2$ was of course found to be toxic in the solution cultures. The same investigators also obtained marked manifestation of stimulation of plants in solid substrata due to lead. Jensen obtained such in quartz-sand cultures, in which greater concentrations were found stimulating than in solution cultures. Stoklasa confirmed the results of the solution cultures by field trials reported in the paper above cited, and also in other experiments[91] with sugar beets, oats, corn, and other crops. Voelcker[92] also found lead to be stimulating to wheat. When

[89] Bot. Gaz., 43, p. 11.
[90] Compt. Rend. Acad. Sci. (Paris), 156, p. 153.
[91] Zuckerrübenbau, 18, p. 193; E. S. R., 26, p. 225.
[92] Jour. Roy. Agr. Soc. Eng., 73, ent. series, 1912.

our data for $PbSO_4$ in greenhouse soil are reviewed in the light of the foregoing, they are found to be in accord with those of Voelcker so far as the second and third crops of barley are concerned. At some concentrations in both of those series, $PbSO_4$ acted as a stimulant to barley and often at very large or at the larger concentrations used. Our results, however, are entirely at variance with those of Jensen and Stoklasa in so far as the first crop is concerned. In that series we noted nothing but evidences of marked toxicity of the $PbSO_4$, with the accompanying effects on the barley plants which are described.

Potash Alum

No literature has been found on the effects on plants of potash alum in soil. The discussion set forth above giving our results with that material will therefore have to suffice.

Manganese

With the possible exception of copper, manganese and its effects on plants have received more attention at the hands of plant physiologists and students of soils than any other element here under consideration. Despite that fact, there would appear to be as much contradiction in results obtained in this case as in those of the other elements above studied. We find reports of toxicity of manganese in solution cultures in the publications of Aso,[93] Loew and Sawa,[94] and Brenchley.[95] On the other hand, the results of the same authors also give evidence of the stimulating effects of manganese at certain concentrations. Miss Brenchley even hints at the possibility of the existence, simultaneously, of a toxic and stimulating effect on the part of manganese and claims that either effect may show predominance, depending on the concentration of the salt employed.

On the toxic action of manganese to plants in solid substrata, principally in soils, we have the reports of experiments of

[93] Bull. Col. Agr., Tokyo Imp. Univ., 5, p. 177.

[94] Bull. Col. Agr., Tokyo Imp. Univ., 5, p. 161.

[95] Inorganic plant poisons and stimulants, Cambridge, 1914.

Namba,[96] Voelcker,[97] Kelley,[98] and Guthrie and Cohen.[99] As opposed to these, however, we have numerous cases on record of the stimulating effects of manganese to plants grown in soil, and even the work of the investigators last named is by no means to be considered as absolute evidence against such action of manganese, since the toxic action observed was in some cases very slight, and some of the concentrations involved were so unusually high as to leave little expectation of anything but toxicity of manganese for the plants tested. Among the investigators referred to who have furnished evidence of the stimulating effects of manganese, may be mentioned Voelcker,[100] Bertrand,[101] Roxas,[102] Loew and Sawa,[103] Nagaoka,[104] Loew and Honda,[105] Fukutoma,[106] Namba,[107] Uchiyama,[108] Takeuchi,[109] Feilitzen,[110] Strampelli,[111] and Lipman and Wilson.[112] While in this review we have omitted a number of the investigations bearing on the subject, enough have been given to indicate clearly the trend of the evidence in hand. Fuller bibliographies may be obtained in the excellent reviews of the literature given by Brenchley[113] and by Kelley.[114]

Comparing the results of other investigators with ours, some interesting differences, as well as similarities, between them become evident. For example, we are in accord with most of the investigations above reviewed as favoring the existence of stimu-

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96 Bull. Col. Agr., Tokyo Imp. Univ., 7, p. 635.

97 Jour. Roy. Agr. Soc. Eng., 64, p. 348.

98 Jour. Ind. Eng. Chem., 1, p. 533.

99 Agr. Gaz. N. S. Wales, 21, p. 219.

100 Jour. Roy. Agr. Soc. Eng., 44, p. 348.

101 Compt. Rend., etc., 124, p. 1032.

102 Philippine Agr. and Forester, 1, p. 89.

103 Flora, 91, p. 264.

104 Bull. Col. Agr., Tokyo Imp. Univ., 5, p. 467; 6, p. 135.

105 Bull. Col. Agr., Tokyo Imp. Univ., p. 6. 125.

106 Bull. Col. Agr., Tokyo Imp. Univ., 6, p. 137.

107 Bull. Col. Agr., Tokyo Imp. Univ., 7, p. 635.

108 Bull. Imp. Cent. Agric. Exp. Sta., Japan, 1, p. 37.

109 Jour. Col. Agr., Tokyo Imp. Univ., 1, p. 207.

110 Jour. für Landw., 55, p. 289.

111 6° Cong. Internat. Chem. Appl. Roma, 4, p. 14.

112 Bot. Gaz., 55, p. 409.

113 Inorganic plant poisons and stimulants, Cambridge, 1914.

114 Hawaii Agr. Exp. Sta., Bull. no. 26.

lation by manganese of the growth of barley so far as the first crop on the soil in question is concerned. In the case of the second crop, however, a depression in yield of considerable magnitude is induced by $MnSO_4$ and a stimulation produced by $MnCl_2$ in the higher concentrations of the salt, while the lower ones depress the yield like $MnSO_4$. In the third crop, as we have already seen, there is a practical disappearance of all toxic effects in both of the manganese series which we had under observation, and taking the place of the former toxic effects we find marked stimulating effects. The indication is therefore that in general our results are in accord with those of the investigators cited above who attributed to manganese stimulating effects for plants.

ADDITIONAL INVESTIGATIONS

Nitrification

Earlier experiments by P. S. Burgess[115] and the senior author had demonstrated the stimulating effects of $CuSO_4$, $FeSO_4$, $ZnSO_4$, and $PbSO_4$ on nitrification in soils. We were therefore led to wonder whether much, if not all, of the stimulation exerted on the higher plants by most of the salts in the first crop was due to the increase in the available supply of nitrogen there through the effects of the salts. Accordingly, tests of the nitrifying powers of the soils in a number of the pots in every series were made by the usual laboratory methods employed for such purposes. Dried-blood nitrogen was used as the nitrifiable material at the rate of 1 per cent of the dry weight of the greenhouse soil. Lack of space forbids the presentation here of the large amount of data collected on the subject now under consideration. We may, however, refer to the striking features thereof, owing to their undoubted connection with the cause or causes of the stimulating effects above noted. In the second crop of the copper series in the greenhouse soil the nitrifying power was from 10 per cent to 50 per cent greater in the "coppered" than in the "uncoppered" soil. In the third crop, which, it

115 Univ. Calif. Publ. Agr. Sci., 1, p. 127.

will be remembered, was grown one year after the second and last copper application had been made, the increases in the nitrifying powers of the treated soils were from 33 per cent to 100 per cent greater than in the control soils receiving no copper. In a general way the highest concentrations of $CuSO_4$ gave the largest increases in nitrifying power in the second crop, but in the third crop there was more or less irregularity in that regard and the smaller concentrations appeared to be as effective as the larger.

In the case of the zinc series, determinations of the nitrifying powers of the different soils were made after the third crop only. In that case also, the nitrifying power was increased by applications of $ZnSO_4$ equivalent to 200, 600, and 1000 p. p. m. The increases, however, were much smaller than in the case of the $CuSO_4$ and varied from 3 per cent to 16 per cent at the different concentrations, the most favorable concentration being 600 p. p. m. An important difference exists between the $CuSO_4$ and the $ZnSO_4$ series in that all the concentrations of the former which were employed increased the nitrifying powers of the soil in the third crop to some extent, while only the concentrations just given were instrumental in imparting such a stimulus in the case of the latter salt. Iron behaved very similarly to zinc in most respects so far as the soil's nitrifying powers were concerned, and 0.2 per cent, 0.4 per cent, 0.6 per cent, and 0.8 per cent were the range of concentration of $FeSO_4$ corresponding to those named for $ZnSO_4$ above. One difference between iron and zinc in their influences on nitrification in the greenhouse soil is that the former does not seem to have been appreciably toxic in any concentration, even though as much as 2 per cent $FeSO_4$ was employed, whereas the latter, as we have already seen, markedly depressed the soil's nitrifying power when used in excess of 0.1 per cent of the dry weight of the soil. Like $ZnSO_4$ and $FeSO_4$, $PbSO_4$ was tested as to its effect on nitrification after the third crop only. Under those conditions it gave, however, very different results from the other salts, since no stimulation to nitrification was noted at all, no matter what amounts of $PbSO_4$ were employed. On the other hand, while $PbSO_4$ was throughout slightly toxic to nitrification under the conditions named, the toxicity seemed to be about the same with the larger as with the smaller concentrations of $PbSO_4$ employed.

The manganese salts were tested in the first crop only, in connection with their powers to affect nitrification. The following were the results: $MnSO_4$ was not toxic under the conditions named in any of the concentrations in which it was employed, 0.6 per cent being the highest. It appeared to be very slightly stimulating at all concentrations. In the case of $MnCl_2$ we find marked toxicity to nitrification at concentrations in excess of 0.4 per cent, and very distinctly toxic effects at concentrations in excess of 0.15 per cent. On the other hand, we also note that nitrification was stimulated by the following concentrations: 0.05 per cent, 0.1 per cent, and 0.15 per cent. The stimulation was very marked only in the case of the latter two concentrations and was very much in excess of that induced by $MnSO_4$ at any concentration.

The nitrifying powers of the Oakley blow sand employed in one copper series, which is described above, were also determined. Marked stimulation to the nitrifying power of the soil was noted at concentrations of $CuSO_4$ equivalent to 100 p. p. m., 200 p. p. m., and 300 p. p. m., the first two being most marked. Ammonium sulfate was employed as the nitrifiable material. Amounts of $CuSO_4$ in excess of 300 p. p. m. were decidedly toxic, and very little or no nitrification occurred in the soil containing more than 700 p. p. m. $CuSO_4$.

While there is considerable discrepancy in the correlation of the effects of the different salts on barley growth and on the nitrifying bacteria, there appears to be a general relation, at least, between the stimulating effect exerted by a salt on the nitrifying flora and its effect on the barley plant. The serious irregularities which seem to militate at present against the definite establishment of such a relationship based on our data can undoubtedly be explained on the basis of certain factors like the residual nitrate supply in soils and the differences in its distribution throughout the soil mass which of course must exist. While therefore we make no attempt to assert that the stimulating effects and perhaps the toxic effects to barley exhibited by the salts here under discussion are to be accounted for by their effects on the nitrifying flora and hence on the available nitrogen supply, we do believe that the latter is one of the few important factors—perhaps the most important—involved in the problem of explaining stimulation of plants in soils particularly, and possibly also, to some extent, the toxicity of salts in soils. That the effects of the salts on the nitrifying powers of the soils here studied are not the exclusive cause of the phenomena above discussed, we can probably believe with confidence. The total quantities of citric acid-soluble phosphoric acid and potash in soils have been found by us to be augmented through the action of the metallic sulfates in question, and we are also aware of the possible inhibiting effects of those salts for certain factors which may be inimical to the proper development of the soil bacteria.

In addition, there can be no question about the profundity of the changes in the soil's physical condition induced by any metallic sulfate and about the effects which follow in its wake. Most notable of all facts in that connection is the fluffy and pulverulent condition of the soils treated with ferrous sulfate, due undoubtedly to the formation of hydrated ferric oxide and other similar compounds. Special studies (unpublished) carried out by Mr. H. H. Coolidge on the soils of the ferrous-sulfate series, showed that the treatment of the soil reduced its power to raise water to a certain point, while at first allowing it to raise it faster; that the hygroscopicity of the soil was reduced; that its total water-holding power and its water-retentiveness were diminished; that its percolation power was increased; that its moisture-equivalent was diminished. Mr. Coolidge also found that, contrary to the effects of $CuSO_4$ and some of the other sulfates, the soil's water-soluble phosphorus and potassium were very much reduced in quantity by treatment with $FeSO_4$. Different and numerous though these effects be, there can be little question that they must influence, to some degree at least, the soil's nitrifying power. A further discussion of this phase of the problem is, however, impossible at this time and must await consideration in connection with some of our other studies.

Nitrogen Content of the Grain

It appeared of interest, in view of the foregoing, to determine to what extent the soil's nitrate content, which was high throughout, had influenced the nitrogen content of the dry matter. We therefore determined the nitrogen content of the grain harvested in a number of the series so as to obtain some idea of the direction taken by the effects of the nitrates, if any were exerted. As a result of these analyses it was found that in the second crop of the copper series the nitrogen content of the grain was in the absolute from 0.14 per cent to 0.57 per cent higher in the case of that grown on the "coppered" soil than in that grown on the control soils. In the third crop of the copper series the nitrogen content was from 0.05 per cent to 0.38 per cent higher in the grain from the treated soils than in that from the untreated soils. In the case of the second crop of the zinc series, the nitrogen content of the grain was from 0.06 per cent to 0.64 per cent higher in the grain of the treated than in that of the untreated soils. In the third crop of the zinc series, the corresponding figures ranged from nothing in one case, in which the lowest concentration of $ZnSO_4$ was used, to 0.42 per cent. Similarly in the case of the iron series, the range was from nothing to 0.68 per cent in the second crop, and from 0.22 per cent to 0.50 in the third crop. No determinations were made in the case of the lead series, but analyses were carried out in the case of the second crop of the potash alum series which indicated that the grain of the treated soils was in most cases only very slightly richer in nitrogen than that from the untreated soils, and that the maximum increase did not surpass 0.09 per cent.

On the whole, and leaving the potash alum out of consideration, it seems that one of the results of stimulation of the barley plant by the metallic sulfates in question was the increase in the nitrogen content of the grain. At all concentrations of all the salts tested, with only one or two exceptions, the grain grown on the treated soils was richer in nitrogen than that on the untreated soils. That this fact should be referable primarily to the increased vigor of the nitrate formation in the treated soils induced by the presence of the salts appears to the writers rational and justifiable. However that may be, there can be no question that even in the second and third crops on the soil under examination the nitrogen content of the grain shows its superiority in the case of the treated soils as against the untreated soils. If this should prove true on soils in general, and there is strong likelihood that it will, should it not offer us a method for increasing the nitrogen content of our grain, a problem which has for some time been agitating agronomists and flour producers in California? While, as has been indicated by other investigators, a high nitrogen content of grain may not necessarily imply a high gluten content of the flour, the latter being the consummation anxiously sought, it is at least likely that the generally higher nitrogen content of grain will also bring with it a higher gluten content. Since, moreover, our investigations indicate that small quantities of the metallic salts are as effective in inducing the enrichment of grain in nitrogen as the larger quantities, it is further possible that the means suggested of raising the gluten content of grain may prove to be a very inexpensive one.

Absorption of Metals by Soil and Plant

In discussing such problems as the one which forms the subject here, the technical chemist will frequently ask to what extent plants will absorb such metals as have been studied by us. The literature on that topic is so rich in evidence that metals are readily absorbed, and in considerable quantity, by the plant that we did not deem it desirable to go at length into such an investigation with our harvested barley plants as a basis. We did, however, make analyses of a number of plants from pots receiving different treatments and also of the soils in some of the pots. We are therefore in a position to answer partly on the basis of our own data, the question above raised. On the subject of the absorption of metals by plants, the reader is referred for full and interesting discussions to Czapek,[116]

[116] Biochemie der Pflanzen, Jena, 1905.

Pfeffer,[117] Müller,[118] Lehmann,[119] and Brenchley.[120] In our analyses both grain and straw were examined, and copper and zinc only were determined. These were both determined electrolytically. Unlike Vedrodi,[121] we could find nothing more than traces of copper or zinc in the grain, but succeeded easily in obtaining definite quantities of those metals in the straw from some of the pots. In the first crop, from thirty-six to forty-three grams of straw were taken for analysis for copper, and, after ashing, the mineral residue was prepared for analysis for copper by the method above mentioned, straw from the pots receiving 100, 800, 1100, and 1200 p. p. m. $CuSO_4$ being employed. In the first case, the percentage of copper in the straw varied from nothing to 0.0006 per cent. In the second case, the percentage of copper was 0.0002. In the third case, it was 0.0033 per cent, and in the fourth case, 0.0044 per cent.

In the pots receiving $ZnSO_4$, there were chosen for analysis the straw produced in those receiving 100, 300, 500, 1000, 1100, 1200, 1300, and 1600 p. p. m. In the first case, the analysis showed the presence of zinc to the extent of 0.00036 per cent; in the second, 0.0008 per cent; in the third, 0.003 per cent; in the fourth, 0.017 per cent; in the fifth, 0.013 per cent; in the sixth, 0.013 per cent; in the seventh, 0.01 per cent; and in the eighth, 0.012 per cent. In the cases of both zinc and copper the percentage of the metals absorbed by the barley plant was smaller than that reported as being absorbed by the plants studied by other investigators whose work is referred to in the literature last cited. In general, it seems that up to a certain point increasing quantities of the metals added to the soil induce larger absorptions of metal by the plant, but beyond that point the addition of metals to the soil appears to be without effect in inducing further absorption. This seems to be particularly true in the case of the zinc. We do not desire, however, to draw any conclusions from the relatively meager data which we have gathered on the subject in question under

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[117] Pflanzenphysiologie, Leipzig, 1897 and 1901.

[118] Ztschr. Pflanzenkrank., 4, p. 142.

[119] Arch. Hyg., 27, p. 1.

[120] Inorganic plant poisons and stimulants, Cambridge, 1914.

[121] Chem. Ztg., 20, p. 399.

the conditions here discussed. Since it is rare in nature that more than the lowest concentrations of copper and zinc here studied ever occur in soils suited to crop production, the question of the danger in the use by man and animals of plants absorbing copper is not a serious one, for with small quantities of copper and zinc present in the soil, very small quantities only are absorbed by the plant. It must be added here, morever, that we employed easily water-soluble salts, whereas in nature the compounds of the metals found are principally those of a very insoluble nature. The latter circumstance would perforce make impossible any large concentration of any metal in the soil solution, and hence only small quantities could be absorbed by plants.

We were interested also in obtaining an inkling as to the fate of the copper and zinc added to the soil after three seasons of plant growth thereon. Accordingly, several soils were chosen for examination. Pots receiving 600, 1800, 2000, and 3000 p. p. m. $CuSO_4$ gave the following results: In the first case all the copper added was recovered. In the second case 1750 p. p. m., instead of 1800, were recovered. In the third case all the copper was recovered, and in the fourth case 2875 p. p. m. were recovered, instead of 3000 p. p. m.

In the case of zinc the pots receiving 800, 1700, and 2000 p. p. m. $ZnSO_4$ were studied. In the first case 750 p. p. m. were recovered. In the second case 1650 p. p. m. were recovered in one soil, and 1500 p. p. m. in another soil. In the third case only 1250 p. p. m. were recovered.

These data indicate that in the case of copper, at least, the soil clings tenaciously to the metal; and most of it, or nearly all of it, can be recovered from the soil even three seasons after it has been incorporated therewith, and three crops of barley grown in the interim. With zinc, there do appear to be losses. These may perhaps be explained in part by the larger amounts of zinc than copper absorbed by plants, and by the lesser accuracy of the method for its determination as compared with that employed for copper. Twenty-gram samples of soil were employed in all cases for obtaining the extracts which were analyzed, and it is therefore believed that the error involved in the analyses could not have been very large.

GENERAL AND PRACTICAL CONSIDERATIONS

The practical as much as the theoretical point of view inspired these investigations. In a time such as this, when the smelter question is of great significance in agricultural districts and when outcries against the damage caused by both smelter fumes and solid smelter wastes are most insistent, it appeared to us that the moment had arrived for wholly disinterested investigators to examine into it. Our experiments as described in this paper have dealt, in the main, with the effects on barley growth in three successive crops of the metals which would be likely to be deposited in the vicinity of smelters and gradually washed down into sources of irrigation water for the territory lying below the smelter plants. Despite the fact that we have used much more soluble forms of the so-called toxic salts than are likely to occur under the conditions just described, and despite the fact that we have employed both large and small amounts of these salts, we are unable to read into our results any serious danger to agriculture from the solids of smelter wastes as they may be transported to cropped lands by irrigation water. In making this statement we are not unmindful that very small areas occur[122] near the smelter plants in which the tailings may be carried down by streams and deposited on land in large quantities. These may, for example, carry enough of the toxic heavy metals to render land poor in producing capacity. But in the first place the most prejudiced persons will not claim that such affected areas of agricultural land are more than negligible quantities when the question is considered in the large; in the second place, even under conditions so extreme, none but the most biased will deny that proper methods of management can be made to render innocuous any harmful effects which the tailings in question may be potentially capable of exerting. These methods of management are clearly indicated and include the impounding of water carrying tailings or the passage of stream water through screens which will separate out

[122] See R. H. Forbes, "Certain effects under irrigation of copper compounds upon crops," Univ. Calif. Publ. Agri. Sci., 1, no. 12, 1917.

the tailings, and, in the case of the land which is already affected, the use of organic matter. The indications of our experiments are that a year or two of fallowing will usually correct the difficulty.

We are therefore obliged to reaffirm the position taken by Lipman and Wilson[123] to the effect that there seems to be little danger in store for our agricultural lands in the metallic residues which are deposited by smelters in their vicinity and from their ultimate solution in small degree in potential irrigation water-supplies which may be subsequently transported to farm lands. On the contrary, we give evidence above that so far from being toxic to barley plants, small amounts of the metals studied may be distinctly stimulating to them. While this is more strictly true in the case of some metals than of others, it appears none the less to be so. Moreover, in cases in which toxicity is effected by the application of any of the metallic sulfates named, it is usually very slight, even when large quantities of the salts are employed. While we have experimented in this series of investigations only with barley, evidences given by ourselves and by others who are above cited, indicate that a number of other plants behave similarly to barley, if not exactly like it. From the practical standpoint, therefore, we cannot see that any other conclusion can be reached than that we may virtually ignore any deleterious effects which may be urged against the metals of smelter wastes which are here discussed. We use the word "practical" here advisedly, because if solution instead of soil cultures were taken as a criterion, our standard of judgment would not be practical. Whatever may be said about soil cultures, one must admit that they approximate most closely of any greenhouse or laboratory methods the natural conditions under which crops grow. We cannot see that any other culture than one which at least offers a solid substratum to the plant may be regarded as valid in the determination of whether or not salts like those here under consideration are, under the conditions of the smelter and its vicinity, a menace to plant growth.

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[123] Bot. Gaz., 55, no. 6, p. 409, June, 1913.

To all this, however, there must be added some other considerations. One of them serves to qualify, in some measure at least, the remarks made above, and the other to supplement them. While the metals studied by us do not seem to have given evidence, under the conditions of our experiment, of any serious injury to barley, a non-metal, arsenic, has given marked evidences of toxicity to barley under similar conditions. Arsenic, being found frequently in conjunction with the other elements in the vicinity of smelters, is necessarily a subject worthy of attention. Our results with its use in soil cultures are not yet ready to be reported, but we hope sometime in the near future to publish them. Suffice it to say now that such compounds of arsenic as arsenic trisulfide and Paris green have proved to be extremely toxic to barley in both heavy and light soils, while lead arsenate has proved to be only slightly toxic. Whether or not arsenic oxide, which is the form to be expected in lands in the vicinity of smelters, will act similarly remains to be shown by further experiments which are now being planned by us.

We are constrained to add to the foregoing that we have borne in mind the difference in the effects produced on a toxic material by the change in a soil's constitution. Indeed, our experiments with copper in three widely different types of soil testify to that fact; and while we have found marked differences in the degrees of stimulation and toxicity of copper in the different soil types, all of the latter appear to have given both stimulation and toxicity. Even in the sandy soil in which the toxicity of $CuSO_4$ became manifest at the lowest concentration for any of the types of soil studied, as much as 0.03 per cent of $CuSO_4$ of the dry weight of the soil still acted as a stimulant to barley. Considering that $CuSO_4$ is an easily water-soluble salt, it would be reasonable to expect that such compounds as $Cu(OH)_2.CuCO_3$, which are the usual forms to be expected in soils near smelters, could be tolerated by plants in much larger quantities.

If, as appears to us reasonable, we should be able to accept the data above offered by us, at least as tentative evidence that we have little to fear from the solids of smelter wastes in the contamination of our irrigation water-supply and therefore in injuring large areas of land, we have another interesting proposition to bring forward. L. T. Sharp and the senior author[124] have already reported preliminary pot experiments in evidence of the fact that H_2SO_4 exerts a remarkable effect on alkali soil with the result of changing the latter from an unproductive state to a productive one. The probable reasons for this action are discussed in the paper referred to above. Suffice it to say here that field experiments which still remain unpublished amply confirm the pot experiments. If this should prove to be a more or less permanent effect on alkali soils which do not contain too high a percentage of salts (from 0.6 per cent to 0.8 per cent), then we could solve the other and really serious phase of the smelter question, namely, the smelter gases. Chemical engineers of note, including F. G. Cottrell of the Bureau of Mines, have often stated to the senior author that the chief reason that SO_2 fumes from the smelters are not made into H_2SO_4 is because there would be no use for such tremendous quantities of that acid. If, however, we should be able to apply H_2SO_4 to many alkali soils with good effect that objection would vanish. If, therefore, the smelters will only produce the acid cheaply enough, as they now seem inclined to do, we shall be able to banish much costly litigation, let the smelter industry develop untramelled, give the smelter companies compensation for oxidizing the SO_2, and last but not least, put large acreages of barren land into good crop-producing condition.

This proposition sounds almost chimerical, but much thought and work on it have convinced us that it is well justified by facts, and we believe that the condition just described will speedily come to pass. We mention the SO_2 problem here only in passing, since much fuller discussion of our experiments with H_2SO_4 on alkali soils is to appear in later papers. Suffice it to say, that we believe we have in it and in the experiments above discussed strong evidence of methods for controlling the smelter nuisance without injuring the industry or the farmer, and, besides, much evidence on the true effects of solids of smelter wastes on barley grown in soils.

124 Univ. Cal. Publ. Agri. Sci., vol. 1, p. 275.

THEORETICAL CONSIDERATIONS

A few words may not be out of place here with regard to the mechanism of the action of the different salts employed in our experiments, be such action in the direction of stimulation or in that of toxicity. In the first place, the salts in question must exercise some effect on the cell of the root itself and, through it, on the whole plant. If this were not so, we should not obtain the stimulating as well as the toxic effects of a given salt in solution cultures, as well as in soil cultures. In the latter, we do of course obtain more definite evidence of stimulation than in the former, and for that reason we may claim with some justice, as we have above, that stimulation effects are chiefly attributable to some influence, not always the same, induced by the salt on the soil, rather than on the root of the plant. This does not, to be sure, deny the existence of the latter effect in soil cultures and particularly in solution cultures; but when the most marked stimulation occurs, it is rarely noted in the latter. We therefore believe it reasonable to suppose that we are dealing under such circumstances with an effect on the soil, rather than with one on the plant root. What such salt effects on the soil may be like are explained above. It is not easy, however, to explain or even to speculate on an explanation of the effect of a salt directly on the plant root in the direction of stimulation. We have no unexceptionable evidence on the subject of compounds of copper, for example, with albuminoid material of living cells, and that increases the difficulty of accounting for observed facts of stimulation. It is nevertheless possible that stimulation of root cells by copper may be due to an effect of the latter in decreasing or increasing the permeability of the cell, or perhaps to the possible small content of iron in the copper compounds employed, the iron acting as one of the essential elements to cell development. Neither of these speculations at present appears to have value other than that of inducing further thought and discussion on the subject. So far as the toxic effects of salts on plants in solution cultures is concerned, nothing need be added here to the excellent discussions already given by Czapek and Pfeffer which are cited above, and by Hober.[125]

[125] Physikalische Chemie der Zelle und der Gewebe, Leipzig, 1914.

With regard to stimulation in soil cultures, there may be added here something which is not mentioned in the discussion above, namely, that the salts of the heavy metals may act with respect to oxydases as Loew[126] has claimed manganese does, augmenting their activity and thus preventing the accumulation of toxic materials in the soil. That such a catalytic effect does exist is, however, very doubtful in the light of present evidence. That other forms of catalytic effects may be exerted by such salts as those employed in our experiments is at least not impossible.

SUMMARY

The authors have been carrying on a series of investigations on the effects of $CuSO_4$, $ZnSO_4$, $FeSO_4$, $PbSO_4$, $MnSO_4$, $MnCl_2$, $KAl(SO_4)_2.12\,H_2O$, and different forms of arsenic on the growth of barley. The experiments were carried out in paraffined earthenware pots nine inches in diameter, greenhouse soil made up from clay adobe soil and barnyard manure being used principally. In the case of $CuSO_4$, two other soils were used in addition to the greenhouse soil, namely, the Oakley blow sand and the Berkeley clay adobe. With the greenhouse soil the experiment continued for three successive crops of barley; with the clay abode soil, for two crops; and with the blow sand for only one crop. The results of these experiments, which are set forth in the tables and discussion above, may be summarized and their significance indicated briefly as follows:

1. In the greenhouse soil, in the first crop $CuSO_4$ acts as a stimulant throughout from concentrations of 50 p. p. m. to 600 p. p. m. inclusive. When the roots are left out of consideration, it acts as a stimulant even to the highest concentration employed, viz., 1500 p. p. m.

In the second crop $CuSO_4$ acts as a stimulant to both roots and tops up to and including 1800 p. p. m., and is without effect on the roots, while stimulating to tops even at 2800 p. p. m. Grain production is stimulated by $CuSO_4$ in the second crop practically throughout the series.

126 Flora, 91, p. 264.

In the third crop both root and top production are stimulated up to and including concentrations of $CuSO_4$ equivalent to 2200 p. p. m. Grain production is almost similarly stimulated.

2. In the clay adobe soil in the first crop straw, grain, and root production are all stimulated up to and including concentrations of $CuSO_4$ equivalent to 800 p. p. m.

In the second crop no stimulation takes place in the 100 and 200 p. p. m. concentrations, but in all higher concentrations, at least including that equivalent to 900 p. p. m. This holds for both straw and root production.

3. In the Oakley blow sand, only one crop being grown, $CuSO_4$ stimulates markedly grain production and slightly straw and root production at concentrations up to and including 300 p. p. m. $CuSO_4$.

4. In the greenhouse soil in the $ZnSO_4$ series the first crop is stimulated both as to root and straw yields throughout at concentrations varying from 100 p. p. m. to 2000 p. p. m. $ZnSO_4$.

In the second crop stimulation to straw and root yields occurs at 200 p. p. m. $ZnSO_4$, and marked stimulation to root yield without effect on straw yields up to 600 p. p. m. $ZnSO_4$. Beyond that point slight toxicity sets in and is maintained almost uniformly throughout.

In the third crop neither stimulation nor toxicity is apparent at concentrations of 200 p. p. m. $ZnSO_4$, but concentrations in excess of the latter are distinctly toxic.

5. In the greenhouse soil in the $FeSO_4$ series, the first crop shows the stimulating effects of $FeSO_4$ throughout in concentrations varying from 0.1 per cent to 1 per cent. The straw yields are increased throughout and the root yields slightly so up to and including the concentration 0.7 per cent $FeSO_4$.

In the second crop $FeSO_4$ stimulates straw production in concentrations varying from 0.2 per cent to 1 per cent inclusive. Grain production is only slightly and irregularly stimulated at the same concentration. Root production is affected similarly to the grain production.

In the third crop concentrations from 1 per cent $FeSO_4$ up to and including 2 per cent are markedly stimulating to straw and grain yields and very slightly effective in both directions in regard to root yields. Smaller concentrations than those mentioned slightly depress straw and root production, but definitely stimulate grain production.

6. In the greenhouse soil in the $PbSO_4$ series, first crop, the straw production is depressed by about one-third the total amount produced in the control. The depression appears to be uniform at concentrations of from 200 p. p. m. to 1500 p. p. m. $PbSO_4$. Likewise, the root yields are depressed by even a greater figure (about 60 per cent), and again almost uniformly throughout.

In the second crop the straw production is nowhere depressed in the entire series and is stimulated at concentrations of from 300 p. p. m. to 600 p. p. m. $PbSO_4$ as well as at scattering concentrations in excess. Root production, on the other hand, is slightly depressed throughout.

In the third crop the straw production is markedly stimulated at concentrations varying from 1000 p. p. m. to 2400 p. p. m. $PbSO_4$, but slightly depressed at lower concentrations. Grain production is similarly affected, and the $PbSO_4$ remains without effect on the roots within the same limits of concentration.

7. In the greenhouse soil in the potash alum series the first crop shows stimulation to straw yields at all concentrations varying from applications of 300 pounds to 2000 pounds K_2O per acre. Root yields are stimulated at the lowest concentration named, but scarcely at all in the others.

In the second crop the straw yields are again stimulated by the doubling of the potash alum application throughout the series. Relatively the stimulation is much greater than in the first crop. Grain production and root production are also markedly stimulated, the former at the smaller applications of potash alum and in other isolated instances, and the latter throughout.

In the third crop the straw yield is markedly depressed throughout. The grain yields are slightly stimulated in some cases, and in the balance remain unaffected. The root yields are depressed similarly to the straw yields.

8. In the greenhouse soil in the $MnSO_4$ series the first crop is stimulated in regard to straw yields at all concentrations be-

tween 500 p. p. m. and 3000 p. p. m. $MnSO_4$, but most markedly at 1500 p. p. m. The root yields are also markedly stimulated, but only at concentrations up to and including 1500 p. p. m. Beyond that concentration, root yields are more or less reduced.

In the second crop the straw yields are stimulated at from 4000 p. p. m. to 6000 p. p. m. $MnSO_4$, but markedly depressed at concentrations below 4000 p. p. m. The grain yields are about equally depressed throughout, but not markedly. The root yields are depressed throughout the series rather markedly, the smallest depression occurring at concentrations of 2000 and 2500 p. p. m. $MnSO_4$.

In the third crop a stimulation is induced toward the production of straw, grain, and roots, the medium concentrations being most effective. Little or no evidence of toxic effects of $MnSO_4$ was observed.

9. In the greenhouse soil in the $MnCl_2$ series the first crop is markedly stimulated in straw production at concentrations varying from 500 to 1500 p. p. m. $MnCl_2$. Beyond the latter concentration, $MnCl_2$ becomes more and more acutely toxic, until almost no straw is produced at 6000 p. p. m. $MnCl_2$. Root production is affected similarly to straw production, in a general way.

In the second crop straw production is stimulated throughout except at the two lowest concentrations—500 and 1000 p. p. m. respectively. Grain yields, however, are depressed almost throughout. The depression is relatively slight (there being one case of stimulation) at concentrations varying from 500 p. p. m. to 3000 p. p. m. Above the latter concentration, the $MnCl_2$ is markedly toxic to grain production. Root production is markedly depressed throughout.

Like $MnSO_4$, $MnCl_2$ exerts a stimulating effect on the yields of straw, grain, and roots in the third crop. Again, little or no evidence of a toxic effect was noted in this series.

10. Results are given on the effect of the salts used on the nitrogen content of the grain produced, on the nitrifying powers of the soils concerned, on the amounts of copper and zinc taken up by some of the barley plants in the different series; and

also correlations are drawn between some of these factors and the complete yields of dry matter.

11. Some practical and theoretical phases of the smelter question are discussed, and the evidence above given is employed to show that from the large practical standpoint the solids of smelter wastes cannot justly be considered a menace to agriculture.

12. Many other points of interest are discussed in connection with the smelter problem as a whole and with the results of our experiments.

Transmitted September 7, 1916.

TABLE II*a*

$CuSO_4$ SET—FIRST CROP—GREENHOUSE SOIL

	$CuSO_4$ added to soil in parts per 1,000,000	Weight of straw	Average weight of straw	Weight of grain	Average weight of grain	Total weight of dry matter above surface	Average weight of dry matter above surface	Weight of roots	Average weight of roots	Total weight of dry matter produced	Average weight of total dry matter produced	Average total difference over control
		gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	
1	50	47.8	42.80	....	....	47.8	42.80	10.2	9.05	58.0	51.85	+12.09
2	50	37.8		....	....	37.8		7.9		45.7		
3	100	43.5	37.75	....	....	43.5	37.75	8.7	9.45	52.2	47.20	+ 7.44
4	100	32.0		....	....	32.0		10.2		42.2		
5	200	47.9	42.20	....	....	47.9	42.20	10.0	8.25	57.9	50.45	+10.69
6	200	36.5		....	....	36.5		6.5		43.0		
7	300	41.6	40.55	....	....	41.6	40.55	9.5	10.75	51.1	51.30	+11.54
8	300	39.5		....	....	39.5		12.0		51.5		
9	400	37.2	39.00	....	....	37.2	39.00	7.9	7.85	45.1	46.85	+ 7.09
10	400	40.8		....	....	40.8		7.8		48.6		
11	500	38.2	36.70	....	....	38.2	36.70	9.8	8.50	48.0	45.20	+ 5.44
12	500	35.2		....	....	35.2		7.2		42.4		
13	600	46.5	47.00	....	....	46.5	47.00	8.2	8.20	54.7	55.20	+15.44
14	600	47.5		....	....	47.5		8.2		55.7		
15	700	38.7	39.85	....	....	38.7	39.85	7.0	6.25	45.7	46.10	+ 6.34
16	700	41.0		....	....	41.0		5.5		46.5		
17	800	50.7	45.35	....	....	50.7	45.35	7.2	6.45	57.9	51.80	+12.04
18	800	40.0		....	....	40.0		5.7		45.7		
19	900	51.2	45.70	....	....	51.2	45.70	4.8	5.35	56.0	51.05	+11.29
20	900	40.2		....	....	40.2		5.9		46.1		
21	1000	44.6	43.55	....	....	44.6	43.55	5.5	5.25	50.1	48.80	+ 9.04
22	1000	42.5		....	....	42.5		5.0		47.5		
23	1100	35.8	39.05	....	....	35.8	39.05	3.9	4.40	39.7	43.45	+ 3.69
24	1100	42.3		....	....	42.3		4.9		47.2		
25	1200	40.0	41.25	....	....	40.0	41.25	4.8	4.35	44.8	45.60	+ 5.84
26	1200	42.5		....	....	42.5		3.9		46.4		
27	1300	38.4	40.10	....	....	39.4	40.10	4.2	4.55	43.6	44.65	+ 4.89
28	1300	40.8		....	....	40.8		4.9		45.7		
29	1400	42.8	38.35	....	....	42.8	38.35	3.8	4.30	46.6	42.65	+ 2.89
30	1400	33.9		....	....	33.9		4.8		38.7		
31	1500	37.2	37.65	....	....	37.2	37.65	6.0	4.75	43.2	42.40	+ 2.64
32	1500	38.1		....	....	38.1		3.5		41.6		
33	Control	31.5	32.50	....	....	31.5	32.50	7.8	7.26	39.3	39.76	
34	Control	31.2		....	....	31.2		6.9		38.1		
35	Control	34.8		....	....	34.8		7.1		41.9		

TABLE II*b*

$CuSO_4$ SET—SECOND CROP—GREENHOUSE SOIL

	$CuSO_4$ added to soil in parts per 1,000,000	Weight of straw gm.	Average weight of straw gm.	Weight of grain gm.	Average weight of grain gm.	Total weight of dry matter above surface gm.	Average weight of dry matter above surface gm.	Weight of roots gm.	Average weight of roots gm.	Total weight of dry matter produced gm.	Average weight of total dry matter produced gm.	Average total difference over control
1	100	9.90	10.25	8.10	9.55	17.0	19.30	5.0	5.60	22.0	24.90	+4.20
2	100	10.60		11.00		21.6		6.2		27.8		
3	200	......	......	......	......	......	......	......	......	......	......	......
4	200	......		......		......		......		......		
5	300	8.15	7.57	11.05	10.02	19.2	17.60	5.5	5.95	24.7	23.55	+2.85
6	300	7.00		9.00		16.0		6.4		22.4		
7	400	14.10	11.10	10.90	10.90	25.0	22.00	7.2	5.85	32.2	27.85	+7.15
8	400	8.10		10.90		19.0		4.5		23.5		
9	500	13.90	10.95	8.10	8.10	22.0	19.00	5.5	7.65	27.7	26.65	+5.95
10	500	8.00		8.00		16.0		9.8		25.8		
11	600	6.10	8.05	12.40	11.20	18.5	19.25	6.0	6.35	24.5	25.60	+4.90
12	600	10.00		10.00		20.0		6.7		26.7		
13	700	13.15	11.75	11.85	12.50	25.0	24.20	6.0	5.10	31.0	29.30	+8.60
14	700	10.25		13.15		23.4		4.2		27.6		
15	800	8.77	10.98	9.23	9.01	18.0	20.00	9.0	7.35	27.0	27.35	+6.65
16	800	13.20		8.80		22.0		5.7		27.7		
17	900	15.45	12.07	9.15	8.22	24.6	20.30	7.3	6.55	31.9	26.85	+6.15
18	900	8.70		7.30		16.0		5.8		21.8		
19	1000	12.45	12.16	15.05	11.39	27.5	23.55	5.5	4.85	33.0	28.40	+7.70
20	1000	11.88		7.72		19.6		4.2		23.8		
21	1100	......	......	......	......	......	......	......	......	......	......	......
22	1100	......		......		......		......		......		
23	1200	7.45	9.27	11.75	13.73	19.2	23.00	5.5	5.00	24.7	28.00	+7.30
24	1200	11.10		15.70		26.8		4.5		31.3		
25	1300	12.75	10.97	8.75	10.02	21.5	21.00	4.9	4.80	26.4	25.80	+5.10
26	1300	9.20		11.30		20.5		4.7		25.2		
27	1400	12.60	12.37	13.20	12.52	25.8	24.90	5.5	5.60	30.3	30.50	+9.80
28	14.00	12.15		11.85		24.0		5.7		29.7		
29	1500	8.45	8.45	10.15	10.15	18.6	18.60	3.2	3.20	21.8	21.80	+1.10
30	1500	......		......		......		......		......		
31	Control	6.00	7.13	9.20	9.37	15.2	16.50	4.0	4.20	19.2	20.70	
32	Control	8.26		9.54		17.8		4.4		22.2		

TABLE II*c*

$CuSO_4$ Set—Third Crop—Greenhouse Soil

	$CuSO_4$ added to soil in parts per 1,000,000	Weight of straw	Average weight of straw	Weight of grain	Average weight of grain	Total weight of dry matter above surface	Average weight of dry matter above surface	Weight of roots	Average weight of roots	Total weight of dry matter produced	Average weight of total dry matter produced	Average total difference over control
		gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	
1	100	23.90	19.45	2.60	2.80	26.5	22.25	6.5	9.75	33.00	32.00	+5.37
2	100	15.00		3.00		18.0		13.0		31.00		
3*	200	18.25	21.17	5.75	4.32	24.0	25.50 }	15.5	{ 7.75	31.75	33.25	+6.62
4*	200	24.10		2.90		27.0				34.75		
5	300	19.42	16.71	2.48	2.48	21.8	17.90	10.2	8.35	32.00	26.25	—0.38
6	300	14.00		......		14.0		6.5		20.50		
7	400	14.05	14.00	4.45	4.25	18.5	18.25	11.0	11.00	29.50	29.25	+2.62
8	400	13.94		4.06		18.0		11.0		29.00		
9	500	16.36	16.03	2.74	3.52	19.0	19.50	9.0	8.25	28.00	27.75	+1.12
10	500	15.70		4.30		20.0		7.5		27.50		
11	600	12.85	17.72	1.15	1.23	14.0	18.95	12.0	10.60	26.00	29.55	+2.92
12	600	22.60		1.30		23.9		9.2		33.10		
13	700	18.05	16.35	3.55	2.85	21.6	19.20	9.0	9.00	30.60	28.20	+1.57
14	700	14.65		2.15		16.8		......		25.80		
15	800	12.30	15.30	3.70	3.20	16.0	18.50	7.8	6.40	23.80	24.90	—1.73
16	800	18.30		2.70		21.0		5.0		26.00		
17	900	21.20	20.75	......	4.30	25.5	25.05	7.2	10.60	32.70	35.65	+9.02
18	900	20.30		4.30		24.6		14.0		38.60		
19	1000	17.65	23.15	1.85	2.60	19.5	25.75	10.0	9.50	29.50	35.25	+8.62
20	1000	28.65		3.35		32.0		9.0		41.00		
21	1100	15.20	17.95	1.80	1.50	17.0	19.45	9.0	9.00	26.00	28.45	+1.82
22	1100	20.70		1.20		21.9		9.0		30.90		
23	1200	14.80	15.60	2.70	2.90	17.5	18.50	5.7	6.85	23.20	25.35	—1.28
24	1200	16.40		3.10		19.5		8.0		27.50		
25	1300	18.20	17.95	3.00	2.75	21.2	20.70	4.5	5.25	25.70	25.95	—0.68
26	1300	17.70		2.50		20.2		6.0		26.20		
27	1400	18.90	20.70	3.30	3.30	22.2	22.35 }	15.3	{ 7.65	29.85	30.00	+3.37
28	1400	22.50		......		22.5				30.15		
29	1500	14.00	17.65	4.50	4.35	18.5	22.00	11.0	8.05	29.50	30.05	+3.42
30	1500	21.30		4.20		25.5		5.1		30.60		
31	Control	12.40	16.53	2.10	2.25	14.5	18.03	9.8	8.60	24.30	26.63	
32	Control	16.20		2.40		18.6		9.0		27.60		
33	Control	21.00		......		21.0		7.0		28.00		

* Second crop.

TABLE IIIa

$CuSO_4$—First Crop—Adobe Soil

	$CuSO_4$ added to soil in parts per 1,000,000	Weight of straw	Average weight of straw	Weight of grain	Average weight of grain	Total weight of dry matter above surface	Average weight of dry matter above surface	Weight of roots	Average weight of roots	Total weight of dry matter produced	Average weight of total dry matter produced	Average total difference over control
		gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	
1	100	9.50	4.89	......	3.72	9.5	8.75	0.80	1.10	10.30	9.85	+1.93
2	100	4.28		3.72		8.0		1.40		9.40		
3*	200	4.00	3.50	......	......	4.0	3.50	1.20	1.00	5.20	4.50	—2.42
4*	200	3.00		......		3.0		.80		3.80		
5	300	5.90	4.25	4.10	4.50	10.0	8.75	1.40	1.05	11.40	9.80	+1.88
6	300	2.60		4.90		7.5		.70		8.20		
7	400	2.70	3.43	3.90	4.38	6.5	7.75	1.20	1.55	7.70	9.30	+1.38
8	400	4.15		4.85		9.0		1.90		10.90		
9	500	5.15	6.30	1.95	2.25	7.1	8.65	.85	1.00	7.95	9.65	+1.73
10	500	7.45		2.55		10.2		1.15		11.35		
11	600	5.05	4.53	4.65	4.02	9.7	8.60	1.00	.92	10.70	9.52	+1.60
12	600	4.10		3.40		7.5		.85		8.35		
13	700	3.20	5.18	3.80	3.58	7.0	8.75	.65	.75	7.65	9.50	+1.58
14	700	7.15		3.35		10.5		.85		11.35		
15	800	4.15	4.63	4.35	3.33	8.5	7.95	1.00	.80	9.50	8.75	+0.83
16	800	5.10		2.30		7.4		.60		8.00		
17	900	6.75	7.43	3.05	3.05	9.8	9.00	.85	1.02	10.65	10.00	+2.10
18	900	8.20		......		8.2		1.20		9.40		
19	1000	2.70	3.10	1.60	1.60	4.3	3.75	.45	.52	4.75	4.42	—3.50
20	1000	3.50		......		3.5		.60		4.10		
21	1200	4.10	4.95	1.90	1.90	6.0	5.90	.70	.70	6.70	6.60	—1.32
22	1200	5.80		......		5.8		.70		6.50		
23	1500	2.90	2.90	.60	.60	3.5	3.50	.20	.20	3.70	3.70	—4.22
24†	1500	......	......	......	......	----	......	......	......	......	......	
25†	2000	......		......		----		......		......	......	
26	Control	5.20	4.14	2.20	3.06	7.4	7.20	.95	.73	8.35	7.92	
27	Control	3.08		3.92		7.0		.50		7.50		

* Poor plants due perhaps to location of pots.

† Nos. 24 and 25—no growth.

TABLE III*b*

$CuSO_4$ SET—SECOND CROP—ADOBE SOIL

	$CuSO_4$ added to soil in parts per 1,000,000	Weight of straw	Average weight of straw	Weight of grain	Average weight of grain	Total weight of dry matter above surface	Average weight of dry matter above surface	Weight of roots	Average weight of roots	Total weight of dry matter produced	Average weight of total dry matter produced	Average total difference over control
		gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	
1	100	6.5	6.25	......	......	6.5	6.25	0.45	0.92	6.95	7.18	—1.91
2	100	6.0		......		6.0		1.40		7.40		
3	200	7.5	7.50	......	......	7.5	7.50	1.55	1.52	9.05	9.02	—0.07
4	200	7.5		......		7.5		1.50		9.00		
5	300	9.0	8.85	......	......	9.0	8.85	1.50	1.60	10.50	10.45	+1.36
6	300	8.7		......		8.7		1.70		10.40		
7	400	6.0	6.25	......	......	6.0	6.25	2.55	2.42	8.55	8.68	—0.41
8	400	6.5		......		6.5		2.30		8.80		
9	500	8.5	8.00	......	......	8.5	8.00	1.95	1.95	10.45	9.95	+0.86
10	500	7.5		......		7.5		1.95		9.45		
11	600	8.8	9.40	......	......	8.8	9.40	3.60	2.95	12.40	12.35	+3.26
12	600	10.0		......		10.0		2.30		12.30		
13	700	10.2	9.35	......	......	10.2	9.35	2.10	1.95	12.30	11.30	+2.21
14	700	8.5		......		8.5		1.80		10.30		
15	800	10.5	9.85	......	......	10.5	9.85	1.40	1.60	11.90	11.45	+2.36
16	800	9.2		......		9.2		1.80		11.00		
17	900	9.5	10.60	......	......	9.5	10.60	2.00	2.00	11.50	12.60	+3.51
18	900	11.7		......		11.7		2.00		13.70		
19	1000	8.8	7.90	......	......	8.8	7.90	2.00	2.75	10.80	10.65	+1.56
20	1000	7.0		......		7.0		3.50		10.50		
21	1200	7.2	7.25	......	......	7.2	7.25	1.65	1.50	8.85	8.75	—0.34
22	1200	7.3		......		7.3		1.35		8.65		
23	1500	10.0	9.00	......	......	10.0	9.00	1.30	1.32	11.30	10.32	+1.23
24	1500	8.0		......		8.0		1.35		9.35		
25	2000	5.1	5.10	......	......	5.1	5.10	0.32	.032	5.42	5.42	—3.67
26	Control	7.0	7.25	......	......	7.0	7.25	1.93	1.84	8.93	9.09	
27	Control	7.5		......		7.5		1.75		9.25		

TABLE IV

$CuSO_4$—First Crop—Oakley Soil

	$CuSO_4$ added to soil in parts per 1,000,000	Weight of straw	Average weight of straw	Weight of grain	Average weight of grain	Total weight of dry matter above surface	Average weight of dry matter above surface	Weight of roots	Average weight of roots	Total weight of dry matter produced	Average weight of total dry matter produced	Average total difference over control
		gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	
1	100	4.78	4.52	1.72	1.79	6.5	6.30	2.10	1.85	8.60	8.15	+2.15
2	100	4.25		1.85		6.1		1.60		7.70		
3	200	3.68	3.43	2.32	2.52	6.0	5.95	2.70	2.40	8.70	8.35	+2.35
4	200	3.17		2.73		5.9		2.10		8.00		
5	300	3.90	3.80	2.30	2.40	6.2	6.20	1.30	1.10	7.30	7.20	+1.20
6	300	3.70		2.50		6.2		.90		7.10		
7	400	2.40	2.40	1.60	1.60	4.0	4.00	.55	.55	4.55	4.55	—1.45
8	400	......		......		....		......		......		
9	500	2.90	2.75	1.20	1.30	4.1	4.05	.15	.15	4.25	4.20	—1.80
10	500	2.60		1.40		4.0		.15		4.15		
11	600	2.85	3.53	2.35	2.67	5.2	6.20	......	......	5.20	6.20	+0.20
12	600	4.20		3.00		7.2		......		7.20		
13	700	2.40	2.80	1.30	1.40	3.7	4.20	......	......	3.70	4.20	—1.80
14	700	3.20		1.50		4.7		......		4.70		
15	800	1.20	1.20	......	......	1.2	1.20	.10	.10	1.30	1.30	—4.70
16	800	......		......		....		......		......		
17	900	.20	.20	......	......	.2	.20	......	......	.20	.20	—5.80
18	900	......		......		....		......		......		
19	1000	......	......	......	......	....	......	......	......	......	......	......
20	1000	......		......		....		......		......		
21	1200	......	......	......	......	....	......	......	......	......	......	......
22	1200	......		......		....		......		......		
23	Control	2.80	3.40	1.30	1.30	4.1	4.05	1.60	1.95	5.70	6.00	
24	Control	4.00		......		4.0		2.30		6.30		

TABLE Va

ZnSO$_4$ Set—First Crop—Greenhouse Soil

	$ZnSO_4$ added to soil in parts per 1,000,000	Weight of straw	Average weight of straw	Weight of grain	Average weight of grain	Total weight of dry matter above surface	Average weight of dry matter above surface	Weight of roots	Average weight of roots	Total weight of dry matter produced	Average weight of total dry matter produced	Average total difference over control
		gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	
1	100	38.9	37.45	......	......	38.9	37.45	8.6	8.55	47.5	46.00	+ 4.30
2	100	36.0		......		36.0		8.5		44.5		
3	300	38.9	36.55	......	......	38.9	36.55	7.5	7.60	46.4	44.15	+ 2.45
4	300	34.2		......		34.2		7.7		41.9		
5	500	37.4	39.10	......	......	37.4	39.10	6.5	9.90	43.9	49.00	+ 7.30
6	500	40.8		......		40.8		13.3		54.1		
7	700	46.8	40.30	......	......	46.8	40.30	8.6	10.60	55.4	50.90	+ 9.20
8	700	33.8		......		33.8		12.6		46.4		
9	900	41.4	41.30	......	......	41.4	41.30	8.1	8.00	49.5	49.30	+ 7.60
10	900	41.2		......		41.2		7.9		49.1		
11	1100	41.1	42.30	......	......	41.1	42.30	7.7	9.25	48.8	51.55	+ 9.85
12	1100	43.5		......		43.5		10.8		54.3		
13	1200	42.2	41.40	......	......	42.2	41.40	8.3	8.50	50.5	49.90	+ 8.20
14	1200	40.6		......		40.6		8.7		49.3		
15	1300	31.2	31.35	......	......	31.2	31.35	12.0	12.00	43.2	43.35	+ 1.65
16	1300	31.5		......		31.5		......		43.5		
17	1400	36.7	34.85	......	......	36.7	34.85	10.8	11.15	47.5	46.00	+ 4.30
18	1400	33.0		......		33.0		11.5		44.5		
19	1500	38.5	38.10	......	......	38.5	38.10	6.2	7.50	44.7	45.60	+ 3.90
20	1500	37.7		......		37.7		8.8		46.5		
21	1600	37.0	36.00	......	......	37.0	36.00	11.3	12.15	48.3	48.15	+ 6.45
22	1600	35.0		......		35.0		13.0		48.0		
23	1700	35.8	36.80	......	......	35.8	36.80	9.3	10.60	45.1	47.40	+ 5.70
24	1700	37.8		......		37.8		11.9		49.7		
25	1800	38.7	38.10	......	......	38.7	38.10	10.0	10.20	48.7	48.30	+ 6.60
26	1800	37.5		......		37.5		10.4		47.9		
27	1900	43.8	41.90	......	......	43.8	41.90	13.0	13.15	56.8	55.05	+13.35
28	1900	40.0		......		40.0		13.3		53.3		
29	2000	31.0	35.60	......	......	31.0	35.60	10.4	10.85	41.4	46.45	+ 4.75
30	2000	40.2		......		40.2		11.3		51.5		
31	Control	30.2	33.40	......	......	30.2	33.40	8.5	8.30	38.7		
32	Control	36.6		......		36.6		8.1		44.7	41.70	

TABLE V*b*

$ZnSO_4$ Set—Second Crop—Greenhouse Soil

	$ZnSO_4$ added to soil in parts per 1,000,000	Weight of straw	Average weight of straw	Weight of grain	Average weight of grain	Total weight of dry matter above surface	Average weight of dry matter above surface	Weight of roots	Average weight of roots	Total weight of dry matter produced	Average weight of total dry matter produced	Average total difference over control
		gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	
1	100	12.50	12.40	3.50	3.50	16.00	15.90	3.5	3.55	19.50	19.45	+2.95
2	100	12.30		3.50		15.80		3.6		19.40		
3	300	8.60	7.95	4.40	4.05	13.00	12.00	6.0	5.80	19.00	17.80	+1.30
4	300	7.30		3.70		11.00		5.6		16.60		
5	500	4.82	4.65	4.38	5.05	9.20	9.70	6.3	4.65	15.50	14.35	—2.15
6	500	4.48		5.72		10.20		3.0		13.20		
7	700	8.80	7.84	......	6.11	8.80	10.90	4.6	4.30	13.40	15.20	—1.30
8	700	6.89		6.11		13.00		4.0		17.00		
9	900	5.80	5.77	6.70	4.98	12.50	10.75	3.0	4.10	15.50	14.85	—1.65
10	900	5.74		3.26		9.00		5.2		14.20		
11	1100	4.93	7.96	3.07	3.07	8.00	9.50	4.3	4.40	12.30	13.90	—2.60
12	1100	11.00		......		11.00		4.5		15.50		
13	1200	7.65	7.40	......	6.35	14.00	13.75	3.7	3.50	17.70	17.25	—0.75
14	1200	7.15		6.35		13.50		3.3		16.80		
15	1300	6.20	7.55	4.30	4.44	10.50	12.00	3.8	3.90	14.30	15.90	—0.60
16	1300	8.91		4.59		13.50		4.0		17.50		
17	1400	6.29	7.66	4.71	4.74	11.00	12.40	2.8	2.50	13.80	14.90	—1.60
18	1400	9.03		4.77		13.80		2.2		16.00		
19	1500	10.40	7.92	......	4.55	10.40	10.20	2.5	3.00	12.90	13.20	—3.30
20	1500	5.45		4.55		10.00		3.5		13.50		
21	1600	5.08	5.49	5.72	4.41	10.80	9.90	3.7	3.35	14.50	13.25	—3.25
22	1600	5.90		3.10		9.00		3.0		12.00		
23	1700	5.08	4.41	3.42	4.24	8.50	8.65	3.2	3.05	11.70	11.70	—4.80
24	1700	3.74		5.06		8.80		2.9		11.70		
25	1800	6.45	6.77	4.05	3.72	10.50	10.50	2.9	3.20	13.40	13.70	—2.80
26	1800	7.10		3.40		10.50		3.5		14.00		
27	1900	6.36	5.97	3.04	2.63	9.40	8.10	1.8	2.80	11.20	10.90	—5.60
28	1900	4.58		2.22		6.80		3.8		10.60		
29	2000	6.52	6.17	3.46	3.30	10.00	9.50	2.5	2.25	12.50	11.75	—4.85
30	2000	5.85		3.15		9.00		2.0		11.00		
31	Control	7.50	8.28	4.70	5.42	12.20	13.70	2.6	2.80	14.80	16.50	
32	Control	9.06		6.14		15.20		3.0		17.20		

TABLE V*c*

$ZnSO_4$ SET—THIRD CROP—GREENHOUSE SOIL

	$ZnSO_4$ added to soil in parts per 1,000,000	Weight of straw	Average weight of straw	Weight of grain	Average weight of grain	Total weight of dry matter above surface	Average weight of dry matter above surface	Weight of roots	Average weight of roots	Total weight of dry matter produced	Average weight of total dry matter produced	Average total difference over control
		gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	
1*	100	23.74	21.32	8.62	5.36	32.29	26.65	9.5	9.00	41.7	35.65	+ 4.89
2	100	18.90		2.10		21.00		8.5		29.5		
3	300	19.50	19.70	2.50	2.15	21.90	21.80	5.0	5.65	26.9	27.45	— 3.31
4	300	19.90		1.80		21.70		6.3		28.0		
5	500	20.70	17.12	3.80	2.87	24.50	20.00	5.0	4.85	29.5	24.85	— 5.91
6	500	13.55		1.95		15.50		4.7		20.2		
7	700	18.32	17.99	2.68	2.52	21.00	20.50	4.8	4.75	25.8	25.25	— 5.51
8	700	17.67		2.37		20.00		4.7		24.7		
9	900	17.40	17.05	1.60	2.45	19.00	19.50	5.5	5.05	24.5	24.55	— 6.21
10	900	16.70		3.30		20.00		4.6		24.6		
11	1100	18.60	17.91	1.80	2.29	20.40	20.20	5.7	5.10	26.1	25.30	— 5.46
12	1100	17.22		2.78		20.00		4.5		24.5		
13	1200	21.75	20.82	2.25	1.62	24.00	22.50	5.0	4.60	29.0	27.10	— 3.66
14	1200	19.90		1.10		21.00		4.2		25.2		
15	1300	15.75	13.65	.75	1.60	16.50	15.25	4.5	4.50	21.0	19.75	—11.01
16	1300	11.55		2.45		14.00		4.5		18.5		
17	1400	15.15	16.55	.85	.75	16.00	17.30	4.0	4.00	20.0	21.30	— 9.46
18	1400	17.95		.65		18.60		....		22.6		
19	1500	14.35	12.90	3.15	2.10	17.40	15.00	5.5	4.25	22.9	19.25	—11.51
20	1500	11.55		1.05		12.60		3.0		15.6		
21	1600	14.55	13.72	2.55	2.40	17.10	16.15	5.5	5.15	22.6	21.30	— 9.46
22	1600	12.90		2.30		15.20		4.8		20.0		
23	1700	9.98	13.45	1.02	1.52	11.00	15.00	3.5	4.00	15.0	19.00	—11.68
24	1700	16.93		2.03		19.00		4.5		23.0		
25	1800	12.75	13.00	1.25	1.25	14.00	14.25	3.0	2.70	17.0	16.95	—13.73
26	1800	13.25		1.25		14.50		2.4		16.9		
27	1900	13.80	13.34	2.50	2.06	16.30	15.40	2.4	2.35	18.7	17.75	—13.01
28	1900	12.88		1.62		14.50		2.3		16.8		
29	2000	11.56	11.17	2.44	1.67	14.00	21.85	2.0	2.65	16.0	15.75	—15.01
30	2000	10.79		0.91		11.70		3.3		15.5		
31	Control	16.50	20.03	2.10	2.25	18.60	21.53	10.5	9.23	29.1	30.76	
32	Control	22.10		2.40		24.50		8.2		32.7		
33	Control	21.50		......		21.50		9.0		30.5		

* Contaminated by rain.

TABLE VI*a*

$FeSO_4$ Set—First Crop—Greenhouse Soil

	$FeSO_4$ added to soil in terms of percentage	Weight of straw	Average weight of straw	Weight of grain	Average weight of grain	Total weight of dry matter above surface	Average weight of dry matter above surface	Weight of roots	Average weight of roots	Total weight of dry matter produced	Average weight of total dry matter produced	Average total difference over control
		gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	
1	0.1	40.0	39.95	......	......	40.0	39.95	10.6	9.05	50.6	49.00	+8.20
2	0.1	39.9		......		39.9		7.5		47.4		
3	0.2	39.7	35.45	......	......	39.7	35.45	6.0	7.20	45.7	42.65	+1.85
4	0.2	31.2		......		31.2		8.4		39.6		
5	0.3	43.7	40.30	......	......	43.7	40.30	7.0	9.45	50.0	49.75	+8.95
6	0.3	36.9		......		36.9		11.9		48.8		
7	0.4	41.0	39.90	......	......	41.0	39.90	6.3	8.65	47.3	48.55	+7.85
8	0.4	38.8		......		38.8		11.0		49.8		
9	0.5	34.0	35.25	......	......	34.0	35.25	9.2	8.40	43.2	43.65	+2.85
10	0.5	36.5		......		36.5		7.6		44.1		
11	0.6	38.5	39.10	......	......	38.5	39.10	9.7	8.50	48.2	47.60	+6.80
12	0.6	39.7		......		39.7		7.3		47.0		
13	0.7	28.2	36.30	......	......	28.2	36.30	13.4	9.60	41.6	45.90	+5.10
14	0.7	44.4		......		44.4		5.8		50.2		
15	0.8	32.8	38.20	......	......	32.8	38.20	4.2	5.65	37.0	43.85	+3.05
16	0.8	43.6		......		43.6		7.1		50.7		
17	0.9	37.1	36.80	......	......	37.1	36.80	6.9	6.70	44.0	43.50	+2.70
18	0.9	36.5		......		36.5		6.5		43.0		
19	1.0	38.7	34.85	......	......	28.7	34.85	5.9	6.35	34.6	41.20	+0.40
20	1.0	41.0		......		41.0		6.8		47.8		
21	Control	34.8	32.50	......	......	34.8	32.50	8.5	8.30	43.3	40.80	
22	Control	30.2		......		30.2		8.1		38.3		

TABLE VI*b*

$FeSO_4$ SET—SECOND CROP—GREENHOUSE SOIL

	$FeSO_4$ added to soil in terms of percentage	Weight of straw	Average weight of straw	Weight of grain	Average weight of grain	Total weight of dry matter above surface	Average weight of dry matter above surface	Weight of roots	Average weight of roots	Total weight of dry matter produced	Average weight of total dry matter produced	Average total difference over control
		gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	
1	0.1	11.20	8.83	2.60	5.16	13.80	14.00	4.3	4.90	18.10	18.90	+2.17
2	0.1	6.47		7.73		14.20		5.5		19.70		
3	0.2	9.90	8.32	6.50	6.47	16.40	14.80	4.7	4.95	21.10	19.75	+3.02
4	0.2	6.75		6.45		13.20		5.2		18.40		
5	0.3	9.30	7.40	6.50	5.50	15.80	12.90	4.7	5.35	20.50	18.25	+1.52
6	0.3	5.50		4.50		10.00		6.0		16.00		
7	0.4	9.45	8.13	4.55	5.01	14.00	13.15	3.0	3.10	17.00	16.25	—0.48
8	0.4	6.82		5.48		12.30		3.2		15.50		
9	0.5	......		......		....		....		....		
10	0.5	8.25	8.25	6.75	6.75	15.00	15.00	3.5	3.50	18.50	18.50	+1.77
11	0.6	6.90	7.49	4.30	4.16	11.20	11.65	3.5	3.60	14.70	15.25	—1.48
12	0.6	8.08		4.02		12.10		3.7		15.80		
13	0.7	6.27	6.33	5.03	6.06	11.30	12.40	3.0	3.00	14.30	15.40	—1.33
14	0.7	6.40		7.10		13.50		3.0		16.50		
15	0.8	8.50	7.20	6.50	4.05	15.00	11.20	2.7	2.40	17.70	13.60	—3.13
16	0.8	5.90		1.60		7.50		2.1		9.60		
17	0.9	......		......	......	....	....	....	......	....	....	......
18	0.9	6.80		......		6.80	6.80	2.5	2.50	9.30	9.30	—7.43
19	1.0	5.40	5.40	1.10	1.10	6.50	6.50	2.5	2.50	9.00	9.00	—7.73
20	1.0	......		......		......		....		......		
21	Control	7.30	7.68	4.70	5.42	12.00	13.13	2.0	3.60	14.00		
22	Control	8.06		6.14		15.20		4.4		19.60	16.73	
23	Control	12.20		......		12.20		4.4		16.60		

TABLE VI*c*

$FeSO_4$ SET—THIRD CROP—GREENHOUSE SOIL

	$FeSO_4$ added to soil in terms of percentage	Weight of straw	Average weight of straw	Weight of grain	Average weight of grain	Total weight of dry matter above surface	Average weight of dry matter above surface	Weight of roots	Average weight of roots	Total weight of dry matter produced	Average weight of total dry matter produced	Average total difference over control
		gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	
1	0.1	19.00	17.55	......	0.47	19.0	19.90	7.0	7.50	26.0	27.40	— 3.15
2	0.1	16.10		4.70		20.8		8.0		28.8		
3	0.2	20.05	17.80	1.85	3.05	21.9	20.85	8.2	8.10	29.9	28.95	— 1.60
4	0.2	15.55		4.25		19.8		8.0		28.0		
5	0.3	13.75	14.27	5.65	4.82	19.4	19.60	4.4	4.80	23.8	24.40	— 6.15
6	0.3	15.80		4.00		19.8		5.2		25.0		
7	0.4	20.70	19.17	4.80	4.07	25.5	23.75	5.8	6.40	31.3	30.15	— 0.40
8	0.4	18.65		3.35		22.0		7.0		29.0		
9*	0.5	34.80	25.87	......	4.05	34.8	27.90	4.0	6.75	38.8	34.65	+ 4.10
10	0.5	16.95		4.05		21.0		9.5		30.5		
11	0.6	14.45	13.87	4.55	4.12	19.0	18.00	5.0	5.40	24.0	23.40	— 7.15
12	0.6	13.30		3.70		17.0		5.8		22.8		
13	0.7	25.62	23.31	4.40	4.10	30.2	27.50	6.2	8.75	36.4	36.35	+ 5.85
14	0.7	21.00		3.80		24.8		11.5		36.3		
15	0.8	31.90	27.41	2.60	3.23	34.5	30.65	6.0	8.15	40.5	38.80	+ 8.25
16	0.8	22.93		3.87		26.8		10.3		37.1		
17	0.9	28.90	21.52	2.30	4.57	31.2	26.10	6.7	7.00	37.9	33.10	+ 2.55
18	0.9	14.15		6.85		21.0		7.3		28.3		
19	1.0	20.10	27.60	8.90	7.40	29.0	35.00	9.7	8.95	38.7	43.95	+13.40
20*	1.0	35.10		5.90		41.0		8.2		49.2		
21	Control	22.40	19.30	2.10	2.25	24.5	21.55	7.5	9.00	32.0	30.55	
22	Control	16.20		2.40		18.6		10.5		29.1		

* Failed to grow second crop.

TABLE VII*a*

$PbSO_4$ Set—First Crop—Greenhouse Soil

	$PbSO_4$ added to soil in parts per 1,000,000	Weight of straw	Average weight of straw	Weight of grain	Average weight of grain	Total weight of dry matter above surface	Average weight of dry matter above surface	Weight of roots	Average weight of roots	Total weight of dry matter produced	Average weight of total dry matter produced	Average total difference over control
		gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	
1	200	16.5	21.00	......	......	16.5	21.00	4.4	4.40	20.9	25.40	—14.95
2	200	25.5		......		25.5		4.4		29.9		
3	300	19.5	21.30	......	......	19.5	21.30	5.1	4.05	24.6	25.35	—15.00
4	300	23.1		......		23.1		3.0		26.1		
5	400	21.3	22.20	......	......	21.3	22.20	5.2	4.75	26.5	26.95	—13.40
6	400	23.1		......		23.1		4.3		27.4		
7*	500	18.4	18.40	......	......	18.4	18.40	3.8	3.80	22.2	22.20	—18.15
8	500	......		......		......		....		......		
9	600	22.2	23.30	......	......	22.2	23.30	3.2	2.80	25.4	26.10	—14.25
10	600	24.4		......		24.4		2.4		26.8		
11	700	24.0	23.60	......	......	24.0	23.60	4.0	3.00	28.0	26.60	—13.75
12	700	23.2		......		23.2		2.0		25.2		
13	800	26.8	21.90	......	......	26.8	21.90	6.8	4.40	33.6	26.30	—14.05
14	800	17.0		......		17.0		2.0		19.0		
15	900	26.8	28.55	......	......	26.8	28.55	3.8	4.20	30.6	32.75	— 7.60
16	900	30.3		......		30.3		4.6		34.9		
17	1000	22.0	21.75	......	......	22.0	21.75	5.4	3.95	27.4	25.70	—14.65
18	1000	21.5		......		21.5		2.5		24.0		
18	1100	18.2	23.35	......	......	18.2	23.35	5.3	5.40	23.5	28.75	—11.60
20	1100	28.5		......		28.5		5.5		34.0		
21	1200	21.9	23.95	......	......	21.9	23.95	3.6	4.55	25.5	28.50	—11.85
22	1200	26.0		......		26.0		5.5		31.5		
23	1300	23.8	25.85	......	......	23.8	25.85	6.8	4.40	30.6	30.25	—10.10
24	1300	27.9		......		27.9		2.0		29.9		
25	1400	25.0	21.60	......	......	25.0	21.60	2.9	3.55	27.9	25.15	—15.20
26	1400	18.2		......		18.2		4.2		22.4		
27	1500	17.8	22.25	......	......	17.8	22.25	1.8	2.50	19.6	24.75	—15.60
28	1500	26.7		......		26.7		3.2		29.9		
29	Control	34.8	30.00	......	......	34.8	30.00	6.5	10.35	41.3	40.35	
30	Control	25.2		......		25.2		14.2		39.4		

* Poor plants.

TABLE VIIb

PbSO₄ Set—Second Crop—Greenhouse Soil

	$PbSO_4$ added to soil in parts per 1,000,000	Weight of straw	Average weight of straw	Weight of grain	Average weight of grain	Total weight of dry matter above surface	Average weight of dry matter above surface	Weight of roots	Average weight of roots	Total weight of dry matter produced	Average weight of total dry matter produced	Average total difference over control
		gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	
1*	200	8.0	7.00	......	......	8.0	7.00	2.0	2.50	10.0	9.50	—8.70
2*	200	6.0		......		6.0		3.0		9.0		
3	300	19.5	20.25	......	......	19.5	20.25	6.2	4.85	25.7	25.10	+6.90
4	300	21.0		......		21.0		3.5		24.5		
5*	400	6.5	8.00	......	......	6.5	8.00	2.5	2.25	9.0	10.25	—9.95
6*	400	9.5		......		9.5		2.0		11.5		
7	500	22.0	17.00	......	......	22.0	17.00	3.0	3.90	25.0	20.90	+2.70
8*	500	12.0		......		12.0		4.8		16.8		
9	600	22.6	21.50	......	......	22.6	21.50	3.1	3.65	25.7	24.70	+6.50
10	600	19.5		......		19.5		4.2		23.7		
11*	700	11.0	13.70	......	......	11.0	13.70	2.1	2.80	13.1	16.50	—1.70
12	700	16.4		......		16.4		3.5		19.9		
13	800	16.2	14.60	......	......	16.2	14.60	3.2	2.95	19.4	17.55	—1.65
14	800	13.0		......		13.0		2.7		15.7		
15	900	14.2	14.10	......	......	14.2	14.10	4.0	3.00	18.2	17.10	—1.10
16	900	14.0		......		14.0		2.0		16.0		
17	1000	15.4	16.20	......	......	15.4	16.20	2.9	2.70	18.3	18.90	+0.70
18	1000	17.0		......		17.0		2.5		19.5		
19	1100	11.0	10.75	......	......	11.0	10.75	2.7	2.00	13.7	12.75	+5.45
20	1100	10.5		......		10.5		1.3		11.8		
21	1200	19.8	18.20	......	......	19.8	18.20	2.4	2.20	22.2	20.40	+2.20
22	1200	16.6		......		16.6		2.0		18.6		
23	1300	14.8	15.80	......	......	14.8	15.80	2.7	2.45	17.5	18.25	+0.05
24	1300	16.8		......		16.8		2.2		19.0		
25	1400	21.0	19.00	......	......	21.0	19.00	3.0	4.00	24.0	23.00	+4.80
26	1400	17.0		......		17.0		5.0		22.0		
27	1500	16.4	14.90	......	......	16.4	14.90	2.2	2.65	18.6	17.55	—0.65
28	1500	13.4		......		13.4		3.1		16.5		
29	Control	15.2	14.00	......	......	15.2	14.00	4.4	4.20	19.6	18.20	
30	Control	12.8		......		12.8		4.0		16.8		

* Plants partly damaged by mice.

TABLE VIIc

$PbSO_4$ SET—THIRD CROP—GREENHOUSE SOIL

	$PbSO_4$ added to soil in parts per 1,000,000	Weight of straw	Average weight of straw	Weight of grain	Average weight of grain	Total weight of dry matter above surface	Average weight of dry matter above surface	Weight of roots	Average weight of roots	Total weight of dry matter produced	Average weight of total dry matter produced	Average total difference over control
		gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	
1	200	16.20	15.10	2.30	2.30	18.5	16.25	8.0	8.00	26.5	24.25	— 4.32
2	200	14.00		......		1.4		8.0		22.0		
3	300	15.70	17.45	2.30	2.30	18.0	19.75	7.2	7.15	25.2	26.85	— 1.67
4	300	19.20		2.30		21.5		7.1		28.6		
5*	400	9.80	11.70	2.40	2.15	12.2	13.85	4.2	3.80	16.4	17.65	—10.92
6*	400	13.60		1.90		15.5		3.4		18.9		
7	500	24.30	24.35	1.90	2.15	26.2	26.50	6.9	7.95	33.1	34.45	+ 5.88
8	500	24.40		2.40		26.8		7.0		33.8		
9	600	24.70	24.60	......	......	24.7	24.60	5.7	7.75	30.4	32.35	+ 3.78
10	600	24.50		......		24.5		9.8		34.3		
11	700	20.90	20.25	4.00	4.00	24.9	22.75	9.5	9.15	34.4	31.90	+ 3.33
12	700	19.60		......		19.6		8.8		28.4		
13	800	22.35	21.17	2.65	2.65	25.0	22.70	5.9	6.10	30.9	28.60	+ 0.03
14	800	20.00		......		20.0		6.3		26.3		
15	900	18.80	20.67	5.60	4.27	24.4	24.95	5.8	7.80	32.2	33.75	+ 5.18
16	900	22.55		2.95		25.5		9.8		35.3		
17	1000	19.72	20.63	2.48	2.82	22.2	23.45	7.0	7.00	29.2	30.45	+ 1.88
18	1000	21.55		3.15		24.7		7.0		31.7		
19	1100	29.22	25.37	4.67	3.06	33.9	28.45	9.0	6.60	40.5	35.05	+ 6.48
20	1100	21.55		1.45		23.0		4.2		29.6		
21	1200	21.05	21.07	3.25	3.22	24.3	24.30	7.0	7.25	31.3	31.55	+ 2.98
22	1200	21.10		3.20		24.3		7.5		31.8		
23	1300	20.77	18.76	5.03	3.14	25.8	21.90	6.8	5.90	31.6	27.80	— 0.77
24	1300	16.75		1.25		18.0		6.0		24.0		
25	1400	17.00	17.45	5.00	4.40	22.0	21.85	7.0	8.00	29.0	29.85	+ 1.28
26	1400	17.90		3.80		21.7		9.0		30.7		
27	1500	16.20	18.90	1.50	1.50	17.7	19.65	4.2	6.10	23.8	25.75	— 2.82
28	1500	21.60		......		21.6		8.0		29.6		
29	Control	16.50	18.65	2.10	2.25	18.6	19.77	10.5	8.80	29.1	28.57	
30	Control	22.10		2.40		24.5		8.2		32.7		
31	Control	14.50		......		14.5		7.5		22.0		
32	Control	21.50		......		21.5		9.0		30.5		

* Plants partly damaged by mice.

TABLE VIIIa

POTASH ALUM SET—FIRST CROP—GREENHOUSE SOIL

	Potash Alum added at rate of K_2O per acre	Weight of straw	Average weight of straw	Weight of grain	Average weight of grain	Total weight of dry matter above surface	Average weight of dry matter above surface	Weight of roots	Average weight of roots	Total weight of dry matter produced	Average weight of total dry matter produced	Average total difference over control
		gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	
1	300	38.8	39.20	......	......	38.8	39.20	6.6	9.15	45.4	48.35	+8.59
2	300	39.6		......		39.6		11.7		51.3		
3	400	38.4	38.30	......	......	38.4	38.30	8.5	7.80	46.9	46.10	+6.34
4	400	38.2		......		38.2		7.1		45.3		
5	500	29.6	35.90	......	......	29.6	35.90	7.7	7.00	37.3	42.90	+3.14
6	500	42.4		......		42.4		6.3		48.5		
7	600	38.8	39.50	......	......	38.8	39.50	7.5	7.85	46.3	47.35	+7.59
8	600	40.2		......		40.2		8.2		48.4		
9	700	36.3	36.50	......	......	36.3	36.50	5.5	7.15	41.8	43.65	+3.89
10	700	36.7		......		36.7		8.8		45.5		
11	800	34.4	33.45	......	......	34.4	33.45	5.7	5.70	40.1	39.15	—0.61
12	800	32.5		......		32.5		....		38.2		
13	900	36.8	39.40	......	......	36.8	39.40	6.8	6.85	43.6	46.25	+6.49
14	900	42.0		......		42.0		6.9		48.9		
15	1000	34.2	36.80	......	......	34.2	36.80	8.0	7.65	42.2	44.45	+4.69
16	1000	39.4		......		39.4		7.3		46.7		
17	2000	35.5	34.95	......	......	35.5	34.95	6.1	5.20	41.6	40.15	+0.39
18	2000	34.4		......		34.4		4.3		38.7		
19	Control	31.5	32.50	......	......	31.5	32.50	7.8	7.26	39.3	39.76	
20	Control	31.2		......		31.2		6.9		38.1		
21	Control	34.8		......		34.8		7.1		41.9		

TABLE VIII*b*

POTASH ALUM SET—SECOND CROP—GREENHOUSE SOIL

	Potash Alum added at rate of K_2O per acre	Weight of straw	Average weight of straw	Weight of grain	Average weight of grain	Total weight of dry matter above surface	Average weight of dry matter above surface	Weight of roots	Average weight of roots	Total weight of dry matter produced	Average weight of total dry matter produced	Average total difference over control
		gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	
1*	300	17.88	13.99	15.12	11.81	33.1	25.80	7.8	6.40	40.8	32.20	+11.61
2	300	10.10		8.50		18.6		5.0		23.6		
3	400	8.70	8.90	11.80	11.75	20.5	20.70	6.0	6.60	26.5	27.15	+ 6.56
4	400	9.10		11.70		20.8		7.2		28.0		
5	500	13.70	11.75	8.80	9.40	22.5	21.15	5.0	6.60	27.5	27.15	+ 6.56
6	500	9.80		10.00		19.8		7.0		26.8		
7	600	13.20	11.35	8.80	9.15	22.0	20.50	7.0	6.75	29.0	27.25	+ 6.66
8	600	9.50		9.50		19.0		6.5		25.5		
9	700	9.50	10.82	7.70	8.17	17.2	19.00	7.0	7.00	24.2	26.00	+ 5.41
10	700	12.15		8.65		20.8		7.0		27.8		
11	800	15.90	11.85	11.10	9.85	27.0	21.70	6.8	7.65	33.8	29.35	+ 8.76
12	800	7.80		8.60		16.4		8.5		24.9		
13	900	9.65	9.85	10.85	10.90	20.5	20.75	5.8	5.80	26.3	26.50	+ 5.91
14	900	10.05		10.95		21.0		5.8		26.8		
15	1000	13.30	12.00	10.50	9.50	23.8	21.50	7.5	7.50	31.3	29.00	+ 8.41
16	1000	10.70		8.50		19.2		7.5		26.7		
17	2000	11.00	10.60	11.60	10.90	22.6	21.50	4.0	4.70	26.6	26.20	+ 5.61
18	2000	10.20		10.20		20.4		5.4		25.8		
19	Control	5.66	7.05	9.54	9.29	15.2	16.33	4.0	4.26	19.2	20.59	
20	Control	8.48		9.32		17.8		4.4		22.2		
21	Control	7.00		9.00		16.0		4.4		20.4		

* Contaminated by rain water.

TABLE VIIIc

POTASH ALUM SET—THIRD CROP—GREENHOUSE SOIL

	Potash Alum added at rate of K_2O per acre	Weight of straw	Average weight of straw	Weight of grain	Average weight of grain	Total weight of dry matter above surface	Average weight of dry matter above surface	Weight of roots	Average weight of roots	Total weight of dry matter produced	Average weight of total dry matter produced	Average total difference over control
		gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	
1	300	14.03	15.51	......	2.78	14.3	16.90	8.2	7.80	22.5	24.70	—2.73
2.	300	16.72		2.78		19.5		7.4		26.9		
3	400	12.65	12.70	1.85	2.05	14.5	14.75	7.3	6.65	21.8	21.40	—6.03
4	400	12.75		2.25		15.0		6.0		21.0		
5	500	11.88	11.29	1.32	2.31	13.2	13.60	5.2	4.85	18.4	18.45	—8.98
6	5.00	10.70		3.30		14.0		4.5		18.5		
7	600	12.44	14.64	1.76	2.20	14.2	16.85	6.0	5.50	19.7	22.35	—5.08
8	600	16.85		2.65		19.5		5.0		24.5		
9	700	12.00	11.25	......	......	12.0	11.25	5.7	6.60	17.7	17.85	—9.58
10	700	10.50		......		10.5		7.5		18.0		
11	800	15.50	14.62	......	1.45	15.5	15.35	7.5	7.50	23.0	22.85	—4.58
12	800	13.75		1.45		15.2		7.5		22.7		
13	900	11.70	11.54	1.20	2.64	12.9	14.15	6.7	6.45	19.6	20.60	—6.83
14	900	11.38		4.08		15.4		6.2		21.6		
15	1000	12.50	12.67	2.10	1.92	14.6	14.60	5.2	4.60	19.8	19.20	—8.23
16	1000	21.85		1.75		14.6		4.0		18.6		
17	2000	13.60	15.32	2.40	2.62	16.0	18.00	7.4	6.50	23.4	24.50	—2.93
18	2000	17.05		2.95		20.0		5.6		25.6		
19	Control	19.40	16.70	2.10	2.25	21.5	18.20	8.2	9.23	29.7	27.43	
20	Control	16.20		2.40		18.6		9.0		27.6		
21	Control	14.50		......		14.5		10.5		25.0		

TABLE IXa

MnSO₄ SET—FIRST CROP—GREENHOUSE SOIL

	$MnSO_4$ added to soil in parts per 1,000,000	Weight of straw	Average weight of straw	Weight of grain	Average weight of grain	Total weight of dry matter above surface	Average weight of dry matter above surface	Weight of roots	Average weight of roots	Total weight of dry matter produced	Average weight of total dry matter produced	Average total difference over control
		gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	
1	500	47.5	51.00	......	......	47.5	51.00	11.5	12.00	59.0	63.00	+10.87
2	500	54.5		......		54.5		12.5		67.0		
3	1000	54.3	54.15	......	......	54.3	54.15	11.5	12.25	65.8	66.40	+14.27
4	1000	54.0		......		54.0		13.0		67.0		
5	1500	56.8	61.90	......	......	56.8	61.90	13.5	12.50	70.3	74.40	+22.27
6	1500	67.0		......		67.0		11.5		78.5		
7	2000	45.6	44.40	......	......	45.6	44.40	7.6	8.30	53.2	52.70	+ 0.57
8	2000	43.2		......		43.2		9.0		52.2		
9	2500	49.2	46.70	......	......	49.2	46.70	9.5	9.60	56.2	55.05	+ 2.92
10	2500	44.2		......		44.2		9.7		53.9		
11	3000	42.0	44.75	......	......	42.0	44.75	10.5	9.00	52.5	53.75	+ 1.62
12	3000	47.5		......		47.5		7.5		55.0		
13	3500	45.7	40.75	......	......	45.7	40.75	9.2	9.45	54.9	50.20	— 1.93
14	3500	35.8		......		35.8		9.7		45.5		
15	4000	39.0	41.75	......	......	39.0	41.75	8.0	7.75	47.0	49.50	— 2.63
16	4000	44.5		......		44.5		7.5		52.0		
17	4500	43.0	43.00	......	......	43.0	43.00	10.7	9.85	53.7	52.85	+ 0.72
18	4500	43.0		......		43.0		9.0		52.0		
19	5000	42.0	45.50	......	......	42.0	45.50	8.0	7.50	50.0	53.00	+ 0.87
20	5000	49.0		......		49.0		7.0		56.0		
21	5500	42.8	39.10	......	......	42.8	39.10	6.5	6.80	49.3	45.90	— 6.23
22	5500	35.4		......		35.4		7.1		42.5		
23	6000	41.0	45.85	......	......	41.0	45.85	8.0	7.35	49.0	53.20	+ 1.07
24	6000	50.7		......		50.7		6.7		57.4		
25	Control	41.1	41.46	......	......	41.4	41.46	12.5	10.66	53.9	52.13	
26	Control	43.0		......		43.0		11.0		54.0		
27	Control	40.0		......		40.0		8.5		48.5		

TABLE IX*b*

$MnSO_4$ SET—SECOND CROP—GREENHOUSE SOIL

	$MnSO_4$ added to soil in parts per 1,000,000	Weight of straw	Average weight of straw	Weight of grain	Average weight of grain	Total weight of dry matter above surface	Average weight of dry matter above surface	Weight of roots	Average weight of roots	Total weight of dry matter produced	Average weight of total dry matter produced	Average total difference over control
		gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	
1	500	14.05	14.05	3.45	3.45	17.5	17.50	10.5	10.25	28.0	27.75	—4.39
2	500	14.05		3.45		17.5		10.0		27.5		
3	1000	16.50	19.45	3.50	3.50	20.0	22.45	7.5	9.25	27.5	26.70	—5.44
4	1000	22.40		3.50		24.9		11.0		25.9		
5	1500	13.40	12.95	4.40	4.70	17.8	17.65	7.5	6.75	25.3	24.40	—7.74
6	1500	12.50		5.00		17.5		6.0		23.5		
7	2000	13.55	12.94	4.25	3.72	17.8	17.65	10.7	12.00	28.5	29.65	—2.49
8	2000	12.32		5.18		17.5		13.3		30.8		
9	2500	11.77	11.89	3.73	3.87	15.5	15.75	12.5	11.60	28.0	27.35	—4.78
10	2500	12.00		4.00		16.0		10.7		26.7		
11	3000	13.33	13.32	4.67	4.19	18.0	17.50	9.7	9.35	25.7	25.75	—6.38
12	3000	13.30		3.70		17.0		9.0		26.0		
13*	3500	7.50	10.24	3.30	4.41	10.8	14.65	6.5	8.25	17.3	22.90	—9.24
14	3500	12.97		5.53		18.5		10.0		28.5		
15	4000	14.67	15.83	2.33	2.33	17.0	17.00	8.3	9.15	25.3	26.15	—5.99
16	4000	17.00		......		17.0		10.0		27.0		
17	4500	12.02	16.80	4.98	4.20	17.0	21.00	9.5	7.75	26.5	29.00	—3.14
18	4500	21.58		3.42		25.0		6.0		31.5		
19	5000	13.56	16.53	4.64	4.64	18.2	18.85	9.8	7.40	28.0	26.25	—5.89
20	5000	19.50		......		19.5		5.0		24.5		
21	5500	18.20	18.20	2.50	2.50	20.7	20.70	9.2	9.20	29.7	29.70	—2.44
22	5500	....		......		......		....		......		
23	6000	21.70	24.03	1.30	.92	23.0	24.95	10.0	7.50	33.0	32.45	+0.31
24	6000	26.36		.54		26.9		5.0		31.9		
25	Control	13.08	13.71	5.05	5.16	18.13	18.88	14.8	13.27	32.93	32.14	
26	Control	12.87		4.13		17.0		13.0		30.0		
27	Control	15.17		6.31		21.5		12.0		33.5		

* One plant died.

TABLE IX*c*

$MnSO_4$ Set—Third Crop—Greenhouse Soil

	$MnSO_4$ added to soil in parts per 1,000,000	Weight of straw	Average weight of straw	Weight of grain	Average weight of grain	Total weight of dry matter above surface	Average weight of dry matter above surface	Weight of roots	Average weight of roots	Total weight of dry matter produced	Average weight of total dry matter produced	Average total difference over control
		gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	
1	500	11.90	11.90	4.70	4.70	16.60	16.60	1.40	1.40	18.00	18.00	+0.57
2*	500	....		.....		....		.....		....		
3	1000	9.54	10.02	3.96	3.98	13.50	14.00	2.00	2.35	15.50	16.35	—1.08
4	1000	10.50		4.00		14.50		2.70		17.20		
5	1500	15.76	13.13	4.24	4.67	20.00	17.80	1.50	1.25	21.50	19.05	+1.62
6	1500	10.50		5.10		15.60		1.00		16.60		
7	2000	21.30	17.20	4.10	3.50	25.40	20.70	1.40	1.50	26.80	22.20	+4.77
8	2000	13.10		2.90		16.00		1.60		17.60		
9	2500	20.15	18.00	5.85	4.50	26.00	22.50	2.60	2.58	28.60	25.08	+7.65
10	2500	15.85		3.15		19.00		2.55		21.55		
11	3000	17.80	16.05	5.00	3.85	22.80	19.90	1.40	1.85	24.20	21.75	+4.33
12	3000	14.30		2.70		17.00		2.30		19.30		
13	3500	13.70	12.95	4.90	4.35	18.60	17.30	1.50	2.05	20.10	19.35	+1.92
14	3500	12.20		3.80		16.00		2.60		18.60		
15	4000	12.25	12.25	4.15	4.15	16.40	16.40	3.50	3.50	19.90	19.90	+2.47
16	4000	....		.....		....		.....		....		
17	4500	12.44	12.40	3.76	3.70	16.20	16.10	2.40	2.40	18.60	18.50	+1.07
18	4500	12.36		3.64		16.00		2.40		18.40		
19	5000	12.40	11.87	3.20	3.83	15.60	15.70	3.20	2.70	18.80	18.40	+0.97
20	5000	11.35		4.45		15.80		2.20		18.00		
21	5500	9.80	9.80	4.40	4.40	14.20	14.20	2.80	2.80	17.00	17.00	—0.43
22	5500	....	....	.....		....		.....		....		
23	6000	9.64	12.52	4.36	3.48	14.00	16.00	2.10	2.30	16.10	18.30	+0.87
24	6000	15.40		2.60		18.00		2.50		20.60		
25	Control	12.25	12.80	3.25	2.73	15.50	15.53	1.40	1.90	16.90	17.43	
26	Control	13.30		2.30		15.60		2.30		17.90		
27	Control	12.85		2.65		15.50		2.00		17.50		

* Contaminated by leaky roof.

TABLE X*a*

MnCL₂ Set—First Crop—Greenhouse Soil

	$MnCl_2$ added to soil in parts per 1,000,000	Weight of straw	Average weight of straw	Weight of grain	Average weight of grain	Total weight of dry matter above surface	Average weight of dry matter above surface	Weight of roots	Average weight of roots	Total weight of dry matter produced	Average weight of total dry matter produced	Average total difference over control
		gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	
1	500	60.0	58.00	......	......	60.0	58.00	12.5	11.75	72.5	69.75	+16.62
2	500	56.0		......		56.0		11.0		67.0		
3	1000	68.2	73.60	......	......	68.2	73.60	13.5	12.00	81.7	85.60	+33.47
4	1000	79.0		......		79.0		10.5		89.5		
5	1500	57.2	65.60	......	......	57.2	65.60	13.5	12.50	70.7	78.10	+25.97
6	1500	74.0		......		74.0		11.5		85.5		
7	2000	37.0	37.55	......	......	37.0	37.55	5.9	6.95	42.9	44.50	— 7.63
8	2000	38.1		......		38.1		8.0		46.1		
9	2500	32.0	35.60	......	......	32.0	35.60	12.5	11.75	44.5	47.35	— 4.78
10	2500	39.2		......		39.2		11.0		50.2		
11	3000	26.0	28.10	......	......	26.0	28.10	6.0	6.75	32.0	34.85	—17.28
12	3000	30.2		......		30.2		7.5		37.7		
13	2500	25.2	22.10	......	......	25.2	22.10	4.0	3.25	29.2	25.35	—26.78
14	3500	19.0		......		19.0		2.5		21.5		
15*	4000	20.0	20.00	......	......	20.0	20.00	1.0	1.00	21.0	21.00	—31.13
16*	4000											
17	4500	14.0	14.45	......	......	14.0	14.45	1.5	1.30	15.5	15.75	—36.38
18	4500	14.9		......		14.0		1.1		16.0		
19	5000	12.9	12.90	......	......	12.9	12.90	1.2	1.20	14.1	14.10	—38.03
20*	5000	......		......								
21	5500	4.5	6.70	......	......	4.5	6.70	1.0	1.05	5.5	7.75	—44.38
22	5500	8.9		......		8.9		1.1		10.0		
23	6000	5.2	3.55	......	......	5.2	3.55	.7	.45	5.9	4.00	—48.13
24	6000	1.9		......		1.9		.2		2.1		
25	Control	41.4	41.46	......	......	41.4	41.46	12.5	10.66	53.9	52.13	
26	Control	43.0		......		43.0		11.0		54.0		
27	Control	40.0		......		40.0		8.5		48.5		

* Plants died during growing period.

TABLE X*b*

$MnCl_2$ SET—SECOND CROP—GREENHOUSE SOIL

	$MnCl_2$ added to soil in parts per 1,000,000	Weight of straw	Average weight of straw	Weight of grain	Average weight of grain	Total weight of dry matter above surface	Average weight of dry matter above surface	Weight of roots	Average weight of roots	Total weight of dry matter produced	Average weight of total dry matter produced	Average total difference over control
		gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	
1	500	14.13	13.07	3.87	3.87	18.00	15.00	8.0	8.25	26.00	23.25	—8.89
2	500	12.00		......		12.00		8.5		20.50		
3	1000	12.72	10.94	4.98	4.67	17.70	15.60	8.8	8.65	26.50	24.25	—7.89
4	1000	9.15		4.35		13.50		8.5		22.00		
5	1500	15.15	15.60	4.75	4.75	19.90	20.35	8.2	7.70	28.10	28.05	—4.09
6	1500	16.05		4.75		20.80		7.2		28.00		
7	2000	25.08	23.12	4.42	4.73	29.50	27.85	6.9	7.95	36.40	35.80	+3.66
8	2000	21.16		5.04		26.20		9.0		35.20		
9	2500	22.00	20.15	5.00	6.45	27.00	26.60	8.0	8.50	35.00	35.10	+2.96
10	2500	18.30		7.90		26.20		9.0		35.20		
11	3000	26.05	23.55	3.95	4.30	30.00	27.85	10.0	7.60	40.00	35.45	+3.31
12	3000	21.04		4.66		25.70		5.2		30.90		
13	3500	20.66	22.83	1.34	1.92	22.00	24.75	9.0	7.75	31.00	32.50	+0.36
14	3500	25.00		2.50		27.50		6.5		34.00		
15	4000	32.07	33.04	.93	1.46	33.00	34.50	6.4	6.20	39.40	40.70	+8.56
16	4000	34.00		2.00		36.00		6.0		42.00		
17	4500	30.40	27.80	......	......	30.40	27.80	6.0	5.70	36.40	33.50	+1.36
18	4500	25.20		......		25.20		5.4		30.60		
19	5000	29.60	26.05	.90	.90	30.50	26.50	6.5	5.25	37.00	31.75	—0.39
20	5000	22.50		......		22.50		4.0		26.50		
21	5500	27.03	28.70	.47	.47	27.50	29.00	6.0	5.50	33.50	34.50	+2.36
22	5500	30.50		......		30.50		5.0		35.50		
23	6000	24.05	27.04	.45	.46	24.50	27.75	6.0	5.50	30.50	33.25	+1.11
24	6000	30.03		.47		31.00		5.0		36.00		
25	Control	13.08	13.71	5.05	5.16	18.13	18.88	14.8	13.20	32.93	32.14	
26	Control	12.87		4.13		17.00		13.0		30.00		
27	Control	15.17		6.31		21.50		12.0		33.50		

TABLE X*c*

MnCl$_2$ Set—Third Crop—Greenhouse Soil

	$MnCl_2$ added to soil in parts per 1,000,000	Weight of straw	Average weight of straw	Weight of grain	Average weight of grain	Total weight of dry matter above surface	Average weight of dry matter above surface	Weight of roots	Average weight of roots	Total weight of dry matter produced	Average weight of total dry matter produced	Average total difference over control
		gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	
1	500	12.68	12.97	2.76	4.52	17.20	18.40	1.40	1.63	18.60	20.03	+ 2.60
2	500	13.25		6.35		19.60		1.85		21.45		
3	1000	16.46	15.23	5.74	5.12	22.20	20.35	1.75	1.83	23.95	22.18	+ 4.75
4	1000	14.00		4.50		18.50		1.90		20.40		
5	1500	12.36	12.40	6.06	4.61	18.40	17.00	2.30	2.05	20.70	19.05	+ 1.62
6	1500	12.45		3.15		15.60		1.80		17.40		
7	2000	17.60	17.93	6.00	4.87	23.60	22.80	2.20	2.70	25.80	25.50	+ 8.07
8	2000	18.25		3.75		22.00		3.20		25.20		
9	2500	14.02	13.89	6.28	5.56	20.30	19.45	2.70	2.55	23.00	22.00	+ 4.57
10	2500	13.76		4.84		18.60		2.40		21.00		
11	3000	21.30	16.90	3.70	3.40	25.00	20.30	2.00	2.60	27.00	22.90	+ 5.47
12	3000	12.50		3.10		15.60		3.20		18.80		
13	3500	14.64	18.12	5.16	5.18	19.80	23.30	2.30	2.95	22.10	26.25	+ 8.82
14	3500	21.60		5.20		26.80		3.60		30.40		
15	4000	17.00	18.60	4.00	5.10	21.00	23.70	1.00	1.90	22.00	25.60	+ 8.17
16	4000	20.20		6.20		26.40		2.80		29.20		
17	4500	23.00	20.30	3.80	4.10	26.80	24.40	1.20	1.20	28.00	25.60	+ 8.17
18	4500	17.60		4.40		22.00		1.20		23.20		
19	5000	27.70	24.65	3.90	4.15	31.60	28.80	1.80	1.90	33.40	30.70	+13.27
20	5000	21.60		4.40		26.00		2.00		28.00		
21	5500	17.36	16.03	5.24	2.97	22.60	19.00	......	.70	22.60	19.35	+ 1.92
22*	5500	14.70		.70		15.40		.70		16.10		
23	6000	26.50	20.60	8.90	6.28	35.40	27.70	.40	.35	35.80	28.05	+10.62
24	6000	16.35		3.65		20.00		.30		20.30		
25	Control	12.25	12.80	3.25	2.73	15.50	15.53	1.40	1.90	16.90	17.43	
26	Control	13.30		2.30		15.60		2.30		17.90		
27	Control	12.85		2.65		15.50		2.00		17.50		

* Contaminated by leaky roof.