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JOURNAL OF AGRICULTURAL RESEARCH

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PUBLISHED BY AUTHORITY OF THE SECRETARY OF AGRICULTURE
WITH THE COOPERATION OF THE ASSOCIATION
OF LAND-GRANT COLLEGES AND
UNIVERSITIES

UNITED STATES
GOVERNMENT PRINTING OFFICE
WASHINGTON : 1929

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Published on the first and fifteenth of each month. This volume will consist of twelve numbers and the Contents and Index.

Subscription price: Domestic, $4.00 a year (two volumes)
Single numbers, 20 cents
Foreign, $5.00 a year (two volumes)
Single numbers, 25 cents

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JOURNAL OF AGRICULTURAL RESEARCH

VOL. 38 WASHINGTON, D. C., JUNE 1, 1929 NO. 11

ELECTRIC STIMULATION OF PLANT GROWTH [1]

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INTRODUCTION

The use of electricity as a means of increasing plant growth is a subject of perennial interest. A year seldom passes without the announcement of a new method by which electric forces are to be utilized to increase the yields of agricultural plants.

Electricity has proved to be such a convenient and serviceable form of energy in many human activities that it seems not unreasonable to hope for a method of utilizing it in plant production. This hope is strengthened by the fact that light and electricity are closely related phenomena and that light is one of the important factors in plant growth.

Consideration of the atmospheric potential gradient to which all plants are exposed gives an added reason for associating electrical currents with growth. The air has been found to be electrically charged with respect to the earth, and the difference in potential increases with height. It follows from this that plants in nature, growing in the earth and with their tops in the air at some distance above the earth, are constantly being traversed by minute but measurable currents of electricity. What could be more reasonable than to expect that an increase or decrease of this current should affect the growth of the plant?

In most of the new methods proposed the energy is drawn from the air by utilizing the atmospheric gradient. None of these methods have succeeded in other hands than those of the originator, and inventions claiming to increase plant growth by utilizing the atmospheric gradient may properly be classed with water witches, sex determiners, and perpetual-motion machines.

There is, however, from careful and capable British investigators, a body of evidence interpreted by them as demonstrating that increased plant growth follows electric excitation of a certain intensity and duration supplied from a charged network suspended above the plants. These investigations, begun by Sir Oliver Lodge as field experiments, have been continued by V. H. Blackman as laboratory experiments under carefully controlled conditions.

Shortly after the results of Lodge's field experiments were announced the Bureau of Plant Industry undertook the verification of these results. An experiment that duplicated in all essential particulars the "set-up" used by Lodge was undertaken. For 10 seasons treated and untreated plots were compared, but there was no measurable

[1] Received for publication Jan. 3, 1929; issued May, 1929.

difference associated with the treatment.[2] It was realized that some detail in equipment might have been overlooked or that the treatment brought about a change in some condition of growth that was a limiting factor in the English experiments but was not a limiting factor under the very different environment of Washington. On the contrary, it was possible that the differences obtained in England on one series of plots of untested uniformity might have been due to causes other than the treatment.

When Blackman subsequently reported positive results from laboratory comparisons it seemed desirable to determine whether a duplication of these more carefully controlled English experiments would give similar results under the conditions prevailing at Washington. In Blackman's experiments electric stimulation was shown to be rather capricious. It would appear that, to get anything approximating uniform behavior, the strength of the field must be controlled within narrow limits and the treatment must be restricted to a certain part of the day. The greatest stimulation appears to take place after the treatment has been discontinued. These restrictions suggest that the observed differences, which are of undoubted statistical significance, may have been due to uncontrolled factors of the environment that obtained in this particular set of trials.

The method used by Blackman was to prepare a series of pots of uniform size, fill them with the same soil, plant them with a uniform lot of seed, and then separate them into groups of 4 to 10 each. One of these groups was maintained as a control, and the others were subjected to potential gradients of known intensity by means of an electrically charged overhead network.

There are two considerations that make it especially difficult accurately to compare plants treated electrically with their untreated controls. The first is that the discharge from an overhead network can not be confined easily to the area immediately below the network. This is especially true if air currents are passing over the treated area. The second obstacle is that there is assumed to be a residual effect of the treatment that persists for an indefinite period after the treatment is discontinued. If this assumption is given weight it precludes the possibility of using the same area alternately as treated and control.

METHODS

In the laboratory two methods of detecting the effects of a given treatment are available: (1) Similar plantings can be divided into treated and control and both exposed to the same environment as nearly as possible, except for the factor under investigation; or (2) the growth of an individual or group of individuals under normal conditions can be observed for a given period. The treatment is then

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[2] The results of field experiments conducted by the Bureau of Plant Industry are reported in the following publication: BRIGGS, L. J., CAMPBELL, A. B., HEALD, R. H., and FLINT, L. H., ELECTROCULTURE. U. S. Dept. Agr. Bul. 1379, 35 p., illus. 1926. This publication may also be consulted for a bibliography of electrocultural experiments. The most important contribution to this subject that has appeared since Bulletin 1379 was issued is the following publication: LIPPERHEIDE, C., NEUERE UNTERSUCHEN ÜBER DEN EINFLUSS DER ELEKTRIZITÄT AUF PFLANZEN. Angew. Bot. 9:561–625, illus., 1927. The method described in this article involved the use of chambers in which the air was subjected to conditions of different ion content. The results were interpreted as indicating definite and appreciable growth increases associated with increase of ions in the air. These investigations are not comparable with the trials herein reported. The method of enhanced atmospheric electrical potential gradient used in the writers' experiments has the effect of increasing the ions available to the plant in unit time, but places restrictions upon the movement of these ions.

applied, and if a change in rate follows it is ascribed to the treatment. There are some rather serious objections to the latter method. Growth rates, especially during seedling stages, are not uniform even under uniform conditions, but show progressive changes. It is necessary, therefore, to determine in advance the form of the normal growth curve and to compare the growth during treatment, not with the growth for the preceding period, but with the growth expected if the normal growth curve had been followed throughout the treated period. Individuals differ in the form of their growth curves, as in other particulars and there is no way of knowing how closely the particular individual treated conforms to the normal or average growth curve. Furthermore, the method is laborious and the results are not readily amenable to biometrical tests of significance. For these reasons the method of comparing similar cultures was adopted in the writers' experiments. With this method duplication is easy and the biometrical treatment of results is simple and direct.

The electroculture experiments here reported were carried out in the Biophysical Laboratory of the Bureau of Plant Industry at Washington, D. C. Each experiment consisted in subjecting a group of seedlings during their early period of development to conditions of modified atmospheric electrical gradient and at the same time in holding a similar group of seedlings to identical environmental conditions except for the presence of the normal atmospheric electrical gradient.

In the initial trials the seedlings were grown in groups of 100 and spaced 1 inch apart in each direction in wooden boxes of coarse sand. When the young plants were about 1 cm. high the two most uniform and similar boxes of the four planted were selected for the experiment. These were placed upon parallel metal bars in two grounded metal cages used for the trials. The two cages, which were identical in structure, were placed upon the same table in the laboratory. The supporting bars for the boxes and the supports of the adjustable metal screens suspended above the plants were mounted in sulphur insulating blocks. In one cage this overhead screen was attached to a source of high-voltage direct current, and the strength of the current passing through the plants was modified by the raising or the lowering of the screen. The current was measured with a sensitive galvanometer, calibrated previous to measurement, and placed in a line connecting the moist soil in the box with the ground. A storage battery, an induction coil, and a Lodge-valve "hook up" permitted the passage of the desired range of current strengths with a space of several centimeters between the plants and the screen. The treatment was not confined to the same cage throughout the experiments, but was changed several times during the course of the experiments. The light conditions within the two cages were equalized as far as possible by the adjustment of overhead electric lights to identical resistance values of a photo-electric cell. The light conditions were subnormal and caused the plants to elongate somewhat, but the foliage was normal in color. The set-up for these experiments is illustrated in Figure 1, which shows the two cages with one side removed to expose the interior arrangements.

Various methods of watering were tested, the object being to maintain uniform moisture conditions in the soil of the several boxes.

The method finally adopted was, after planting, to place all the boxes in water until the soil was thoroughly soaked. As soon as the surplus water had drained away the boxes were placed in their final positions. With the type of soil used enough water usually was held in the soil to supply the plants until the end of the experiment without further watering. Weighing the boxes before and after immersion showed the range of moisture content to be less than 3 per cent.

EXPERIMENTS IN 1924 AND 1925

The experiments were begun in December, 1924. Between this date and July, 1925, 36 experiments were completed, 24 with maize and 12 with barley. A current of 10^{-9} amperes per plant, which had been found by Blackman to give the most promising results, was employed with few exceptions. In some of the experiments the treatment was continuous, and in others the current was applied only during either the day or the night. The results are given in Tables 1 and 2. In most of the experiments the difference between the treated and the control was clearly significant, but the control exceeded the treated about as often as the treated exceeded the control. Evidently unknown variables were as potent as the treatment.

TABLE 1.—*Results obtained in the study of the influence of an electric current on the growth of maize seedlings in 1924 and 1925*

Experiment No.	Treatment (amperes per plant)	Time of application	Treated plants: Mean height (cm.)	Treated plants: Standard deviation (cm.)	Control plants: Mean height (cm.)	Control plants: Standard deviation (cm.)	Difference (treated−control)	Difference ÷ probable error	Treated ÷ control
1	-10^{-9}	Day	4.09 ±0.090	1.296	4.35 ±0.105	1.486	−0.26 ±0.138	1.88	0.940
2	-10^{-9}	do	5.03 ± .159	2.328	6.81 ± .145	2.126	−1.78 ± .215	8.28	.739
3	$+10^{-9}$	do	7.18 ± .155	1.549	7.21 ± .149	1.565	− .03 ± .215	.14	.996
4	$+10^{-8}$	do	23.80 ± .255	3.772	24.37 ± .275	4.014	− .57 ± .375	1.52	.977
5	$+10^{-7}$	do	11.164± .120	1.750	11.391± .135	1.976	− .227± .181	1.25	.980
6	$+10^{-7}$	do	7.319± .068	1.000	7.306± .071	1.044	.013± .098	.13	1.002
7	$+10^{-9}$	do	8.858± .184	2.726	9.846± .189	2.774	− .988± .264	3.74	.900
8	$+10^{-10}$	do	11.72 ± .180	2.819	11.700± .172	2.511	.02 ± .249	.08	1.002
9	$+10^{-9}$	Night	12.707± .125	1.843	11.920± .121	1.798	.787+ .174	4.52	1.066
10	$+10^{-9}$	do	8.816± .094	1.379	7.927± .160	2.336	.889± .186	4.77	1.112
11	$+10^{-9}$	do	8.404± .174	2.573	7.616± .174	2.578	.788± .246	8.20	1.103
12	$+10^{-9}$	do	12.903± .123	1.772	12.583± .139	2.024	.320± .186	1.72	1.025
13	$+10^{-9}$	do	8.979± .152	2.226	8.632± .090	1.312	.347± .357	.97	1.040
14	$+10^{-9}$	do	8.740± .079	1.172	7.320± .149	2.218	1.42 ± .169	8.40	1.194
15	$+10^{-9}$	do	10.380± .223	3.037	10.822± .224	3.249	− .442± .316	1.40	.959
16	$+10^{-9}$	do	10.285± .212	3.010	10.451± .231	3.313	− .166± .314	.53	.984
17	$+10^{-9}$	do	11.342± .106	1.514	10.770± .122	1.725	.572± .162	3.53	1.053
18	$+10^{-9}$	do	8.388± .255	2.459	7.193± .236	2.331	1.195± .347	3.44	1.166
19	$+10^{-9}$	Day	17.690± .227	3.212	15.217+ .269	3.817	2.473± .352	7.02	1.162
20	$+10^{-9}$	do	13.077± .370	3.617	14.165± .560	5.369	−1.088± .671	1.62	.923
21	$+10^{-9}$	Day and night	8.324± .203	1.956	9.542± .225	2.114	−1.218± .303	4.02	.872
22	$+10^{-9}$	Day	11.004± .425	4.071	13.644± .348	3.348	−2.640± .549	4.81	.806
23	$+10^{-9}$	do	21.449± .357	3.347	18.292± .484	4.687	3.157± .601	5.25	1.172
24	$+10^{-9}$	Day and night	16.735± .215	2.980	18.222± .245	3.280	−1.487± .326	4.56	.918
Mean			11.182	2.392	11.137	2.625			1.004

TABLE 2.—*Results obtained in the study of the influence of an electric current on the growth of barley seedlings in 1924 and 1925*

Experiment No.	Treatment (amperes per plant)	Time of application	Treated plants: Mean height (cm.)	Treated plants: Standard deviation (cm.)	Control plants: Mean height (cm.)	Control plants: Standard deviation (cm.)	Difference (treated − control)	Difference ÷ probable error	Treated ÷ control
1	$+10^{-9}$	Day	9.948±0.138	2.023	8.328±0.252	2.496	1.620±0.287	5.6	1.194
2	$+10^{-9}$	do	7.669± .308	2.858	7.184± .308	2.831	.485± .436	1.1	1.068
3	$+10^{-9}$	do	8.000± .160	1.529	7.988± .092	1.293	.012± .184	.1	1.002
4	$+10^{-9}$	do	9.405± .148	1.510	9.165± .145	1.519	.240± .210	1.1	1.026
5	$+10^{-9}$	do	10.572± .156	1.554	9.560± .160	1.608	1.012± .223	4.5	1.106
6	$+10^{-9}-10^{-5}$	Night	9.628± .196	1.645	10.907± .170	1.762	−1.279± .259	4.9	.883
7	-10^{-9}	do	9.914± .331	3.318	12.792± .344	3.101	−2.878± .478	6.0	.775
8	$+10^{-9}$	Day	8.803± .172	1.741	10.219± .135	1.959	−1.416± .190	7.4	.861
9	$+10^{-9}$	do	12.399± .274	2.767	9.573± .327	3.072	2.826± .427	6.6	1.295
10	$+10^{-9}$	Night	7.876± .126	1.835	6.074± .120	1.741	1.802± .174	10.4	1.297
11	$+10^{-9}$	Day	11.246± .315	2.562	10.442± .173	2.498	.804± .352	2.3	1.077
12	$+10^{-9}$	do	8.607± .308	2.894	10.868± .276	2.721	−2.261± .414	5.5	.792
Mean			9.505	2.186	9.425	2.217			1.031

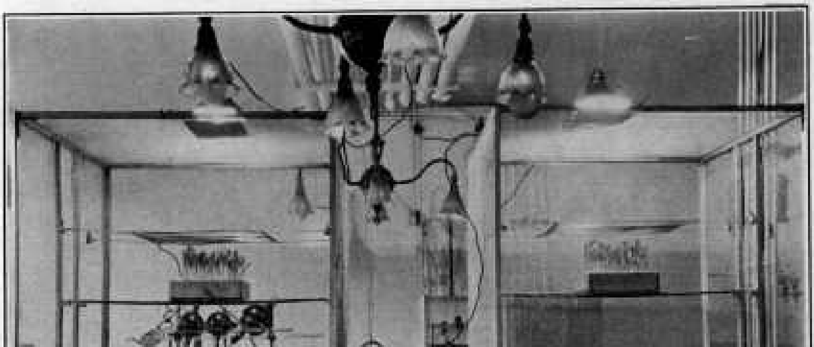

FIGURE 1.—Apparatus used in electric treatment of growing plants in 1924 and 1925. One side of each cage has been removed to expose the interior arrangements

An examination of the various combinations of time of treatment and intensity of current showed the most favorable combinations to be in the group of experiments in which maize was treated with a current of 10^{-9} amperes per plant during the night hours. There were 10 experiments of this kind, and in 8 the mean height of the treated was greater than that of the control. In three of these the difference was over four times the probable error. In the two experiments in which the control was larger than the treated the difference was insignificant.

Disregarding the probable errors of the individual experiments, the array of the 10 differences examined by Student's [3] method showed that, due to chance, a result as favorable as this was not to be expected more often than once in one hundred times.

[3] ANONYMOUS. THE PROBABLE ERROR OF A MEAN. By Student. Biometrika 6: 1–25, illus. 1908.

The significance of the mean difference was somewhat lessened by the fact that this group of experiments, showing the greatest mean difference, was chosen from among a series of such groups. Had the series been sufficiently extensive an individual departure of the observed magnitude would have occurred as a chance departure. At any rate the results were encouraging, and it was planned to conduct a more carefully controlled series, repeating this combination of maize treated at night with a current of 10^{-9} amperes per plant.

EXPERIMENTS IN 1926

With stationary cultures it seemed possible that the results might be influenced by environmental differences associated with the locations of the boxes. To eliminate this possible source of error, all cultures, both control and treated, were placed on a slowly revolving clinostat. Suitable connections were provided to permit an electrical treatment corresponding to that of the early trials. This arrangement is shown in Figure 2.

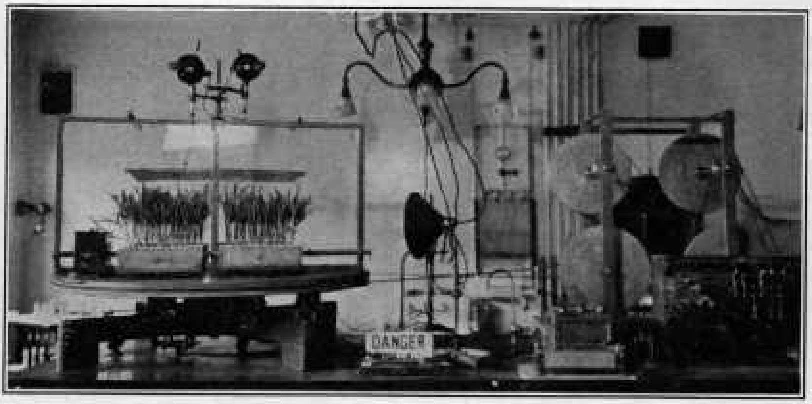

FIGURE 2.—Apparatus used in electric treatment of growing plants in 1926, 1927, and 1928

In this series of trials the current was taken from an alternating-current generator and stepped up with a large induction coil. From this coil it was passed through rectifying Lodge valves to the adjustable screen suspended above the plants. Additional light was furnished through the installation of 100-watt daylight lamps directly over the clinostat.

Sandy loam was substituted for the sand of the earlier trials. The number of boxes was increased from two to four. This gave two treated and two control boxes and made it possible to estimate the chance variations in box means.

The growth of the plants during a night's treatment shortened the distance to the screen, and the plants were thereby subjected to increased current. By taking readings of the amperage at the beginning and at the end of a treatment period, however, it was possible to estimate the range of this effect and to compensate for it in a measure by reducing slightly the current flow at the beginning of the subsequent treatment. By this means the fluctuations in current were controlled within narrow limits. Each of the experiments extended over a period of about two weeks from the planting of the seeds. The plants were treated 6 to 10 days.

In the 1926 experiments the mean elongation instead of the mean final height of the seedlings was used as an index of plant response to treatment. The mean elongation was computed by subtracting the mean initial height from the mean final height. A comparison of the variability of the seedling elongation with that of final height, in boxes having the same treatment, indicated that the large differences in final height of similarly treated boxes, were associated with differences in the initial height. This was doubtless the case in the early experiments when initial height was not measured.

Since the boxes of any experiment were all prepared and treated alike, significant differences in initial height were not to be expected, and the reason for their occurrence is an interesting problem, which is being investigated. Whatever the causes of such differences, it is obviously desirable to eliminate them from comparisons of the effect of subsequent treatment.

To restrict the comparison to the elongation made during treatment does not completely eliminate the effect of diversity in initial height, since there is usually a slight correlation between initial height and elongation. When based on individual plants, this correlation, though small, is always positive in sign, but when based on box means it is usually insignificant and may be of either sign.

In 1926, 10 experiments were tried with maize seedlings treated with a current of 10^{-9} amperes during the night. The mean differences in elongation between treated and control are given under the column heading "Treated − control" in Table 3. In 7 of the 10 experiments the treated made a greater elongation than the control, and in at least one of these the difference is too large to be ascribed to chance. On the other hand, in one of the three experiments in which the control exceeded the treated the difference is also significant.

TABLE 3.—*Differences in growth rates associated with the electric treatment of maize seedlings with a current of 10^{-9} amperes applied at night compared with differences associated with an irrelevant factor*

Experiment No.	Treated − control			High number − low number [a]		
	Mean difference in elongation (mm.)	Probable error	Difference ÷ probable error	Mean difference in elongation (mm.)	Probable error	Difference ÷ probable error
1	6.0	4.5	1.3	−2.0	4.5	0.4
4	1.3	3.4	.4	−3.0	3.3	.9
5	10.2	3.4	3.0	−17.0	2.8	6.1
6	23.9	2.6	9.2	−8.2	2.8	2.9
8	3.1	1.9	1.6	−4.1	1.9	2.2
9	6.8	3.3	2.1	.2	3.2	.1
11	−1.5	1.9	.8	−2.4	1.7	1.4
13	−14.7	2.2	6.7	−7.9	2.2	3.6
20	−3.3	2.5	1.3	1.0	2.5	.4
21	11.1	3.3	3.4	−17.2	3.2	5.4
Mean	4.29	2.18	2.0	−6.06	1.39	4.36

[a] See p. 592 for explanation of high number and low number.

The mean of the array of differences, treated − control, is 4.29 ± 2.18, $t = 1.33$. The probability of this being due to chance is about one in five.[4] Notwithstanding the great care exercised to insure uniformity of exposure, there were many instances in which boxes similarly treated showed significant differences in the mean elongation. This suggested that the observed individual differences between treated and control, although of undoubted significance statistically, might have but a chance association with the treatment.

To determine whether similar differences might occur when no electrical treatment was involved, the boxes of each of the 10 experiments were divided in such a way as to place one treated and one control box in each pair.

It will be recalled that in each experiment four boxes were used, of which two were treated and two were controls. In making the final comparison the individual measurements of the two treated boxes were combined into a single population, which was compared with the combined population of the two control boxes. It was now proposed to return to the original measurements and again combine them into two populations, each of which would consist of a treated box combined with a control.

In making the combinations it was necessary to devise a method for selecting at random the treated and control boxes to be combined. It was thought that a completely random choice could be effected by utilizing the serial numbers that had been stenciled on the boxes when they were made.

In starting the original experiments the boxes had been taken without regard to the stenciled number, and it was not until the boxes were segregated into treated and control that the box numbers were entered in the record. The plan now adopted was to combine the measurements of the treated box having the highest stenciled number with those of the control box having the highest number. As an example, experiment 1 was grown in boxes 1, 7, 10, and 11, of which 1 and 7 were treated and 10 and 11 were controls. Box 7 was now combined with box 11, the combined population was designated "high number," and boxes 1 and 10 combined were designated "low number." A similar procedure was followed in each of the 10 experiments, and the mean of the high number minus the mean of the low number with the probable error of the difference was calculated for each. These mean differences gave a series similar to that in which the treated was compared with the control. The results are given in Table 3 under the heading "High number − low number."

The individual differences do not show such a wide range as in the original series, although in two experiments the difference is more than five times the probable error, but the mean of the array of differences is -6.06 ± 1.4. The statistical significance of the mean difference calculated by Student's method gives $t = 2.9$ and $P = 0.01$, or odds of 1 in 100.

Taken at their indicated value, it would be necessary to conclude that the numbers that happened to be stenciled on the boxes in which the seedlings were grown had influenced the rate of growth more than did the electric treatment.

The clearly significant difference in favor of boxes bearing low numbers is an illustration of the difficulty of eliminating uncontrolled

[4] For the method of deriving the probability, see: FISHER, R. A. STATISTICAL METHODS FOR RESEARCH WORKERS, p. 106–110. Edinburgh and London. 1925.

factors that may be associated with the factor under investigation. Had a difference of such unquestionable significance been obtained when the boxes were divided into treated and control, it might have been thought superfluous to question the conclusion that the effect of treatment had been demonstrated. With the division made on an utterly irrelevant difference, such as the ordinal standing of the labels, it is known, of course, that some uncontrolled factor must have been associated with the arbitrary classes. In this particular instance the difference probably is to be explained by the fact, subsequently established, that certain boxes exercise a deleterious effect on the growth of seedlings. These boxes chanced to bear high numbers and were used in a sufficient number of experiments to bias the results. At the time the 1926 experiments were made, differences in the boxes themselves had not been thought of as even a possible factor. The boxes were of the same dimensions, were made from the same stock of pine lumber, and were to all appearances identical. It was shown subsequently that the boxes having a deleterious effect on growth lost water more rapidly than other boxes.

In view of the significant mean difference in elongation associated with particular containers, it is obvious that no confidence should be placed in the much smaller difference associated with the electric treatment. On the other hand, it would not be permissible to conclude from these results that the treatment was without effect. The mean elongation of the plants in the control boxes in the 10 experiments was 65.44 mm., and since the probable error of the mean difference was 2.18, an increase or decrease in the mean elongation of less than 15 per cent would not have inspired confidence in the reliability of the difference.

Of the 1926 results the most that can be said is that the treatment did not influence the elongation of seedlings by as much as 15 per cent.

It would be necessary to make approximately 20 repetitions of this type of experiment to detect a difference of even 10 per cent with reasonable certainty. To avoid this unsatisfactory expedient, a further effort was made to obtain a more uniform behavior of similarly treated boxes. The analysis just reported indicated that a part of the diversity was associated with the box itself. That certain boxes ran either low or high with a measurable consistency was verified by direct experiment.

There were selected six boxes that showed no correlation with seedling growth. Efforts to obtain uniform growth with the use of these boxes were continued by taking still greater care in the mixing and distribution of the soil. The planting was further standardized by using for planting a mechanical device that placed all seeds at a uniform depth and in the same position.

Some of these refinements seem to have removed the disturbing factors, and two experiments were completed in which all six untreated boxes behaved with a satisfactory degree of uniformity. A comparison of the variance of row means with that of box means, using the method proposed by Fisher,[5] showed the variance in the means of the boxes to be no greater than was to be expected from the variance of the means of the rows.

[5] FISHER, R. A Op. cit., p. 192–194.

EXPERIMENTS IN 1927 AND 1928

The procedure adopted for the experiment of 1927 and 1928 was to start six boxes on a large clinostat and, when the plants were ready for the initial measurement, to select the four boxes with the most uniform initial height, to pair them in a way to make the mean height of the pairs as nearly identical as possible, and to apply the treatment to one of the pairs chosen at random.

The first step in analyzing the results of an experiment was to compute the means and standard deviations of the elongation of the plants of each box separately. The uniformity of the two treated boxes and that of the two controls was then examined by comparing the difference in the means with the standard error of the difference. If neither the treated boxes nor the controls showed a difference between the two boxes exceeding twice the standard error, the individual measurements of elongation of the two treated boxes were combined into a single population and the mean and standard deviation calculated. The measurements of the two control boxes were similarly treated.

With this improved technic five experiments were run with no significant differences between the means of duplicate boxes and with standard deviations sufficiently low to detect mean differences of the order of 5 per cent. The results are shown in Table 4.

TABLE 4.—*Effect of electric current on maize seedlings as measured by various indices of growth*

Experiment No:	Initial height (mm.)		Character measured	Final measurements			
	Treated seedlings	Control seedlings		Treated seedlings	Control seedlings	Treated − control	Difference ÷ probable error
125	76.17±.41	75.00±.43	Final height (mm.)	157.9 ±1.76	155.4 ±1.88	2.5 ± 2.6	1.0
125	76.17±.41	75.00±.43	Dry weight (mgm.)	690.2 ±8.95	652.4 ±9.55	37.8 ±13.1	2.9
126 [a]	57.96±.42	59.83±.42	Green weight (mgm. per plant).	801.2 ± .90	852.5 ± .92	−51.3 ±12.8	4.0
127	49.38±.50	49.62±.44	do	806.3 ±7.2	814.6 ±6.7	− 8.3 ± 9.8	.8
128	39.48±.27	39.89±.29	Elongation (cm.)	15.54± .07	15.52± .07	.02± .099	.2
129	50.94±.32	51.45±.35	do	18.24± .08	18.25± .09	−.01± .12	.1
130 [b]	22.86±.22	22.82±.21	do	13.19± .07	13.40± .07	−.21± .10	2.1

[a] The control of the current was defective and for a part of the time the treated plants received more than the prescribed amperage.
[b] The treated plants were given the maximum current possible without sparking.

All of the plants used in experiments 125, 126, and 127 were treated with 10^{-9} amperes at night, and the comparison was based on weight instead of elongation. In experiment 125 the plants from each row were oven dried and the box means and standard deviations determined from the mean dry weight per row. In later experiments green weights were used. This was made possible by a simple device by which an entire row of plants could be cut with one movement. As each row was cut it was placed in a closed weighing can, and as soon as the harvesting of a box was completed the cans were weighed and the net green weight was recorded. With this technic green weight proved a more sensitive and reliable measure than dry weight, though not so sensitive as comparisons based on individual plant elongation.

The experiments based on weight serve to show that the electric treatment did not increase the weight of the aboveground parts of the plant by as much as 8 per cent. Experiment 126, which showed an apparently significant decrease in green weight, may be disregarded, since the overhead network slipped and for a part of one night gave a greatly increased current with enough sparking to injure some of the plants.

Experiment 127 provided the most satisfactory test based on weight. Here the control exceeded the treated plants by an insignificant amount, and a difference of 5 per cent could have been detected with assurance.

Experiments 128 and 129, in which the treated boxes were also given 10^{-9} amperes at night, afford conclusive evidence that under the conditions of these experiments the treatment produced no measurable effect on elongation. The plants were remarkably uniform, and the treatment ran smoothly. If the rate of elongation had been either increased or decreased by as much as 3 per cent the difference would have been apparent.

Experiments 128 and 129 were analyzed further by sorting the individual plant measurements into groups corresponding to the initial height, and comparing the mean elongation of the treated plants of each group with the mean of the control plants having the same initial height.

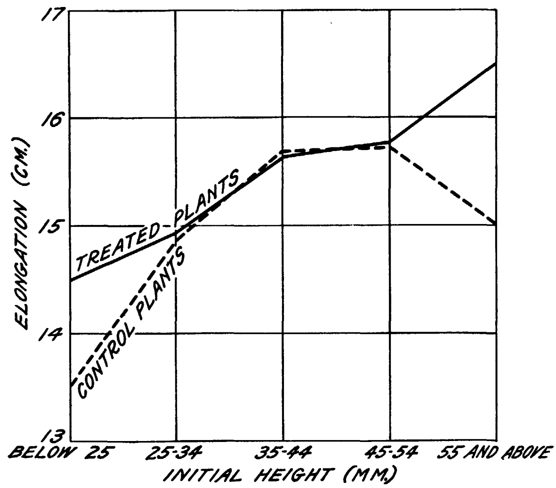

FIGURE 3.—Elongation of growing maize plants treated with a current of 10^{-9} amperes at night, experiment 128. Graph of data given in Table 5, showing the relation of elongation to initial height under treated and control conditions

In experiment 128 the measurements were sorted into five groups according to initial height. The class range was 10 mm., except that all plants with initial height below 24 mm. were combined, as were those above 54 mm. Fortunately, the numbers of treated and control in the several groups were nearly equal. The comparison is shown in Table 5 and Figure 3.

With plants ranging from 0 to 90 mm. in height and receiving the charge from a network only about 60 mm. above the tallest plant, it might be urged that some plants would be receiving too much and others too little current. If this were the case the agreement of the general mean of the treated with that of the control might result from combining plants that were stimulated with those that were retarded.

TABLE 5.—*Elongation of growing maize plants treated with a current of 10^{-9} amperes at night, experiment 128*

[Plants grouped according to initial heights. Treated plants compared with the control ones of the same group]

Initial height (mm.)	Treated		Control		Elongation difference (treated − control)	Difference ÷ probable error
	Number of plants	Mean elongation (cm.)	Number of plants	Mean elongation (cm.)		
0–24	6	14.50	6	13.50	1.00	
25–34	45	14.93±0.21	40	14.85±0.23	.08±0.31	0.26
35–44	194	15.64± .08	195	15.68± .08	−.04± .11	.36
45–54	41	15.78± .15	40	15.75± .23	.03± .27	.11
55–90	2	16.50	4	15.00	−1.50	

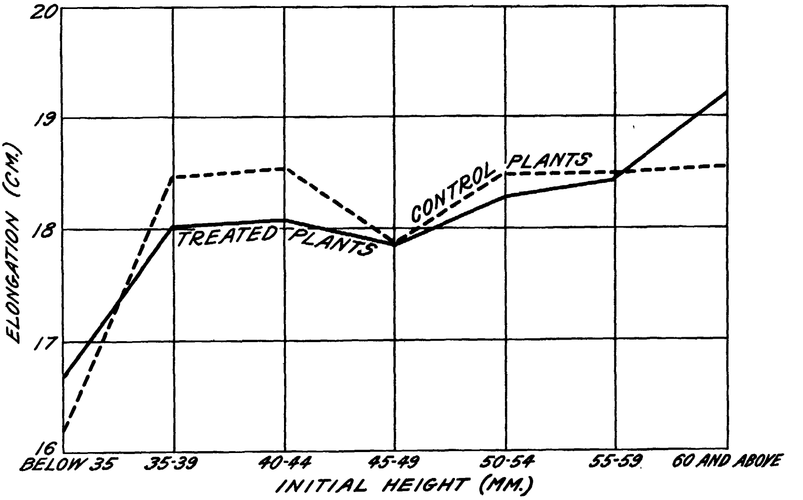

FIGURE 4.—Elongation of growing maize plants treated with a current of 10^{-9} amperes at night, experiment 129. Graph of data given in Table 6, showing the relation of elongation to initial height under treated and control conditions

With plants standing close together, as in this experiment, it seems certain that a great preponderance of the charged ions would pass to the taller plants. The close agreement of mean elongation in treated and control for all initial-height classes that are adequately represented fails to show any disturbing effect.

If the increased charge received by the taller plants was deleterious, the treatment should decrease the variability of elongation by permitting the shorter plants to overtake the taller ones in which growth is retarded. If, on the contrary, the treatment was so light as to affect the taller plants only, the variability should be increased through the increased growth of the taller plants. The standard deviation of elongation for the 288 treated plants was 1.72 cm., and that of the 285 control plants was 1.76, a difference of 0.04 cm., with a probable error of 0.07. Thus the comparison of variability gives no evidence that the treatment produced any measurable effect.

A similar analysis of experiment 129 is shown in Table 6 and Figure 4. The class range was 5 mm., and there were 7 classes. In none of the classes is the difference in elongation significant.

TABLE 6.—*Elongation of maize plants treated with a current of 10^{-9} amperes at night, experiment 129*

[Plants grouped according to initial heights. Treated plants compared with control ones of the same group]

Initial height (mm.)	Treated		Control		Elongation difference (treated − control)	Difference ÷ probable error
	Number of plants	Mean elongation (cm.)	Number of plants	Mean elongation (cm.)		
Below 35	9	16.67±0.85	10	16.20±0.70	0.47±1.10	0.42
35–39	12	18.00± .38	11	18.45± .33	−.45± .50	.90
40–44	26	18.04± .30	21	18.52± .48	−.48± .57	.84
45–49	62	17.84± .16	66	17.85± .16	−.01± .23	.04
50–54	88	18.27± .15	74	18.43± .16	−.16± .22	.73
55–59	50	18.42± .17	55	18.47± .15	−.05± .23	.22
60 and above	36	19.22± .21	48	18.52± .17	.70± .27	2.59

The standard deviation of the 283 treated plants was 2.107 cm., and that of the 285 control plants was 2.131 cm., a difference of 0.024 cm., with a probable error of 0.08.

If there is any particular intensity of current that increases growth it might be expected that a very much stronger current would be detrimental. An experiment, therefore, was tried in every way similar to experiments 128 and 129 except that the current was increased to the maximum possible without sparking. The plants in this experiment, No. 130, received about 75×10^{-9} amperes each, or seventy-five times the intensity of the current in experiments 128 and 129.

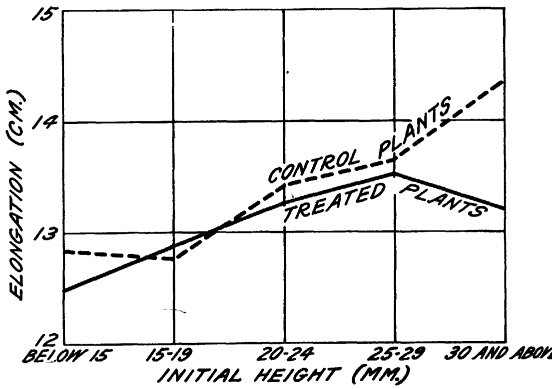

FIGURE 5.—Elongation of growing maize plants treated with a current of 75×10^{-9} amperes at night, experiment 130. Graph of data given in Table 7, showing the relation of elongation to initial height under treated and control conditions

A comparison of the mean values is given in the last line of Table 4. The results parallel those of experiments 128 and 129. Treated and control plants made practically the same elongation, and the uniformity of the experiment was such that a difference of 3 per cent would have been obvious. The standard deviation of the 282 treated plants was 1.66 cm., and that of the 284 control ones 1.79 cm. The smaller standard deviation of the treated plants should follow if the tallest plants were retarded, but the difference of 0.13 cm. is not significant.

The individual plant measurements were sorted on initial height as in experiment 129. The mean elongation of plants in the several initial-height classes are given in Table 7 and shown graphically in Figure 5. The agreement between treated and control is very close except in the group with the largest initial height. In this comparison of 30 treated plants with 28 control plants the means of the control exceeded the treated by 3.5 times the probable error of the difference ($t=2.3$ and $P=$about 0.03). Although a difference of this magnitude would be expected once in about thirty-five times, it suggests that the very tallest plants in the experiment may have been retarded in their growth. The five treated plants with the largest initial height had an elongation of 12 cm. The five largest control plants had a mean of 14.6 cm., and a difference of 2.6 ($t=2.3$, and $P=$about 0.7).

TABLE 7.—*Elongation of growing maize plants treated with a current of 75×10^{-9} amperes at night, experiment 130*

[Plants grouped according to initial heights. Treated plants compared with control ones of the same group]

Initial height (mm.)	Treated		Control		Elongation difference (treated − control	Difference ÷ probable error
	Number of plants	Mean elongation (cm.)	Number of plants	Mean elongation (cm.)		
Below 15	23	12.48±0.28	17	12.82±0.41	−0.34±0.49	0.69
15–19	54	12.83± .15	65	12.78± .13	.05± .20	.25
20–24	96	13.26± .12	95	13.41± .12	−.15± .16	.94
25–29	79	13.54± .12	79	13.68± .12	−.14± .16	.87
30 and above	30	13.20± .23	28	14.32± .22	−1.12± .32	3.50

DISCUSSION

It is doubtless permissible to assume that, theoretically at least, all environmental changes will be found associated with changes in the growth rate if comparisons can be made with sufficient accuracy. In biological work, however, to measure the effect of a single factor with a probable error of 1 per cent represents a rather high degree of accuracy. It is quite possible to detect much smaller differences, but the difficulty is to associate these small differences with the factor under investigation.

The mean elongation of seedlings in a single box is so sensitive that unless great care is exercised uncontrolled and apparently insignificant differences in preparation will cause significant differences in the box means. Little difficulty was experienced in obtaining uniform behavior within the box. The variance of the row means, taken in either direction, was always of a magnitude to be expected from the variance of the individual measurements. Nevertheless it was only in the later experiments, where the precautions for uniformity of treatment were carried to what seems an absurd length, that four untreated boxes could be prepared in which the variance of box means was not significantly larger than the individual variance within the box. The negligibility of the electrical treatment is well shown by the fact that, although differences in the pine boxes that were of the same dimension and apparently alike were associated with different rates of growth, no effect of electrical treatment could be detected.

The 1927 and 1928 experiments appear to demonstrate that currents of the order of 10^{-9} amperes per plant applied during the night do not change the growth rate of maize seedlings.

The permutations of plant species, intensity of current, and time of application are very numerous, and the labor necessary to make an adequate test of any particular combination is not small. In view of these considerations and the impracticability of utilizing any small increases that might be obtained by this means, further investigation of such permutations is not contemplated.

Great difficulty was experienced in providing an environment sufficiently uniform to eliminate significant differences in the rate of growth of cultures given the same treatment. This led to a demonstration that in many instances the association between treatment and a changed growth rate was not in the nature of cause and effect, and indicates that in experiments of this nature caution should be exercised in accepting conclusions based on the statistical significance of one type of experiment.

SUMMARY

The effect of electric currents on the growth of plants was tested by growing seedlings in small boxes in the laboratory. Current was supplied by suspending a charged network above the plants. Control boxes were treated in the same way except that the network was not charged.

Preliminary experiments with barley and maize, with a series of different intensities of current, and with the current applied for the entire period or restricted to the day or the night, indicated that maize treated at night with a current intensity of 10^{-9} amperes per plant gave most promise of positive results.

In the early experiments the measurement used was the height of the seedlings at the end of the experiment. In later experiments elongation of seedlings during the period of treatment was substituted for height. Elongation proved to be a more sensitive measure than height, since it eliminated a large part of the variation due to differences in the time of germination.

Slight differences in exposure due to the position of the boxes were found to cause differences in the rate of growth that masked any possible effect of the current or led to erroneous results. A more uniform exposure of treated and control boxes was provided by placing the entire experiment on a revolving table with the boxes symmetrically disposed about the center.

In the later experiments two boxes were subjected to treatment and two were grown as controls. Significant differences between the two treated or the two controls were taken as indicating the existence of uncontrolled factors that were differentiating the boxes. Differences of this nature were so common and of such magnitude as to destroy confidence in the results of any single experiment, although the statistical significance of the difference between treated and control might not be questioned.

A series of experiments, aimed to determine the nature of the disturbing factors that were causing significant differences in the growth of seedlings in boxes that were treated alike, was only partially successful. Although the boxes were of the same dimensions and all were made of the same kind of lumber, it was found that certain boxes were consistently associated with a slower growth of the seedlings. However, differences in the boxes did not account for all the observed differences in growth between similarly treated boxes.

By exercising extreme care in the preparation and planting of the boxes, and by planting more than the four boxes needed for an experi-

ment and selecting the four boxes showing the greatest uniformity, it was possible eventually to obtain a satisfactory degree of uniformity. Two preliminary series were run in which all four boxes were without treatment, and in no instance did the mean elongation of any box depart significantly from the mean of the experiment.

With similar precautions four experiments were run in which two of the boxes were subjected to a charge from the overhead network that induced a total discharge equal to 10^{-9} amperes per plant. In none of these experiments was there a measurable difference between treated and control in either weight or elongation. In the most uniform experiment a difference as small as 2 per cent of mean elongation would have been detected with practical certainty. In two of the four experiments the mean of the treated exceeded the control, and in two the reverse was the case.

The possibility that some plants received an excess of current that retarded their growth, while others were stimulated, was investigated by comparing the standard deviations of the treated and the control. There was no significant difference in the variability of the two series.

Three of the most satisfactory experiments were analyzed further by sorting the measurements of elongation into groups based on the initial size of the plant and restricting the comparison of the elongation of treated and control to plants of the same initial height. In no instance was there a significant difference. Since tall plants would receive more current than short ones, this constitutes, in effect, a test of the effect of currents both stronger and weaker than the prescribed current. While this method restricts the number of plants in any particular comparison and makes it impossible to detect small differences, the results may be taken as proving that under the conditions of these experiments no significant response is to be expected by altering the intensity of the treatment.

To test further the possibility of a detrimental effect of excessive currents, an experiment was tried with the maximum current possible without sparking. This was about 75 times the current used in the previous experiments. Even this excessive current did not produce any significant change in the rate of growth, though a difference of 3 per cent could have been detected under the conditions of the experiment.