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(WITH SIX PLATES)

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INTRODUCTION

Experiments on the carbon-dioxide assimilation of young wheat plants reported by Hoover, Johnston, and Brackett (*3*) [1] covered a wide range of light intensities and carbon-dioxide concentrations. Under the artificially controlled conditions used, it was shown that there was a linear variation of carbon-dioxide assimilation with carbon-dioxide concentration in the presence of excess light over a limited range. With the maximum light intensity, approximately one-fourth that of sunlight on a cloudless summer day in Washington, carbon dioxide became a limiting factor at a concentration of about that of normal air. Since sunlight intensity for a number of hours per clear day is much higher than the highest intensity employed in these experiments, it was thought that interesting and important data might be obtained from experiments conducted with sunlight under more natural conditions out of doors and with the carbon-dioxide concentration surrounding the plants some 3 to 4 times that of normal air.

It is not feasible here to make an extended review of the large amount of work covering the subject of aerial fertilization of plants with carbon dioxide. Many experimenters report beneficial effects. Several sources of carbon dioxide have been utilized, including carbon-dioxide generators, commercial tanks of the compressed gas, scrubbed flue gas, and that arising from animal and plant manures. Both greenhouse and field experiments have been tried. Carbon dioxide from blast furnaces, after being freed of matter injurious to plants and piped to fields where it was allowed to spread over extended areas, caused marked improvement in crop yields. Because of the difficulty of confining the gas over such large areas in open fields, aerial fertilization with carbon dioxide is better adapted to greenhouse work.

Relatively little work on increasing the products of photosynthesis by enriching the air with carbon dioxide has been done in this

[1] Italic numbers in parentheses refer to list of references at end of paper.

country as compared with such studies in England, France, and Germany. Cummings and Jones (*2*), using open cases in the greenhouse, liberated the carbon dioxide from sodium-bicarbonate sulphuric-acid generators in such a manner that the plants were bathed in an atmosphere rich in carbon dioxide for 8 hours a day. Closed cases were not satisfactory, since they subjected the plants to such abnormal conditions that consistent results were not obtainable. Experiments with a rather wide variety of plants indicated a general increase in plant production and that plants can use to good advantage more carbon dioxide than occurs normally in air. The optimum quantity of carbon dioxide, as found by these authors, for plants grown in open boxes (26 x 18 inches and 26 inches deep for the larger plants, and 52 x 28 x 12 inches for the smaller ones) varied with the plant. For lettuce this quantity was about 300 liters of carbon dioxide a day. Cummings and Jones further conclude that the continuity of supply is as important as the total amount.

Arthur, Guthrie, and Newell (*1*), working at the Boyce Thompson Institute for Plant Research, Inc., have studied the effects on plant growth and chemical composition of increased carbon-dioxide concentrations in greenhouses and in constantly conditioned rooms. The air was enriched with carbon dioxide to about 0.3 percent, or 10 times that of normal air. In addition to sunlight one of the greenhouses received supplementary artificial light, and one of the rooms had artificial light only. Several types of plants were used, the small grains being represented by barley, wheat, and oats. Their spring wheat (variety blue stem) data are shown in table 1.

TABLE 1.—*Experimental Results on the Chemical Composition of the Aerial Portion of Wheat* [*from Arthur, Guthrie, and Newell* (*1*)]

			Nitrogen (percent dry weight)		Carbohydrate (percent dry weight)			
Treatment	Weight per plant (grams)	Moisture (percent)	Soluble	Total	Acid hydrolyzable	Sucrose	Dextrose	Total
Control greenhouse. No heads produced	3.4	86.4	0.93	3.42	13.56	2.73	2.87	19.16
Greenhouse 1. Straw only.	3.3	76.4	0.47	2.15	15.46	8.07	3.26	26.79
Greenhouse 2. Straw only.	6.3	68.2	0.25	1.16	15.50	20.29	1.88	37.17
24-hour day. Straw only..	1.8	64.6	0.29	1.15	18.11	14.13	2.93	35.17
Greenhouse 1. Heads only.	0.6	71.3	0.60	2.18	25.43	28.07	6.79	60.29
Greenhouse 2. Heads only.	2.1	64.7	0.51	2.11	40.53	10.83	3.12	54.48
24-hour day. Heads only..	0.5	61.5	0.26	1.26	30.01	14.14	3.80	47.95

Greenhouse 1 received 6 hours supplementary light each night from crane.
Greenhouse 2 received same illumination and additional carbon dioxide.
24-hour day plants grown in constant-light room.

As can be seen from the table, the plants that received both additional light and carbon dioxide were heavier and contained a greater quantity of carbohydrates than the control plants. No signs of heading in the control plants were noted at time of sampling, whereas those in greenhouses 1 and 2 had been in head for some time. These authors conclude that:

> Small grains, such as barley and spring wheat, in contrast to potatoes, will grow and yield well at a high temperature (78° F.) if given additional light and carbon dioxide. The production of these grains is not favored by low temperature when day length is long and carbon dioxide supply is abundant. The weight per plant of barley increases with day length up to a 19-hour day. Total carbohydrates also increase and nitrogen decreases. The feeding of nitrate was found to make little or no difference in the total percentage of nitrogen in the barley plant, the percentage remaining high only when carbohydrate synthesis was restricted by short days.

EXPERIMENTATION

In the laboratory experiments of Hoover, Johnston, and Brackett, in which growth was entirely under artificial conditions, the wheat plants were confined to a double-walled glass cylinder with their roots extended into a flask of nutrient solution. In the first type of experiments run outside, Marquis wheat was planted in six 8-inch earthenware pots (not glazed) containing a good garden soil. The pots were buried to their rims in wet peat moss placed in a long, narrow cypress box. Cylinders 30 inches in length with conical tops were made from clear cellulose acetate sheeting and so constructed that they fitted into the tops of the pots. The purpose of these cylinders was to confine air of a given carbon-dioxide concentration about the plants. In order to insure a fairly constant carbon-dioxide concentration, the desired air mixture was introduced through a glass tube emerging centrally just above the surface of the soil. Holes cut in the cylinders at the tops just beneath the aprons of the cones provided an exit for the air.

It was thought the flow of air through these cylinders would be sufficient to keep the plants cool. It was soon realized, however, that additional cooling would have to be employed. A means was devised for flowing a thin sheet of water over the outer surfaces of the cylinders. Near the tops of the cylinders small jets of water from copper tubings wet short cloth curtains wrapped around the upper portions of the cylinders. This gave a fairly even distribution of water over the surfaces of the cylinders. Even with this additional equipment, the temperatures within the cylinders were still excessively high on clear days. This was in part due to the high temperature of the tap water used for cooling, which frequently had a temperature of

25° to 28° C. as it came from the pipe line. A further reduction in temperature was brought about by placing a white cloth reflecting surface back of the plants and by operating a movable " half-shade."

A battery of these cylinders is shown in plate 1. They were placed on a small platform about 6 feet above ground and in front of a small frame building that faced south. The flow of water was adjusted by the valves at the top. The waste pipe is shown below. On cloudy days, and at night, the " half-shade " was raised by means of a rope and pulleys.

In the space beneath the platform were located the air and carbon-dioxide flow gauges, the mixing flasks, and the gas tanks. These are illustrated in plate 2. Commercial carbon dioxide of high purity, supplied in heavy steel cylinders, was passed under 15 pounds pressure into a cushion tank and then through a flow gauge into the mixing flask for the proper dilution with air. The air was supplied from the high-pressure compressed-air line from the United States National Museum. It was reduced to 15 pounds pressure and passed into a cushion tank and then into the mixing flask. The proper mixture of air and carbon dioxide was then passed into the cellulose acetate cylinders. The concentration of carbon dioxide in these growth cylinders was checked from time to time by analyses.

Several preliminary experiments were run during the summer of 1933, but the wheat grew so poorly that no definite conclusions could be made other than that the plants receiving the higher concentrations of carbon dioxide grew better than those receiving the lower concentrations. Because of the fact that the plants were too closely confined in the cylinders, where the temperature was abnormally high, and because of the necessity for using a shade and water filter, it was decided to repeat the experiment the following summer after modifying the conditions so as to make them a little less artificial.

On April 14, 1934, Marquis wheat was planted in the six 8-inch pots used the previous summer and in three plots of soil 2 x 2 feet laid off in the yard of the Astrophysical Observatory. The conical tops of the cylinders were removed to minimize the rise in temperature of the air surrounding the plants. Neither the water screen nor the " half-shade " was used. At the corners of two of the 2 x 2-foot plots were placed slotted posts into which sheets of glass 24 x 30 inches in size could be fitted. A plot with glass walls either 30 or 60 inches high could be built up as circumstances warranted. To minimize the removal of carbon dioxide from within these glass-walled plots by air currents, there was laid across the top a frame over which two layers of fly netting were stretched.

POT EXPERIMENTS

The results of the experiments in which wheat plants were grown in pots and enclosed in clear cellulose acetate cylinders are summarized in table 2. The general appearance of the plants in this experiment is shown in plate 3.

TABLE 2.—*Summary of 1934 Experiment with Wheat Grown in Pots*

Data	Pot 1	Pot 2	Pot 3	Pot 4	Pot 5	Pot 6
CO_2 concentration (relative to normal air)	7.1	4.0	1.3	0.9	1.0	1.3
Plants per pot	3	3	3	3	2	2
Average data per plant:						
Number of tillers	10	8	3	2	4	8
Number of stalks	6	6	1	1	2	6
Length of stalks (cm.)	52	54	35	40	43	45
Weight of heads (g.)	1.2	1.2	0.1	0.2	2.3	0.9
Weight of straw	4.8	4.4	1.0	0.7	2.7	3.8
Total weight	6.0	5.6	1.1	0.9	5.0	4.7
No. of grains	4.7	10.7	1.3	3.3	60.5	11.5
Weight of grains	0.134	0.283	0.029	0.050	1.500	0.279
Weight per grain	0.029	0.026	0.022	0.015	0.025	0.024

Culture 3, no forced ventilation.
Culture 4, ventilated by slow stream of air.
Culture 5, not enclosed.

As noted above, Marquis wheat was planted in these pots on April 14. On April 23 the carbon dioxide and air mixture treatments were started. The rate of flow was approximately 2 liters a minute. By May 24 the plants in pot 5 had the best color, although all were slightly yellow, with leaves somewhat rolled. Temperatures on clear, hot days continued to be excessive in these cylinders in spite of the open tops. Heads appeared on plants in pots 1, 2, and 6 by June 11. On July 13 the plants were photographed (pl. 3), and on the 19th they were harvested.

Although the conditions of this experiment were not so ideal as could be desired, a few interesting facts appear from the data in table 2. The number of grains and the weight of grain per plant were much higher in pot 5 than in any of the others. The wheat plants in this culture were not enclosed, but were entirely open to the outside air. The lowest yield in number of grains and in weight of grain per plant occurred in no. 3, where the plants were enclosed in a cellulose acetate cylinder and deprived of forced ventilation. The weight of straw was greatest in the cultures receiving the highest concentration of carbon dioxide. It is to be expected that vegetative growth would be helped by the addition of carbon dioxide, but it is evident that grain production was depressed in comparison with no. 5, the open control, when the number and weight of grain were used as the criteria of measurement. When compared with nos. 3 and 4, the enclosed controls, the number and weight of grain were greater for the carbon-dioxide-treated cultures.

The weight per grain was somewhat higher for the plants receiving the greater quantity of carbon dioxide. One other point of interest is that these same plants put out a greater number of tillers than the ones treated with less carbon dioxide. Those in no. 6 appear to be an exception.

PLOT EXPERIMENTS

Owing to the poor stand in one of the 2 x 2-foot plots from the planting made on April 14, these three plots were replanted on May 9. Because of this delay, seeds sprouted in the laboratory were used for the second planting. A good stand was obtained by May 14, at which time the carbon dioxide-air mixture at the approximate rate of 2 liters a minute was turned into the glass enclosure surrounding plot *A*; *B* served as the enclosed control plot, and *C* as the open one. On May 17 the glass sides were increased in height from 30 to 60 inches.

The results of this experiment are summarized in table 3. The general appearance and arrangement of these three plots and of the 6-pot experiment described above are shown in plate 4. The wheat in the three plots, harvested July 25, is illustrated in plate 5. The dry weight data were determined after the plants were air dried for about 2 months.

TABLE 3.—*Summary of 1934 Experiment with Wheat Grown in 2 x 2-foot Plots*

Data	Plot A (in glass enclosure)	Plot B (in glass enclosure)	Plot C (open)
Average CO_2 concentration (relative to normal air)	3.8	1.1	0.9
Number of seeds planted	36	36	36
Number of plants harvested	34	33	31
Average data per plant:			
Weight (grams) at harvest	14.52	6.39	3.47
Weight after air drying	8.02	5.00	3.02
Weight of water lost in drying	6.50	1.39	0.45
Number of heads	7.44	4.03	2.74
Weight of heads	2.88	2.51	1.26
Weight per head	0.39	0.62	0.46
Weight of straw	5.14	2.49	1.75
Weight of grain	0.85	1.70	0.77
Number of grains	26.08	57.70	37.52
Weight per grain	0.0326	0.0295	0.0205
Number of grains per head	3.51	14.32	13.68

At time of harvest the total weight per plant of those treated with carbon dioxide was over twice that of the enclosed control plot (*B*) and over four times that of the open control plot (*C*). This great difference was due largely to the water content as is evidenced by the dry weights, which, however, still indicate a substantial increase of the carbon-dioxide-treated plants over both controls. The number and weight of heads per plant are also greater. However, the weight per head and the number of grains per plant are less in the carbon-dioxide-treated plot. The large increase in total weight is due to the weight of straw. Although the weight per grain of the plants on the carbon-dioxide-treated plot was somewhat greater than those of the two control plots, the number of grains per head was much less. This experiment likewise indicates the accelerating effect of carbon-dioxide aerial fertilization on vegetative growth and an apparent depressing effect on grain production.

During the following summer the plot experiment was repeated with one additional treatment. It was thought that if phosphorus and potassium fertilizers were added to one of the carbon-dioxide-treated plots at time of heading, these plants might be improved with respect to their grain production. The general procedure in this experiment was similar to that of the previous year. However, the rate of air flow was increased to about 5 liters a minute, and the enclosed control plot was changed to the east end of the row. The appearance of the plants when harvested is shown in plate 6, and the data are summarized in table 4.

TABLE 4.—*Summary of 1935 Experiment with Wheat Grown in 2 x 2-foot Plots*

Data	Plot 1 (in glass enclosure)	Plot 2 (in glass enclosure; CO_2 added)	Plot 3 (in glass enclosure; CO_2, P, and K added)	Plot 4 (open)
Average CO_2 concentration (relative to normal air)	0.9	4.6	4.1	1.1
Number of stalks harvested	83	112	125	114
Total weight (grams) at harvest	230.0	313.0	378.0	144.0
Total weight after air drying	150.0	177.5	220.0	112.0
Weight of water lost in drying	80.0	135.5	158.0	32.0
Number of heads	79	104	117	84
Dry weight of heads	71.5	77.0	102.0	40.5
Dry weight per head	0.91	0.74	0.87	0.48
Dry weight of straw	78.5	100.5	118.0	71.5
Dry weight of grain	54.20	56.15	74.00	25.25
Number of grains	1,786	1,927	2,419	1,251
Dry weight per grain	0.0303	0.0291	0.0306	0.0202
Number of grains per head	22.6	18.5	20.7	14.9

Each plot was planted to 72 grains of wheat, two to the hill, during the first week of April. By April 26 the plants showed a fair start. The glass sides, 60 inches high, were placed around plots 1, 2, and 3, and the carbon-dioxide mixture turned into plots 2 and 3 on April 29. The average carbon-dioxide analyses showed the concentration in plot 2 to be somewhat greater than that of plot 3, the one to which phosphorus and potassium fertilizers were added. This fertilizer combination was applied in a solution of KH_2PO_4 at four different times after the plants started to head out. The total quantity added was about 10 grams.

When the plants were harvested, the number to the hill could not be determined. For this reason the data have been expressed as total for each plot rather than the average per plant, as in table 3.

On May 10 the leaves of the plants in plots 2 and 3 showed a slight yellowing. This yellowing of the carbon-dioxide-treated plants during their early growth was also observed in the previous year's experiments. Later the plants overcame this initial handicap and outgrew the plants of the control plots. By June 7 plants in plots 1 and 4 had started to head out, but no signs of heading were in evidence in plots 2 and 3 (those receiving extra carbon dioxide) until a day or two later. This was also in keeping with observations made the previous year. By June 27 vegetative growth had practically ceased, and the carbon-dioxide treatments were discontinued.

So far as vegetative growth and the amount of tillering are concerned, this experiment showed a beneficial effect of the carbon-dioxide treatment. The weight of straw was increased, as was also the number of heads produced. Although the weight of grain was greater on the carbon-dioxide-treated plots, the greater number of grains produced reduced the average dry weight per grain of these plots to practically the same value as the enclosed control, approximately 0.03 grams. The number of grains to the head was but slightly greater in the enclosed control plot, whereas in the previous year's experiment it was considerably greater.

SUMMARY AND CONCLUSIONS

Three different experiments were carried out with Marquis wheat to study the effects in sunlight of increased carbon-dioxide concentration (in most cases about four times that of normal air) of the air surrounding the plants during their growth. In one experiment 8-inch pots were used, and in the two other experiments plots 2 x 2 feet were employed. Commercial carbon dioxide of high purity was mixed with the air surrounding the plants. The carbon dioxide was confined to the space about the plants by cylinders of clear cellulose acetate in one experiment and by square glass sides in the others.

The main conclusions to be drawn from these experiments are that air enriched with carbon dioxide (1) increased the tillering of the wheat, (2) greatly increased the weight of straw, increased (3) the number and (4) weight of heads, (5) increased the number of grains produced, and (6) slightly delayed the time of heading. The weight per grain was practically the same as that of the controls even in the experiment in which phosphorous and potassium fertilizers were added at time of heading.

Great differences in growth were obtained in the plot experiments between the enclosed plants and those grown in the open. The enclosed plants were larger, heavier, and more succulent, and the weight per grain was somewhat greater. In the pot experiment the plants in the open culture (no. 5) grew better than those of the corresponding control (no. 4). There appears to be some evidence, since this pot experiment, of a toxic effect of cellulose acetate. If this is true, it may account for the poorer growth of the plants enclosed in the cellulose acetate cylinders. It would appear that the higher humidity within the enclosed plots was beneficial to these plants. The evidence, however, is not conclusive, since the temperature was also higher within than without the enclosures.

The aerial fertilization of plants with carbon dioxide raises a number of interesting questions. Many of these can be answered, however, by laboratory experiments under controlled conditions. The practical application of this type of fertilization in field experiments and the supply of carbon dioxide in sufficient amounts for practical field work are still unsolved problems, in spite of the work that has been done. Even its application to greenhouse culture requires the utmost precaution. The escape of the gas mixture into a greenhouse is not sufficient in itself, but a recirculating system, as noted by Owen (*4*) aids materially toward obtaining uniform distribution. While experiments in which carbon dioxide is used as an aerial fertilizer are of important scientific value, the practical application of this type of fertilizer in commercial work is far from being satisfactory, although its application to greenhouse culture appears to be most promising.

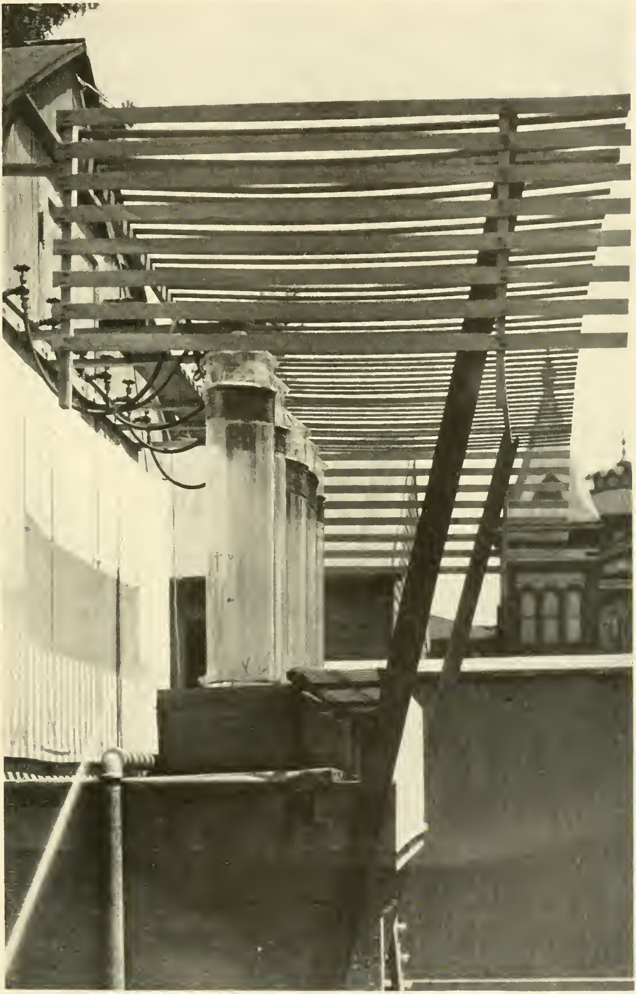
REFERENCES

(1) Arthur, John M., Guthrie, John D., and Newell, John M.
1930. Some effects of artificial climates on the growth and chemical composition of plants. Amer. Journ. Bot., vol. 17, pp. 416-482.

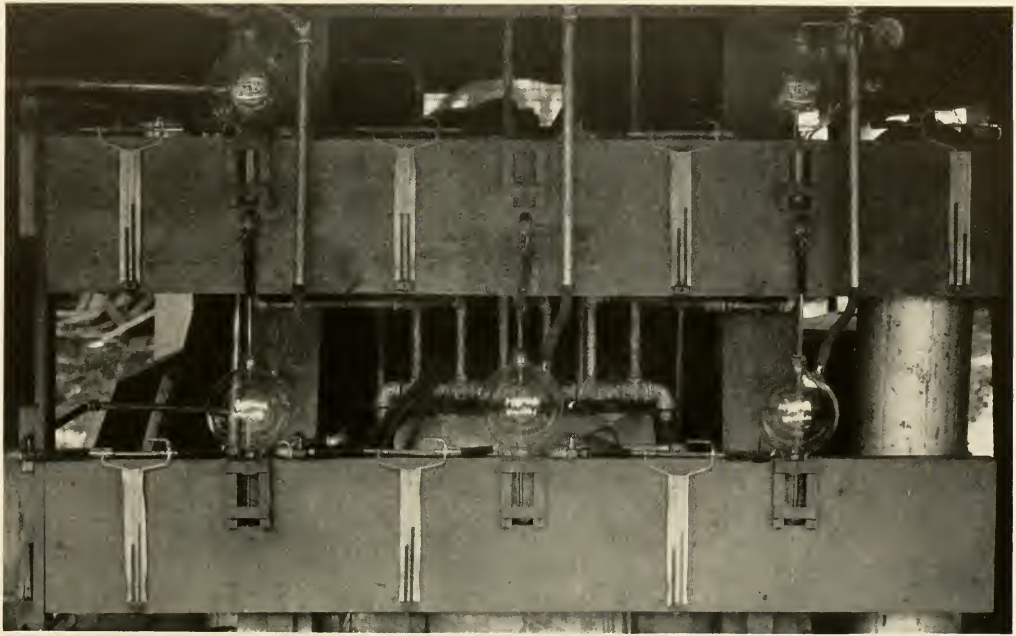
(2) Cummings, M. B., and Jones, C. H.
1918. The aerial fertilization of plants with carbon dioxide. Vermont Agr. Exp. Stat. Bull. 211, pp. 1-56.

(3) Hoover, W. H., Johnston, Earl S., and Brackett, F. S.
1933. Carbon dioxide assimilation in a higher plant. Smithsonian Misc. Coll., vol. 87, no. 16, pp. 1-19.

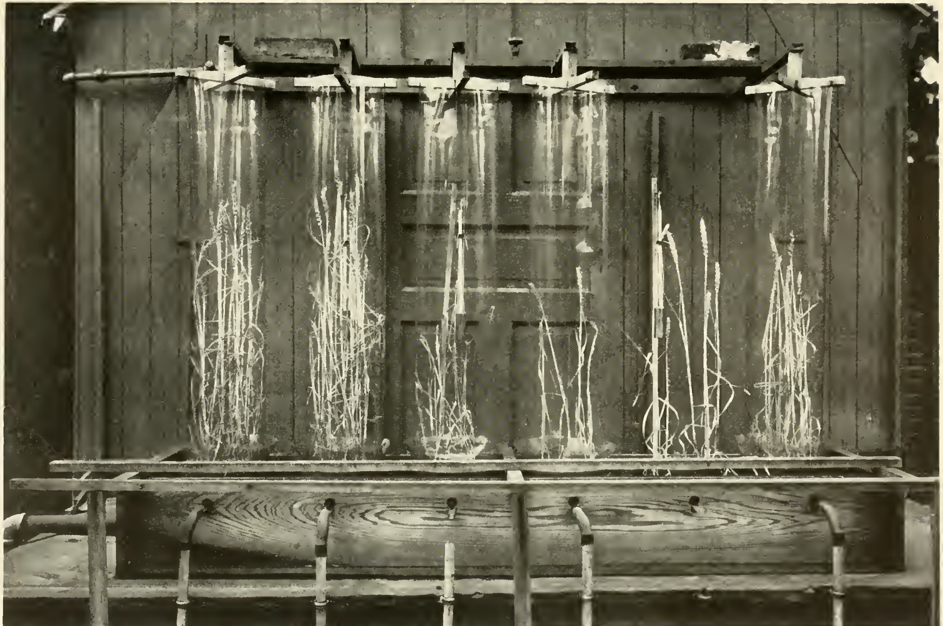
(4) Owen, Owen.
1923. Carbon dioxide investigations. Exp. and Res. Sta., Nursery and Market Garden Industries' Development Soc., Ltd., 9th Ann. Rep., pp. 82-94.



WHEAT CULTURES ENCLOSED IN TRANSPARENT CYLINDERS OF CELLULOSE ACETATE

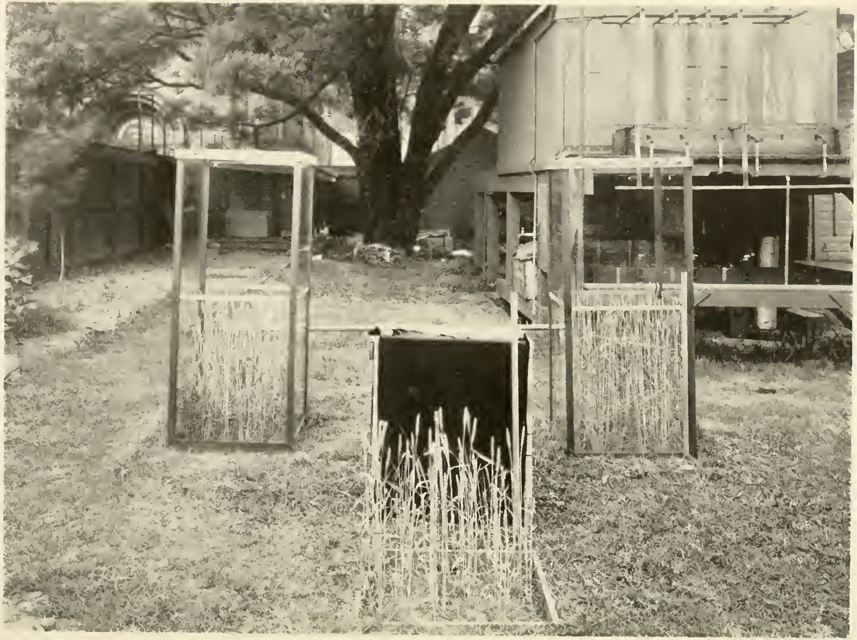


APPARATUS FOR CONTROLLING THE FLOW AND MIXTURE OF CARBON DIOXIDE AND AIR



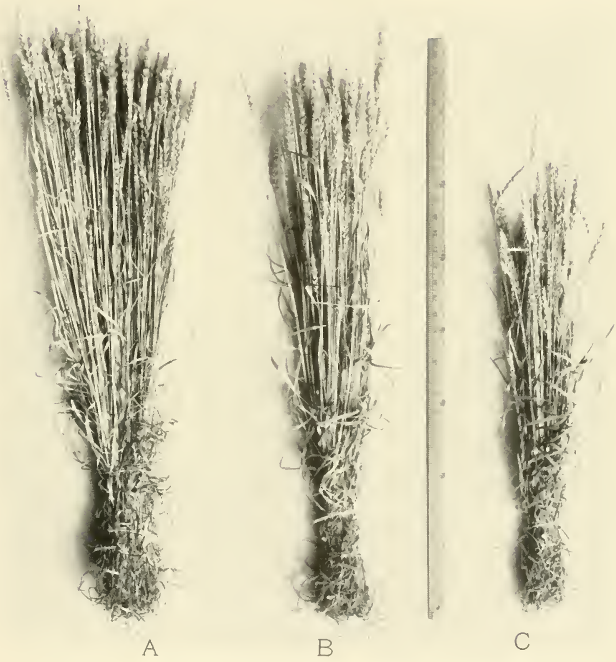
General Appearance of Wheat Plants Grown in Clear Cellulose Acetate Cylinders

Cultures are numbered from left to right. (See table 2.)



General Appearance of Wheat Pot and Plot Experiments of 1934

(See tables 2 and 3 respectively.)



APPEARANCE OF WHEAT HARVESTED FROM THE 1934 PLOT EXPERIMENTS

Average carbon-dioxide concentration relative to normal air was: A, 3.8; B, 1.1; C, 0.9. (See table 3.)

APPEARANCE OF WHEAT HARVESTED FROM THE 1935 PLOT EXPERIMENT

Average carbon-dioxide concentration relative to normal air was: 1, 0.9; 2, 4.6; 3, 4.1; 4, 1.1. (See table 4.)