STUDIES ON THE ROOT GROWTH OF WILLOW CUTTINGS AT CONTROLLED TEMPERATURES.

by

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CONTENTS

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INTRODUCTION

Although many studies have been made upon the relation of temperature to plant growth, the work has largely been restricted to the above ground portions, so that knowledge concerning the effect of temperature on the growth of roots is very slight. This comparative lack of information regarding these normally underground organs may perhaps be explained by the greater difficulties which accompany their study.

Aside from their physiological interest, studies concerning the effect of temperature on root growth have obvious practical value. Particularly are they of value to the plant propagator, for whom slight deviations from the optima of the various factors which influence the production and development of roots from his cuttings, may spell the difference between success and failure.

REVIEW OF LITERATURE

This resume' of previous investigations is not concerned with the literature relative to the effect of temperature on the growth of the above ground portions of the plants, but only with that relating to root growth.

Such studies on the root growth of cuttings have been quite limited. Swingle (8) using 50 apples (Springdale variety) and willow (*Salix alba*) cuttings for each temperature experiment within a range of 7.7° to 46.5°C., determined the optimum as that temperature at which the largest proportion of cuttings showed root formation after seven to ten days. The optimum reported for apple rooting is 24° - 29°C., and for willow rooting near 29°C., although good rooting was secured at all temperatures tested between 20° and 33°. The minimum temperature varied, for apple rooting from 8° to 14°C, and for willow from 13° - 18°. The maximum temperature at which roots developed in the case of both apple and willow cuttings was 38° to 39°.

Zimmerman and Hitchcock, (10) using ten cuttings of holly (*Ilex verticillata*) in each lot, determined the optimum temperature for root development as that at which rooting took place in the shortest time. They conclude that the optimum temperature for rooting is between 24° and 27°C., although the results show rooting in the shortest time at 27°. If temperatures between 27° and 35°C. were tried, the results were not included in the data. At 35° the cuttings rotted before they had time to form roots. Their results indicate a minimum temperature for rooting between 10° and 15°C.

True (9) determined the influence of sudden changes in temperature on seedling roots of the broadbean (Vicia faba). With an external temperature control, he measured the root growth in water, through a horizontal microscope. Changes from the extremes of 18° - 21° and .5° - 1.5°C. produced turgor changes tending to cause a shortening in length of the root when the temperature was lowered, and tending towards elongation when the temperature was raised. An increase in temperature was followed by a slow resumption of the growth rate characteristic of the higher temperature. Sudden changes between 18° and 30°C. seemed to cause only turgor changes, apparently causing no momentary depression in the growth rate.

Leitch (5) using a gas thermostat to control temperature and measuring the root growth of Pisum sativum through a microscope, determined the optimum temperature to be 28° - 30°C. and the maximum-rate growth to take place at 30.3°C. There was no growth at 44.5°C., growth ceased in one hour at 42.7°C, and in two hours at 40.5°C. The minimum temperature for root growth is concluded to be -2°C. The roots were frozen at that temperature but resumed growth when the temperature was raised.

A review of the literature on root growth discloses a lack of any careful measurements on the effect of temperature, the temperature range at which root growth can take place, and of the optimum temperature except within rather indefinite limits. None of the work takes into careful consideration the grand period of growth with its possible influence on temperature studies.

MATERIALS AND PROCEDURE

It was deemed advisable to study one species intensively rather than a number of species in a more superficial way. The willow (Salix nigra) was selected because cuttings root quickly and it was found that the growth is sufficiently rapid to easily detect differences in rate of growth at different temperatures.

Dormant cuttings were placed in beakers of tap water and allowed to root in the greenhouse. Water, instead of sand or soil, was used as a rooting medium for several reasons. The cuttings root easily in water, and since a solution was used during the measurements of root growth, less readjustment of the root to change of condition was necessary. Furthermore, no injury was sustained by the roots in transferring them to the experimental medium, as might have been experienced if sand of some other solid medium had been used for rooting. The nutrient solution used was prepared by Johnston's formula (4), and was changed every two days except in those cases in which an experiment was run for a longer time.

<u>Assemblage of Equipment</u>: The general arrangement of equipment is diagramed in Figure 1. The cutting selected was fastened securely in the clamp as shown and adjusted so that the lower portion of the cutting with its root was submerged in the nutrient solution contained in a glass vessel on the microscope stage. A glass staining dish was found to be satisfactory as a container. The root to be measured was in a horizontal position and the root tip directly under the microscope objective. To keep the root tip in the field of observation, the microscope base was placed on a greased glass surface which allowed its movement in any direction without disturbing the position of the root.

Preliminary experiments showed an error in the measurements due to the natural tendency of roots to grow downward. To overcome this difficulty, a glass microscope slide was bent and fitted in the stage dish as shown in Figure 2. Since the slide was adjustable in the dish, the dish movable on the microscope stage and the clamp adjustable on the ring stand, it was a relatively easy matter to keep the root resting properly in position.

<u>Temperature control</u>: Constant temperatures of the nutrient solution in the vessel on the microscope stage were maintained by the flow of water through a coil in the constant temperature bath (W) and from there through a coil in the microscope vessel (Y) as shown in the diagram of

Figure 1. Water siphoned through tube (B) from the reservoir bottle (A) insured a water supply of constant pressure. When temperatures above that of the room were required, the water was passed through coils of glass tubing in the electrically controlled water bath (W) and directly through coils in the dish containing the nutrient solution. A thermometer was kept in the solution continuously and placed as near as possible to the growing root tip. The temperature maintained in the dish depended on the temperature of the water bath and the rate of flow of water controlled by the pinch cock on tube (B).

Temperatures below that of the room were secured by adding ice instead of heat to the bath (W). This easily provided temperatures in the stage dish as low as 7°C. For temperatures below 7°C, a cold brine was passed through the coils of the staining dish. The brine was kept in a large tank and cooled by the addition of quantities of ice. By this method it was possible to maintain a temperature as low as 0.5°C. in the solution. The temperature maintained again depended on the temperature of the brine and the rate of flow through the coil in the dish.

<u>Aeration</u>: It was observed that the water in the overflow tube (C) from the reservoir bottle (A) of Figure 1, carried over with it a large amount of air, the tube being larger than was necessary to take care of the excess water. This overflow, when controlled, provided a continuous source of air for the aeration experiment. Referring to Figure

4, the air and water entering through tube (C) developed a pressure in the bottle which forced water up tube (D) and air out tube (E). By proper adjustment of the pinch cocks, a constant supply of air was maintained. The air was released directly under the growing root in the nutrient solution as shown in Figure 3. Obviously the glass slide in Figure 2 could not be used successfully with the aeration apparatus in operation. Since it was found that willow roots would grow equally as well without aerating the solution, the aeration devise was abandoned after preliminary studies.

<u>Measurement of Root</u>: It was found advisable to remove the lens of the microscope objective to obtain a convenient degree of magnification. An eyepiece micrometer provided a means of measuring growth increments accurately within .02 of a millimeter. An elongation as small as .015 of a millimeter per hour could be observed and estimated.

Readings were taken hourly and the period of observation of a single root ranged from twelve to sixty-two hours. The period of exposure to different temperatures when a temperature change was made, varied from three to eight hours. In the calculation of all averages, however, the reading for the first hour immediately following the change in temperature was omitted in order to be certain the root had assumed the growth rate characteristic of the new temperature.

Although the above methods were used in study-

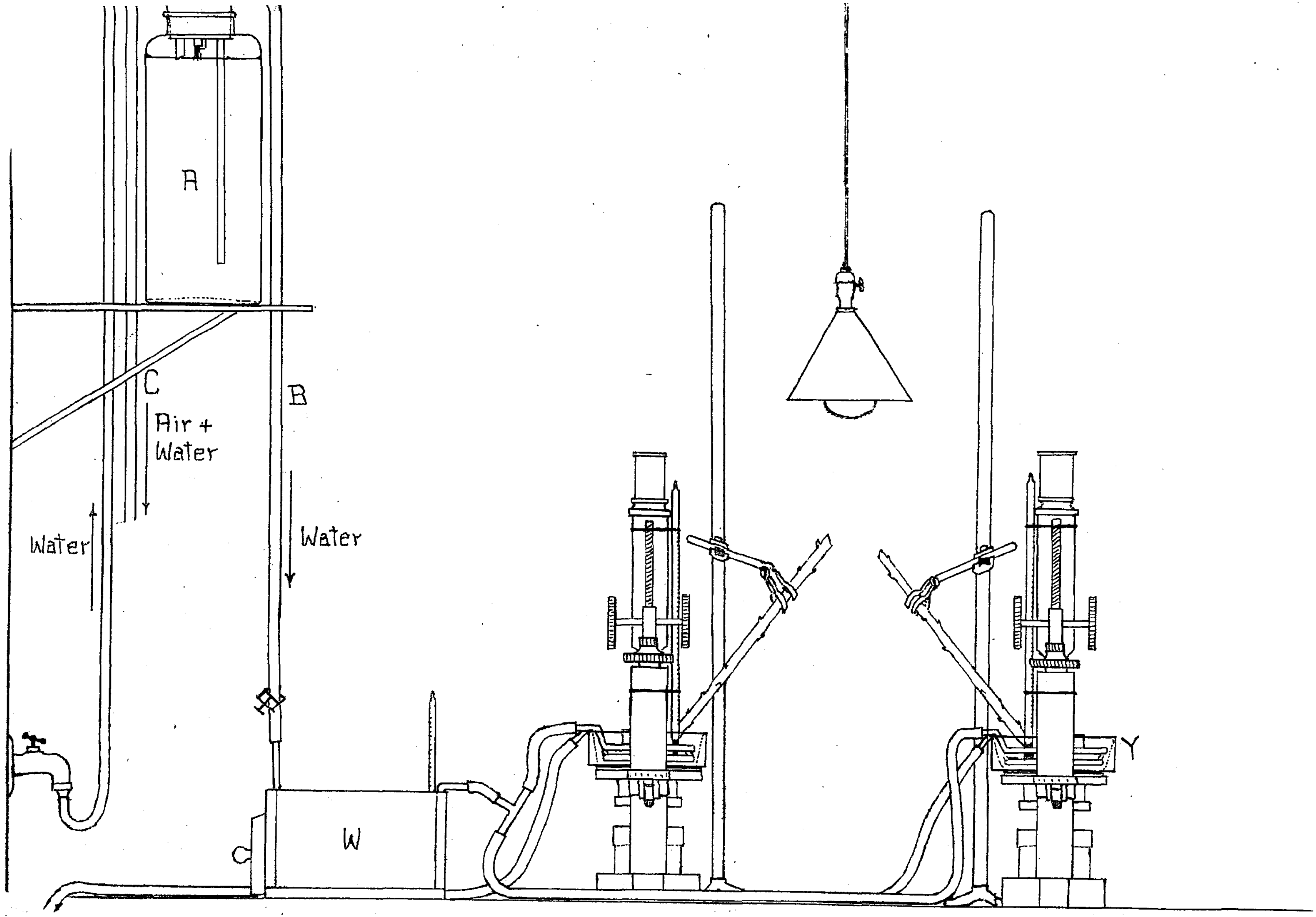

Fig. 1. Arrangement of Equipment

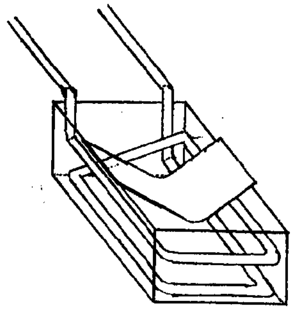

Fig. 2.

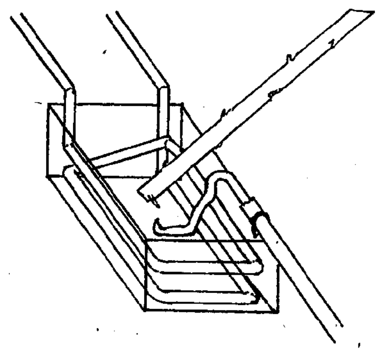

Fig. 3.

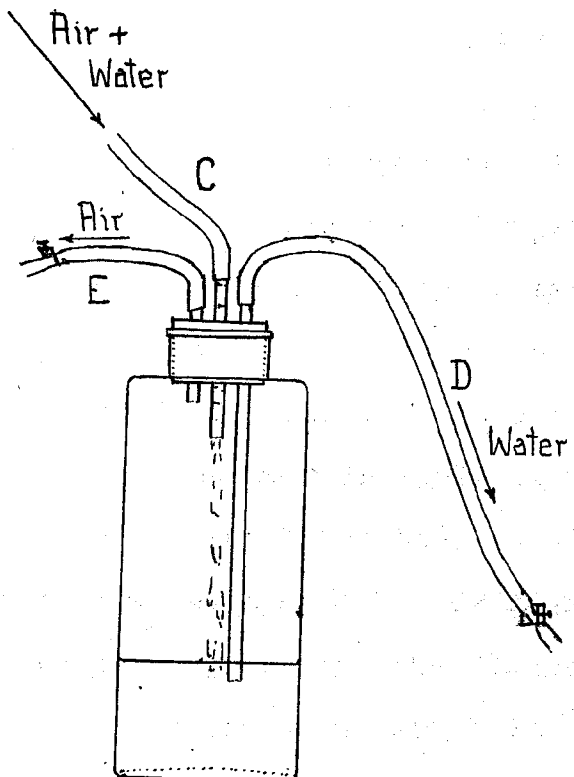

Fig. 4.

ing only one species (Salix nigra), they are equally applicable to the study of rooted cuttings of other species. An outstanding advantage of the method lies in the opportunity to secure comparative results on a single root, thus eliminating the variability between different individuals. Differences in growth rate can thus be ascribed only to temperature changes.

PRESENTATION OF DATA

Preliminary Observations.

Normal Growth: A cutting of normal appearance with one root only three millimeters long was selected. The solution was maintained at a temperature thought to be near the optimum, 30°C., for a period of sixty-two hours. The deviation from the temperature of 30°C. was no greater than 1° at any time, and then only for very short periods until the temperature could be again regulated at 30°C. The increments in growth are presented in Table 1. From these data the growth curve of Figure 5 has been constructed showing the length of the root at each hour. If measurements could be secured for a long enough period the figure would probably show the complete S-shaped curve which is characteristic of growth in general. Enough of the total curve is obtained, however, for the purpose of this experiment, namely; to show the period in the growth of the root when measurements at different temperatures can be relied upon as being true functions of the temperature and not the result of a different

TABLE I

ELONGATION OF ROOT 1-a MAINTAINED AT 30°C. for 62 HOURS.

Hour	Time	Growth (mm)	Elongation.			Temp. Deg. C.
			1 hr. (mm)	2 hr.	3 hr.	
0	10:30	0.0	0.0			30
1	11:30	.27	.27			30
2	12:30	.6	.33	.6 mm		30
3	1:30	.9	.3		.9 mm	30
4	2:30	1.28	.38	.68		30
5	3:30	1.56	.28			30
6	4:30	1.84	.28	.56	.94	30
7	5:30	2.11	.27			30
8	6:30	2.43	.32	.59		30
9	7:30	2.95	.52		1.11	30
10	8:30	3.43	.48	1.0		30
11	9:30	3.93	.5			30
12	10:30	4.45	.52	1.02	1.50	30
13	11:30	5.08	.63			30
14	12:30	5.83	.75	1.38		30
15	1:30	6.755	.925		2.305	--
16	2:30	7.68	.925	1.85		30
17	3:30	8.45	.77			30
18	4:30	9.28	.83	1.6	2.525	30
19	5:30	10.21	.93			30
20	6:30	11.31	1.1	2.03		--
21	7:30	12.44	1.13		3.16	30
22	8:30	13.47	1.03	2.16		30
23	9:30	14.72	1.25			30
24	10:30	15.98	1.26	2.51	3.54	31
25	11:30	17.06	1.08			30
26	12:30	18.53	1.47	2.55		30
27	1:30	19.53	1.0		3.55	30
28	2:30	20.73	1.2	2.2		31
29	3:30	21.86	1.13			30
30	4:30	22.88	1.02	2.15	3.35	30
31	5:30	24.18	1.3			30
32	6:30	25.35	1.17	2.47		30
33	7:30	26.82	1.47		3.94	30
34	8:30	28.2	1.38	2.85		30
35	9:30	29.5	1.3			30
36	10:30	30.78	1.28	2.58	3.96	30
37	11:30	32.38	1.6			30
*38	12:30		)			)
39	1:30		)--			)-- 28-32
40	2:30		) Av.			)
41	3:30		)1.35			)
42	4:30		)			)
43	5:30		)			)
44-1/4	6:45	41.81	1.33	2.68		
45-1/4	7:45	42.88	1.07		3.75	30
46-1/4	8:45	44.11	1.23	2.30		30
47-1/4	9:45	45.33	1.22			30
48-1/4	10:45	46.43	1.10	2.32	3.55	30
49-1/4	11:45	47.53	1.10			30
50-1/4	12:45	48.78	1.25	2.35		30
51-1/4	1:45	49.85	1.07		3.42	30
52-1/4	2:45	50.88	1.03	2.10		30
53-1/4	3:45	51.95	1.07			30
54-1/4	4:45	53:02	1.07	2.14	3.17	30
55-1/4	5:45	54.09	1.07			31
56-1/4	6:45	55.19	1.10	2.17		30
57-1/4	7:45	56.19	1.00		3.17	30
58-1/4	8:45	57.26	1.07	2.07		30
59-1/4	9:45	58.33	1.07			30
60-1/4	10:45	59:40	1.07	2.14	3.21	30
61-1/4	11:45	60:40	1.00			30
62-1/4	12:45	61.40	1.00	2.00		30

* Records unreliable from 11:30 to 6:45. Averages have been considered.

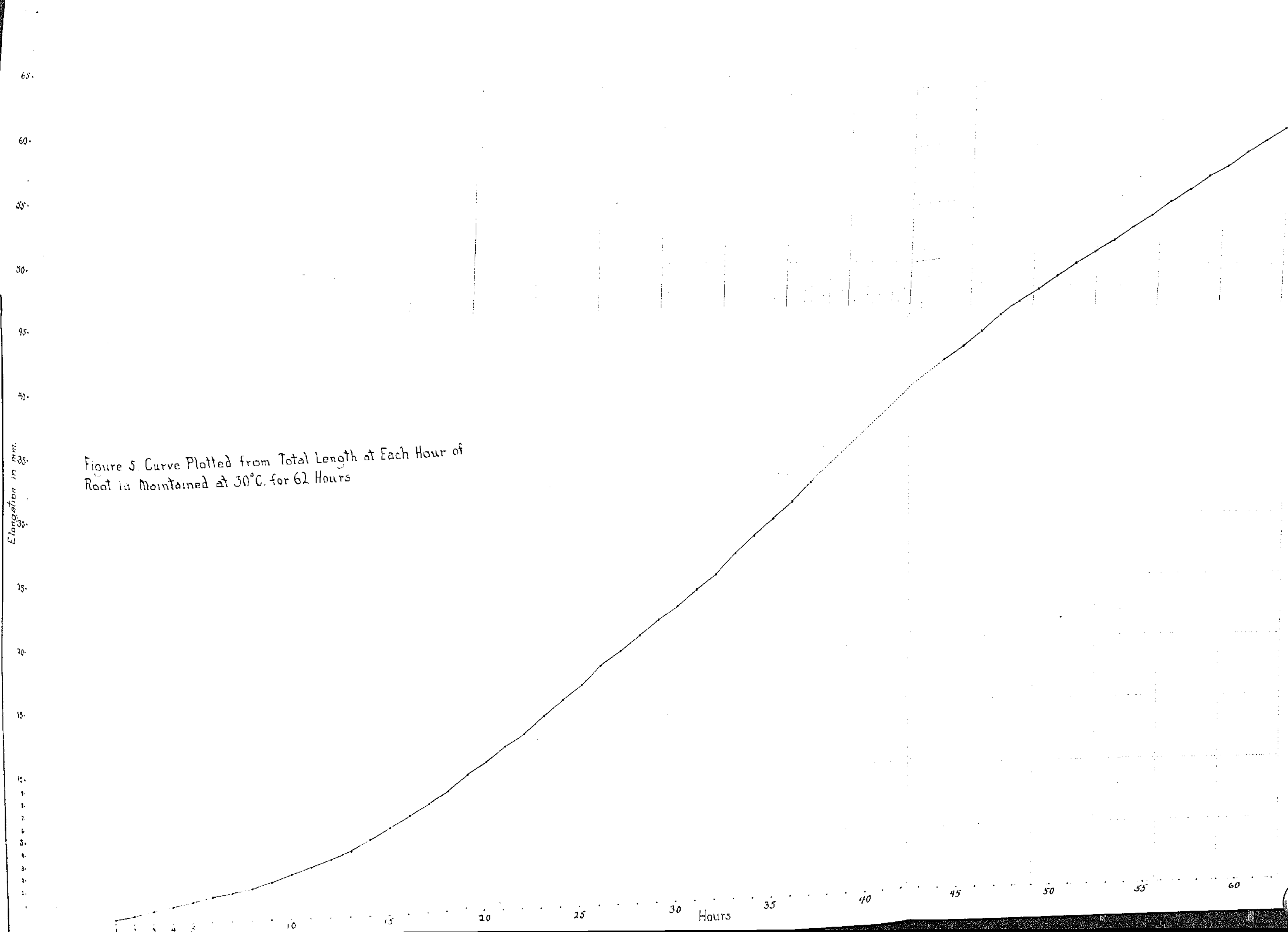
Figure 5. Curve Plotted from Total Length at Each Hour of Root in Maintained at 30°C. for 62 Hours
Elongation in mm.
Hours

growth rate within the grand period. It is obvious that reliable measurements on the effect of temperature can be secured only after the root has attained a length of ten to twelve millimeters. How much farther the straight portion of the curve would continue before flattening out can only be conjectured. It is shown, however, to be of sufficient length for the studies which follow.

The data of Table 1 are also shown in Figure 6 as growth increments, using time intervals of one, two and three hours. The variations in rate of growth between hourly periods is graphically illustrated in curve A. These variations were expected and have been found in most growth studies in which methods of measurement have been sufficiently accurate for their detection.

The curves of Figure 6 present an opportunity to determine the possible presence of rhythmic periodicity in root growth of this species. Although the differences between each succeeding hour's growth, as represented in curve A, is so great that any periodicity might be masked, it should become apparent in Curves B and C, in which the irregularities have been smoothed out by plotting the growth at two and three hour intervals. However, an examination of curves B and C shows no consistent rhythmic growth to be present. Friesner (2), with seedlings of *Pisum sativum*, *Cucurbita pepo*, *Lupinus alba*, and *Allium cepa*, presents results from which he concludes there are two to four waves of root elongation during a twenty-four hour period. A careful examination of his data, which is presented for two roots of _Pisum sativum_ only, does not justify similar conclusions.

The Effect of Shoot Removal: A cutting was selected which had a root one centimeter in length and eight green shoots, none of which was longer than 1.5 centimeters. The temperature was maintained at 29°C. and readings were taken hourly for several hours before and after the shoots

TABLE II.

EFFECT OF REMOVING SHOOTS ON THE RATE OF ROOT GROWTH OF 7b, MAINTAINED AT 29°C.

Hour.	Elongation (mm)	
1	.81	
2	.77	
3	.85	
4	1.07	
5	.94	
6	.91	
7	1.00	
8	.94)	
9	1.02)	
10	1.00)	-- .98 ± .01167
11	.93)	
12	1.03)	
13	.96)	Shoots removed.
14	1.03)	
15	.96)	
16	1.15)	
17	1.00)	-- 1.0017 ± .0237
18	.89)	
19	.98)	

Difference - .0217 ± .0262

were removed. Growth increments are given in Table 2, with mean hourly increments for the six hours previous to and following removal of shoots. It is evident that the removal of shoots had no effect on the growth rate of the root, the probable error of the difference in growth rate being larger than the difference itself.

It is concluded that if any food material is elaborated by the very young leaves present on the cutting used in this experiment, it is not a factor in the growth of roots, and therefore, that illumination of the cuttings was not essential. The results also indicate that the young shoots, in their early stages of growth, do not compete with the roots for the stored foods of the cutting. The demands for food of both shoots and roots are probably satisfied locatlly. A further indication is the probable absence of any alternating periodicity between root and shoot growth, or any correlation agency between the two which might affect the rate of root growth.

The Effect of Aeration:

Table III. gives the record of hourly elongation of a normal root with and without aeration. The average elongation of 1.18 millemeters per hour for the four hours without aearation as compared with an average of 1.12 millimeters for the next four hours with aeration, indicates very little effect from aeration and certainly no benefit. This is not surprising for Livingstone and Free (6) have reported that willow (Salix nigra) is capable of enduring almost

TABLE III.

EFFECT OF AERATION ON THE GROWTH RATE OF ROOT 3b, MAINTAINED AT 29°C.

Hour.	Elongation (mm).	
1	.67	Without Aeration.
2	.92)	
3	1.14)	
4	1.44)	-- 1.18 Av.
5	1.22)	
6	1.18)	With aeration
7	1.00)	
8	1.07)	-- 1.12 Av.
9	1.29)	
10	1.29	
11	1.22	
12	1.29	

complete exclusion of oxygen from the roots. In view of this fact, all of the following studies were made without aeration.

The Effect of Sudden Changes in Temperature: True's (9) results indicate that a sudden temperature change in itself might influence the growth rate of roots, regardless of the temperature extremes. Askenasy (1) who measured the growth rate of maize seedling roots at controlled temperatures, found with temperature changes from 26° to 9°C., the expected decreased growth rate at 9°C was assumed slowly, but apparently there was no decrease in the growth rate below that characteristic for 9°C. Pedersen (7), exposing seedlings of *Vicia faba* to sudden and to gradual changes of temperature

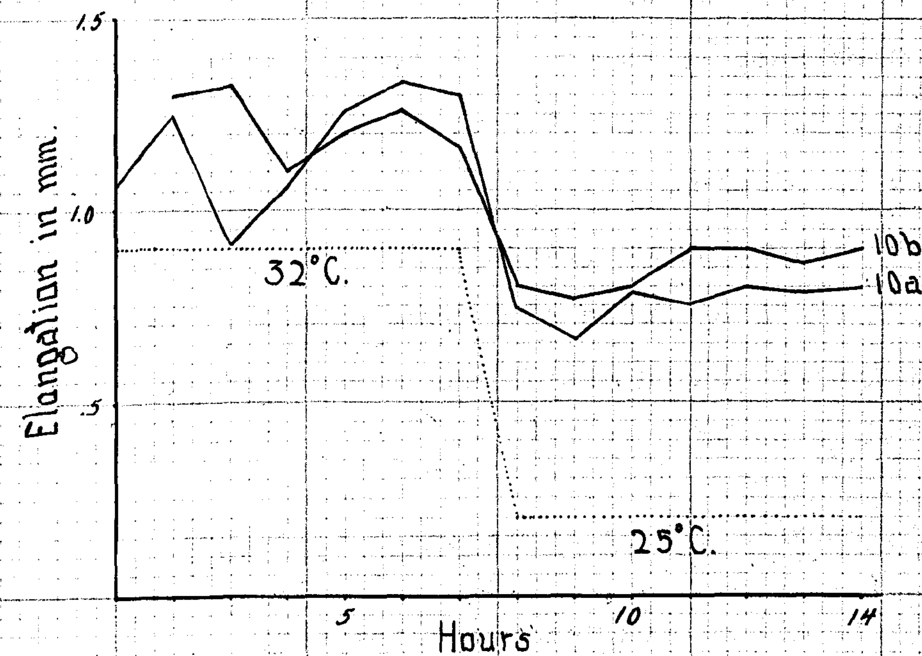

Figure 8. Effect of a Rapid Decrease in Temperature on the Growth Rate

between 12.5° and 25°C. reported no evidence of retardation in the growth rate of shoots. He concluded the growth rate to be dependent on the temperature itself, a change having no influence.

Two willow roots were maintained at 32°C. for several hours and the temperature then lowered rapidly to 25°C. Graphs plotted from the hourly observation records are presented in Figure 7. It may be seen that this sudden decrease in temperature at 7°C. brings about a temporary growth rate slower than that characteristic of the low temperature. For this reason, temperature changes in the studies which follow were made slowly and the first observation at the new temperature discarded for calculation of averages.

Effect of Temperature on the Growth Rate.

Observations were made on the elongation rate at different temperatures of root 1-b in order to determine the relation between root growth and temperature. The record of observations is given in Table 4, with graphs plotted on the basis of hourly elongation for one and two hour intervals in Figure 28. Graph A illustrates clearly the marked effect even small changes of temperature have on the rate of elongation. Graph B, which eliminates some of the hourly variation apparent in A, makes more evident the effect on growth of the less temporary changes

TABLE 4

ELONGATION OF ROOT 1-b DIFFERENT TEMPERATURES DURING A 61 HOUR PERIOD

Hour	Elongation		Temp. Deg. C.
	1 hour	2 hours	
0	0.0		29
1	.555		29
2	.555	1.11	29
3	.55		29
4	.63	1.185	29.5
5	.67		29
6	.61	1.28	24
7	.5		24
8	.52	1.02	24
9	.555		24
10	.555	1.11	24
11	.63		24
12	.89	1.52	29
13	1.04		29
14	1.11	2.15	29
15	1.16		29
16	1.16	2.32	29
17	.81		21
18	.44	1.25	19
19	.33		18
20	.41	.74	18
21	.44		19
22	.67	1.11	19
23	.92		29
24	1.29	2.21	30
25	1.41		29
26	1.055	2.465	29
27	1.26		29
28	.78	2.04	15
29	.29		16
30	.33	.62	14
31	.22		14
32	.26	.48	14
33	.22		14
34	.22	.44	14
35	.22		14
36	.63	.85	29
27	1.02		29
*38	Avr.		28--31
39	1.14		
40			
41			
42			
43			
44-1/4	1.14	2.28	29
45-1/4	1.26		29
46-1/4	1.11	2.37	29
47-1/4	.85		29
48-1/4	1.44	2.29	29
49-1/4	.555		12
50-1/4	.18	.737	12
51-1/4	.15		12
52-1/4	.18	.33	12
53-1/4	.2		13
54-1/4	.24	.44	13
55-1/4	.29		17
56-1/4	.2	.49	11
57-1/4	.22		16
58-1/4	.24	.46	10.5
59-1/4	.13		10
60-1/4	.15	.28	10
61-1/4	.15		10

*Records unreliable from hours 37 to 44-1/4. Averages have been considered.

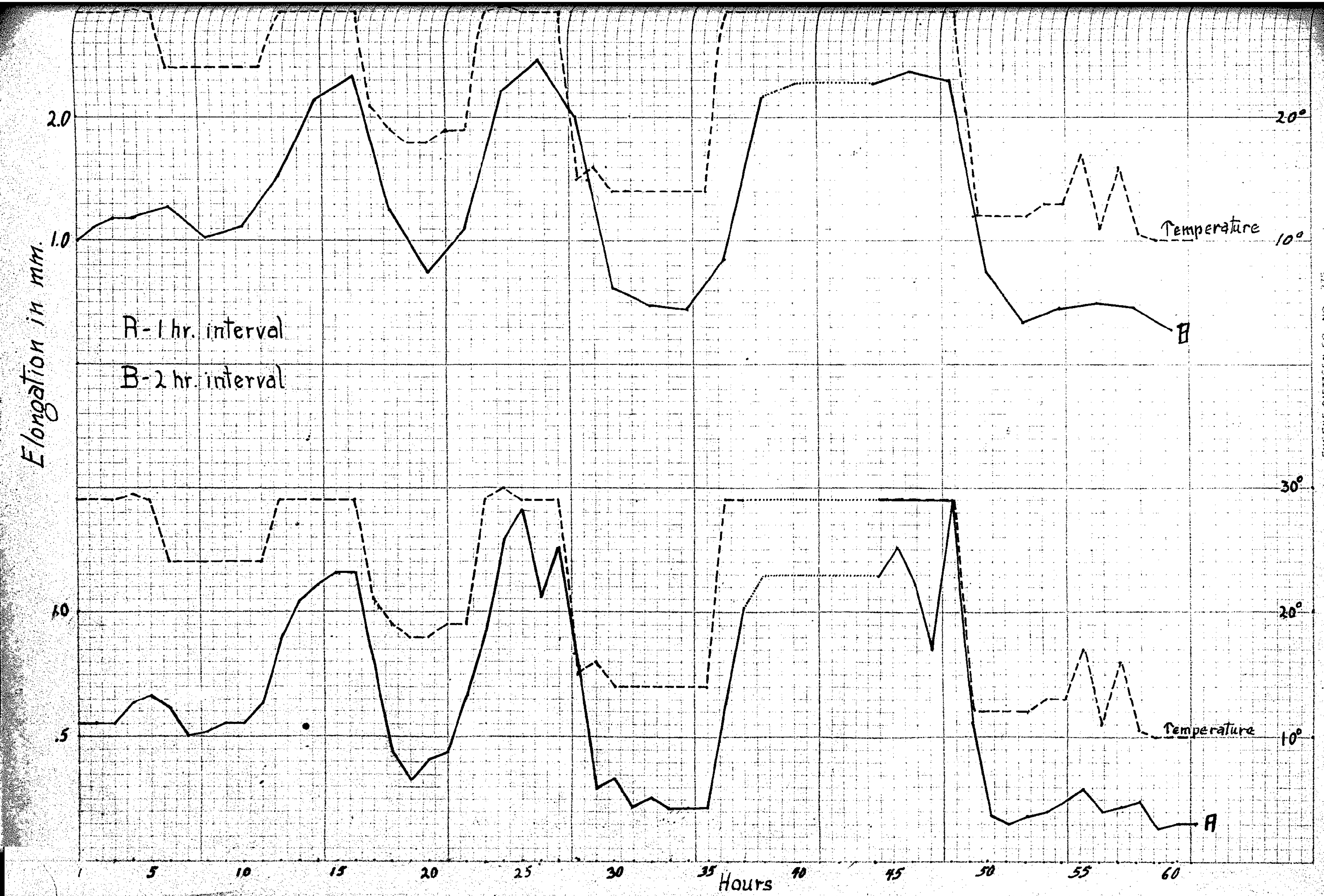

Figure 9. Effect of Temperature on the Growth Rate of Root 1b

in temperature, and shows a small but definite lag on the part of the root in following the temperature changes.

Cardinal Points of Temperature

Optimum Temperature for Root Growth: The data in Table V. are the results of observarions made on three roots maintained at temperatures between 24° and 33°C. An examination of the roots 6-a and 12-b show a greater rate of growth at 29°C. than at either 27° or 31°C. The probable errors of the averages show distinctly significant differences in growth rate changes of 2°C. This definitely fixes an optimum temperature between 28° and 30°C. The record of root 6-b, although observations are not as complete as originally planned, shows a greater average hourly elongation at 30°C than at 28°C. From these results it seems safe to conclude that the optimum temperature for the root growth of willow is 29°C to 30°C.

The data for root 6-a furthermore show that although the temperatures of 31°C and 33°C which are above the optimum, decrease the rate of growth, yet this decrease is not abrupt. Even for temperatures considerably above the optimum, as shown later in Table VI. the growth rate is gradually decreased as the temperature increases above the optimum. This gradual, rather than abrupt, decrease in growth rate, together with the fact that the rates are maintained over a considerable length of time, suggests that the decrease in growth rate above the optimum temperature

TABLE V

ELONGATION NEAR OPTIMUM TEMPERATURES.

Hr.	6a Temperature T °C	6a Elongation mm	6a Elongation Average	6b Temperature °C	6b Elongation mm	6b Elongation Average	12b Temperature °C	12b Elongation mm	12b Elongation Average
1	25	.37		24	.63		27	.48	
2	"	.47		"	.48		"	.74	
3	"	.45		"	.61		"	.68	.717
4	"	.47	.478	"	.63	.588	"	.68	± .0152
5	"	.47	± .0080	"	.59	±.0189	"	.77	
6	"	.53		"	.63		29	1.0	
7	27	.47		26	.67		"	1.0	
8	"	.6		"	.85		"	.93	.972
9	"	.77		"	.92		"	1.03	± .0170
10	"	.74	.708	"	.92	.927	"	.93	
11	"	.7	±.0182	"	.92	±.0159	31	1.03	
12	"	.77		"	1.03		"	.85	
13	"	.67		"	.92		"	.81	
14	29	.77		28	1.26		"	.74	.71
15	"	.97		"	1.26		"	.52	±.0407
16	"	.87		"	1.15		"	.63	
17	"	.83	.848	"	.122	1.192	33	.59	
18	"	.77	±.0233	"	1.11	±.0183	"	.81	
19	"	.8		"	1.22		"	.55	
20	31	.68		30	1.37		"	.74	.71
21	"	.6		"	1.48		"	.74	± .0376
22	"	.63		"	1.41	1.42			
23	"	.67		"*	1.37	±.0220			
24	"	.67	.643						
25	"	.63	±.0070						
26	"	.67							
27	"	.63							
28	33	.6							
29	"	.6							
30	"	.67							
31	"	.57	.574						
32	"	.53	±.0198						
33	"	.5							

* Root accidentally injured after this reading

is not due to definite injury to the tissues.

The temperature generally recommended for the rooting of cuttings is 65° to 70°F. This is considerably below the optimum temperature of 86°F. (30°C.) for root growth of willow cuttings. It may, however, be the experience of propagators that the increased value of a higher temperature for rooting is lost through a greater tendency of the cuttings to decay in the rooting media. This point needs special investigation.

TABLE VI.

MAXIMUM TEMPERATURE FOR ROOT GROWTH.

Hour	Temperature °C.	Elongation (mm).
1	37	.58
2	37	.38
3	37	.52
4	37	.44
5	37	.42
6	39	.18
7	39	.18
8	39	.17
9	39	.18
10	41	--
11	41	.074
12	41	.074
13	41	.085
14	43	.074
15	43	.026
16	43	.026
17	43	.007
18	43	.018
19	44	.02
20	44	.02
21	44	.037
22	44	.00
23	44	.00

Maximum Temperature for Root Growth: Preliminary observations indicated a maximum temperature for willow root growth between 41.5° and 45°C. Root 12-b was maintained for several hours at temperatures of 37°, 39°, 41°, 43°, and 44°C. with observations as recorded in Table VI. It may be seen that after a period of three hours at 44°C., elongation ceased. The root tip had become brown even before growth had entirely stopped.

Root Growth at Low Temperatures: Little information is available regarding the degree of low temperature at which root growth of plants can take place. Harris (3), working with apple and filbert trees, is of the opinion that root growth is not checked during the winter months unless actual injury to the roots by low temperature occurs.

Table VII. gives the records of observations for willow roots 8-b and 11-b maintained at various degrees of low temperature.

The results of observations on 8-b show considerable elongation at temperatures above 7°C. Results of observations on root 11-b show that the elongation rate is decreased as the temperature is lowered. At temperatures below 5°C., the growth per hour is very slight, but nevertheless evident. A definite minimum temperature for root growth was not obtained, since the root continued to grow at a temperature of 0.5°C. Below this temperature the solution in the dish started to freeze. It is probable that the minimum temperature for the root growth of willow cuttings is that temperature which actually injures the root.

TABLE VII.

EFFECT OF LOW TEMPERATURES ON ROOT ELONGATION

Hour	8-b		11-b	
	Temperature	Elongation	Temperature	Elongation
	°C.	mm.	°C	mm.
1	11	.11	5.0	.022
2	11	.11	5.0	.018
3	11	.148	5.0	.015
4	11	.185	5.0	.018
5	11	.11	5.0	.015
6	8	.129	4.0	.015
7	8	.129	4.0	.013
8	8	.11	4.0	.009
9	8	.074	4.0	.013
10	8	.11	3.0	.007
11	7	.11	3.0	.015
12	7	.11	3.0	.015
13	6.5	.092	3.0	.011
14	6.5	.055	0.5	---
15	7	.092	0.5	.015*
16	7	.11	6.0	.015
17	7	.11	6.0	.015
18	7	.192	6.0	.018
19	7	.11	6.0	.015

* For two hours. The small growth in a one hour period could not be accurately measured.

Temperature Coefficients

Two roots were maintained at the temperatures indicated in Table VIII. with the average elongation per hour as presented.

The temperature coefficients, calculated from the average elongation per hour at two temperatures differing by 10°C., are given in column five. In Table IX. the temperature coefficients calculated from the data of Table IV. and the data used in plotting the graph of Figure 7, are presented. The abnormally high coefficient of 9.53 determined

TABLE VIII.

TEMPERATURE COEFFICIENTS

Number of Hours.	Temperature (Deg. C)	Mean elongation, (mm)	Temperature Coefficients: Temperature Change, °C.	Temperature Coefficients: Coefficient
Root 8-a				
5	13	.072 ±.00809		
6	18	.029 ±.0258	13 - 23	9.53
5	23	.686 ±.01875		
5	28	1.074 ±.01437	18 - 28	3.71
Root 8-b				
8	7	.101 ±.00107	7 - 17	3.47
5	12	.198 ±.01286		
6	17	.352 ±.03055	12 - 22	3.24
5	22	.642 ±.01055		
5	27	.702 ±.0395	17 - 27	1.99

for a change of temperature from 13° to 23°C. as recorded in Table VIII. is due to the very low rate of elongation observed at 13°. It is probable that these records were taken before the root had assumed the characteristic growth rate for that low temperature. Assuming this explanation to be correct for this one exception, it seems safe to conclude that the elongation of roots on willow cuttings conforms, within limits, to vant Hoff's law, the rate of elongation being doubled or trebled for each 10^{o} rise in temperature.

TABLE IX.

SUMMARY OF TEMPERATURE COEFFICIENTS CALCULATED FROM PREVIOUS DATA.

Number of Hours	Temperature (Deg. C)	Mean elongation. mm.	Temperature Coefficients.	
			Temperature Change. °C.	Coefficient
Table IV.				
10a--(6	25	.857 ±.0158		
(5	32	1.214 ±.0268	25 - 32	2.04*
10b--(6	25	.782 ±.0155		
(6	32	1.19 ±.1403	25 - 32	2.17*
Table V.				
3	10	.143 ±.0045	10 - 18 - 19	3.76*
5	14	.228 ±.0054		
6	18-19	.458 ±.04224	14 - 24	2.42
5	24	.552 ±.0149		
5	29	1.16 ±.04458	19 - 29	2.53

* Calculated on basis of 10^{o} change in temperature.

SUMMARY AND CONCLUSIONS

1. The root growth of willow (Salix nigra) cuttings was studied at carefully controlled temperatures by placing the rooted cutting in a glass vessel filled with nutrient solution and observing the rate of elongation through a microscope.

2. Hourly observations for sixty-two hours of one root at 30^{o}C. disclosed that until the root obtained

a length of 10 - 12 millimeters, the growth at this constant temperature was steadily increasing. After this initial acceleration the rate of growth remained relatively constant. The data, when plotted, form a portion of the S-shaped curve which is typical of growth in general. Subsequent measurements on rate of growth were made on roots after their initial acceleration period.

3. There was no evidence of rhythmic periodicity, although hourly variations in the rate of root growth at constant temperatures were present.

4. The removal of young shoots from the cuttings had no influence on the rate of root growth, indicating that the leaves of the young shoots were not supplying food materials to the roots, and also that there was no competition for stored foods between shoots and roots. The demands of each, in their early stages of development, are probably satisfied locally.

5. The growth rate of the roots of this species in nutrient solution was not increased by aeration.

6. A sudden decrease of temperature from 32° to 25°C. caused a short period of depressed growth rate below that characteristic for 25°C.

7. A graph which shows the close relation existing between temperature and rate of elongation, is presented. A definite lag on the part of the root following temperature changes is evident.

8. The optimum temperature for elongation of roots on cuttings of <u>Salix nigra</u> was determined as 29° to 30°C.

9. The maximum temperature at which root growth could continue was found to be 43°C. Growth stopped completely after three hours at a temperature of 44°C.

10. Roots were grown at a temperature of 0.5°C. although the rate of elongation was very slow. It is probable that there is no minimum temperature for willow root growth above that which injures the root by actual freezing.

11. Temperature coefficients indicate that the growth of roots tends to conform to vant Hoff's law, the rate of growth being doubled or trebled for each ten rise in temperature.

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