EFFECT OF TEMPERATURE UPON THE RATE OF ELONGATION OF THE STEMS OF ASPARAGUS GROWN UNDER FIELD CONDITIONS

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(WITH FIVE FIGURES)

Introduction

In connection with investigations on the use of asparagus (*Asparagus officinalis* Linn.) as a food product (**2**), an opportunity was afforded to study some of the factors that influence or control its growth. All tests were confined to field-grown material. Since the effect of temperature upon the rate of growth of asparagus in the field is of considerable practical as well as physiological interest, it was decided to make a sufficient number of measurements to permit accurate determination of the relationship of the rate of elongation of the stem or stalk to the prevailing temperatures. In general, the method has been to study the behavior of a large number rather than that of individual plants. The procedure employed was to record the climatic variations that occurred and the behavior of the plants under these conditions, and then to correlate the values obtained in the two sets of records, a method frequently employed by investigators.

Studies have been made upon the rate of growth of the stem of asparagus by BÜCHNER (**1**), TIEDJENS (**9**), WICHERS and TOLLENS (**11**), and WORKING (**12**) but no very thorough study has been made of the effect of temperature upon the behavior of field material in mass.

Materials and methods

The material employed in these studies was grown at the Arlington Experiment Farm, Arlington, Virginia, during the seasons 1928, 1932, and 1933. The plot, approximately $\frac{1}{10}$ of an acre, had been planted in 1919, so that when the first tests were made, the planting was nine years old. The soil was a deep sandy loam of good fertility formed by dredging operations along the Potomac River. The plants were vigorous and healthy, and generally continued growth until they were 230 to 250 cm. in height. The variety was a strain of Martha Washington used in some of the breeding and selection work conducted in the U. S. Department of Agriculture.

The air temperature of the field was recorded in °F. by means of a carefully calibrated thermograph placed in a Weather Bureau instrument shelter in the center of the plot. Records were kept for the entire cutting season from about April 1 to June 15, and as usual, fluctuations in the temperature were rather wide and irregular. The lowest temperature recorded was approximately 45° F. and the highest 94° F. The temperatures given in the tables and charts for any growth period are the hourly means for the respective periods.

Methods of measuring growth

The rate of growth was determined by direct measurement of stalk height, using a rule graduated in mm. A small stake was driven into the soil beside the stalk so that its upper end was about 2.5 cm. below the surface of the soil, and all measurements of growth of the stalk were made from the top of this stake as a base. The measurements were begun at the time, or very soon after, the stalks appeared above ground and in most cases were continued until growth had practically ceased. The measurements were usually made once each day at approximately 9:30 A.M. In a number of cases an additional reading was made at about 4:00 P.M. All stalks of the plot not being measured were cut at regular intervals as in commercial practice. Cutting was discontinued May 17, while in commercial practice it is usually continued until about June 15.

The measurements were begun on April 20, or shortly after the first stalks began to appear above the ground, and continued until the latter part of June.

The total elongation of the stalks for any period was determined by taking the difference in height at the beginning and at the end of the time interval. The height for the growth interval was calculated as the average of the height at the beginning and at the end of the interval.

To determine the rate of elongation in different regions, marks were made with a small brush and waterproof ink at suitable intervals on the bases of the leaf scales, generally from 0.5 to 1 cm. apart, in the rapidly growing part of the stalk. The increase in the length of the segments thus marked was determined for successive time intervals. The elongating part of the stalk was divided into 5 to 15 segments, the number in each case depending upon the length of the growing region. As the stalks increased in height new marks were made from time to time near the tip to keep the intervals of measurement appropriately located along the growing zone. The method was essentially that originally employed by SACHS (8) in his studies of the grand period of growth of plants.

At the beginning of the season measurements were started on about a dozen stalks which were identified by means of numbered tags. Every second or third day thereafter 2 to 5 new stalks just showing above the ground were tagged and measurements begun. Soon stalks of all heights were being measured at every period. In all, several thousand measurements were made upon a total of 130 stalks.

Methods of analyzing and plotting data on growth rates

TOTAL ELONGATION OF THE STALK.—It was obvious from inspection of the data that individual stalks varied considerably in the ultimate height reached and in their rate of elongation. In order to determine the general behavior and to get the mean values, it appeared to be advantageous to employ a system of cross classification. The data were first classified according to the prevailing temperatures of the growth periods. Five-degree class intervals were established, extending over the range from 50° to 90° F. This gave eight temperature groups.

Inspection showed that each group included data for stalks of all heights and that the rate of elongation at a given temperature was different in stalks of different heights. The measurements in each temperature group were then classified according to the height of the stalk, as follows: All values for the growth of stalks below 10 cm. in height were put into one class, those between 10 and 20 cm. were put into another class, and so on at 10 cm. intervals until stalks 80 cm. in height were reached; then, 20 cm. classes were used up to 200 cm. in height. The values in each class were then averaged and tabulated in a manner similar to that of table I. There were 14 classes for each of the eight temperature groups, making 112 classes in all. The number of measurements in each of the classes ranged from 10 to 64. The smallest number of values in any class was for the taller stalks at the lower temperatures.

These values were plotted in two ways: the rate of growth against the tem-

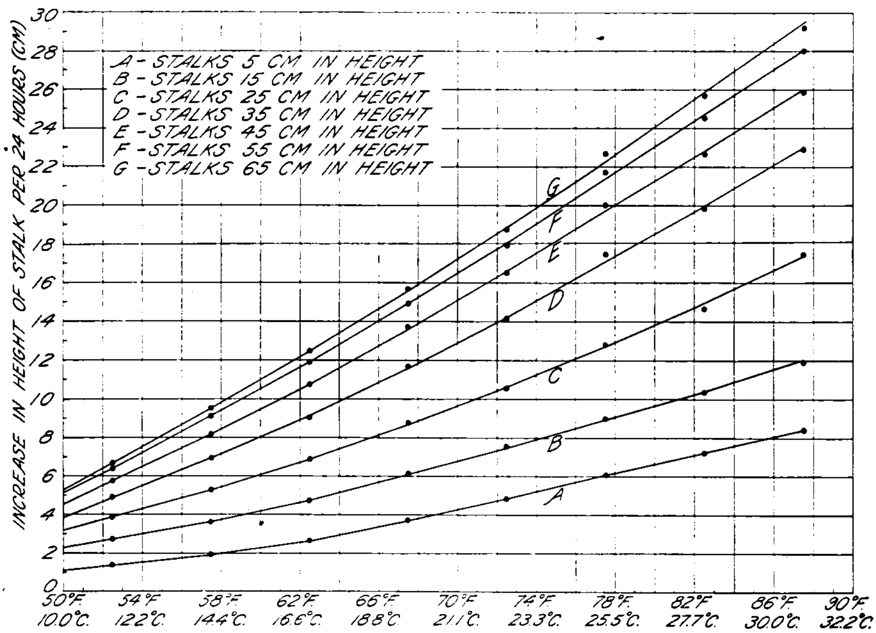

FIG. 1. Effect of temperature on the total elongation of asparagus stalks of various heights between 5 and 70 cm. The plants were grown under field conditions and the results are expressed as cm. growth per 24 hours. Average height of stalks for the 24-hour period.

TABLE I

RATE OF GROWTH OF ASPARAGUS STALKS AT DIFFERENT HEIGHTS AND TEMPERATURES, EXPRESSED IN CM. OF ELONGATION PER 24 HOURS

AVERAGE TEMPERATURE	AVERAGE HEIGHT OF STALK (CM.)													
	5	15	25	35	45	55	65	75	90	110	130	150	170	190
	RATE OF GROWTH													
°F.	cm.	cm.	cm.	cm.	cm.	cm.	cm.	cm.	cm.	cm.	cm.	cm.	cm.	cm.
52.5	1.35	2.6	3.9	4.9	5.8	6.4	6.6	6.3	5.5	4.5	3.5	2.65	2.1	1.55
57.5	1.90	3.6	5.3	6.9	8.2	9.1	9.5	9.0	7.85	6.45	5.05	3.85	3.0	2.25
62.5	2.60	4.7	6.9	9.1	10.75	11.9	12.4	12.5	10.75	8.8	6.95	5.25	4.0	2.95
67.5	3.7	6.1	8.7	11.65	13.6	14.9	15.6	15.25	13.65	11.35	8.9	6.7	5.2	3.80
72.5	4.8	7.4	10.6	14.2	16.5	18.0	18.8	18.6	16.85	13.9	10.85	8.15	6.3	4.7
77.5	6.1	9.0	12.7	17.3	19.85	21.5	22.45	22.15	20.3	16.8	13.0	9.7	7.55	5.65
82.5	7.2	10.4	14.9	20.05	22.8	24.65	25.8	25.5	23.45	19.5	15.15	11.3	8.9	6.65
87.5	8.4	12.0	17.45	22.95	25.95	28.0	29.35	29.0	26.9	22.45	17.4	13.1	10.4	7.85

perature, giving a series of 14 curves; and against the height of the stalk, giving a series of eight curves. The first method of plotting is shown in figures 1 and 2, and the second in figure 3.

When the growth rates were plotted against either temperature or height, the points did not fall exactly upon a smooth curve. By means of a spline, or curve rule, a smooth curve was drawn through the points in such a manner that the sum of the squares of the deviations was as nearly a minimum as could be estimated by simple arithmetical calculations.

The values were plotted upon coordinate paper upon a large scale. The new average or adjusted values of the rates of growth for the midpoints of each of these 112 classes were read from the chart for both systems of curves. Obviously, these values should be the same in both systems of curves but they were not identical in many cases, some being higher and some lower in one system than in the other. The two values for each of the corresponding points were averaged and the new values tabulated in the same way as was done at first. These new values were again plotted as had been done in the first place and new curves drawn in the same way. When the values were read from the new curves they agreed much more closely than at first. After plotting and averaging in this way three times, the values (table I) finally obtained, when plotted, form loci of points that lie almost exactly upon smooth curves. They represent estimated mean values of the growth rates of the stalks of asparagus in this plot as a whole.

Different regions along the stalk.—In order to avoid the presentation of an excessive amount of tabular matter, the data for rate of growth in different regions of the stalk were classified in the same manner as the data for the total elongation of the stalk. A particular stalk in each of these classes had, instead of one reading as in the values for the total elongation, a series of readings made at various points from base to tip. The values for the growth rates at corresponding points along the stalks of all the individuals in the class were averaged. This was done at a sufficient number of points (7 to 12) to permit plotting of the results. When these values were plotted, the line represented the rate of growth along the entire growing region for the stalks of a particular height at a particular temperature. Obviously, to plot the rates of growth for 112 classes would require a great amount of space. Consequently, the data for the growth rates of stalks of only two heights, 15 and 75 cm., have been calculated for the temperatures between 52.5° and 77.5° F. This is believed to be sufficient to illustrate the general character of the results.

Observations

Effect of temperature upon total elongation

After making a few measurements it was obvious that there was a very definite positive correlation between the growth of asparagus and the prevailing temperatures as shown in table I. The results for all plants 70 cm. or less in height are illustrated in figure 1, while those for plants more than 70 cm. in height are shown in figure 2. It is evident that the relationship between temperature and total elongation per 24 hours is in all cases represented by nearly straight lines. They are slight curves which slope upward a little more sharply in the portion of the curves representing the higher temperatures. This is true for stalks of all heights. The form of the curve

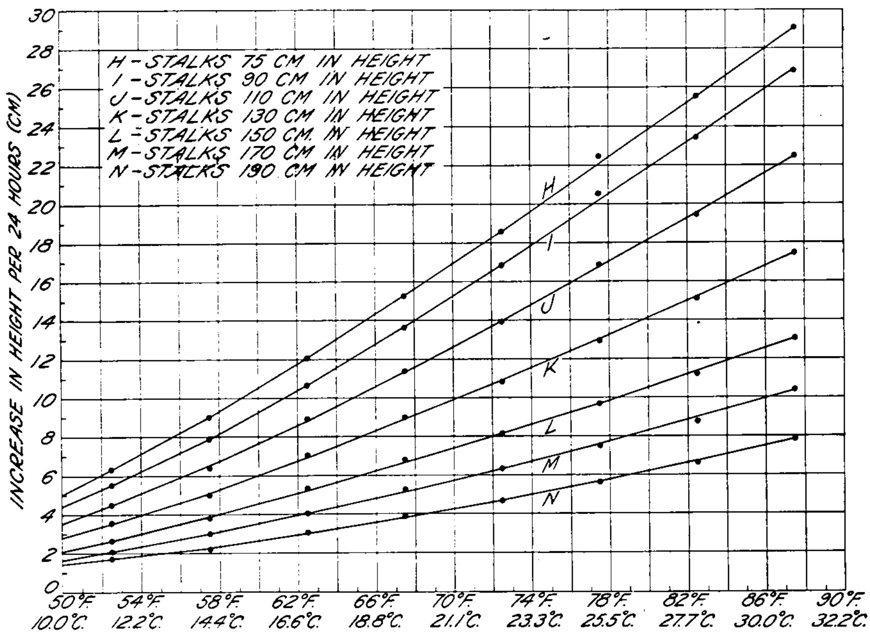

FIG. 2. Effect of temperature on the total elongation of asparagus stalks of various heights between 70 and 200 cm. The plants were grown under field conditions and the results are expressed as cm. growth per 24 hours. Average height of stalks for the 24-hour period.

is nearly the same whatever the height of the stalk may have been at the time of measurements. The difference in slope of the lines indicates that stalks 60 to 70 cm. high are a little more sensitive to changes in temperature than those that are taller or shorter. The reason for this is not clear but it seems to be associated with the length of the growing zone. Also the very old stalks are not quite so sensitive to increases in temperature as are the very young stalks. This may be due in part to failure to transport water and food materials to the growing region of the tall stalks at the higher temperatures as rapidly as the materials are required for the formation of new tissues. It would be of interest to have comparable data on material with the prevailing temperatures both higher and lower than those which prevailed under these

TABLE II

RATE OF GROWTH AT VARIOUS 10° C. INTERVALS AND THE RATIO OF THE RATE OF GROWTH AT THE END TO THAT AT THE BEGINNING OF THE INTERVAL

TEMPERATURE	HEIGHT OF STALKS IN CM.														
	5			25			65			130			190		
	GROWTH RATE		RATIO b/a	GROWTH RATE		RATIO b/a	GROWTH RATE		RATIO b/a	GROWTH RATE		RATIO b/a	GROWTH RATE		RATIO b/a
	LOWER TEMP. a	UPPER TEMP. b		LOWER TEMP. a	UPPER TEMP. b		LOWER TEMP. a	UPPER TEMP. b		LOWER TEMP. a	UPPER TEMP. b		LOWER TEMP. a	UPPER TEMP. b	
°C.	cm.	cm.		cm.	cm.		cm.	cm.		cm.	cm.		cm.	cm.	
10 and 20	1.08	3.77	3.49	3.18	8.81	2.77	5.28	15.90	3.01	2.80	9.03	3.22	1.43	3.90	2.72
11 and 21	1.30	4.18	3.21	3.65	9.50	2.60	6.27	17.04	2.88	3.30	9.80	2.97	1.60	4.20	2.62
12 and 22	1.50	4.60	3.06	4.20	10.20	2.43	7.29	18.24	2.50	3.81	10.52	2.76	1.80	4.50	2.50
13 and 23	1.68	5.02	2.98	4.70	10.95	2.33	8.30	19.43	2.34	4.40	11.28	2.56	1.96	4.86	2.47
14 and 24	1.87	5.48	2.92	5.20	11.70	2.25	9.33	20.63	2.21	4.98	12.02	2.41	2.20	5.18	2.35
15 and 25	2.10	5.90	2.81	5.72	12.43	2.17	10.38	21.88	2.10	5.60	12.80	2.28	2.47	5.54	2.24
16 and 26	2.36	6.33	2.68	6.30	13.22	2.10	11.41	23.17	2.03	6.27	13.59	2.16	2.72	5.90	2.20
17 and 27	2.64	6.75	2.56	6.91	14.03	2.03	12.52	24.43	1.95	6.94	14.38	2.07	3.00	6.30	2.10
18 and 28	2.97	7.20	2.42	7.43	14.92	2.01	13.50	25.80	1.91	7.54	15.22	2.01	3.26	6.7	2.07
19 and 29	3.38	7.60	2.26	8.15	15.75	1.93	14.72	27.06	1.84	8.32	15.96	1.92	3.58	7.08	1.98
20 and 30	3.77	8.02	2.12	8.80	16.63	1.89	15.88	28.37	1.79	9.04	16.74	1.84	3.90	7.48	1.92
21 and 31	4.18	8.50	2.03	9.51	17.6	1.84	17.04	29.60	1.73	9.80	17.55	1.79	4.20	7.90	1.88

conditions. By extrapolation of the curves it may be inferred that below 40° F. very little or no growth will occur. It is also evident that at 87.5° F. (30.8° C.), the highest average temperature recorded, the rate of elongation had not reached its maximum. From the slope of the curves it appears unlikely that under field conditions, temperatures high enough for maximum rate of elongation will often prevail in this latitude.

In order to see how closely the rate of elongation of the growing asparagus stem conforms to the VAN'T HOFF-ARRHENIUS principle (**10**) the ratio of the rate of elongation at the end of various 10° C. (18° F.) intervals of temperature to that at the beginning has been calculated. According to this principle, the rate of growth may be expected to double for each 10 degrees of increase. It may be noted in table II that, over a considerable range of temperature, the rate of elongation of the stem does roughly double for an increase of 10° C. The rate almost exactly doubles as the temperature is raised from 16° to 26° C. for stalks of all heights except those 5 cm. tall. In the upper range of the temperatures prevailing in this study, the rate of elongation fails to double, while for intervals in the lower range it more than doubles for each rise of 10° C. It is apparent that this relationship between the prevailing temperature and the growth rate does not conform exactly to

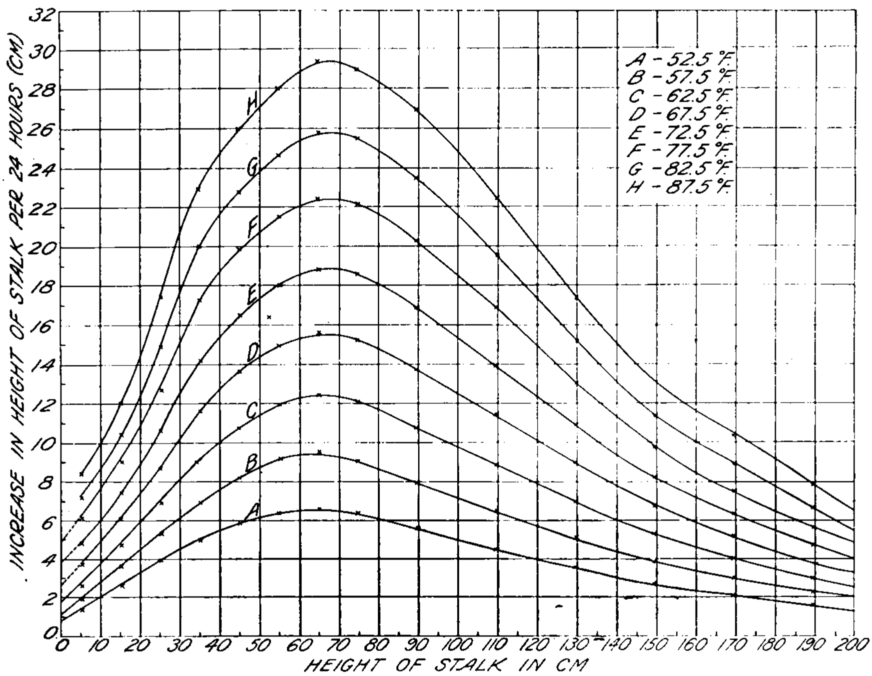

FIG. 3. Rate of growth of asparagus stalks at different heights for various temperatures expressed in cm. per 24 hours.

the VAN 'T HOFF-ARRHENIUS principle. It may be inferred however, that it would be advantageous for a grower to cut the field twice as often at 26° C. (78.8° F.) as at 16° C. (60.8° F.).

RELATION OF HEIGHT OF STALK TO RATE OF GROWTH

Many writers have noted that the rate of growth varies continuously with differences in age or size of the plant. In the case of asparagus, WORKING (**12**) has presented the relationship very clearly. It may be noted from figures 1 and 2 that the stalks intermediate in height elongate much faster than the very tall or the very short ones. The relationship of the height of the plant to the rate of elongation is shown much more clearly in figure 3. As the material increases in height, the rate of elongation increases rapidly to a maximum and then gradually decreases to low values in the very tall stalks. The height of the stalk at which elongation is at a maximum is between 60 and 70 cm. for any given temperature.

Under the conditions of these measurements, the temperature might be low one day and high the next, or might vary in almost any manner. The present results are consequently a record of the response of plants of different heights to changes of temperature, and it should be remembered that the same magnitudes of change cannot be expected with material grown under uniform conditions of temperature throughout the entire period of their growth.

SUMMATION OF THE TEMPERATURE

It is clear from the above discussion that the height of the stalk at any time is a function of both time and temperature. It has often been considered that the development of the plant is dependent upon the amount of heat that it receives, the amount of heat being dependent upon the temperature and the length of the exposure. This idea has led to the working out of several systems of temperature indices (**5**, **7**). One of the first of these is known as the remainder system, in which effective heat is estimated as total degree-hours above an arbitrary base temperature. The most essential thing in the employment of this system is the establishment of a correct temperature at which to begin counting the heat units. It has often been considered that the proper temperature for use as a base line is that at which growth first occurs. This may not always be the most practical or workable base line, as has been suggested by MAGOON and CULPEPPER (**6**). By extrapolation of the curves in figures 1 and 2 it may be inferred that growth in asparagus first becomes appreciable somewhere near 40° F., but no attempt was made to determine definitely the most appropriate base line. After considering the data to some extent it was concluded that 42.5° F. was fairly suitable, and using this as a base line, the temperatures have been summated for stalks 20, 50, 100 and 150 cm. in height, at 8 temperatures differing by 5° F. The results are shown in table III.

TABLE III

DEGREE-HOURS REQUIRED FOR ASPARAGUS STALKS TO GROW TO VARIOUS HEIGHTS WHEN EXPOSED TO VARIOUS ATMOSPHERIC TEMPERATURES, BEGINNING WITH STALKS 2.5 CM. BELOW THE SURFACE OF THE SOIL

HEIGHT OF STALK	GROWTH TEMPERATURE IN °F.							
	52.5	57.5	62.5	67.5	72.5	77.5	82.5	87.5
	DEGREE-HOURS ABOVE 42.5° C.							
cm.								
20	3000	3312	3226	3000	2736	2688	2688	2700
50	4608	5076	4848	4860	4680	4512	4608	4536
100	6564	7164	7128	6900	6660	6510	6480	6480
150	9792	10476	10320	9960	9648	8324	9180	9660

It may be noted that roughly the same number of degree-hours are required for a stalk to grow from the base (2.5 cm. below the surface of the soil) to any given height for any temperature between 52.5° and 87.5° F. A perfect agreement could not be expected as the growth temperature relationship is only approximately linear. According to these calculations about 2900 degree-hours are required for a stalk to grow from the base to a height of 20 cm. and about 9800 degree-hours to grow to 150 cm. in height.

TIME REQUIRED FOR STALKS TO GROW TO DIFFERENT HEIGHTS

Knowing the rate of elongation of the stalk at all heights at every temperature, it is a simple matter to calculate the time required to reach any given height. By summating the growth rates day after day the number of days required to reach various heights have been obtained for material growing at various temperature levels. This was done by adding to the height of the plant at the end of the first day the growth made during the second day, which gives the height of the plant at the end of the second day, and so on until the ultimate height is reached. The data are given in table IV, and figure 4 shows very clearly the effect of temperature upon the time necessary to reach different heights. It may be expected that 6 days will be required for plants to reach a height of 100 cm. when the temperature averages 87.5° F.; 11.5 days when it averages 67.5° F.; and 27.2 days when it averages 52.5° F. The curves for 82.5 and 87.5° F. are of theoretical interest only for it is improbable that an average temperature as high as 87.5° F. for any 24-hour period would occur during the harvest season of asparagus. It must also be remembered that in this case the average daily temperature was never as high as 87.5° F. or as low as 52.5° F. for the entire growth period of any stalk and therefore these values will probably not hold for long periods of growth at the indicated temperatures. It is believed they will hold for short periods of growth and therefore may be of

TABLE IV

ESTIMATED HEIGHT OF STALKS OF ASPARAGUS AFTER GROWING FOR DIFFERENT LENGTHS OF TIME AT VARIOUS TEMPERATURES. ESTIMATED FROM THE GROWTH RATES AT DIFFERENT TEMPERATURES

GROWING PERIOD	GROWTH TEMPERATURE IN °F.							
	52.5	57.5	62.5	67.5	72.5	77.5	82.5	87.5
	HEIGHT OF STALK							
Days	*cm.*	*cm.*	*cm.*	*cm.*	*cm.*	*cm.*	*cm.*	*cm.*
0	0	0	0	0	0	0	0	0
2	1.5	2.2	3.6	5.5	8.1	10.8	13.2	15.7
4	3.4	5.3	8.9	14.0	20.8	29.0	36.7	47.2
6	5.9	9.4	16.7	27.2	42.5	63.0	82.3	102.7
8	9.1	15.3	28.0	48.5	76.9	106.3	127.2	145.0
10	13.2	23.3	45.0	78.2	111.4	138.0	155.5	171.0
12	18.5	34.0	67.6	106.4	136.6	159.4	175.4	190.2
14	25.1	48.3	91.7	128.6	155.1	175.7	191.0	204.8
16	33.3	66.1	111.7	145.8	169.7	188.9	203.3	
18	43.5	84.5	128.1	159.5	181.9	200.0		
20	55.2	100.5	141.7	170.9	192.2			
22	68.1	114.2	153.0	180.7	200.8			
24	81.0	126.0	162.7	189.2				
26	92.7	136.3	171.2	196.6				
28	103.2	145.4	178.8					
30	112.6	153.4	185.6					
32	121.1	160.6	191.8					
34	128.7	167.1	197.5					
36	135.7	173.2						
40	147.9	184.2						
44	158.3	193.6						
47	165.3	200.0						
48	167.5							
54	179.7							
60	190.0							
64	196.1							
67	200.3							

some practical importance in indicating how often the crop should be cut when the cutting of the stalks is to be made between certain definite heights.

According to these measurements, for stalks to grow from 10 cm. to 25 cm. in height, 5.3 days would be required at 52.5° F., 4.2 days at 57.5° F., 3.4 days at 62.5° F., 2.4 days at 67.5° F., 2.1 days at 72.5° F., and 1.9 days at 77.5° F. If a farmer restricted the cutting to stalks between these heights, he would have to cut the field at least as often as indicated or some of the stalks would be too tall at each cutting. In other words, it may be expected that about 1400 degree-hours of temperature would be required for stalks to elongate from 10 cm. to 25 cm. Of course the degree to which this rate of production would be realized would vary considerably with the fertility and moisture content of the soil, vigor of the plants, and possibly other factors. The plants in these tests were very vigorous as shown by the fact that the stalks finally reached a height of 230 to 250 cm.

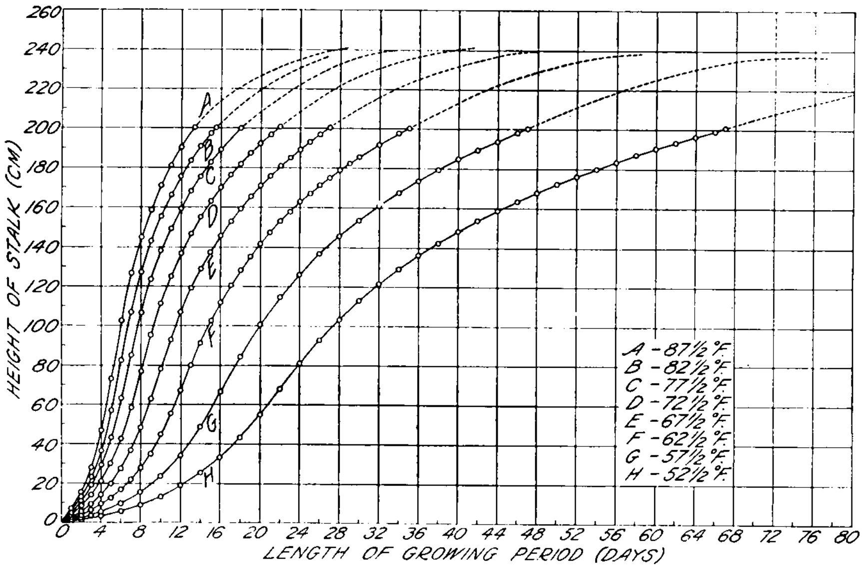

FIG. 4. Height in cm. of asparagus after growing for various lengths of time at various temperatures. The time values are expressed in days and the temperature in °F.

EFFECT OF TEMPERATURE UPON THE RATE OF ELONGATION ALONG THE STALK

The amount of elongation in different portions of the growing zone has been determined by WORKING (**12**). The rate of elongation per unit length of the stalk is maximum in a zone a short distance below the tip. The manner of growth is evident from figure 4.

It would be expected that the effect of temperature upon the rate of elongation in different zones along the stalk would be similar to the effect upon total elongation.

The results obtained from these measurements are given in table V and figure 5.

It is apparent from figure 5, L and M, that temperature affects the rate of growth of the stalk at every point throughout the entire growing region. The zone of maximum rate of growth, however, seems to be somewhat more sensitive to changes in temperature than zones above or below. The difference in sensitiveness is apparently small and may not be significant.

The curves indicate that growth stops at a point somewhat higher on the stalk at the low temperature than at the higher temperature. This may be attributed to error in selecting stalks for measurement.

The effect of the temperature upon the rate of growth at any point along the stalk appears to be approximately the same as for the total elongation, as shown in figures 1 and 2. In figure 5, N, the rates of growth at 5 different

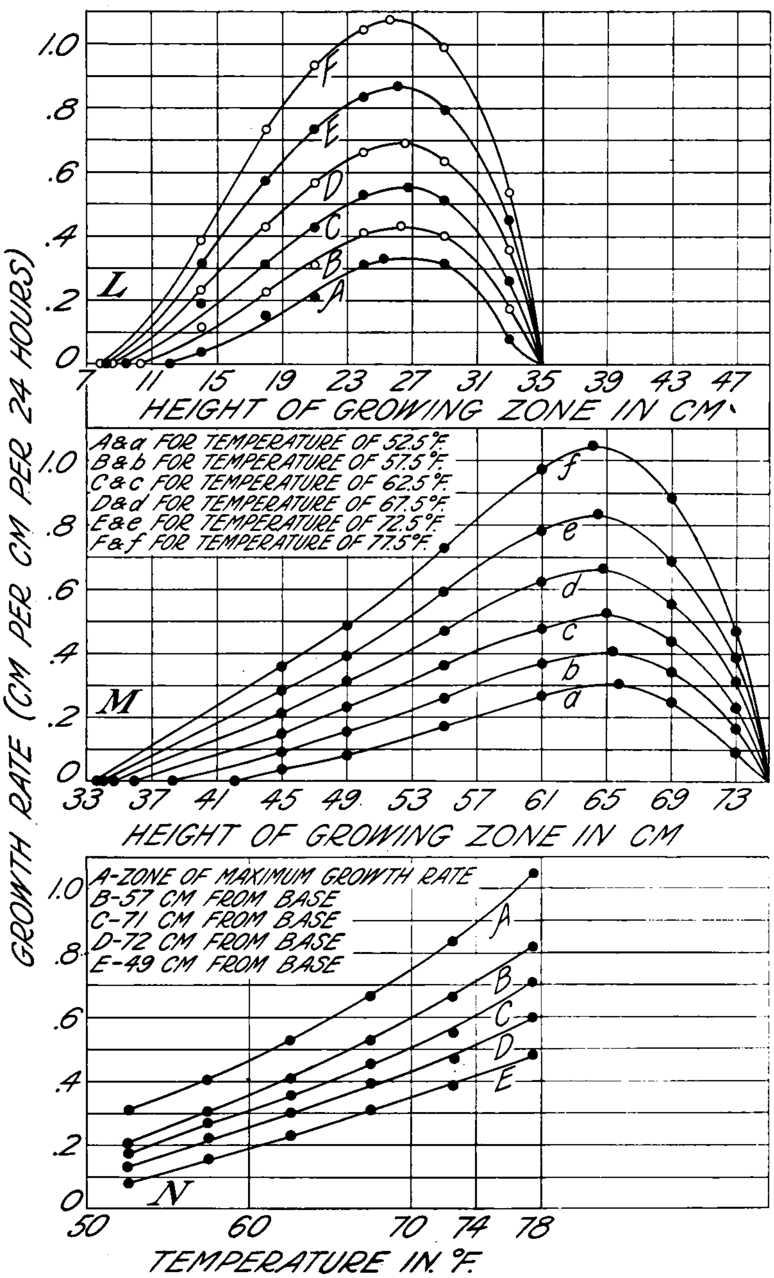

FIG. 5. Effect of temperature upon the rate of growth in various zones along the stalks of asparagus after they have reached the total height of 35 and 75 cm. L, stalks 35 cm.; M, stalks 75 cm. in height. N, the effect of temperature upon the rate of growth in different regions of stalks 75 cm. in height.

TABLE V

RATES OF GROWTH ALONG THE STALK OF ASPARAGUS UNDER VARIOUS TEMPERATURE CONDITIONS FOR STALKS 35 AND 75 CM. TALL, EXPRESSED IN CM. PER CM. PER 24 HOURS

TOTAL HEIGHT OF STALK	TEMP.	HEIGHT OF GROWING SEGMENT	RATE OF GROWTH	HEIGHT OF GROWING SEGMENT	RATE OF GROWTH	HEIGHT OF GROWING SEGMENT	RATE OF GROWTH	HEIGHT OF GROWING SEGMENT	RATE OF GROWTH	HEIGHT OF GROWING SEGMENT	RATE OF GROWTH	HEIGHT OF GROWING SEGMENT	RATE OF GROWTH
cm.	°*F.*	*cm.*	*cm.*	*cm.*	*cm.*	*cm.*	*cm.*	*cm.*	*cm.*	*cm.*	*cm.*	*cm.*	*cm.*
35	52.5	12.1	0.000	15.0	0.055	17.0	0.101	19.0	0.160	21.0	0.224	23.0	0.283
"	57.5	10.3	0.000	15.0	0.118	17.0	0.187	19.0	0.257	21.0	0.323	23.0	0.379
"	62.5	9.3	0.000	13.0	0.112	16.0	0.230	19.0	0.352	21.0	0.435	23.0	0.498
"	67.5	8.6	0.000	13.0	0.175	16.0	0.327	19.0	0.474	21.0	0.565	23.0	0.636
"	72.5	8.1	0.000	11.0	0.115	14.0	0.315	17.0	0.510	20.0	0.680	23.0	0.804
"	77.5	7.9	0.000	11.0	0.150	14.0	0.385	17.0	0.635	20.0	0.870	23.0	1.064
"	52.5	25.0	0.325	25.2	0.328	27.0	0.325	29.0	0.310	31.0	0.233	32.0	0.167
"	57.5	25.0	0.418	26.3	0.431	27.0	0.429	29.0	0.400	31.0	0.320	32.0	0.253
"	62.5	25.0	0.537	26.8	0.551	27.0	0.550	29.0	0.510	31.0	0.415	32.0	0.343
"	67.5	25.0	0.678	26.6	0.689	27.0	0.683	29.0	0.630	31.0	0.540	32.0	0.460
"	72.5	25.0	0.852	26.2	0.864	27.0	0.858	29.0	0.790	31.0	0.663	32.0	0.563
"	77.5	25.0	1.064	25.6	1.073	27.0	1.063	29.0	0.985	31.0	0.832	32.0	0.710
75	52.5	42.2	0.000	45.0	0.037	49.0	0.080	53.0	0.138	57.0	0.202	59.0	0.237
"	57.5	38.2	0.000	45.0	0.090	49.0	0.154	53.0	0.220	57.0	0.301	59.0	0.338
"	62.5	36.0	0.000	41.0	0.078	45.0	0.145	49.0	0.230	53.0	0.318	57.0	0.405
"	67.5	35.7	0.000	41.0	0.132	45.0	0.210	49.0	0.310	53.0	0.410	57.0	0.527
"	72.5	34.0	0.000	41.0	0.174	45.0	0.280	49.0	0.390	53.0	0.522	57.0	0.667
"	77.5	33.7	0.000	41.0	0.232	45.0	0.355	49.0	0.484	53.0	0.640	57.0	0.820
"	52.5	63.0	0.285	65.8	0.301	67.0	0.284	69.0	0.245	71.0	0.177	72.0	0.134
"	57.5	63.0	0.390	65.4	0.404	67.0	0.385	69.0	0.340	71.0	0.268	72.0	0.220
"	62.5	61.0	0.477	65.1	0.524	67.0	0.494	69.0	0.438	71.0	0.356	72.0	0.300
"	67.5	61.0	0.623	64.8	0.664	67.0	0.618	69.0	0.550	71.0	0.456	72.0	0.393
"	72.5	61.0	0.780	64.5	0.839	67.0	0.778	69.0	0.687	71.0	0.550	72.0	0.475
"	77.5	61.0	0.970	64.2	1.048	67.0	0.990	69.0	0.880	71.0	0.710	72.0	0.600

locations along the stalk for material 75 cm. in height have been plotted against temperatures between 52.5° and 77.5° F. Each series of points forms loci that lie in almost a straight line. The slight curve slopes upward a little more sharply with the higher temperatures. It appears that the region of maximum growth is slightly closer to the base at high temperatures than at low temperatures. This may be a response that is related to the growth behavior early and late in the season. The differences are not large and may not be significant. These results should be interpreted as responses to variations in temperature during short intervals of time under field conditions and may not be the same as would occur under conditions where the temperature is constant. It has been shown by LEHENBAUER (**3**) and LEITCH (**4**) that the temperature for maximum growth depends upon the length of the period of exposure.

It may be concluded that the growth rate of asparagus is similar to that of many other plants and the results of these field measurements agree essentially with the results of SACHS (**8**) and many other investigators.

Summary

1. The effect of temperature upon the rate of elongation of asparagus stalks has been studied under field conditions. Averages of a large number of measurements have been obtained by a method of cross classification, followed by a system of two-way plotting, the final values forming smooth curves when plotted in either of the two ways.

2. For temperatures between 52.5° and 87.5° F., the relationship between the growth rate and the temperature is represented by lines that are almost straight. The rate of total elongation approximately doubled with each increase of 10° C. (18° F.) over a limited range of temperatures.

3. The relationship between the rate of total elongation and the height of the stalk has been determined for the stalks in these tests and the results plotted. The rate of increase in height was slow at first, increased rapidly to about 65 cm. in height when it was at a maximum, and then slowly decreased as the stalks became taller.

4. The growth responses of these plants have been interpreted in terms of time required to reach different total heights. The lines representing this relationship take the form of the S-curve characteristic of growth processes. It may be seen from these rates that if it is desired to cut asparagus between the heights of 10 and 25 cm. the field would need to be cut at least every 5.3 days when the average temperature was 52.5° F., every 4.2 days when the average was 57.5°, every 3.4 days when it was 62.5°, every 2.4 days when it was 67.5°, and every 2.1 days when it was at 72.5° F. Likewise the time required for growth from any initial height to any other height at any designated temperature may be readily ascertained from the curves.

5. Variations in temperature affect the rate of growth along the stalk in about the same way as they affect the total elongation. The growth rate increases for a short distance below the tip to a point where it is maximum and then decreases to the lower limits of the growing region. The results indicate that the zone of maximum growth is a little more sensitive to changes of temperature than regions either above or below this zone.

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LITERATURE CITED

1. BÜCHNER, EMIL. Zuwachsgrossen und Wachstumsgesschwindigkeiten bis Pflanzen. Inaugural dissertation. University Leipzig. 1901.
2. CULPEPPER, C. W., and MOON, H. H. Composition of the developing asparagus shoot in relation to its use as a food product and as material for canning. U. S. Dept. Agr. Tech. Bull. 462. 1935.
3. LEHENBAUER, P. A. The growth of maize seedlings in relation to temperature. Physiol. Res. **1**: 247–288. 1914.
4. LEITCH, I. Some experiments on the influence of temperature on the rate of growth in *Pisum sativum*. Ann. Bot. **30**: 25–46. 1916.
5. LIVINGSTON, BURTON E., and LIVINGSTON, GRACE J. Temperature coefficients in plant geography and climatology. Bot. Gaz. **56**: 349–375. 1913.
6. MAGOON, C. A., and CULPEPPER, C. W. Response of sweet corn to varying temperatures from time of planting to canning maturity. U. S. Dept. Agr. Tech. Bull. 312. 1932.
7. PRICE, H. L. The application of meteorological data in the study of physiological constants. Virginia Agr. Exp. Sta. Ann. Rept. 1909–1910: 206–212. 1911.
8. SACHS, JULIUS VON. Lectures on the physiology of plants. Translated by H. Marshall Ward. 1887.
9. TIEDJENS, V. A. Some physiological aspects of *Asparagus officinalis*. Proc. Amer. Soc. Hort. Sci. **21**: 129–140. 1925.
10. VAN'T HOFF, J. H. Lectures on theoretical and physical chemistry. Translated by R. A. Lehfeldt. London. Part I, p. 227 *ff*. 1898.
11. WICHERS, J. L., and TOLLENS, B. Über die in den Spargeln und den Spargel-Wurzeln enthaltenen Bestandteile. Jour. Landw. **58**: 101–112. 1910.
12. WORKING, E. B. Physical and chemical factors in the growth of asparagus. Arizona Agr. Exp. Sta. Tech. Bull. 5. 1924.