The Effect of Temperature Upon the Growth and Yield of Sugar Beets

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MATERIAL PRESENTED in this paper represents conclusions drawn from three seasons' collection of temperature and sugar beet growth data in the Yellowstone Valley near Billings, Montana. The initial objective of this project was to establish the form of the growth rate curve with respect to temperature, and to devise therefrom a method whereby early and mid-season temperatures might be used to predict the final yield in the fall. While results of this study are not conclusive in all respects, a reasonably satisfactory growth rate curve for sugar beets has been established, and a new method of predicting final yield in eastern Montana is being advanced In addition, a substantial volume of reliable growth data has been accumulated, and will be made available to others who have a need for it.

It has long been known that plants grow more rapidly in warm than in cool weather. Brandes and Coons (1)[2] found that sugar beets are grown most profitably in regions having a mean summer temperature between 67 and 72 degrees. Furthermore, it is common knowledge that July and August are the months in which beet tonnage is made. Knowing this general relation between temperature and growth, then, numerous attempts have been made to establish a practical working formula based upon temperature records which might be used to predict final yield at some convenient date in spring or summer. The most successful work along this line was done by Swift and Cleland (5), who found a reliable correlation between annual yield in western Montana and the average temperature of the preceding cold season. A similar, but less satisfactory relationship, was established in 1944 by Pierce, Bush, and Wood (3) between yield and average June temperature. Realizing that a fully satisfactory solution to this problem in the Billings district must await the accumulation of more accurate knowledge concerning the way in which growth is related to the level of temperature, the author, in collaboration with R. R. Wood of the Great Western Sugar Company, set up a project in 1945 near Billings for actually measuring the growth of beet roots and relating it to the prevailing level of temperature.

Materials and Methods

Growth and temperature measurements were made during the 1945, 1946, and 1947 growing seasons, starting about July 1. Test plots during these 3 years were located in fields adjoining one another at a point about 4 miles up the valley from Billings. The level of fertility in these three

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[2]The numbers in parentheses refer to literature cited.

fields was about the same, and definitely above the district average as reflected in yields.

Instrumental equipment included a conventional air thermograph, exposed in the usual Weather Bureau shelter, a soil thermograph with the element buried directly beneath one row of beets at a depth of 8 inches, and about 25 root measuring devices attached at the maximum diameter to randomly selected roots. A sketch of this device is shown in figure 1. It consists of a 2-foot length of oiled silk fishline, marked in inches with India ink, a 4-inch section of small diameter glass tubing, and a test tube, assembled as shown in the sketch. One end of the line was attached to the outer end of the glass tube, extended around the root, then passed up through the glass tube and into the test tube where the excess was coiled. As growth proceeded, the line was drawn out and weekly circumference measurements were read with reference to an index mark etched on the glass tube 2 inches from its outer end. All readings were made once a week, the instruments were checked for accuracy, and weekly temperature averages were computed from daily values. Thus this basic data were available in the form of weekly circumference increase, together with air and soil temperature as summarized in table 1. A preliminary report of this same project was presented before this Society at its 1946 General Meeting in Denver (4).

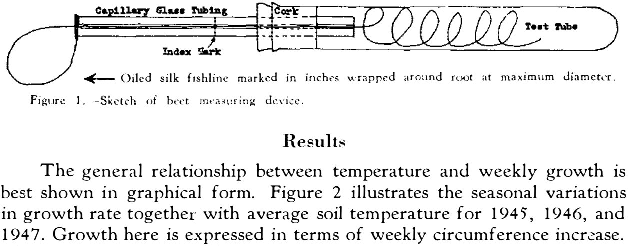


Figure 1. -Sketch of beet measuring device.

Results

The general relationship between temperature and weekly growth is best shown in graphical form. Figure 2 illustrates the seasonal variations in growth rate together with average soil temperature for 1945, 1946, and 1947. Growth here is expressed in terms of weekly circumference increase. The parallelism between these curves is quite striking, but is to be expected because of the normal seasonal variation in both temperature and growth. However, I submit that growth normally varies in such a manner primarily because of the seasonal march in temperature. It is significant, however, that practically all increases in temperature from week to week are accompanied by corresponding increases in growth rate, and vice versa. The most obvious exception to this is seen in the week of July 27 on the 1946 chart, when a decided slump in growth occurred following a hail storm on July 17. The subject of hail damage will be mentioned briefly later on.

Figure 3 shows the same data converted to tons-per-acre increments and plotted in the form of a scatter diagram so as to show the relative growth rate with respect to temperature. Solid lines are regression curves

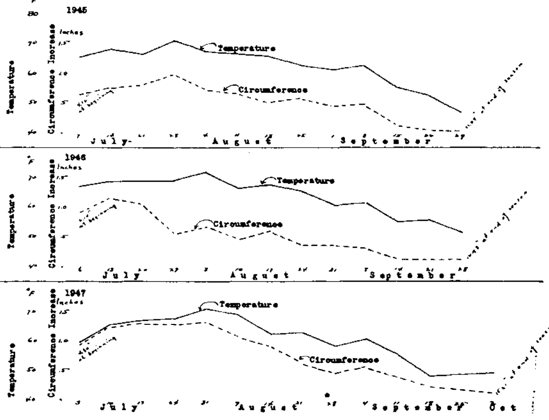
Table 1.—Average temperature and weekly growth data.

1945						1946						1947					
		Average temperature		Increase				Average temperature		Increase				Average temperature		Increase	
Date		Air	8-inches Soil	Circumference[1]	Tons per acre[2]	Date		Air	8-inches Soil	Circumference[1]	Tons per acre[2]	Date		Air	8-inches Soil	Circumference[1]	Tons per acre[2]
July	7	64.4	65.5	.66	.653	July	6	68.3	67.2	.99	1.284	July	3	59.3	59.2	.92	.456
	14	69.1	68.7	.76	.911		13	70.0	68.7	1.16	1.865		10	71.5	65.7	1.28	.822
	21	71.4	66.8	.81	1.313		20	70.0	68.9	1.07	2.074		17	72.4	67.0	1.30	1.098
	28	74.8	70.8	.98	1.764		27	70.6	68.7	.56	1.223		24	71.1	67.4	1.29	1.376
August	4	73.4	67.8	.73	1.526	August	3	73.0	71.2	.67	1.592		31	73.2	70.4	1.34	1.702
	11	71.1	66.4	.68	1.598		10	66.0	66.4	.45	1.129	August	7	72.9	69.0	1.09	1.648
	18	69.6	66.0	.54	1.410		17	61.1	67.4	.58	1.583		14	66.0	62.8	.93	1.566
	25	63.6	63.2	.60	1.726		24	69.5	65.8	.37	1.059		21	69.0	63.0	.64	1.179
Sept.	1	64.9	61.4	.46	1.368		31	59.4	61.2	.36	1.098		28	62.9	58.6	.49	.966
	8	68.2	62.6	.48	1.548	Sept.	7	61.4	60.8	.32	.987	Sept.	4	68.1	60.2	.59	1.237
	15	57.6	55.6	.13	.424		14	57.0	55.4	.13	.392		11	61.6	56.0	.41	.885
	22	47.4	52.6	.06	.221		21	56.5	55.6	.12	.408		18	51.2	48.9	.27	.578
	29	44.8	47.3	.02	.077		28	53.2	51.6	.10	.330		25	53.3	49.6	.22	.501
												October	2	52.2	49.7	.14	.347

[1]Actual measurements.
[2]Adjusted to average field yield: 1945, 16 tons per acre; 1946, 18 tons per acre; 1947, 15 tons per acre.

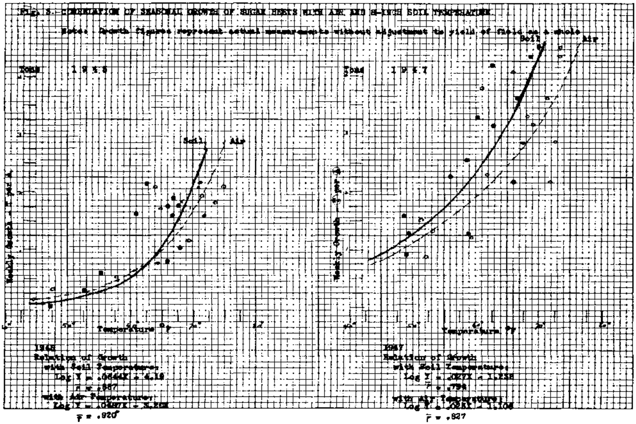
relating growth with soil temperature for 1945 and 1947, while dashed lines represent air temperature. Solid dots are used for soil, and open circles for air temperature. Curvilinearity of the relationship as plotted suggested use of a regression equation of the form log Y = a + bX; and individual equations are quoted in each case, together with the computed indices of correlation. Rho values for 1945 data are 0.887 and 0.927, respectively, for soil and air temperature; while the corresponding figures for 1947 are 0.794 and 0.841. All are well above the 1 percent level of significance, the figures being 0.684 and 0.661, respectively, for 1945 and 1947 data.

Fig. 2.—WEEKLY GROWTH (CIRCUMFERENCE) AS RELATED TO 8-INCH SOIL TEMPERATURE.



Conversion to Tons per Acre.—Growth was measured throughout this project in terms of circumference increase at the maximum diameter, which necessitated conversion into weights for reasons of convenience. The following regression equation, derived from weight and circumference measurements at harvest time was used for this purpose: log W = 2.355 log C—2.259. While this formula yields a fairly good representation of weight increments, it cannot be strictly accurate because it assumes that the roots maintain a constant shape throughout the season, while it is known that they change shape gradually as the growth proceeds. Having no usable information about this progressive change, however, it was necessary to base the conversion formula upon measurement of mature samples which included a wide variety of shapes.

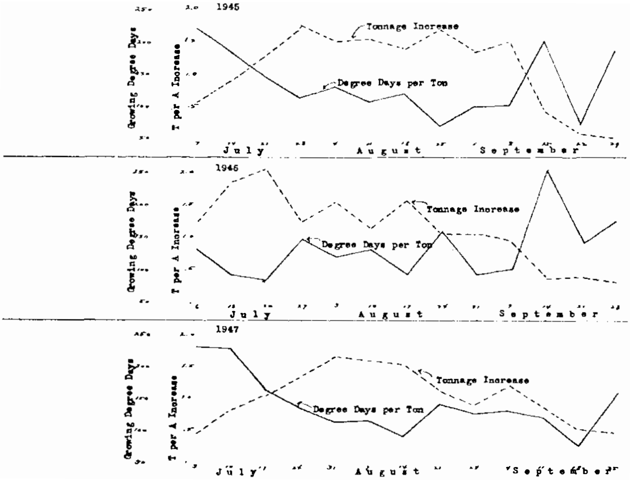
Generally speaking, increases in linear measurements, such as circumference, bear a closer relation to soil than to air temperature, correlation indices being 0.917 in 1947 and 0.957 in 1945, compared with 0.868 and 0.894, respectively, for air temperature. When increments are expressed in terms of weight, however, the correlation is higher with air than with soil temperature. This shift comes about as a result of the curvilinear relation between linear and volumetric measurements of the roots. The index of correlation between air temperature and tons-per-acre increase for example, is 0.920, compared with 0.887 for soil temperature. This seems to indicate that it is quite as satisfactory to use air temperature for this type of work as soil temperature, and it surely is much easier to measure.



Estimated Hail Damage in 1946. —No detailed correlation has been shown for 1946 data because of the hail storm which interrupted the normal growth pattern on July 17. However, this accident did provide an opportunity to estimate the loss caused by the hail, which at the time was thought to be about 20 percent. Reconstruction of the growth rate curve on the basis of the temperature relationship established in 1945 and 1947 gives a hypothetical final yield of 26 tons per acre in 1946, compared with the actual field average of 18 tons. This represents a paper loss of 31 percent which appears to be too high since the 18-ton yield exceeded the average for the factory district by a comfortable margin. Had hail not occurred, something else would likely have served as a limiting factor. This high production in spite of hail damage may be partly explained by the fact that the weight of roots in the ground on July 17 had already attained 8¼ tons per acre.

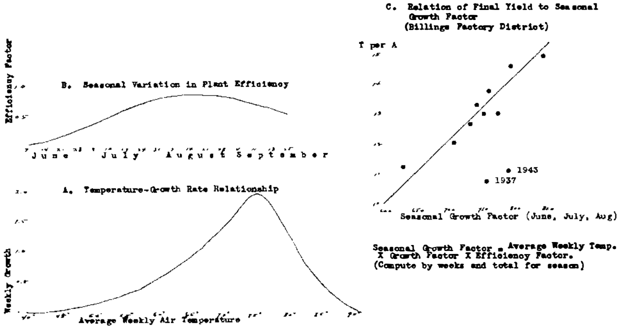
Heat Requirements. So far as I know, the heat requirement of growing beets has not yet been established—neither has a standard heat unit been settled upon. I have, therefore, used a form of "growing degree day," which is simply the average daily temperature minus 45 degrees. This figure is logical because 45 degrees is close to the lowest limit of growth. Weekly or monthly "growing degree days" can be readily computed by subtracting 45 from the mean temperature for any time interval and multiplying by the number of days. This method can be used directly so long as daily values are all above 45 degrees; and a simple correction can be used if any daily averages below 45 degrees are encountered.

Fig. 4 NUMBER GROWING DEGREE DAYS REQUIRED TO PRODUCE 1 TON OF SUGAR BEETS



"Growing degree days" obtained in this manner were computed for each week during the three seasons beginning with July 1, and from these results the number of such heat units required to produce a ton of beets was obtained for successive weekly intervals. These figures are quoted in table 2 and are shown in figure 5-B plotted on a time scale for the 3 years. It should be noted that this curve is plotted from the last columns of table 2, headed "Tons per 100 DD." From this chart, it is seen that less heat is required to grow a ton of beets during the 6 weeks from late July to early September than during earlier or later weeks. During the early part of the season the plant is engaged in assembling the production machinery in the form of leaves and a root system; hence it cannot attain full efficiency as a producer of root tonnage until about the middle of July. Peak efficiency, then, is maintained until about the first week of September, when gradual deterioration sets in, and efficiency drops because of shortages in raw materials such as duration of sunshine, favorable temperatures and available plant nutrients. During the first 3 weeks of July an average of 166 "growing degree days" are required to produce a ton of beets, and in the last 3 weeks of September the requirement is 156; while the average for the 7 weeks between late July and early September was only 118, with individual weeks below 100.

Fig. 5 METHOD OF COMPUTING FINAL YIELD FROM TEMPERATURE DATA



Practical Applications.—As previously stated, one of the initial objectives of this project was to devise a method whereby final tonnage yield might be predicted on the basis of the seasonal temperature record. Such a method has been developed which, while it may not exceed in accuracy the preharvest sampling procedure now in use, can at least be used as a convenient check. This method involves computation of weekly mean temperatures, and their adjustment by two factors representing the growth rate at specific temperature levels, and the efficiency of the plant on successive dates.

The curve shown in figure 5-A represents the manner in which sugar beet growth varies with temperature, and is based mainly upon results of the present study. The descending portion of this curve, however, is based upon studies made by B. S. Pickett (2), working in Texas with red beets. Mr. Pickett quotes 68.6 and 73.4 degrees F., respectively, as optimum

Table 2.- Relation between number "growing degree days" and tons-per-acre increase.

1945						1946						1947					
Date		No. DD	Tonnage increase[1]	DD per Ton	Tons per 100 DD	Date		No. DD	Tonnage increase[1]	DD per Ton	Tons per 100 DD	Date		No. DD	Tonnage increase[1]	DD per Ton	Tons per 100 DD
July	7	144	.65	222	.45	July	6	169	1.28	132	.758	July	3	105	.46	230	.438
	14	169	.91	186	.538		13	174	1.86	93	1.069		10	188	.82	229	.436
	21	191	1.31	146	.686		20	175	2.07	85	1.182		17	185	1.10	168	.594
	28	208	1.76	118	.847		27	180	1.22	148	.678		24	186	1.38	135	.742
August	4	198	1.53	129	.769	August	3	194	1.59	122	.820		31	197	1.70	116	.863
	11	178	1.60	111	.899		10	146	1.13	129	1.142	August	7	195	1.65	118	.846
	18	174	1.41	123	.811		17	155	1.58	98	.620		14	147	1.57	94	1.068
	25	130	1.73	75	1.330		24	174	1.06	164	1.548		21	170	1.18	145	.694
Sept.	1	138	1.37	101	.993		31	104	1.10	95	.864		28	124	.97	128	.781
	8	162	1.55	105	.950	Sept.	7	102	.99	103	.970	Sept.	4	163	1.24	132	.760
	15	85	.42	202	.694		14	102	.39	262	.382		11	108	.88	122	.815
	22	16	.22	72	1.374		21	60	.41	146	.683		18	45	.58	78	1.288
	29	15	.08	187	.533		28	59	.33	179	.559		25	78	.50	156	.691

[1]Increase adjusted to agree with final yield for the field: 1945, 16 tons; 1946, 18 tons; 1947, 15 tons.

growing temperatures for Crosby Egyptian and Early Wonder varieties, respectively; and 86 degrees F., as the absolute upper limit of growth. These figures have been adjusted upward for sugar beets on the basis of observation and estimate to 75 and 92 degrees, respectively. Growth in this figure is expressed in tons per acre per week, adjusted to an arbitrary final yield of 15 tons per acre. The efficiency factor, figure 5-B, although it is dimensionless in the chart, actually represents the number of tons increase per acre per 100 "growing degree days" at successive stages during the season. This chart runs from June 1 to September 25, but for predictive purposes September figures were omitted.

The procedure followed in arriving at a yield prediction was first to adjust each average weekly temperature for growth rate, multiplying by a factor extracted from the first curve 5-A, and then to make a second adjustment for plant efficiency, multiplying by the seasonal factor taken from the curve in 5-B. The final products, which I have chosen to call "weekly growth factors" were then totaled for each season from 1936 through 1947 and plotted against actual yield in figure 5(c). Of the 12 years considered, only 1937 and 1943 failed to fall in line. Yield in both of these years was unusually low due to serious hail damage, flood, frosts and other well-recognized reasons.

The period included in these summations extended from June 1 to August 31 only, in order that a prediction of final yield might be made sufficiently early in the season to be of practical value. The average error in estimating yield as of September 1 for the 10 years (1937 and 1943 being omitted) was .34 ton, and it is likely that if needed, a fairly reliable estimate could be made a week earlier. Temperatures in this case were taken from Airport Weather Bureau records at Billings—400 feet above the valley floor. Yields used were Billings Factory District averages, the district extending from Columbus to Forsyth, Montana, in the Yellowstone Valley.

The most attractive feature of this method of prediction is that it requires only that temperature records be maintained at some representative location in the area, to provide data from which the yield may be estimated with the aid of tables constructed from the three correction curves shown. Figure 5 is strictly applicable of course, only to the Billings area, but the curves could be adjusted to serve in other regions without too much trouble.

Summary

Results of this study may be summarized under the following items:

1. A high correlation has been shown to exist between growth rate of sugar beets and the level of temperature.

2. There is no significant advantage of soil over air temperature as an indicator of growth rates.

3. "Growing degree days" computed on a 45-degree base is suggested as a convenient means for expressing the amount of heat available for crop growth in any season.

4. The efficiency of the plant in producing root growth varies significantly from week to week, reaching a peak during the period from late July to early September, and may be expressed as the number of "growing degree days" required to produce a ton of beets, or the number of tons produced per unit "growing degree days," each being the converse of the other.

5. A new method of predicting final yield on September 1 is proposed. Weekly "growth factors" may be computed by multiplying average weekly temperatures first by a temperature-growth factor, then by an efficiency factor, and totaling to obtain a "seasonal growth factor," which correlates well with final yield.

6. A substantial volume of reliable growth measurements has been accumulated, which will be made available to others having need for such data.

Further Research Needed. The author is convinced that further experimental work is required to supplement information presently available, as follows:

1. To verify the temperature-growth rate curve presented herewith and determine whether critical temperatures have been correctly established, also to find whether or not it is applicable in other parts of the country.

2. To develop a more accurate seasonal conversion factor for translating linear root measurements into terms of weight. This requires more definite information regarding the manner in which roots change shape as growth proceeds.

3. To establish the effect of sunshine intensity and length of day upon growth rate.

4. To determine more accurately the nature of progressive changes in the ratio of tops to roots throughout the growing season.

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