Sugarbeet Yield and Theoretical Photosynthesis in the Northern Great Plains[1]

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Sugarbeets have been grown for several decades in the Red River Valley of North Dakota without irrigation and in the Yellowstone Valley of eastern Montana with irrigation. Part of the sugarbeet's acceptance by farmers is attributable to the fact that, unlike most annual plants, it can recover after being damaged by hail or some other adverse weather condition and still produce a partial yield. In fact, Afanasieve (1)[3] showed that the midseason removal of 50% of the leaves in Montana reduced root yields by about 10% and sugar yields by about 4%. In addition, sugarbeets grow well in northern latitudes and are a high-value crop under favorable growing conditions. As new lands are brought under irrigation as part of the Garrison Diversion Project in North Dakota, growers will likely consider the growing of sugarbeets on their irrigated lands.

However, in spite of the sugarbeet's general acceptance by farmers, field yields for irrigated sugarbeets have been relatively low at the Carrington Irrigation Branch Station of the North Dakota Agricultural Experiment Station, Carrington, North Dakota. Between 1962 and 1969, sugarbeet yields averaged only 12.2 tons/acre and ranged from 8.0 to 18.4 tons/acre.[4] Sucrose content averaged **16.9%** and varied less from year to year than root yields. Compared with the 44-year average yield of 10.2 tons/acre and 16.0% sucrose, without irrigation, in Grand Forks County, North Dakota,[5] these yields with irrigation are indeed mediocre.

Large variability of yield with years suggests climatic influences on yield. Climate affects yield several ways. For example, Radke and Bauer (9), in laboratory studies, found that the optimum soil temperature for sugarbeet germination was between 77° and 95°F. Shaw and Buechele (10) found that soil ridges were warmer than flat surfaces for several hours during the day, and Benz, et al. (3) reported that a clear plastic germination cap over the seed row increased soil tempera-

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ture by 5° to 11°F in the top 3 inches of soil during the last week of May. Even so, soil temperatures in North Dakota seldom rise above 77°F for many hours of the day during early spring. Therefore, stand establishment is a problem usually overcome by high seeding rates and subsequent thinning. Swift and Clelland (11) stated that sugarbeets grew well where the summer isotherm was about 70°F. The long-term average air temperatures at Carrington are 62.4°, 69.4°, 67.1° and 56.1°F for June, July, August, and September, respectively (16).

Laboratory experiments by Ulrich (12, 13) have shown that low night temperatures produced greater sucrose concentrations and less top growth, and that sucrose production was maximum with 8 hours of sunlight per day and a night temperature of 63°F. However, for 13.5-hr. day lengths, sucrose concentrations increased as night-time temperatures decreased to 39°F. Conversely, Radke and Bauer (9) found that sucrose content increased from 10.5% to over 13% as constant root temperature ranged from 66° to 99°F for a 15-hr. day length in the laboratory, and that sucrose yield was high for constant root temperatures between 64° and 90°F. A field study (14) on the effect of climate on sugarbeets grown under standardized conditions indicated that a night temperature of about 41° during the last 4 weeks before harvest caused the highest sucrose concentrations but total sucrose production was not reported.

We conducted the following experiments to determine the relative significance of climate and endogenous factors on early season sugarbeet growth and to evaluate the effect of yearly climatic differences on sugarbeet yield and theoretical photosynthesis in North Dakota.

Materials and Methods

Sugarbeets were grown in well-irrigated field plots at the Carrington Irrigation Branch Station, Carrington, North Dakota on nonsaline, calcareous Heimdal loam (*Udic Haploboroll*). Results from both replicated and nonreplicated experiments are included. Sugarbeet cultivar HH-10[6] was planted in 24-in. rows and thinned to a population of 26,000 plant/acre for all experiments. Irrigation water was applied in surface furrows the first year (1966) and with a rotating-boom type sprinkler irrigator (4) in 1967, 1968 and 1969.

The basic experiment was a randomized block design using years as treatments with three replications. For this experiment, sugarbeets were grown on the same plots during four consecutive years (1966 to 1969). Supporting experiments included a variety of different treatments each year but treatment differences were not significant during any year. Hence, these treatment yields are used as components of

[6]Holly Sugar Corporation, Sidney, Montana. (Trade and company names are given for the reader's benefit and do not imply endorsement or preferential treatment of any product by the U.S. Dept. of Agriculture.)

the average yield for that year. We tested flat vs ridged planting; clear plastic germination cap vs no germination cap; rototilling vs plowing (11-in. deep) vs soil compaction; chloride fertilization; and phosphorus fertilization treatments during the 4 years.

Nitrogen (N) as ammonium nitrate (33-0-0) was broadcast at a rate of 100 lb N/acre/year on the experimental area before planting in 1966 through 1968, and at 150 lb N/acre in 1969. Treble superphosphate (0-46-0) was broadcast at a rate of 100 lb P_2O_5/acre on the experimental area before planting in 1966 and 1969, and at a rate of 50 lb P_2O_5/acre in 1967 and 1968. All fertilizer was disked into the surface soil.

The replicated plots were planted on May 10, May 17, May 2, and May 9, and 104-ft^2 were harvested on Sept. 27, Sept. 26, Oct. 16, and Oct. 1 in 1966 through 1969, respectively. Both fresh and dry matter yields of roots and tops were determined.

Four additional nonreplicated main plots were established on May 17, 1967 for growth-rate measurement over a range of tillage treatments. One 60-ft^2 subplot from each main plot was harvested for both fresh and dry matter yields of roots and tops on July 12, 17 and 27, on Aug. 3, 9, 16 and 30, and on Sept. 13 and 26.

Nonreplicated plots were established again in 1968 for growth-rate determination as functions of calendar date and days since planting. These plots were planted on 4 dates — April 18, and May 2, 16, and 28 — and were dovetailed together so progressive harvests could be taken from adjacent rows and include one row planted on each date. From each date-of-planting plot, 60-ft^2 were harvested for both fresh and dry matter yields of roots and tops on July 10, 18 and 26, on Aug. 2, 7, and 22, on Sept. 4 and 16, and on Oct. 2 and 16.

In 1969, the three planting dates were replaced by three chloride fertilizer treatments in plots planted on May 9. Growth rate measurements were obtained by harvesting one 40-ft^2 subplot from each fertilizer treatment to determine both fresh and dry matter yields of roots and tops on July 23 and 29, on Aug. 13 and 26, on Sept. 9 and 24, and on Oct. 6.

All fresh root yields were adjusted for the sugar factory tare, but root dry matter yields were not.

Theoretical photosynthetic rates (P_r) were calculated according to the method described by deWit (17). The following standard conditions were defined by deWit and have been assumed for these theoretical calculations: (1) maximum P_r for very high light intensity is about 20 kg CH_20 $ha^{-1}hr^{-1}$; (2) light intensity at which half-of-maximum P_r occurs is about 0.056 langley min^{-1}; (3) canopy density is about 0.1; (4) leaf area index is 5, and (5) $C0_2$ exchange resistance is 0.5 sec cm^{-1}. Approximate values of clear sky radiation in the 400 to

700 mμ wavelength range (HC), photosynthetic rate on clear days (PC), and photosynthetic rate on overcast days (PO) were calculated by linear interpolation from deWit's Table 6. To perform a series of calculations involving different time intervals for different years at one location, calculation time can be reduced by preparing curves to describe HC, PC, and PO as functions of date.

Cloudiness (F) and P were calculated as follows (17):

$$F = 1.25 - \frac{1.25\ PAR}{HC}$$

$$P_r = F\ (PO) + (1\text{-}F)\ (PC)$$

where PAR is the measured photosynthetically active radiation (400-700 mμ wavelength range) in langleys/day, HC is in langleys/day, and PC, PO, and P_r are in kg carbohydrate $ha^{-1}day^{-1}$. Theoretical photosynthesis (P) for a time interval is calculated as follows:

$$P = \Sigma \left[(P_r)_i \cdot (\Delta t)_i \right]$$

Photosynthetic efficiency (PE) is the actual increase in plant dry matter expressed as a percent of P. The plant dry matter actually measured is assumed equivalent to an equal weight of carbohydrate.

Results and Discussion

Long term weather records (16) indicate that Carrington has 121 days during which the chance is 50% that the temperature will not drop below 32°F, and 137 days during which the chance is 50% that the temperature will not drop below 28°F. Hence, the growing season is about 130 days. The 1968 growing season is an example of the adverse weather extremes that can and do occur. The last spring frost (T = 22°F) was on May 5, a severe hail storm occurred on July 19, and the temperature dropped to 30°F on August 14 — giving a true frost-free period of only 101 days.

Root growth and total dry matter production are shown as functions of calendar date in Figures 1 and 2, respectively, for 1967, 1968, and 1969 at Carrington. Even though these experiments were non-replicated, treatment differences were small each year except 1968. Final dry matter yields for the three earliest planting dates in 1968 were within ±6% of the mean, but the yield for the latest planting (May 28) was only 64% of that mean and the data for that latest 1968 planting were excluded. Hence, the data points in Figures 1 and 2 are averages for four plots in 1967 and for three plots in 1968 and 1969.

These data show that (1) about 64, 87, and 72 days after planting were needed to produce the first ton/acre of fresh roots in 1967, 1968

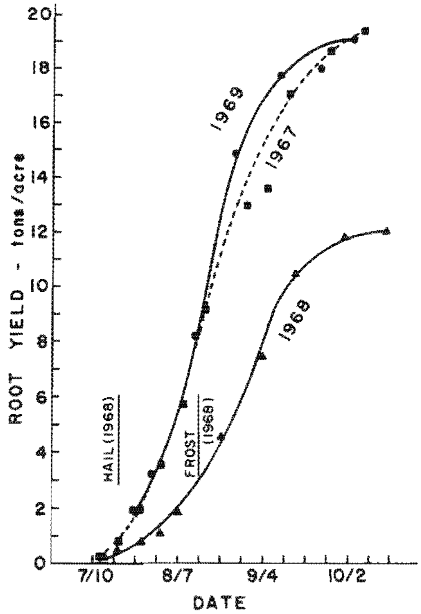

Figure 1. — Average root yield as a function of time for 3 years at Carrington, North Dakota.

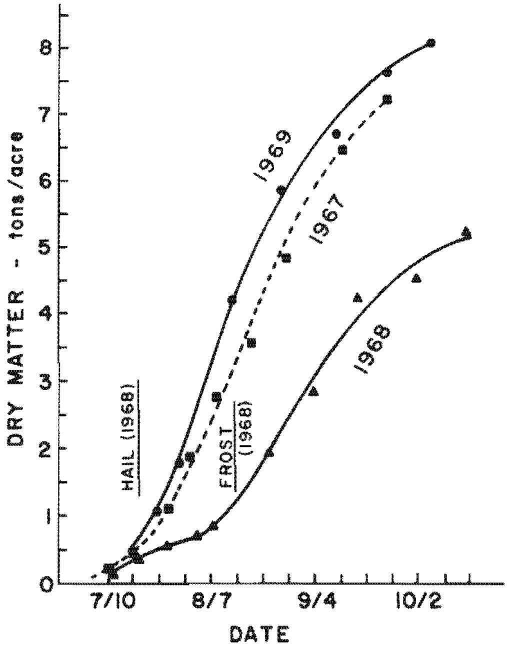

Figure 2. — Average dry matter yield as a function of time for 3 years at Carrington, North Dakota.

and 1969, respectively (Fig. 1); and (2) about the same number of days (69, 100, and 74 days in 1967, 1968, and 1969, respectively) were needed to produce the first ton/acre of dry matter (Fig. 2). These intervals represent between 50% and 75% of the available growing season at Carrington. Data published by Campbell and Viets (5) indicated that about 80 days were needed to produce the first ton/acre of roots at Huntley, Montana. Data published by Follett, et al. (7) indicated that about 80 days were needed to produce the first ton/acre of dry matter at Fort Collins, Colorado.

These data also show that once the sugarbeets began storing photosynthetic products they grew very well at Carrington. During late July and all of August of 1967 and 1969, maximum growth rates (in lb/acre/wk) were about 6,000, 900 and 2,000 for roots, sucrose and dry matter, respectively. Even with the adverse weather in 1968, growth rates were more than half those for more favorable years (1967 and 1969). Yield is a function of both growth rate and time, so any practice extending this active production period to earlier in the summer would significantly increase final yield.

The results of the early-season root-growth study in 1968 are summarized in Figure 3. Figure 3A presents the root-growth data as

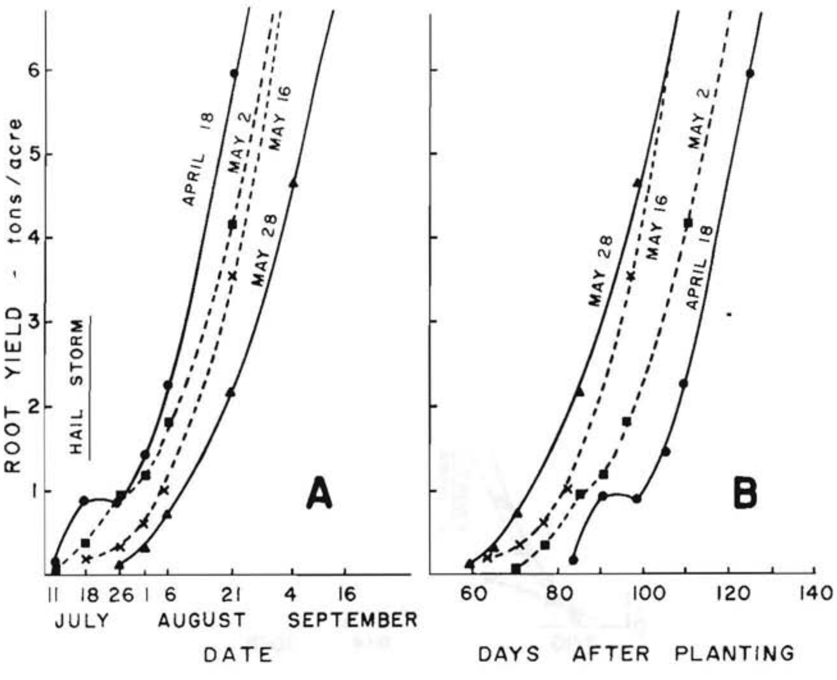

Figure 3. — Root yield for various dates of planting as functions of calendar date (A) and days after planting (B) at Carrington, North Dakota.

functions of calendar date and Figure 3B presents them as functions of days after planting. If initiation of bulking were principally a function of ambient weather conditions, the root yield curves would cluster in Figure 3A. If initiation of bulking were principally a function of endogenous characteristics of the sugarbeet plant, the root yield curves would cluster in Figure 3B. Since the curves did not cluster in either A or B, dominance of neither climate nor endogenous factors can be concluded. However, the fact that the root yield curves by days after planting (Figure 3B) are arrayed in reverse order from those by calendar date (Fig. 3A) indicates that both climatic and biological factors exert significant influence.

The effect of the hail storm is particularly evident in the root yield curves for April 18, the earliest planting (Fig. 3). The earliest planting produced greater yields than the later plantings at each harvest until mid-September. By final harvest in mid-October, the root yields for the April 18, May 2 and May 16 plantings were about equal. As has been previously noted, the root yield for the May 28 planting was consistently less; so early planting is important when the limited length of the growing season is considered. Carlson et al. (6) reached a similar conclusion about early planting of sugarbeets in the northern Great Plains.

In replicated experiments conducted with a variety of treatments in 1966, 1967 and 1969, treatment differences each year were not statistically significant. Analysis of variance for the randomized block experiment with years as treatments and with sugarbeets grown on the same plots each year (1966 and 1969) showed that years were significantly different. Since (1) the investigations included several treatments, (2) weather is obviously different from year to year, and (3) only years had a significant effect on yields, it follows that yearly weather **must be a regulator of sugarbeet growth and yield.**

Since treatment differences each year at Carrington were not significant, average annual yields are presented in Table 1. Average yields from Campbell and Viets (5) at Huntley, Montana and Follett, et al. (7) at Fort Collins, Colorado (for the commercial sugarbeet cultivar) are also included in Table 1 for comparison, even though those averages include statistically significant treatment differences. The latitudes for the three locations are 47°31′ N, 45°45′ N, and 40°35′ N for Carrington, Huntley, and Fort Collins, respectively. Therefore, Carrington is about 125 miles north of Huntley and about 500 miles north of Fort Collins. Carrington, Huntley and Fort Collins are 1,580, 3,100 and 5,000 ft above mean sea level, respectively. Sugarbeets were planted on April 2, 1961 at Huntley and on April 4, 1962 at Fort Collins — 37, 44, 29 and 36 days earlier than the planting dates at Carrington in 1966, 1967, 1968 and 1969, respectively.

For all measured components of yield, production was highest

Table 1. — Average yields and calculated theoretical photosynthesis for Carrington, Huntley[2], and Fort Collins.[3]

	Carrington				Huntley[2]	Fort Collins[3]
	1966	1967	1968[1]	1969	1961	1962
Number of plots	18	22	3	33	40	12
Average dry matter (tons/acre)	6.3	7.0	6.3	6.9	7.9	8.9
Average root yield (tons/acre)	14.9	19.4	14.2	17.8	21.6	24.1
Average sucrose (cwt/acre)	50.9	62.7	42.5	51.8	58.8	81.0
Theoretical P (tons DM/acre)[4]	10.4	11.7	11.0	12.1	17.2[5]	18.7[5]
Weighted-average cloudiness (%)	42	23	29	24	36[5]	30[5]

[1]Hail in July, frost in August
[2]From Campbell & Viets (1967)
[3]From Follett, et al. (1970)
[4]By deWitt method for period from first ton of roots per acre to harvest
[5]June 22 was selected as date for first ton of roots per acre

at Carrington in 1967. Yield differences between years and locations are obvious (Table 1). If adjustments can be made for differences in ambient weather conditions, the remaining differences would be due to treatment differences, i.e. soil, fertility, variety, etc.

One method of adjusting for weather is to express each growing season in terms of a standard environment like that described by deWit (17). Using the deWit model requires that photosynthetically active radiation (wavelength range of 400 to 700 mμ) be measured during the growing season. Photosynthetically active radiation (PAR) data were not available for Carrington, but PAR is about half of the total solar radiation (2, 8, 17). Total solar radiation data were available for Bismarck, North Dakota (15), which is about 40 miles south and 100 miles west of Carrington.

To justify using a 2:1 ratio to relate total solar radiation and PAR, five years (1965 to 1969) of daily total solar radiation data were compared to twice deWit's light intensity values. The results are shown in Figure 4, and the curve constructed by doubling deWit's HC values satisfactorily envelopes that measured total radiation from mid-May through October. The fact that the deWit envelope is low for March and April is of little or no consequence because sugarbeet plants are usually too small to justify photosynthesis calculations before about mid-June in the northern Great Plains.

Theoretical photosynthetic rates (P_r) are easily calculated as described by deWit (17) after the appropriate curves for photosynthetic rates on clear and overcast days have been constructed. Table 1 shows theoretical photosynthesis for the part of the growing season between the production of the first ton/acre of roots and harvest during six different years and at three locations. With P values thus predicted by the deWit model ranging from 10.4 to 18.7 tons/acre, the growing season weather conditions were indeed different. Using only that part of the growing season after the first ton/acre of roots were produced

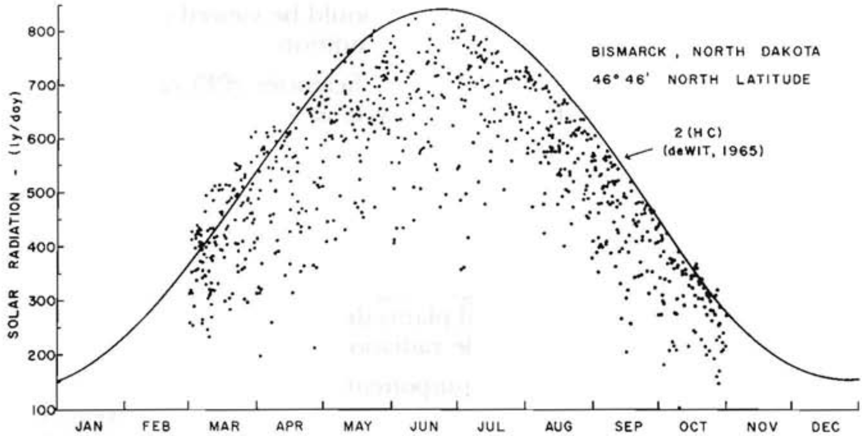

Figure 4. — Comparison of measured solar radiation for 1965-1969 at Bismarck, North Dakota (15) and 2 times deWit's HC (17).

is justified on the basis of the growth data presented in Figs. 1 and 2. The first ton/acre of roots is produced about the time when the leaf area index equalled or exceeded 2. Hence, the plant canopy could intercept and utilize the available radiation.

Maximum radiation is expected during the latter part of June in the northern Great Plains. The first ton/acre of roots was produced by about June 22 for both the Huntley (5) and Fort Collins (7) experiments. Hence, the accumulation of root dry matter and sucrose occurred during the period when radiation decreased with time. At Carrington, the situation was even less desirable because the first ton/acre of roots was not produced until the latter part of July, about 4 or 5 weeks after the peak of the radiation cycle. Thus, a significant amount of available radiation was not used for photosynthesis, particularly at Carrington, because the plants were too small.

Cloudiness and atmospheric contamination which reduces the effective radiation level at the land surface is related to daily weather. Daily weather varies considerably from place to place at any one time. At any one place, daily weather varies considerably with time as a result of weather systems that generally move from west to east across the northern Great Plains. Because of these moving weather systems, average cloudiness for different locations in the northern Great Plains during any one growing season will be about equal; and weighted-average level of cloudiness from year to year becomes a function of the intensity and frequency of occurrence of those weather systems from year to year. Calculation of relative cloudiness is involved in the calculation of theoretical photosynthesis. Even though the weighted-average levels of cloudiness ranged from 23% to 42% (Table 1) and were calculated for the same time interval as the corresponding P, weighted-average levels of cloudiness should be viewed only as qualitative indicators of a growing season condition.

Table 2 presents photosynthetic efficiencies (PE) calculated for the root storage part of the growth cycle at Carrington plus the reported PE for Huntley (5) and Fort Collins (7). Although average yields at Carrington were lower than those at the other two locations, PE were highest at Carrington. Theoretical P values (Table 1) were considerably larger at both Huntley and Fort Collins than at Carrington. Therefore, yields at Huntley and Fort Collins must have been higher because of the longer growing season that resulted because earlier planting was possible and plants developed in time to intercept and utilize more of the available radiation.

By expressing each yield component as a fraction of the corresponding yield component for one set of conditions, or one year, the results for various years or locations are referenced to a common base. This has been done in the top half of Table 3, arbitrarily using 1967 yield components as common denominators. Each yield component for 1967 is thus reduced to unity, and all other yield components become ratios relative to 1967 production components.

Table 2. — Photosynthetic efficiencies for the root storage portion of the growth cycle at Carrington, Huntley,[1] and Fort Collins.[2]

	Days	PE %
July 19 to Sept. 26, 1967	69	56
Aug. 2 to Oct. 16, 1968	75	41
July 23 to Oct. 6, 1969	75	57
July 10 to Oct. 5, 1961[1]	87	39
June 9 to Oct. 11, 1962[2]	124	39

[1]From Campbell & Viets (1967)
[2]From Follett, et al. (1970)

Table 3. — Yield ratios for 4 years at Carrington and 1 year each at Huntley[1] and Fort Collins,[2] using 1967 yield components and calculated theoretical photosynthesis as bases.

	Carrington				Huntley[1]	Fort Collins[2]
	1966	1967	1968*	1969	1961	1962
Theoretical P	0.89	1.00	0.94	1.03	1.47	1.60
Dry matter	0.90	1.00	0.90	0.99	1.13	1.27
Fresh roots	0.77	1.00	0.73	0.92	1.11	1.24
Sucrose	0.81	1.00	0.68	0.83	0.94	1.29
Theoretical P	1.00	1.00	1.00	1.00	1.00	1.00
Dry matter	1.01	1.00	0.96	0.96	0.77	0.79
Fresh roots	0.87	1.00	0.78	0.89	0.76	0.78
Sucrose	0.91	1.00	0.72	0.81	0.64	0.81

*Hail in July, frost in August
[1]Derived from Campbell & Viets (1967)
[2]Derived from Follett, et al. (1970)

Table 4. — Theoretical photosynthesis ratios and yield components for six different years normalized to 1967 weather conditions at Carrington, North Dakota.

	Carrington				Huntley[1]	Fort Collins[2]
	1966	1967	1968*	1969	1961	1962
Theoretical P ratio	0.89	1.00	0.94	1.03	1.47	1.60
Normalized yields						
Dry matter (tons/acre)	7.1	7.0	6.7	6.7	5.4	5.6
Fresh roots (tons/acre)	16.7	19.4	15.1	17.3	14.7	15.1
Sucrose (cwt/acre)	57.2	62.7	45.2	50.3	40.0	50.6

*Hail in July, frost in August

[1]Derived from Campbell & Viets (1967)

[2]Derived from Follett, et al. (1970)

By further dividing each component by that year's theoretical P ratio, the theoretical difference in climate as described by the deWit model is removed, and the resultant yield component ratios are all referenced to standard conditions represented by 1967 production components and 1967 weather conditions at Carrington. These results are presented in the lower half of Table 3. Since this normalizing procedure did not reduce all yield component ratios to unity, we can conclude that the remaining yield difference between years and between locations were caused by something other than climatic factors evaluated by the deWit model, i.e. soil conditions, variety differences, disease, fertility, management differences, or other treatment conditions.

Equivalent comparisons can be developed with each yield component expressed in usual yield units instead of ratios by dividing first the theoretical P values for each year by the theoretical P value for the chosen year. Each year's measured yield component is then divided by that year's theoretical P ratio to give the expected yield for the standardized condition. The procedure is illustrated in Table 4, with the yields normalized to 1967 weather conditions at Carrington.

Summary

Sugarbeet growth in the northern Great Plains varies considerably from year to year. During four study years at Carrington, North Dakota, irrigated plot yields averaged 16.6 tons/acre of roots while field yields averaged 13.6 tons/acre. Sucrose yields averaged 52.0 cwt/acre for the plots and 47.8 cwt/acre for the field.

Growth studies during favorable growing seasons revealed that from 64 to 72 days (over half the growing season) were required to produce the first ton/acre of roots. Similarily, from 69 to 74 days were required to produce the first ton/acre of dry matter. Consequently, the root storage portion of the growth cycle occurs after the maximum in the annual radiation cycle.

Both weather and endogenous factors influenced the initiation of root bulking. Once the first ton/acre of roots were produced, weekly growth rates were as high as 6,000, 900 and 2,000 lb/acre for roots, sucrose and dry matter, respectively. Hence, genetic or cultural changes which hasten the initiation of bulking would significantly increase sugarbeet yields.

Calculation of theoretical photosynthesis by deWit's method revealed that weather conditions during six different years at three locations were indeed different. Theoretical P values for the six growing seasons ranged from 10.4 to 18.7 tons/acre of dry matter. For these calculations, only the root storage part of the growth cycle was used, i.e. the time interval starting with production of 1 ton/acre of roots and a leaf area index of about 2 and ending with harvest.

Photosynthetic efficiencies based on measured dry matter production and the deWit model for calculating theoretical photosynthesis ranged from 41% to 57% during the root storage part of the growth cycle at Carrington.

A method is described by which deWit's theoretical photosynthesis can be used to compensate for climatic differences between years and locations. The deWit model accounts primarily for radiation differences in combination with cloudiness and related atmospheric contamination. Continuous losses of dry matter by respiration, advected energy, wind, air temperature, etc. are not considered. In spite of these limitations, however, the method is easy to use and provides a means of evaluating growing season climatic conditions so that growth at different locations and during different years can be compared.

Acknowledgement

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