Seasonal Leaf Area, Dry Weight, and Sucrose Accumulation by Sugarbeets[1]

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Introduction

Much research has been done on the sugarbeet in trying to solve problems of obtaining high-quality, high-yielding crops. The effect of too much N on the quality and yield of sugarbeets is one of these problems.

The increased use of commercial fertilizer by growers emphasizes that sugarbeets are being grown increasingly under conditions that may have excessive N. N fertilization increases the production of tops and the amount of N in the leaves, while storage of sucrose may remain unchanged or decrease (9).[3] The maintenance of top growth at the expense of storage root formation and sucrose content of the roots may also be seen in the changes in dry weight of the tops, the fresh and dry weights of the blades of living leaves (16), leaf area and its duration and sucrose content of the roots (3).

The degree to which nitrogen affects sugarbeet growth can be influenced by genotype (8). Sucrose percentage can be increased on high-fertility soils by breeding varieties of sugarbeets adapted to growing under these conditions (10). Since excessive fertility, especially N in soils, decreases quality in sugarbeets; breeding of varieties that will maintain sucrose percentage under such conditions is one promising possibility (6,10).

Measures of the efficiency of a sugarbeet's growth are the direct physical measurements of its weight, leaf area, or some other factor. These methods are simple in principle but provide valid measures of the effects of treatment on the growth patterns, efficiency, and even the nutritional status of the sugarbeet. The results reported here are from a field study of leaf area, dry weight accumulation, and sucrose accumulation throughout a growing season as affected by nitrogen fertilization and variety.

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[3] Numbers in parentheses refer to literature cited.

We will use the following terms, abbreviations, and accepted definitions throughout this paper[4]:

Leaf area is the area of one surface of the leaf blade(s).

Leaf area index (LAI) is the ratio of leaf area to ground area.

Leaf area duration (LAD) is the sum of the weekly average LAI's expressed as weeks.

Net assimilation rate (NAR) is the increase in total dry plant weight per unit of leaf area per unit time expressed as $g/m^2/day$.

Materials and Methods

Sugarbeets were grown in a field experiment at the Agronomy Research Center, Fort Collins, Colorado (40°35'N) on a non-saline, calcareous Nunn clay loam. The soil was adequately fertile for production of sugarbeets since the commercial variety produced 24 tons per acre without N fertilization. The experiment was designed as a factorial with three nitrogen rates and two varieties randomized in each of four replications. Concentrated superphosphate was broadcast in the spring and disked into the surface soil at the rate of approximately 55 lbs of P per acre. Nitrogen, as Uran[5], was applied in bands after emergence and before thining. The nitrogen rates were 0, 100, and 200 lbs of N per acre.

The experimental plots were furrow irrigated 5 times during the growing season: June 8, June 29, July 12, August 1, and August 24. Approximately 2 inches of water were applied per irrigation; percipitation added an additional 2.6 inches of water for the same total period of time.

The varieties were: 1) the monogerm variety distributed locally in 1962 (commercial variety), and 2) a yellow-rooted high-tonnage experimental variety (hybrid variety)[6].. Both varieties were planted in 20-inch rows on April 4 and thinned in mid-May. The stands for both populations should have been the same after thining; because of differences in germination of the two varieties, the commercial variety was spaced in the row at the average rate of 123 and the hybrid variety at the average of 101 beets per 100 feet of row. Stand differences are not considered serious because of the distinctly different characteristics of the two varieties. Also, previous research (13) with a commercial variety showed no significant differences in yield or

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[4] Metric units will be used in this paper where they are the accepted form of a measurement and the English equivalent is not.

[5] 32% total nitrogn by weight; 16.5% from urea and 15.5% from NH_4NO_3. 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. Department of Agriculture.

[6] An F_2 hybrid between a CMS variety having a broad genetic base and the yellow stock beet A 58-5. Obtained from LeRoy Powers (deceased), Principal Geneticist, Sugar Crops Section, Agricultural Research Service, U. S. Department of Agriculture.

qualtiy of roots for stands of 92 and 133 beets per 100 feet of row.

The experimental plots were harvested 10 times during the growing season: June 8, June 25, July 5, July 15, July 31, August 15, August 30, September 13, September 27, and October 11. A harvest consisted of removing 13 consecutive beets in each plot and computing the ground area from row length harvested times row spacing. The harvested areas were randomized so that harvested beets had normal competition with other beets.

The beets were separated into leaf blades, crowns plus petioles, and roots. The leaf blades and crowns plus petioles were dried at 150 F and weighed. The roots were washed free of soil, and green and dry weights were taken. The sucrose content of the roots was determined by a polariscopic method similar to that outlined in A.O.A.C. (1). Extractable sucrose percentage and yields of extractable sugar per acre were calculated by the methods of Dexter *et al.* (5) for beets from the final harvest only. A standard factory loss constant of 0.3 and molasses purity of 62.5 were assumed in the calculations. Thin juice purity was determined on the beet pulp by The Great Western Sugar Company.

At each harvest one beet per plot was chosen randomly to correlate leaf area with dry leaf weight. The leaf blades were separated from the petioles, placed on blueprint paper, flattened with a pane of glass, and exposed to sunlight. The area of the leaf image on the developed blueprint was determined with a planimeter and correlated with the dry weight of the leaf. Plot leaf areas were calculated from the total dry weights of the harvested leaves.

Total solar radiation was measured at a station about 3 miles from the experiment with a 16-junction Eppley pyrheliometer. Soil temperature was measured with a recording thermometer placed at a 6-inch depth within the row, 5 feet inside the field, and air temperature was measured by the Colorado State University weather station located about 4 miles from the experiment. Solar radiation and temperature data for the experiment were averaged for periods coinciding with the interval between harvests. Both air and soil temperatures were expressed as the means of the daily maximum-minimum for each growth period.

Results

The solar radiation, air and soil temperature during the season averaged for the intervals between each harvest are shown in Figure 1. The maximum mean solar radiation occurred during the period ending July 5; thereafter, there was a steady decline. The mean of the daily maximum-minimum air temperatures reached a high plateau for the period ending July 5, and remained there through August before decreasing. Soil temperatures in the field at a 6-inch depth reached a maximum at the same time as radiation and then decreased through the season.

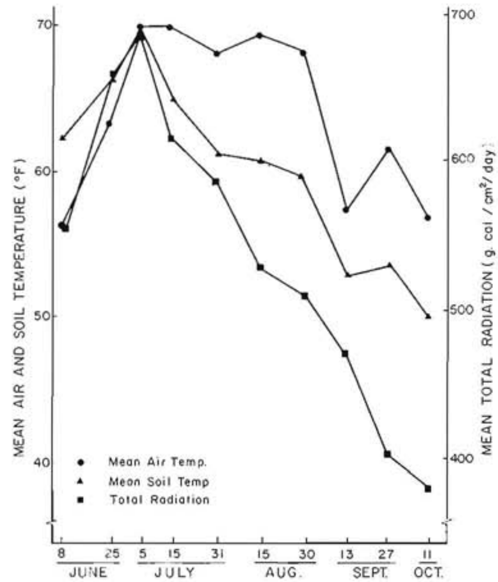

Figure 1.—Radiation and temperature patterns for the 1962 growing season.

Leaf Area Index

Leaf area index (LAI) is the ratio of leaf area to ground area. Nitrogen fertilization increased LAI significantly over that of the nonfertilized plots from mid-July until the last of September. The highest values of LAI reached during the season were 5.9 for the commercial variety and 4.9 for the hybrid variety; these values were obtained on N fertilized plots during the last half of July. Average values for the check plots of both varieties were never more than 1.5 units of LAI less than the N treated plots. The average difference for the season between the check plots and the N treated plots was about 0.5 LAI unit. LAI, averaged for the season, was about the same for the plots fertilized with 100 and 200 lbs. of N/acre. The average values for the three nitrogen rates are shown in Figure 2. Final harvest values are given in Table 1.

The maximum values of LAI were reached about 2 weeks after the maxima in radiation and soil temperature. This was probably a lag period while the newly initiated leaves were expanding.

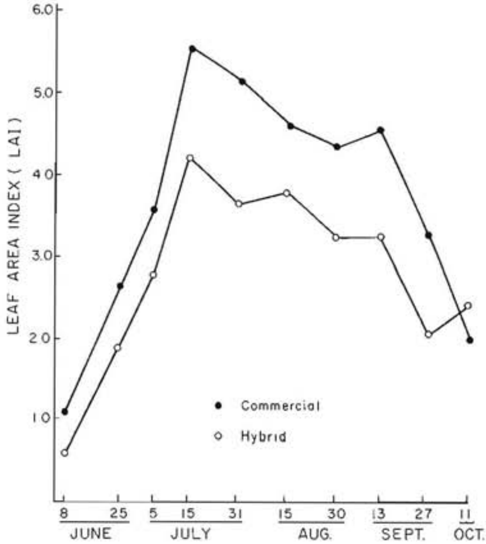

Figure 2.—Effect of variety and date of harvest on leaf area index.

That LAI decreased only very slowly for 2 months after reaching a maximum may be attributed to the rate of initiation and production of new leaves continuing at a rate nearly equal to the dying of shedding of old leaves. The high N and K fertility levels of the soil probably aided in preventing senescence of existing leaves (18). The abrupt decline of LAI during the last part of September and into October corresponds with rapid declines of petiole nitrate, temperatures and solar radiation. Average NO_3-N in the petioles of the commercial variety decreased from 4700 ppm on August 13 to 1100 ppm on September 20; the decrease for the hybrid variety was from 7800 to 1900 ppm. Leaf area development has been reported to depend more on N supply than on weather factors (3). The decrease in petiole nitrate from late August to early October supports this conclusion.

To understand leaf area trends, a detailed study of the number of leaves per beet and average area per leaf was initiated for the last five harvests on one randomly selected beet per plot. The statistically significant results were as follows: a) the number of leaves per beet increased from the sixth through

Table 1.—The effect of N fertilization and variety on yield, quality and root/top ratio of sugarbeets at final harvest.

	Commercial variety				Hybrid variety			
	Check	100 lb. N/acre	200 lb. N/acre	Average	Check	100 lb. N/acre	200 lb. N/acre	Average
Fresh root yield, tons/acre (**P)	24.2	25.1	23.1	24.1	32.6	37.2	36.2	35.3
Sucrose content, % (*N) (**P)	17.7	16.7	16.0	16.8	13.2	12.2	11.9	12.4
Extractable sucrose, % (*N) (**P)	15.6	14.2	13.2	14.3	11.1	9.9	9.9	10.3
Extractable sugar yield, tons/acre	3.8	3.6	3.1	3.5	3.6	3.7	3.6	3.6
Juice purity, %	94.3	92.4	91.1	92.6	91.5	90.8	91.8	91.4
Leaf area index	2.2	1.7	2.1	2.0	2.2	2.1	3.1	2.4
Leaf area duration,[1] (**N) (**P)	65.0	72.5	75.8	71.1	47.3	54.5	58.1	53.3
Top dry weight, tons/acre (**P)	2.8	3.4	3.1	3.1	1.6	2.0	2.2	1.9
Root dry weight, tons/acre (**P)	6.0	6.0	5.4	5.8	6.2	6.8	6.5	6.5
Dry matter in pulp, % (**P)	24.7	23.9	23.1	23.9	19.2	18.1	17.9	18.4
Root-top, dry weight ratio (**P)	2.1	1.8	1.8	1.9	3:9	3.4	3.0	3.4
Total dry weight, tons/acre	8.8	9.4	8.5	8.9	7.8	8.8	8.7	8.4

** Significant at the 1% level.
* Significant at the 5% level.
N Significance is a result of N fertilization.
P Significance is a result of genetic population.
[1] Summation of LAI for all weeks.

the ninth harvest; b) average area per leaf decreased; c) the commercial variety had more leaves per beet than the hybrid, but no difference in average area per leaf; and d) N fertilization increased the average area per leaf, but not the number of leaves per beet.

Leaf Area Duration

Leaf area duration (LAD) is the sum of the weekly average LAI's. As seen in Table 1, mean values at final harvest ranged from 47.3 to 75.8 weeks over a period of 18 calendar weeks. Both N fertilization and variety effects were highly significant.

LAD and dry matter production have been shown to be highly correlated by Power, *et al.* (11) in growth chamber work on barley. They noted that a linear relationship of yield to LAD was little affected by soil temperature, P fertilization, or stage of development. Campbell and Viets (3) and Goodman (7) have noted that increases in LAD from treatments are offset by smaller NAR's. The decline of NAR related to increase in LAD was attributed to self-shading of leaves. In England, the limit of useful LAD has been reported to be about 36 weeks measured over a period of about 18 weeks (7).

A plot of total dry weight as a function of LAD for the growing season is shown in Figure 3. Excellent linear correlations can be obtained by fitting the data in two sections for each variety. There was a significant difference in regression between varieties but not among N-rates. Intersection of the linear fits for early season and late season occurred at a LAD

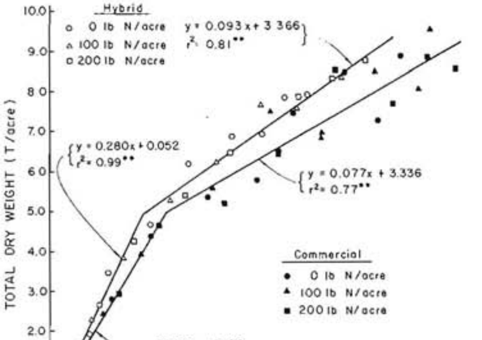

Figure 3.—Relation between green leaf area and total dry weight of sugarbeets from all harvests (June 8 to October 11).

of 21.3 for the commercial variety and 17.6 for the hybrid.

These observations indicate that a high rate of dry matter production associated with high early summer radiation and limited leaf area occurred during the early part of the growing season. A lower rate of dry matter production began around mid-July and continued until final harvest. The relationship of dry matter production and LAD appeared to be independent of N fertilization. Radiation and possibly temperature would be expected to affect the relationship (14). However, their effects appear minimal, possibly because of insufficient duration and intensity of the fluctuations of radiation and temperature. The change in the relationship of dry matter production to LAD after the July 15 harvest may be related to physiological change or "maturing" of the sugarbeet in response to increased storage demands. This possibility is enforced by data shown in Figures 4 and 5. Around July 15 the roots accounted for nearly one half of the total dry weight, and reduced root succulence had commenced. Other plant characteristics which correspond to the July 15 harvest are maximum LAI's and leaf weights,

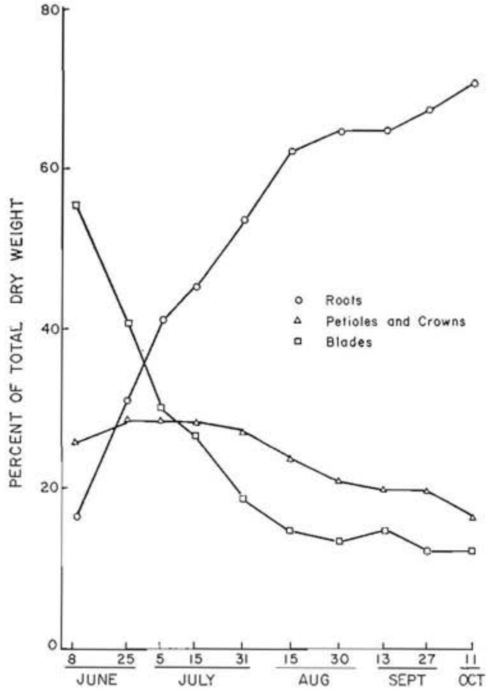

Figure 4.—Distribution of total dry weight among blades, petioles and crowns, and roots as a function of harvest date.

a significant drop in NAR, and a cessation of rapidly increasing leaf succulence.

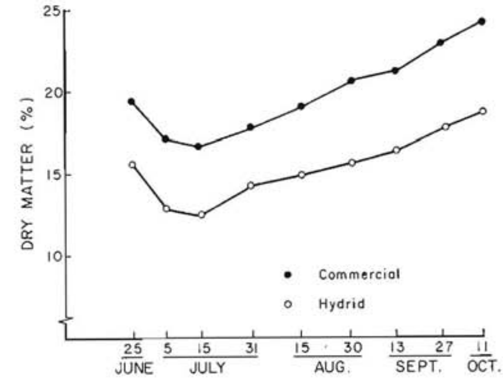

Figure 5.—Effect of variety and date of harvest on dry matter content in root pulp.

Net Assimilation Rate

Net assimilation rate (NAR) is the increase in total dry plant weight per unit leaf area per unit time expressed as $g/m^2/day$. Calculation of NAR was based on the assumption that dry weight accumulation was a linear function of leaf area index during the time between harvest dates (12).

Rate of N application did not affect NAR for a variety, so only the average values for the three nitrogen rates, as shown in Figure 6, will be discussed. Discussions of LAI and dry weight in this section are also limited to the average values for the three nitrogen rates.

Bodlaender (2) reports that temperature and light intensity influence development and yield. The results of this study show that maximum NAR, 8.9 for the commercial and 10.8 for the hybrid variety, was obtained at about the same time as maximum radiation. LAI was between 1.9 and 3.6 while NAR was maximum; however, NAR was only slightly lower for the July 15 harvest when LAI was 4.2 for the hybrid and 5.5 for the commercial variety. The hybrid beet had the highest NAR until the September 13 harvest, at which time NAR was negative. The NAR for the commercial variety was negative at the September 27 harvest. Then NAR for both varieties increased until the final harvest.

The high values of NAR through the July 5 harvest resulted from high early season radiation brightly illuminating a rapidly expanding, yet small, LAI. NAR was still high at the

July 15 harvest even though LAI had reached a maximum and total radiation was beginning to decrease; this was possibly due to a more erect orientation of the young succulent leaves allowing more light penetration into the canopy.

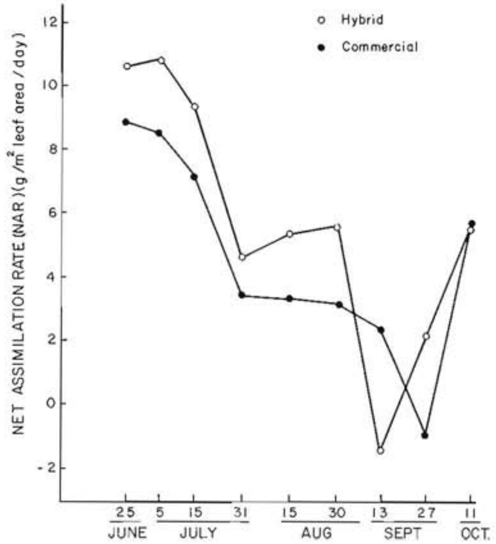

Figure 6.—Effect of variety and date of harvest on net assimilation rate.

The period from July 31 through August 30 and possibly to September 13 was a period in which NAR was significantly lower than the previous period. LAI ranged from 5.2 to 3.2, providing adequate leaf surface to utilize incoming light. Top weights remained relatively constant and dry weight accumulation in the roots increased at a constant rate. The decreases in root weights and total dry weights for the two varieties at the September 13 and 27 harvests (Figure 8) were not significant. Watson (17) and more recently Campbell and Viets (3) have noted considerable variation of NAR measured in the field. We noted such variation primarily in September and October. In contrast to prior harvests, the values of NAR for the last three harvests were so variable that a more detailed sampling of the plots would have been required for proper interpretation to be made.

NAR was higher and LAI was smaller for the hybrid than for the commercial variety through most of the season. Goodman (7) noted that large leaf areas during the season are offset by smaller net assimilation rates. This led him to conclude that optimal root and sugar yield depend on the largest possible proportion of the leaf area being brightly illuminated and the smallest possible proportion being shaded.

Other possible explanations of the higher values of NAR for the hybrid beet are: a) the hybrid beet may have been able to increase the rate of photosynthesis because the large roots provided a better sink for assimilation (15) or, b) leaf orientation differences allowed more effective light utilization by the canopy of the hybrid (4).

Dry Matter Accumulation

Nitrogen fertilization caused a significantly greater dry weight of the crown plus petiole section through most of the season. A trend of more dry weight accumulation could also be noted in the leaf and root sections of both populations. In general, the high nitrogen treatment gave the larger total dry weight yields. The higher nitrogen treatments resulted in the sugarbeet accumulating a larger proportion of dry material in the tops of the plants than in the roots. Variety interactions with N supply on dry matter production were not significant, therefore, only averages for N rates are discussed.

The seasonal accumulation of dry matter by the blades, crowns plus petioles, roots, and total dry weight of the two varieties are shown in Figures 7 and 8. The two varieties showed similar seasonal trends for each plant part, but the blades and crowns plus petioles of the commercial variety weighed more than those of the hybrid for all harvest dates. The reverse was generally true for the dry weight of the roots. There was little difference between the two varieties in total dry weight, thus, the root-top ratio was greater for the hybrid throughout the season.

Figure 7 shows the dry weight of the leaves reached a high on July 15 at the same time as LAI (Figure 2). Leaf area began to decline in mid-July (Figure 2) but leaf weight remained relatively constant (Figure 7), indicating a progressive increase in leaf weight to leaf area ratio or thickening of the leaves. Campbell and Viets (3) and Storer, Schmehl and Hecker (14) have also noted leaf thickening as the season progressed. In addition Campbell and Viet (3) obtained linear correlation coefficients of over 0.9 for the ratio of LAI to commercial top weight, leaf blade weight, or petiole weights with little effect caused by treatment. Leaf thickening and the crowns and petioles growing relatively heavier are assumed to be among the physiological changes associated with "maturing" of the sugarbeet as the season progresses.

The petiole plus crown section did not attain maximum dry weight until about August 30. The decrease in dry weight from

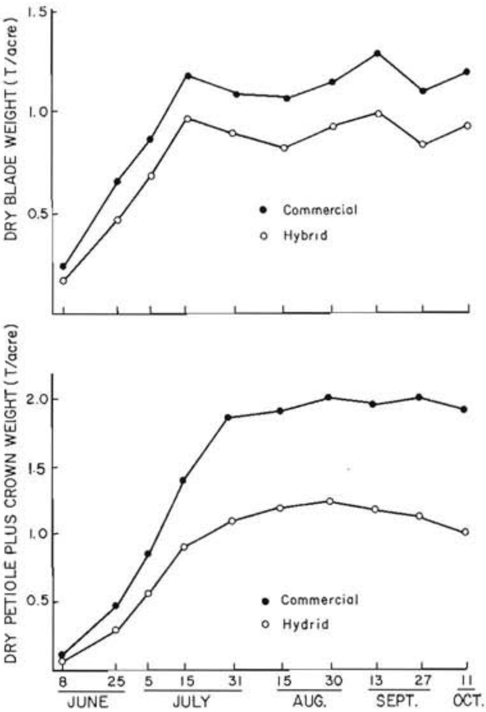

Figure 7.—Effect of variety and date of harvest on dry weight of blades and crowns plus petioles of sugarbeets.

August 30 to final harvest was not significant for the commercial variety, but was for the hybrid. No environment responses other than a seasonal increase in dry weight were observed.

The roots showed general increased dry weights throughout the season. Dry weights of the roots of both varieties were still increasing at the final harvest and may have increased more if harvest had been delayed.

Total dry weight accumulation patterns reflect top growth in early season and root growth from about midseason on. Therefore, interpretations for early season total dry weight accumulation will be similar to the interpretations for dry top weight accumulation and late season interpretations will be similar to those for dry root weight accumulation.

Sucrose Formation.

There was no significant difference in total sucrose accumulation in the root per unit ground area (sucrose production) between nitrogen fertility treatments for the season. The lack of response to applied nitrogen resulted from the relatively high fertility level of the experimental field. Treatments which gave higher green root yields had lower sugar contents. As a result, the final extractable sugar yields were nearly the same for all treatments.

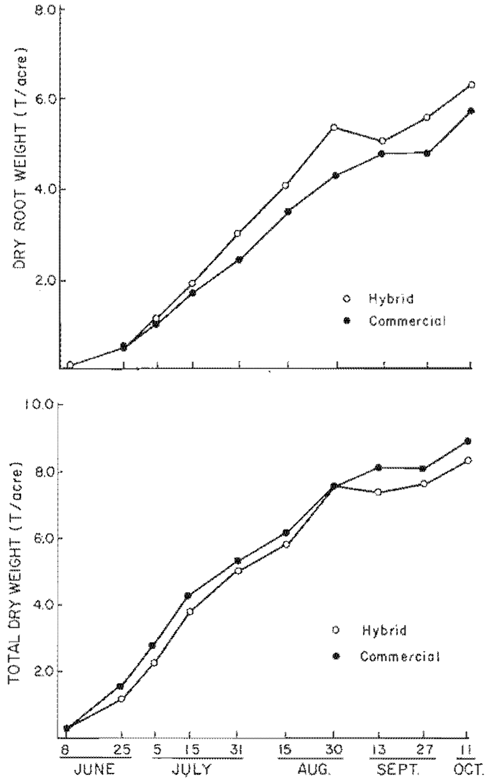

Figure 8.—Effect of variety and date of harvest on dry weight of roots and total dry weights of sugarbeets.

Sucrose production (Figure 9) was, in general, greater for the hybrid throughout the season, but sucrose content (percentage) of the root was always higher in the commercial variety, Figure 10. The lower sugar content of the hybrid resulted largely from dilution of sucrose and dry matter by the high moisture percent in the roots. The dry matter content of the roots changed throughout the season (Figure 5), but at every sampling the commercial beet root had the higher percent dry matter. When calculated at 24% dry matter in the roots, there was little difference between varieties in percentage sucrose and the seasonal changes in sucrose content were much smaller.

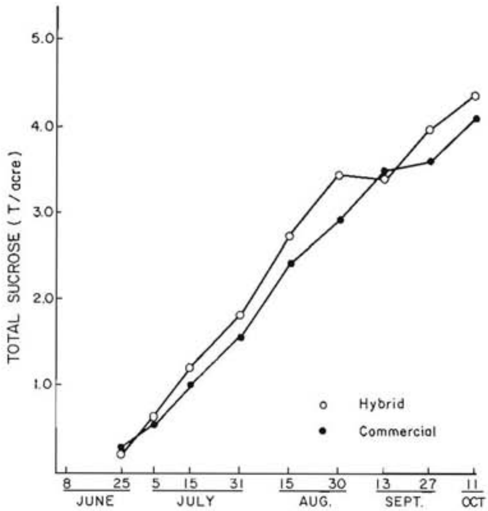

Figure 9.—Effect of variety and date of harvest on total sucrose production.

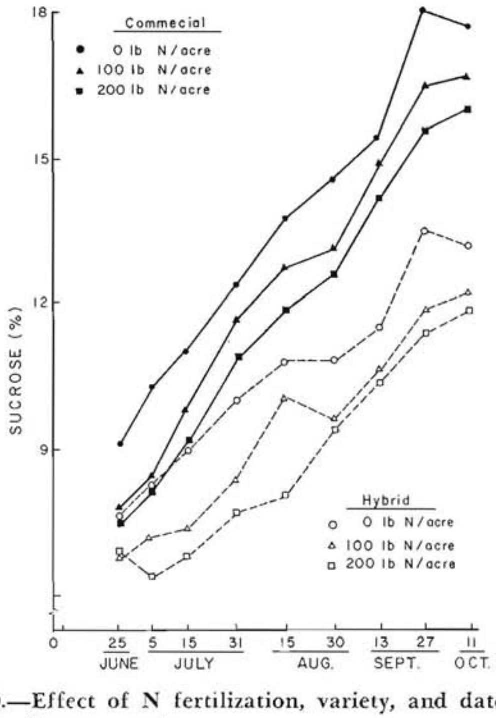

Figure 10.—Effect of N fertilization, variety, and date of harvest on sucrose content of green roots.

Photosynthetic Efficiency

DeWit (4) has outlined a method for calculating theoretical photosynthetic rates in leaf canopies. We obtained standard values of daily total photosynthesis under very clear and overcast skies for Fort Collins (40°35'N) by interpolation from Table 6 in deWit's report. These values were in turn used to calculate photosynthetic efficiencies of both varieties for the observed radiation conditions. From June 9 to October 11, the commercial variety increased in total dry weight approximately 8.5 tons per acre or 39.4% of deWit's theoretical photosynthesis of 21.5 tons per acre. The hybrid increased 8.2 tons per acre of 37.9% of deWit's theoretical photosynthesis. Campbell and Viets (3) obtained a photosynthetic efficiency of 30.2% of the 21.7 tons per acre theoretically possible at Huntley, Montana from June 1 to October 5 using the same methods of calculation. DeWit's methods do not take into account continuous losses of dry matter by respiration which may be particularly high from midseason on as plant mass becomes high. The process of root exudation of organic compounds would result in dry weight losses also unaccounted for in the deWit model. Loss of unmeasured dry weight because of the dying and shedding of leaves and petioles from mid-July on would give low total dry weight estimates, as would the loss of the smaller roots during beet pulling. Such losses were not estimated in this study, but they would be expected to be significant for sugarbeet crops when considered over the entire growing season.

Discussion

The effects of N fertilization and variety on yield, quality, and root-top ratio for the last harvest are summarized in Table 1. N fertilization significantly decreased percent sucrose in the green root, root-top ratio, and percent purity; leaf area duration was increased. Although N fertilization did not increase extractable sugar yield, this does not mean that N fertilization is not needed in less fertile fields.

The hybrid variety outyielded the commercial variety by an average of 11 tons of fresh roots per acre. The hybrid provided a larger root system and stored as many tons of sucrose per acre as the commercial variety, but with a smaller LAI and top weight. The commercial variety accumulated a higher percentage of dry matter and sucrose in its roots; the differences in percentage sucrose were accounted for by extra moisture in the hybrid root. When the sucrose content of the roots of the two varieties were calculated on a dry weight basis, there was no significant difference between the two varieties in extractable sugar yield.

Figure 9 shows the beets were accumulating sucrose at a significant rate at the time of final harvest and possibly should have been grown longer. Methods or varieties developed to extend the season earlier into the spring to utilize high early-season radiation and the higher NAR's which occur in early season should be considered. Root-top ratios and percentage dry matter in the root pulp appear to offer very useful criteria for determination of sugarbeet performance and should be used in conjunction with measurement of sucrose production, LAD, and dry weight production.

Recently, Campbell and Viets (3) stated that it did not appear that LAI need exceed 3 for the season and 2 at harvest in the Rocky Mountain region. Storer, *et al.* (14) stated that optimum LAI at Fort Collins, Colorado was between 3 and 4. This study appears to substantiate their work. The maximum values of NAR for the season were obtained while LAI was between 2.1 and 3.5 . However, NAR was greater than 6 $g/m^2/day$ when LAI was between 4.2 and 5.5 on the July 15 harvest. This indicates that early season leaf canopies have potentially higher optimum LAI's. Young leaf canopies and high radiation were involved in all cases where NAR exceeded 6 $g/m^2/day$. Where LAI and NAR were both high, leaf erectness probably allowed better light penetration into the leaf canopy and is a genetic trait probably useful in a breeding program. Leaf number was significantly less for the hybrid variety, with average leaf size approximately the same as the commercial variety. N fertilization significantly increased leaf size but not the number of leaves. The leaves of the hybrid produced nearly as much total dry matter and significantly more dry root weight. Therefore, fewer and/or smaller erect leaves may allow better light utilization and provide a superior leaf canopy by reducing self-shading.

The use of deWit's model for calculating photosynthetic efficiencies, provides a very useful tool for comparison of yield and radiation differences occurring between localities and/or years. The photosynthetic efficiency of beets grown at Fort Collins, was higher than that of those grown at Huntley, Montana for growing seasons having nearly equal potential for theoretical total photosynthesis using deWit's model.

In conclusion, the data from this study have pointed to several possible genetic traits that might be used to obtain superior varieties of sugarbeets. Methods of studying those traits in the field have also been discussed. Varieties grown in the future should be adapted to high fertility soils. Future varieties should also produce a large root-top ratio and high dry matter, sucrose, and purity percentages in the roots. Methods for extending the growing season earlier into the spring and later into the fall appear to have a potential for increasing yields.

Summary

Effects of variety and N fertilization on the leaf area index (LAI), leaf area duration (LAD), net assimilation rate (NAR), dry weight production, and sucrose production were measured on irrigated beets at Fort Collins, Colorado. Solar radiation and air and soil temperatures were measured through the season.

Maximum values of NAR occurred at the same harvest as maximum values of mean solar radiation and soil temperature; maximal values of LAI and dry blade weight per unit ground area were reached about two weeks later.

Net photosynthesis was calculated to be 38 to 39% of the theoretical total photosynthesis for the climatic conditions.

N fertilization increased LAI, LAD, and the dry weight of crowns plus petioles, but had little effect on NAR. Nitrogen decreased the sucrose percentage significantly and tended to reduced the ratio of roots to tops and purity of the thin juice.

The two varieties studied showed similar growth patterns through the season. The commercial variety had higher values of LAI, LAD, dry blade weight, dry crown plus petiole weight, percent sucrose, and percent dry matter in the roots. The hybrid variety had higher fresh root yield, dry root yield, and root/top ratio; there were no significant differences in total dry weight and sucrose production between the two varieties.

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