Space Relationships as Affecting Yield and Quality of Sugar Beets

G. H. Coons[1]

THE EFFECTS OF SPACE relationships on yield and quality of sugar beets have received consideration from the very beginning of sugar beet culture. Achard in his treatise on the sugar beet gave detailed directions that the beets were to be grown in rows 12 inches apart and at 12-inch spacings in the row. The placement was to be such that a staggered arrangement resulted. In view of Achard's careful approach to similar problems with other crop plants, it seems a safe assumption that this recommendation was based upon experimental evidence.

The industry started out with a dense population of plants which may very well have suited plant culture performed exclusively with hand labor. As machines began more and more to replace hand labor, and as horse-drawn and motor-driven machines were introduced, changes from the close patterns were necessary.

In the early period, replicated experimental trials to determine space relationships were few if any. Judgment was based on the treatment giving the largest yield. Obviously, replication in time was necessary to establish a conclusion and to avoid the effects of chance occurrence. This early work will be summarized. It furnished the basis for the more modern agronomic experience. There may be some surprises. Sugar beet agriculture arrived at the satisfactory space allotment per plant by trial and error methods. In this regard, the sugar beet does not differ from corn, potatoes, soy beans or other important crop plant, for with these crop plants also, the accepted space allotments per plant are the result of farm experience rather than exhaustive agronomic experiment.

European technology largely dominated sugar beet agriculture from 1890 to World War I. American practice was often influenced by its teachings. One of the surprises will be the nature of the experimental work on which recommendations were based and may explain why European advice was not wholly followed in our agriculture. Another surprise may be the significance of the American contributions to this field of work. It will be seen that our research pioneered in application of the newer agronomic methods to the problems of space relationships.

Because of the complexity of the problem and the need for taking cognizance of the changing nature of sugar beet agriculture, final recommendations as to optimum space allotments for the sugar beet cannot be made. These must be determined by studies conducted under particular soil and climatic conditions and must take into account the type of sugar

[1]Principal Pathologist, Division of Sugar Plant Investigations, Bureau of Plant Industry, Soils, and Agricultural Engineering, Agricultural Research Administration, United States Department of Agriculture.

beet culture to be employed. The plant reactions must be recognized as the key factors in the situation. Agronomic techniques available for such a research attack will be reviewed and a few beacons will be set up to guide a renewed and vigorous research program.

Early Work on Spacing of Sugar Beets

Probably in his day, Hollrung (24)[2] had the most authoritative voice among sugar beet technologists. In 1894, on basis of experiments conducted by Marek, Ladureau and Petermann, he concluded that the greater the available space, the larger the beet, and that foliage size dropped off with decrease of growing space. He stated that with narrow spacing, sugar beets yield more sugar than with wide placement, and that beets standing close together contain not only a greater weight of sugar, but lesser amounts of non-sugars, two items of greatest importance in processing.

Although Hollrung's conclusions may be readily accepted since these plant reactions are not greatly at variance from what would be expected, exception could be taken to the meagerness of the experimental data from which they were drawn. In the experiments cited, row widths ranged by 2-inch steps from about 14 inches to 20 inches. Intervals in the row were approximately 8 inches or 10 inches. Within a given experiment the results were not concordant; judgment was commonly based upon the largest value. Replication was scanty or non-existent. Whereas at least 10 percent or more as a difference would be required even to approach significance, the values on which decisions were based were about 100 or 200 pounds of sugar per acre. Obviously such differences do not fall outside of chance occurrences.

As extensive tests as any, and, in their day, very influential, were those of Vanha and his associates (39). Here, we find an experiment on sugar beet space allotments, in which some spacings occurred in 3-fold replication, some in 2-fold, and one as a single plot. As luck would have it, the last named turned out to be the highest yielder. The unbalanced experimental design makes determination of statistical significance impossible, but here again one could assume that at least a 10 percent differential would be required for significance. The tests compare 14-, 16-, and 18-inch row widths, as combined with 8-, 10-, and 12-inch row intervals. Obviously only very precise, many-times replicated experiments could appraise such small differences in space allotments. It is not surprising, therefore, to find that these comparisons in which the space per plant ranged about 112 to 216 square inches gave, in 1902, the highest sugar production per surface unit from the widest spacing, whereas the next highest and differing only by 107 pounds of sugar per acre, was from the closest spacing! Similar experiments (not cited) were conducted by these investigators in 1903 and again in 1905. They were inconclusive, and if anything, contradictory of the 1902 tests. The difference between the highest and lowest value was only 160 pounds sugar per acre, clearly a non-significant difference. In 1905,

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

other than a suspiciously high value for one trial of the 18- x 10-inch space, all other values fall very close to 4,800 pounds per acre. Inasmuch as the 1903 and 1905 values were so contradictory of the 1902 results, the authors made no attempt to draw conclusions, other than to discuss effects of space on top size.

In 1921, Gerlach (20), also a leader of the industry, deplored lack of adequate experimental evidence on space relationships. Prevailingly sugar beets were grown on a 16- x 10-inch pattern. In his opinion, increase of row width to 19 inches would not be hazardous. He pointed out that 20- x 20-inch spacing as advocated meant reduction of the customary population of 100,000 plants per hectare (about 40,000 per acre) to 40,000 per hectare (about 16,000 per acre) so that average size of root would need to increase 2½ times if yields were not to go down. At the same time sucrose percentage would need to be maintained if sugar production were not to drop. Gerlach pointed out that experimental evidence proved that this does not occur and that some halfway step would be advisable to give 25,000 or, at least, 21,000 plants per acre, so that weight of the average root would only need to increase 1.2- to 1.6-fold. Sucrose percentage would not be seriously affected. Krüger (20, 26) in his discussion of Gerlach's proposals stated that low sucrose percentage of widely spaced beets was merely a matter of ripening. For sugar beets to ripen, nitrogen must be brought to a minimum as evidenced by yellow leaves. This is not reached with widely spaced beets. In a field with little nitrogen reserve, the added nitrogen can quickly and profitably be utilized, then the beets ripened. Narrow placement is necessary since wide spacing brings about unripe beets. In his opinion, row width may be increased to approximately 19 inches, but "we dare not depart from closest possible spacing in the row if we wish to have good beets."

In 1924 Zwoboda (40) attacked separately the problems involved in determining (a) most favorable row width and (b) the best spacing within the row. In a 3-times replicated test with a fixed interval in the row of 12.6 inches, he obtained the highest yield of sugar per acre from a 14.7-inch row width, the 16-inch giving 7 percent less, the 18-inch width 10 percent less, and the 20- to 22-inch widths about 20 percent less than the 14-inch row width. Having settled on the best row width he varied the interval in the row by a 2 inch differential 8-, 10-, and 12-inch spacing—with the result that highest yield of sugar came from the 12-inch row interval, the 10-inch interval being 3 percent less and the 8-inch row interval, 14 percent less. His conclusion, therefore, was that the best pattern is a quadrat about 14.7 x 12 6 inches. This finding is reminiscent of Achard's early recommendation.

In 1927, C. Bonne (4) summarized spacing experiments as conducted at Schlanstedt, Germany, in the period 1923-1928. The various spacings had been tested in 3-fold replications in 1923 and 1924, and in 4-fold replications in 1925-1928. Long, rectangular plots, 3 rows each, with the center row harvested, were used. Only normal beets growing in complete stands were harvested to determine yields. The results are given only as the combined averages for the 6 years of test. The closest spacing 14.8 x 13.8 inches gave roots with an average weight of 1.166 pounds, whereas the widest spacing 19.7 x 15.8 inches gave roots averaging 1.576 pounds. For the intermediate spacings the root weights follow about a straight line relationship.

Sucrose percentages deviated numerically only by 0.5 from smallest (203 square inches) to largest space allotment (310 square inches). Sugar production was highest in the plots with the smallest space allotment per beet. It dropped about 14 percent below this figure in the largest space allotment, which gave approximately 35 percent more plant room than the smallest. Between the extremes, the production showed a uniform decline.

The work of other European investigations may be briefly cited. Soucek (37) held the space between the rows constant at 42 centimeters (16.8 inches) and had intervals in the row ranging from 6.36 inches to 15.64 inches. The greatest yield came from the beets having the smallest space allotment per plant. The yield of beets with the largest space allotment fell about 16 percent below that of the closely spaced beets. Intermediate spacings were uniformly or regularly disposed between these extremes. It is to be noted that the space allotments in these experiments are all smaller than those of chief interest in American tests.

DeHaan and Klijnhout (13) conducted a population study on three fields of different fertility levels. They determined the space allotment and weight of each plant of a selected strip. The weight data were combined according to space allotments by steps of 200 square centimeters. An average weight was thus determined for each space allotment in each field. From these data, numbers per hectare were computed. The authors had theoretical populations ranging from 40,150 to 110,865 plants. They concluded that to increase the yield of beets, it is necessary to increase the number per hectare above a minimum of about 63,000. Taking 60,000 as a base, the authors computed that increasing the number of beets per hectare by 25 percent, increased the yield of roots almost 8 percent, whereas an increase of 50 percent in the number of plants increased the root weight 13 percent.

Roemer (34, page 168-169) states that in the period 1890-1900, there was a move toward narrow spacing some even going so far as to propose 20 centimeters x 20 centimeters (8 inches x 8 inches) or 33 centimeters x 15 centimeters (about 13 inches x 6 inches). In the period 1906-1916, a common pattern was 37 centimeters x 18 centimeters (about 15 inches x 7 inches). He states further as justifying the change to wider spacing "Newer investigations have shown that the present, highly bred beets will permit recommendations of a spacing formerly out of the question. The argument for this is, above all, that wider row distance permits frequent deep cultivation, considered to be favorable. Under such assumption, a row width of

50 centimeters (20 inches) is permitted and spacing in the row of 20-25 centimeters (8-10 inches), but wider spacing than 20 inches is not safe."

European technology at first recommended close spacings for sugar beets but rather generally moved to wider patterns after World War I. The European literature indicates that managers of estates and technologists arrived at a width of approximately 18 inches between rows and a row interval from 10 to 12 inches as the preferred pattern. Almost from the beginning of the culture of sugar beets in America, close patterns were not recommended unless some factor such as curly top indicated an important reason for crowding the plants (Nuckols, 31). The greater use of machines for planting, cultivation and harvesting as compared with continental Europe was undoubtedly the decisive factor. In a country accustomed to wide rows for corn, 20 inches for sugar beet rows seemed very close indeed. A gain of 10 to 15 percent from close spacing was more than offset by other forms of crop cost, or even by crop loss, as occasioned by reduction of row width. American practice very early took as a standard the 20- x 12-inch pattern. European practice, especially when the use of drills and cultivators increased, accepted a similar pattern.

Application of Modern Agronomic Techniques

The preceding review of the observational, or trial and error, period of sugar beet agronomy has shown that in spite of the complexity of problems and the shortcomings of the older methodology a solution was reached for the space relation problem then existent. Some recent experimental studies in which statistical controls were employed to safeguard against conclusions being based upon chance occurrence may now be reviewed. This work may be expected to be more efficient than the older work, and it should confirm or deny older conclusions. It should be able to meet new problems with sureness and dispatch. Not all pertinent work can be noticed. Reference will be limited to those contributions that have special interest because of the methodology employed or because they emphasize a new concept or approach to the subject.

One of the first of these studies was made in 1927 in England by W. Engledow and his associates (17). It was essentially a census study of 6 representative beet fields. Numerous sampling stations were established in the fields. By counts of initial stand and by 9 stand counts throughout the season, together with harvest data, the course of the plant populations was followed. Some important conclusions were derived. Loss of plants after seedling emergence was negligible. In each of the 6 fields there was a steady decline of root size with increase in plant population. All the tests that the authors applied supported the conclusion that the number of plants and the yield per unit of length were directly related, or that they were in fact, of the nature of cause and effect. Broadly speaking, soil fertility and culture are the controllable factors that govern yield. The points of practice about which doubt remains are those which affect plant population. When the definite distances between the rows or between plants have been decided, yield per acre depends very directly upon the extent to which the theoretical "full plant" is secured. Roots that have more than average space grow to more than average size, but every root or gap counts in determining yield per acre. "The beet is a costly crop to grow if only half a full plant is secured."

These authors give an excellent model for a detailed study of plant population by census methods, and their conclusions are noteworthy in placing in relief the importance of soil fertility and cultural treatments as the real determiners of yields, once a reasonable plant population is set up. Their comments on necessity of a "full plant" foreshadowed results obtained independently in the United States.

Brewbaker and Deming (6) made a highly important contribution to the problem of space relationships of the sugar beet. They applied to the data obtained from experiments at Fort Collins, Colorado, in 1930 and 1931, and at Rocky Ford, Colorado, in 1931, the newer statistical techniques. Immer (25) had previously made a start in this direction with his application of the analysis of variance to certain problems of sugar beet plot technique. The authors confirmed that for a unit area the correlation of weight of beets with stand is positive and significant. Within the limits of the tests the relationship is essentially linear. The authors illustrate their finding with a forceful example, pointing out that, as an average, each drop of 10 percent in stand means a drop in yield of 1.25 tons per acre. In the yield and stand study based on competitive beets only, row widths from 18- to 24 inches were used with row spacings from 6- to 16 inches. Heavier tonnages were produced by the 18- and 20-inch row widths than by the 22- or 24-inch widths. As to space interval in the row, the authors call attention to the fact that with 8-inch spacings there are 50 percent more beets per acre than with 12-inch spacings, and 100 percent more than for the 16-inch spacing. The increase of average yield for the 8-inch interval in comparison with that from the 12-inch spacing in the row was not significant. Significant differences in yield were found between 8-inch and 16-inch intervals. These were in favor of the close spacing. A highlight of the paper was the assessment of relative importance between adjustments of row widths or row intervals and uniformity of stand. They found that uniformity of stand is relatively a far more important factor in determining final yield than is the particular row width or spacing used. The authors were aware of the far-reaching effects of their conclusion since they state "The placement of major emphasis on uniformity of stand involves almost every field practice particularly the operations preceding and immediately following blocking and thinning, and, to a somewhat lesser extent cultivation, irrigation and protection against insect pests." An important contribution from this study, and basic in explaining the conclusions drawn, was the evidence that the 8 beets surrounding a blank space in a 20- x 12-inch spacing were so increased in weight that there was a compensation for 96.2 percent of the loss due to a single missing beet. Other investigators have not obtained so great a compensation (Garner and Sanders (19), Finney (18)).

Another and highly significant contribution in light of later developments was the finding that even if 25 percent of all hills were doubles the root yields were not significantly lowered. This confirmed certain early work that at the time was not fully accepted by growers. More recent work by Deming (14), Nuckols (32), and others (16, 27) have amply verified the finding that in commercial fields a relatively high percentage of doubles and some triples does not significantly reduce yield. In a further follow up of this line of investigation, Deming (15) has shown that so long as hills do not have more than 2 or at most 3 plants, the number of hills per acre and not the plant population is the significant thing affecting yields. A directive is thereby given to agricultural engineers permitting them to concentrate on a pattern of hills, not of single plants.

Nuckols (32) questioned the blanket use of the "competitive" beet technique by showing the futility of seeking to salvage results from an experiment with poor stands by the device of saving a limited number of so-called "normally competitive" samples. Since a plot with 80 percent stand could by certain placement of gaps yield only 10 percent of its beets as growing under normally competitive conditions, it is obvious, he points out, that the poorer stands automatically mean inadequate sampling, and the yields calculated to a 100 percent basis are unreliable. In plots of excellent stands, results from actual plot yields and computed yields from normally competitive beets would tend to merge whereas with gappy stands it is obvious that the beet selected would reflect the competition conditions of its growth. This report had highly salutary effect in curbing misuse of the normally competitive beet technique. It is now retained as a means of judging quality of sugar beet experimental plots since a plot that would not yield chiefly normally competitive beets is likely to show bias. For the selection of sugar samples it has value. Agronomists are becoming increasingly critical of conclusions based upon plots with poor stands.

The British investigators, Garner and Sanders (19), concerned themselves with many of the problems studied by Brewbaker and Deming and by Nuckols. They reviewed earlier work in England citing that of Davies who showed that, within limits, yield was not related to the number of roots per acre but was affected by the distribution. Wide spacing of rows could not be compensated by narrower spacings within the row. They quote Pedersen's work on the relationship of gaps to yield. In these Danish experiments with both sugar beets and mangel-wurzels, the compensation of growth of roots bordering a gap amounted to 76 percent for a single gap, but the percentage of compensation decreased as the size of gap increased. Garner and Sanders' own experiments with sugar beets in 1934 consisted of a 5-times replicated test with row spacings of 12, 18, and 24 inches with intervals in the row of 6, 9, and 12 inches for each row spacing.

In 1936 the same variables were used except the 6-inch row interval was omitted. The authors found that although yields of roots and sugar increased as distance between rows decreased, there is little indication that rows narrower than 18 inches are worthwhile. Spacings in the row from 6 to 12 inches produced no differences in yields of roots or sugar, consequently, for convenience of working a spacing distance in the row of 12 inches is most desirable. The data were further applied to the solution of the problem of effects of gaps on root and top weight. In a dry year the roots immediately surrounding a gap compensate to the extent of 80-89 percent for the missing plant, the allocation to individual neighbors being about inversely proportional to the square of their distance from the site of the gap. In a wet year the compensation was less complete amounting to from 41 to 84 percent. In both years, compensation was less complete for tops than for roots.

From a study of individual root records, the authors, basing their study on plants with no gaps in the immediately surrounding ring, showed that 18 x 9 inches was the optimum spacing. From their experiments they state that 400 plants per plot is necessary to reduce the plot error due to genetic variability to 2 percent of the mean.

Hey and Kemsley (23) in related studies on the same data took into account the effects on the sugar beet plants of very small and very large beets in the surrounding rings of plants Extreme sizes may produce effects comparable with that of the gap itself. Their technique was to select an area covering about 10 to 30 beet sites. The unit area studied was 6 x 3 feet and regression of yield on percentage stand was determined. They compared yields as estimated from 100 percent stands of the "perfect" beet and by the method of regression lines. Since there are gaps in the second ring, a beet in the first ring may tend to become too large and thus cause the central beet to be subnormal. The second method tends to over-estimate, but has the advantage of using all the data.

Other important publications by American and European investigators can be given only brief mention. Brewbaker (7) gave additional data from experiments at Fort Collins and Eaton, Colorado, to reenforce his earlier recommendations for increased population density as a means of increasing yields. Bilian (3) for Czechoslovakia, conducted experiments with 4 varieties of sugar beet and 5 varieties of mangel-wurzels. Yields from plants with 1,000 square centimeters of space were compared with those from 2,000 square centimeters. The smaller space allotment gave the greatest total weight of roots, crowns, leaves and dry substance. Buschlen (8) and Bradford (5) each found that yields were increased by planting in rows closer than 28 inches. Astrand (2) from a statistical study of factory records in Sweden showed that yield of sugar increased with density of plant populations. Dahlberg (10) had made a comparable report of the Swedish experience for 1932, in which fields averaging 16,000 beets per acre gave 10.79 tons as compared with 15.58 tons for fields of 24,000 beets per acre. He reported that increase in yield due to greater number of plants much more than offsets any decrease due to reduction in size of average beet.

Similar statistical studies of factory data have been made by sugar companies in the United States. The recent study as made by Lill (28) may be cited as indicative of what may be shown from such records. Material for the population study of sugar beets was supplied by Manager John Kelly of the Lake Shore Sugar Company. The data consisted of the tare records for 1938-1942 inclusive with numbers of beets recorded for each sample. Having the weight of the tare sample, the tare, the number of beets, the total weight of clean beets in the sample was obtained. The total weight of clean beets for the samples of a given contract divided by the total number of beets in the samples resulted in an estimated average weight for the individual beet delivered under the contract. The yield per acre in pounds for the contract as obtained from factory records divided by the estimated weight of the individual beet gave the estimated plant population per acre. Factory records also gave the row width for the individual fields. A total of 5,605 fields were included as a total of the 5 years, the numbers ranging from a high of 1,365 fields in 1938 to a low of 913 in 1941. Plant populations ranged from a low of 6,245 to a high of 24,244 per acre. The distribution showed a fairly uniform curve centering at about 14,000 plants per acre. Lill's conclusions were that (a) the relation between plant populations and acre yields, although varying slightly with season, remained essentially the same. The highest yields came from the highest plant populations. (b) Width of row (rows ranged from 22- to 28 inches) had a slight but definite influence upon the relationships, the higher plant populations having been maintained and higher acre yields obtained, on the average, in the fields with narrow rows. (c) The relationship between estimated plant populations and acre yields is essentially linear. The study revealed the arresting fact that plant populations on many commercial fields are too low to give more than half of a possible yield.

Data as used by Lill could become available from all factory districts if the number of beets were systematically recorded for each tare sample. Such data along with factory records would constitute a mine of information for the technologist.

Attention is called to the very useful summarizations made by Armer (1), based on data from The Netherlands (13), Woodland, California, and Granger, Utah. The data were graphed to answer the questions: How does sugar production vary with populations per acre and, with plant populations held constant, how does sugar per acre vary with distribution of plants? When the plant population falls below 25,000 per acre, sugar production was found to drop sharply. Sugar production also was found to drop when the distribution ratio (ratio of row width to row interval) increases beyond 2.0. It is pointed out that these findings completely justify the customary 20-inch rows with 10- to 12-inch spacing in the row, corresponding, respectively, to about 31,000 and 26,000 plants per acre. These patterns have distribution ratios of 2.0 and 1.67, respectively. Row widths much wider than 20 inches, for example, 26- to 36 inches, will reduce sugar production markedly even if, to maintain population levels, the beets are spaced closely in the row.

Interaction of space allotment with variety and the interaction of space allotment × variety × fertility level have only partially been explored. The information is such as to indicate the desirability of much further investigation.

Lindner (29) in comparing spacing effects upon yield and sucrose varieties found in 1933 that the sucrose variety gave yields little affected by the space allotment, whereas the yield type gave largest production at the narrowest spacing. In 1934, both types gave highest yields at the narrowest spacing. In a series of contributions, Decoux, Vanderwaeren and Simon (cf. summary by Decoux 11:213-229) showed the importance of relatively dense populations of sugar beets per hectare if yields are to be maintained. They concluded (12) that the size of foliar bouquet as characteristic of certain varieties is a factor in determination of the appropriate spacing. However, Ginneken (21) found that a variety with large foliar bouquet at 55,000 plants per hectare (22,260 per acre) gave 10 percent less yield than was obtained from a stand of 70,000 per hectare (28,340 per acre). Lüdecke (30) stated that as width of row is increased, use of nitrogen increases the weight of individual roots, but only proportionately, over-compensation not being obtained. Skuderna and Doxtator (35, 36) conducted studies of spacing effects with varieties of sugar beets at different levels of fertility. They obtained significant differential responses of varieties to both fertilizer and spacing and the first and second order interactions were significant. Thus the techniques of the complex experiment were applied to the problem.

Tolman (38) also employed the techniques of multiple factor experiments to determine interactions between variety, space allotment and fertility level. The varietal responses to the other factors differed significantly and certain interactions appeared significant. It is not unlikely that a given variety may be found to require a definite planting pattern for its best performance. These experiments, taken in connection with others that have been cited (12, 16, 35, 36), indicate that the multiple factor experiment may prove an effective research method, greatly facilitating the experimental attack, and at the same time broadening applicability of findings.

Discussion

The problems of space relationships of sugar beet consist of a series of interlocking phases involving plant populations, field patterns, compensation for missing hills and tolerance of multiple occupancy of hills. A sugar beet plant is the summation of the environmental factors that impinge upon it, as within the genetic limits, it reacts in response to those factors. Solar radiation, temperature, soil moisture, soil fertility and other factors of the environment in their effects on plant characteristics such as capacity for growth, foliar bouquet, root size and type, and other genetic characters, produce the end result. Usually a single factor cannot be detached from the complex so that its particular influence may be determined but conclusions must be drawn from associated effects.

The slow development of our knowledge with respect to the requirements of the sugar beet and the present status of the rules and recommendations for space relationships find parallels among other crop plants. Space allotments in current use with them are now being studied with the result that old accepted planting patterns are being revised better to suit the demands of certain varieties. Soil and season, however, are found to be significant in their effects slowing up changes until the case is completely proved. A new pattern needs to show very significant effects to justify the changes in machine equipment and methods that are necessarily involved.

From the array of European work and what has been done in United States and England, it seems clear that highest yields of sugar beet come from the close spacings and such spacings also give roots of highest quality. We may derive from the curves a theoretical optimum of plant populations. But this value may and does stand in decided contrast with what, because of practical considerations, is adopted.

We have seen that American practice long since refused to strain for the ultimate crop goal but was content with less than a theoretically possible yield in order to use drills, cultivators and other horse-drawn tools. It is an open question whether or not the hypothetical loss in yield of 10- to 15 percent calculated as associated with our standard procedures was an actuality, or whether the very close spacings would not, of themselves, have engendered new forms of loss not present in controlled experiments but likely to enter in field practice. DeHaan and Klijnhout pointed out that increase in plant population from 70,000 to 90,000 plants per hectare (28,340 to 36,430 per acre) meant in their experiments a gain of 6 or 7 percent, but entailed handling very many more plants smaller in size and having increased tare.

We do need to ask what fundamentally is responsible for the greater acre yields of roots and sugar and for the improved quality that comes with close spacing both of rows and of plants in the row. Obviously, the greatest yields merely mean most efficient use of field space and fertility. It will be recalled that European and American experience was positive that if row width were increased, reduction in row interval would not compensate for it. Armer's study on distribution ratios indicated the same. Clearly there is a problem of plant response here, since apparently the plant refuses to abide by arithmetic.

In most sugar beet districts of the Temperate Zone, the growing season is limited in length. Commonly the early part of the growing period is cool and not conducive to rapid root growth, so that the soil space reached early by plant roots is limited. If the plants are wide apart, roots will only slowly permeate the space allotted. Hence closely spaced plants more completely occupy the soil space in the early half of the season than do widely spaced plants. Although soil temperatures in late April, May and early June are cool, they, along with soil moisture conditions, nevertheless are more conducive to root growth than the soil conditions of September, October and November—so much so that in many districts a lag in planting date may require nearly twice as much extension of the harvest date for equal root growth to be attained (Godard 22). A limiting factor in closeness of spacing is the length of time before interference of roots and tops of neighboring plants nullifies the early advantages. Furthermore commercial practice prescribes that roots must reach a minimum size to be marketable. If the time factor and if the slowing up of growth in the fall were not involved—were it not a matter of efficiency—then a widely spaced individual root would eventually attain a weight commensurate with the sum of weights of the closely spaced plants occupying the given surface area. The hurdle that Gerlach (20) presented, namely that to maintain yields, the average individual from a population of 40,000 plants per hectare must be 2½ times heavier than one from a population of 100,000, probably could be surmounted if, in so many places, frost did not dictate harvest.

The suggestions by Krüger (21, 26) explaining the effect of spacing on quality seem accurate. That sucrose percentages of the beet reflect the degree of ripening and that ripening occurs earlier with close spacing only hints at the basic reactions involved. The whole concept of growth of the sugar beet needs to be extended beyond this postulate. Storage of sucrose in the sugar beet must be recognized as a plant response opposed to the growth responses. A fundamental consideration in this connection is the fact that photosynthesis takes place over a far wider range of conditions, including temperature, than does growth (Coons, 9). As a result of this, sucrose percentages of the sugar beet may attain extremely high levels in California if growth is checked by the combination of high temperature and low soil moisture. In other sections of the country, cool weather conditions in the fall, accompanied usually by a low moisture content of the soil, serve to check growth allowing photosynthesis to bring about the increase of sucrose percentage in the roots from about a 12 percent level in September to 16 to 18 percent in November. In districts where rainy, mild fall weather favors growth, as at Beltsville, Maryland, a sucrose percentage of about 12 attained in September continues without much increase into October and November.

Yield and sucrose types of sugar beet differ in their responses to the major factors of the environment—the former being less sensitive to climatic and soil changes than the sugar types. The yield types, therefore, continue under early fall conditions to increase in size and remain succulent, i.e. moderate in sugar content, whereas the more sensitive sugar types stop utilizing the elaborated carbohydrates for growth and accumulate sucrose in the roots.

It is known that nitrogen fertilizers promote growth. Krüger would explain favorable effects of close spacings as due to the ripening brought about by nitrogen depletion. He is emphasizing that a full quota of plants to the soil space utilizes more or less completely the soil nitrogen, bringing about an eventual check of growth. The low sucrose percentages associated with heavy applications of nitrogen frequently indicate improper timing and disregard of proper fertilizing practice. The proper function of nitrogen fertilizer is to produce a large plant body fully expanded over the soil space. It should be clearly understood that nitrogen must be applied early to sugar beets and certainly long before midseason. After midseason, nitrogen content of the soil should decrease so that growth may not continue at the expense of sucrose storage.

We must recognize that other factors of the environment, temperature, solar radiation, water, and soil fertility if favorable for growth may bring about utilization of carbohydrates for production of plant tissue instead of promoting sugar storage. Hence factors must be manipulated so that growth is checked in order that the products of photosynthesis may accumulate, sugar be stored in the root, and, as is said, to "ripen" the plant. One factor may not replace another, but we can magnify effects of a factor by manipulation of it and associated factors. Such advance as we may make in space adjustments will come about by proper application of the principles of plant growth.

American practice has, by compromise, accepted certain field patterns and has set up, for a given surface area, certain norms of plant population. Under our current method of culture these have effectively removed space relations from a dominant position and made yield and quality dependent upon the play of other factors principally soil fertility, culture and plant disease. Our principal depressions of yield have come from lack of stand uniformity rather than from improper space allotment. Our low levels of production reflect our failures to give the best environment for sugar beet growth.

But we now are about to enter the mechanized era of sugar beet culture. A distinguished agricultural engineer when asked how far apart the beet rows needed to be in order to give best operation of his machines said "As wide as the agronomist will let me have them." In a phrase, this puts before us the pressing problem of space relations.

We may approach the problems hopefully. If we understand and apply the basic principles, we may sometimes manipulate factors of the environment to get around apparently insurmountable difficulties. Suppose we grant that with things as they are, sugar beets grown in 30-inch rows with 8-inch spacing in the row, do not yield the same as if grown in 20-inch rows with 12-inch spacing in the row (16). Assume that it is necessary in mechanizing the job that the former be used. The agronomist faces first an appraisal of the situation. He must decide if the advantage of the wider row warrants taking a loss, and how much. He must recognize that all districts are not climatically alike and must guard against blanket application of his findings. He may need to fit the plant to the required environment. He may try extending the growing season by early planting, he may seek by rational fertilizer practice to manipulate the intake of plant foods to promote early growth and proper balance. Sugar beet varieties differ in their reactions to space allotments, so that this phase will need to be thoroughly explored. And there remains the attack on the problem through the breeding of plants suited to mechanization. One can immediately visualize a need for a vigorously growing, large topped variety with a globe-shaped root, streamlined for easy lifting.

The new problems that face the agronomist are, therefore, not without clues for their solutions. We do not know the best way to fit the sugar beet for fully mechanized culture. The problems present a challenge to the investigator. The activities stressed in this review were chosen for a purpose—either to show the limits natural to the sugar beet, to show the physiological response of the sugar beet to space allotment, or to show a methodology of research. As the major contribution of the review, some basic physiological principles of sugar beet growth and development have been outlined as guides to plant manipulation. Application of these principles is needed for solution of the problems lying ahead. Agricultural patterns as designed for hand labor had to be changed to permit utilization of power equipment. We must now expect equally radical changes as sugar beet growing advances to fully mechanized production. It is the function of agronomic research to seek out the requirements for the improvement of practice, to appraise them, and to develop a new and successful sugar beet agriculture.

Literature Cited

(1) ARMER, AUSTIN
1947. What is the best row spacing? Spreckels Sugar Beet Bul. 11: 36-38.

(2) ASTRAND, H.
1938. (Spacing of sugar beets). Centralbl. f. die Zuckerindus. 46: 3 pages. (Suppl. to No. 29.)

(3) BILIAN, Z.
1938. (Effect of density of stand on quality and yield of sugar beets). Listy Cukrovar 56: 203-252. (abst. in Sugar 33(10): 76).

(4) BONNE, C.
1933. Untersuchungen zur Ertragsfähigkeit der Zuckerrübe dargestelt an Standweiten-und Inzuchtversuchen. Ztschr. des Ver. der Deut. Zuckerindus. (Tech. Teil) 83: 357-375.

(5) BRADFORD, G. M.
1939. Spacing and fertilizer tests in the Monitor Sugar Company territory. Proc. Amer. Soc. Sugar Beet Tech. Eastern Region Meeting, 1939: 42-46 (mimeographed).

(6) BREWBAKER, H. E. AND DEMING, G. W.
1935. Effect of variations in stand on yield and quality of sugar beets grown under irrigation. Jour. Agr. Res. 50: 195-210.

(7) BREWBAKER, H. E.
1935. Studies on spacing of sugar beets within the row at Fort Collins, Colo.; at Eaton, Colo. Through the Leaves 23(2): 37, 39-43; 23(5): 74-76.

(8) BUSCHLEN, M. J.
1937. Sugar beet yields increased by planting in closer rows. Sugar Beet Jour. 2(7): 132-133.

(9) COONS, G. H.
1941. Climatic relations of sugar beet. U. S. Dept. of Agr. Yearbook 1941: 431-438.

(10) DAHLBERG, H. W.
1935. Sugar beet stands in Sweden. Through the Leaves 23: 60, 62.

(11) DECOUX, L.
1945. Dix années de recherches a l' Institut Belge pour l' Amél ioration de la Betterave à Tirlemont. 436 pp., Brussels.

(12) DECOUX, L., VANDERWAEREN, J., AND SIMON, M.
1945. Densité de plantation, azote et variété. Inst. Belge pour l' Amélior. de la Betterave Pubs. 6: 519-529.

(13) DEHAAN, K. AND KLIJNHOUT, C. C.
1931. (Investigations on the lack of uniformity in the weight of the individual beets resulting from differences in the distance between the beets and from the fertility of the soil.) Instit. v. Suikerbietent. Meded. 1(5): 129-166.

(14) DEMING, G.
1940. Comparative yields of equal plant populations of sugar beets with different spacing relations. Proc. Amer. Sugar Beet Tech. 3: 32-36.

(15) DEMING, G.
1947. Effect of multiple-plant hills on yield and quality of sugar beets. Proc. Amer. Soc. Sugar Beet Tech. Western Region Meeting 1947: 47-53. (mimeographed).

(16) DOXTATOR, C. W., AND SKUDERNA, A. W.
1946. Beet population studies. Proc. Amer. Soc. Sugar Beet Tech. 1946: 157-162.

(17) ENGLEDOW, F. L., MAHER, C. A., HUNTER-SMITH, J., RHYS-WILLIAMS, H., FAIL, H., AND RAYNS, F.
1928. Yield and plant populations in sugar beet. Jour. Agr. Sci. (England) 18: 574-601.

(18) FINNEY, D. J.
1941. The relationship of plant number and yield in sugar beet and mangold. Empire Jour. Expt. Agr. 9: 52-64.

(19) GARNER, F. H. AND SANDERS, H. G.
1940. Experiments on the spacing of sugar beet I, II. Jour. Agr. Sci. (England) 29: 48-57 (1939); 30: 58-68 (1940).

(20) GERLACH, N.
1921. Ueber den Einfluss der Düngung und Standweite auf den Ertrag und die Zusammensetzung der Zuckerrübe. Ver. der Deut. Zuckerindus. Ztschr. 71 (Allg. Teil): 195-205.

(21) GINNEKEN, P. J. H. VAN
1936. (Influence of number of plants per hectare in leafy beet varieties). Inst. v. Suikerbietent. Meded. 6 (4): 73-91.

(22) GODARD, M.
1937. Influence des facteurs climatiques sur la croissance de la betterave sucrière. Ann. Agron. (Paris) 7: 696-727.

(23) HEY, G. B. AND KEMSLEY, W. F. F.
1940. Experiments in the spacing of sugar beet III. Jour. Agr. Sci. (England) 30: 69-74.

(24) HOLLRUNG, M.
1894. Die Standweite der Zuckerrüben. Bl. f. Zuckerrübenbau 1: 161-167.

(25) IMMER, F. R.
1932. A study of sampling technic with sugar beets. Jour. Agr. Res. 44: 633-647.

(26) KRÜGER, W.
1927. Die Standweitenfrage beim Zuckerrübenbau. Deut. Zuckerindus. 52(7): 187-189. Feb. 19, 1927.

(27) LARMER, F. G.
1938. The effect of spacing and density of stand on hill production of sugar beets. New. Agr. 20(7): 8. (April, 1938.)

(28) LILL, J. G.
1947. Plant population and sugar beet yields. Proc. Amer. Soc. Sugar Beet Tech. East Region Meeting: 1947: 14 pages (mimeographed).

(29) LINDNER
1935. Einfluss der Standweite auf Ertrag und chemische Zusammensetzung der Zuckerrüben. Centralbl. f. die Zuckerindus. 43: 214-216. (March 16, 1935.)

(30) LÜDECKE, H.
1937. Wahl zweckmaessiger Standweiten im Zuckerrübenbau. Deut. Landw. Presse 64(10): 115-116. (March 6, 1937.)

(31) NUCKOLS, S. B.
1928. Beet spacing and yield. Facts about Sugar 23: 355. (April 14, 1928.)

(32) NUCKOLS, S. B.
1936. The use of actual and competitive yield data from sugar beet experiments. Jour. Amer. Soc. Agron. 28: 924-934.

(33) ....
1946. Results in 1945 from hand-singled and hand-blocked sugar beets as grown from sheared seed. Proc. Amer. Soc. Sugar Beet Tech. 1946: 253-256.

(34) ROEMER, T.
1927. Die Kultur der Rübe. Handbuch des Zuckerrübenbaues, 366 pages, Berlin.

(35) SKUDERNA, A. W. AND DOXTATOR, C. W.
1940. A study of spacing effects with two varieties of sugar beets on a high and low level of fertility. Proc. Amer. Soc. Sugar Beet Tech. 1940: 100-102 (mimeographed).

(36) ....
1942. A study of sugar beets on two fertility levels of soil. Proc. Amer. Soc. Sugar Beet Tech. 1942: 112-119.

(37) SOUCEK, J.
1924. Beziehung zwischen der Anzahl des Rüben auf den Flaecheneinheit des Rübenfeldes auf ihrem Gewicht. Ztschr. f. die Zuckerindus. Czechoslovak. Repub. 48: (293)-300.

(38) TOLMAN, BION
1942. Multiple versus single-factor experiments. Proc. Amer. Soc. Sugar Beet Tech. 1942: 170-180.

(39) VANHA, J. AND KYAS, O.
1903. Versuche über die passendste Standweite der Zuckerrübenbau. Ztschr. f. das Landw. Versuchsw. Oesterr. 6: 60-79.

(40) ZWOBODA, A.
1925. Wie weit soll man Zuckerrüben bauen? Deut. Landw. Presse 52(11): 125-216. (March 14, 1925.)