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PLANT POPULATION AND SPATIAL ARRANGEMENT EFFECTS ON PRODUCTIVITY, NUTRIENT STATUS, AND MICROCLIMATE RELATIONSHIPS OF SNAP BEANS (PHASEOLUS VULGARIS L.)

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ABSTRACT

During 1974 the large-leaved Early Gallatin snap bean cultivar was observed for growth and yield relationships under varied population and spacing systems. The spacings and relative densities employed were 91 by 4 cm (100 per cent), 12 by 3 and 15 by 15 cm (150 per cent), and 46 by 4 and 23 by 8 cm (200 per cent). Three crops were included which were subject to extremes in moisture and disease conditions.

Competitional influences were not indicated until about the flowering stage which coincided generally with early canopy closure in the higher densities. Additions of leaf area and dry weight per plant were favored by greater available space, but on a land area basis the higher densities had productivity exceeding the conventional row spacing. Competitional pressure in the highest density suppressed productivity increases over the middle density except under very favorable growing conditions. In only one case were growth differences noted between spacings within densities. No consistent trends in mean CGR, RGR, or NAR were associated with the different populations.

Pod maturities and numbers per unit area were little affected by treatment. The exception was under very favorable growing conditions where vegetative growth encroached on the reproductive period. Over all crops yield improvements were obtained with higher populations, but only the square, middle density and wide row, high density spacings were consistently highest.

Fertilizer was broadcast at rates 1.5 times that recommended for normal populations. Petiole analysis throughout the growth periods indicated this rate was fully sufficient for the highest density. At harvest the leaf, stem, and pod contents of N, P, K, Ca, and Mg were also unaffected by spacing.

Conventional rows left 20 to 30 per cent of the inter-row space exposed at harvest. Attenuation of light was a direct function of the LAI and canopy continuity, and intra-canopy air temperatures were generally lowered 1 to 2^{o}C by increasing canopy densities. Surface soil moisture levels did not differ between open and closed canopies, and differences in diffusion resistance related to higher population use of moisture rather than canopy density and were very small. No dense canopy-depletion of CO_2 was observed as soil and ambient air replenishment was apparently quite rapid in this relatively low growing crop. Shading effects from closer spacing on stomatal densities and chlorophyll contents of basal leaves were not observed.

With equal biological and economic productivity to the highest density studied, the square, middle density spacing exhibited better efficiency. Depending on development of a planter commercially acceptable, this square spacing with less seed investment presents a viable option to currently employed "double-conventional" high density planting systems.

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CHAPTER I

INTRODUCTION

The snap bean (Phaseolus vulgaris L.) is an important vegetable crop both commercially and for the home garden in Tennessee and throughout the United States. Commercial production has increased extensively, due to improvements in cultivars, management, pest control, and primarily from the introduction of mechanical harvesting about 1956 (47). From that time, production has shifted from small plots for supplemental farm income to specialized operations which could justify investment in the mechanical harvesters.

The practicality of growing vegetable and agronomic crops in higher than customary plant densities has been studied for many years. For snap beans the prospects were improved with the commercial availability of a multiple-row harvester capable of handling any planting pattern (37). Although other cultural equipment has not yet reached the same adaptability to high density snap beans, the future appears optimistic for development of cropping systems to make the conversion a profitable and relatively safe venture.

Most efforts in high density snap beans to the present have dealt with pod yield and quality and management practices. Resultant yields have been variable, and it is important to consider the effects of increased interplant competition from these high densities on plant growth and biological productivity under varied conditions as they relate to economic productivity.

Increasing plant density increases canopy development with varying effects on light, CO_2, and temperature conditions within the canopy and on crop moisture requirements. Morphological changes may result from the relative levels of these varying environmental factors, and all may be varied with differing competitional influences as the spatial arrangement is altered within a population density.

These studies were initiated to evaluate the effects of five selected spatial arrangements representing three population densities of snap beans on: (1) plant biological and economic productivity, (2) nutrient accumulation from a constant broadcast rate, and (3) canopy influences on light, CO_2, temperature, and soil and plant moisture conditions and how these may relate to leaf morphology represented by density and size of stomata and leaf chlorophyll content. Three crops were studied during 1974 to include climatic influences on crop growth and development.

CHAPTER II

LITERATURE REVIEW

I. HISTORY AND IMPORTANCE

The snap bean is one of many forms of bean included in the species Phaseolus vulgaris. This species is commonly termed the kidney, field, garden, or haricot bean, and snap beans form a distinct subgroup where the immature pod or legume is consumed.

The species is of New World origin with probable nativity in tropical America, possibly Brazil (50, 54). It was spread throughout North and South America prior to arrival of European explorers, and the dry bean was readily recognized as a valuable food source. However, specific reference to the origin of consumption of immature pods is not evident, but the impetus for breeding truly stringless, nearly fiberless, tender-podded varieties initiated in America about 1890 (50).

Nearly all of the snap beans grown in Tennessee are processed. In the United States snap beans for processing in 1974 involved 289,380 acres with 743,150 tons harvested at a value of 114,782,000 dollars (67). The Tennessee crop ranked fourth nationally with 30,350 tons produced on 12,000 acres and third in value at 4,644,000 dollars. Tennessee acreage had been increasing through 1973, but low yields that year reduced the 1974 acreage (66, 67).

II. GENERAL NATURE OF PLANT COMPETITION

Since many production costs are direct costs per unit of land area (5), an important means of increasing returns is to increase the number of plants being grown in an area. However, as the population is increased, a point is reached where the plants begin competing for available light, moisture, and nutrients.

Two forms of competition are recognized (26). Intraplant competition generally involves fruit or flower size on a given plant, a condition exemplified by the pomological crops. A more important form is interplant competition which influences yields on a unit area rather than plant basis.

Crop plant species differ in their morphological plasticities to competition (5). Some, like the cereal grains, adjust to wide variations in plant density through changes in branching pattern. Others, such as head lettuce, require precise planting patterns to insure maximum space utilization. Low populations of high plasticity crops allow individual plants to closer approach their potential yields. However, current cropping practices create intense competitional pressures which make individual plants subnormal, but it is the community of suppressed plants which offers the best yield per unit area even though the yield per plant is markedly reduced.

Morphological plasticity also relates to the plant part constituting the economic yield. Holliday (24) generalized that if the yield component is some part of the vegetative growth phase, a plot of yield

per unit area against population will increase to a maximum and then decline with further population increases, a parabolic relationship. If yield is from a reproductive part, an asymptotic relationship exists with yield per unit area increasing to a maximum which remains fairly constant with further population increases. The former case is also termed semilogarithmic as a straight line results from plotting population and the logarithm of yield per unit area (26). The latter case is logarithmic with a straight line obtained from plotting logarithms of both population and yield per unit area. Beans (and presumably snap beans) are noted by Janick (26) as following the asymptotic or logarithmic relationship with yield increasing as the population is increased but at a continuously decreasing rate.

Bleasdale (5) points out that present row cropping systems result mainly from allowance made for mechanical inter-row cultivation to replace hand labor. Even though row widths have been decreased somewhat, they remain quite wide, leaving plants crowded in the row. This not only introduces a great lack of precision in intra-row spacing but also reduces the capability of the plants to fully exploit the soil and air space available. On the other hand, commercial planting patterns must involve a compromise among economics of operation, maximum space utilization, and the particular crop's morphological plasticity as they affect yield (30). Populations which provide complete canopy coverage and maximum primary productivity are undesirable for economic yield of a reproductive part. Even with high levels of carbon

assimilation per unit land area, reproduction may be suppressed as the amount of photosynthate available per plant becomes limiting.

Donald (17) suggested that yields on an area basis would be optimized by minimizing inter- and intraplant competition and that it is reasonably secure that square planting will give highest yields from the advantage of maximizing distance to the nearest shade-casting neighbor. Hexagonal planting achieves this end, but square planting provides a practical approximation.

III. POPULATION AND SPACING STUDIES

Considerable study had been made on snap bean pod yield and quality resulting from higher than normal populations even before availability of the multiple-row harvesting system.

In 1967 Cutcliffee (16) reported on three years of high density study with snap beans in Canada. Although limited by the available harvester to a 76-cm inter-row width, four intra-row distances from 2.5 to 10.2 cm were tested. Yields from the highest density were consistently highest in this row-oriented study, and the distribution of premium pods of sieve size 1 to 4 were unaffected.

Having the perennially highest state average yield (66, 67), Oregon workers have extensively studied the potentials for high density snap beans. Mack and Hatch (34) compared six square plantings from 4 by 4 inches to 9 by 9 inches with comparable populations in rows of 12, 24, and 36 inches. Yields were higher, to 36 per cent, with square arrangement than for the same population in rows. Providing 25 to 36

square inches per plant was superior for the square plantings. Further study of several inter-row spacings and per plant areas in research plots and commercial fields concurred with the earlier conclusions that 24 to 36 square inches per plant was optimal with 6 by 6 inches best but 8 or 9-inch rows satisfactory if preferred by the grower (32, 33).

Similar conclusions were reached in New York where Peck et al. (47) anticipated general yield improvements of 20 to 25 per cent from plantings in 6 by 6 to 8 by 8-inch squares rather than 36-inch rows.

Tompkins et al. (63) compared 9 and 40-inch rows with 6 and 12 plants per foot of row, respectively. With two hand harvests employed, yields of total and sieve size 1 to 4 pods were increased with the narrow rows. No effects were observed on plant height, flowering date, or taste panel judgments of smoothness, texture, or taste of canned pods. However, in the Early Gallatin cultivar pod enlargement was delayed three to four days in narrow rows, and the narrow row pods were lighter green in color at the first harvest. Equivalent populations in 12, 18, and 36-inch rows were subsequently studied (62). Early Gallatin was taller at harvest with lighter pods as the row width was decreased. Recommendations for Arkansas conditions were made for 18-inch rows with five to six plants per foot as some existing planters could be adapted, there would be sufficient seedlings to break a soil crust that might form after a heavy rain, and one or two irrigations per week should be adequate.

Using a constant intra-row spacing of six plants per foot, Mullins et al. (43) obtained yield increases with successive reductions

in inter-row width from 36 to 24 to 18 inches. However, further reductions to 12 and 6 inches were no better than 18 inches.

In testing further spacing variations in Tennessee using a new design of precision planter, Bledsoe et al. (6) found highest yields of the Early Gallatin cultivar in a 6 by 2-inch intended nominal spacing. Because of planter and germination problems the actual mean spacing was closer to 6 by 4 inches. Resultant yields were nearly three times those of conventional 36 by 2-inch spacing.

The study by Mullins et al. (46) included cultivars of different growth types, from upright to sprawling, with cultivar behavior similar at all row widths. As snap bean cultivars do vary greatly in their growth types, e.g. Lake Shasta with small leaves which remain upright until after pod set as compared to the large-leaved Early Gallatin (62), Peck (46) expresses the need for research to determine optimum high density spacings for each specific plant type.

Peas exhibited similar responses to spacing in nine combinations of row width and plant population reported by Gritton and Eastin (23). Little effect was observed on maturity, plant height, total number of nodes, lowest pod bearing node, average shelled pea size, and the number of ovule initials. The productivity per plant was inversely proportional to population, and yields generally increased with higher density and/or decreased intra- or inter-row spacing.

Planting time has been shown to affect the choice of plant spacing in soybeans. Caviness and Johnson (11) found soybeans planted

before June 10 in Arkansas to have equivalent yields whether in 6 or 36-inch rows. This resulted from more severe lodging and drought stress in the higher population. If planting was delayed past June 20, however, a dramatic yield increase was obtained with high populations of four to five plants per foot of six-inch row appearing optimum.

IV. PLANT GROWTH ANALYSIS

Watson (70) points out that the knowledge of practical application in agriculture involves relationships established between crop yield and environmental variation, especially variation effected by changes in cultural practices or breeding modifications of internal factors. Light relations constitute a major influence on plant growth and development, and study of this factor advanced considerably through development of growth analysis methods (38).

As the physical sciences have been advanced by development of empirical generalizations for extensive data, e.g. Boyle's Law or Ohm's Law (19), so also have past and present attempts been made to characterize and predict biological phenomena. Gregory (22) developed the concept of net assimilation rate (NAR) defined as the "rate of increase in total plant weight per unit of assimilating material." Blackman (4) related plant growth rates on the basis of the compound interest law with the rate of total dry weight increase a function of dry matter present. However, since not all dry matter is productive, i.e. some is skeletal, then leaf size provides a better measure of productive capital. Briggs, et al. (8) brought these concepts together by combining

NAR and leaf area ratio (LAR, the ratio of leaf area to total plant dry weight) with their product the relative growth rate (RGR) which Blackman defined.

The absolute rate of growth in dry weight, the crop growth rate (CGR), is the product of leaf area and NAR (70). In this manner the progress of dry matter accumulation and final yield may be completely described by the two attributes NAR and leaf area. Other interrelations occur with the LAR which may be considered the product of two components: (1) the leaf weight ratio (LWR) or ratio of leaf dry weight to total plant weight, and (2) the specific leaf area (SLA) or ratio of leaf area to leaf dry weight (4). This allows attributing LAR differences, for LWR, to differential photosynthate distribution between leaf and other plant growth or, for SLA, to differences in leaf thickness (49).

As agricultural yield is usually measured in terms of crop weight or volume per unit of land area, it is appropriate to express crop leaf area on the same basis, the leaf area index (LAI) (38, 49, 70). Watson (70) notes that for a single species grown at nearly constant spacing, the variation in LAI depends mainly on changes in leaf area per plant, but as the spacing varies the LAI varies with the population as well. Radford (49) further points out that under conditions of a continuous canopy cover, then both leaf area and plant dry weight are appropriately expressed as functions of land area.

V. HIGH CROP DENSITY LIGHT RELATIONSHIPS

In field crops the dependence of NAR and LAI is most obviously investigated by varying the plant population, but it is possible that

the LAI may be limited by competitional pressure and not be greatly affected by plant numbers except at very early growth stages (70). For this reason yields may often become relatively independent of plant numbers at higher populations rather than having increased LAI affected by a decreased NAR. Ničiporovič (44) similarly states that variation in dry matter production is far more dependent on LAI variations than on NAR. Provision of optimal LAI and an optimal course of leaf formation for highest yields may be accomplished by: (1) spacing for an LAI during the growth period sufficient to maximize absorption of incoming radiation, (2) preventing mutual shading from being so severe as to cause parasitism by lower leaves, (3) adjusting density to available soil moisture, and (4) adjusting for the crop's purpose, e.g. corn for grain or silage (44).

Sakamoto and Shaw (53) found light interception by field soybeans occurred primarily at the canopy periphery and was later restricted to the canopy top after closure of the inter-row space. While the plants were small with exposed canopy sides, 77 to 98 per cent of the LAI was effective in light interception, but as the canopy closed this effectiveness dropped to 41 to 67 per cent.

By thinning overplanted stands of corn and soybeans, Buttery (10) created a range of LAI's for growth analysis. For both crops the RGR and NAR increased and CGR and LAR decreased as the plant density and LAI increased.

Beuerlein et al. (3) also artificially adjusted soybean LAI. In square plantings the canopies were opened by repeated branch removal

to improve light penetration. Seed yields were improved by increasing the population of pruned plants in a unit area or by decreasing the population of normal plants, both effects corresponding to the LAI differences.

Skip-row planting systems were employed by Parks et al. (45) to vary exposure of soybean canopy peripheries. In a plant one, skip one row arrangement nearly 180-degree exposure is available for light interception to produce yields similar to a plant two, skip one arrangement having one-third more plants per unit area but row exposure of only about 110 degrees.

Shibles and Weber (57) found soybean population increases to increase the crop LAI and decrease the days required to reach 95 per cent interception of incoming solar radiation. However, with increased population or close inter- or intra-row spacing, there was a concomitant decrease in the harvest index, the ratio of economic to biological yield. As no differences were observed in leaf arrangement, they concluded that plant arrangement affects productivity only in the context of energy intercepted. Similarly, as no optimum LAI was described for soybeans, i.e. the dry matter production rate does not decline at LAI greater than that needed for full light interception, it was concluded that shaded leaves are not "parasitic" on productive portions of the canopy and do not detract from net community photosynthate production (56). While overproduction of LAI was not indicated by itself as detrimental to yield, an inefficient use of photosynthate is suggested. In a companion paper Weber et al. (71) discussed this lowered efficiency

reflected by the low harvest index for the highest populations or closest spacings in any one direction. Even though the greatest rates of dry matter accumulation were favored by those treatments favoring rapid attainment of high LAI, maximum seed yields were obtained from 10-inch rows with 104,544 plants per acre while maximum dry matter was obtained with 5-inch rows having the same intra-row spacing and, hence, twice the population.

A notable factor suspected to be related to excessive LAI production by soybeans in narrow rows was that the cultivar used was probably selected in the commonly employed 40-inch row (57). In this case there would be little excess leaf area, but adaptability of growth form to narrow rows may be reduced.

In peas Eastin and Gritton (18) found LAI to be a function of population rather than spacing. Of three populations the higher two reached LAI maxima which then declined drastically while the lowest population maintained its relatively lower LAI throughout the growth period. From just prior to bloom through the canning stage, and especially during pod filling, they found a given unit of leaf area more efficient in producing dry matter than at earlier stages. As CGR increased while LAI and LAR decreased, the conclusion was that sink size affects positively the photosynthetic apparatus activity. Calculated values for NAR were extremely variable, but the rates were generally inversely proportional to populations.

Similar results were obtained with high seeding rates of peas in one-to-one rectangularity studied by Meadley and Milbourn (39). NAR was again inversely related to population. The highest seeding rate reached

a peak LAI of 8.3 one week after flowering but the LAI also declined rapidly while the lowest rate reached and maintained an LAI of 4.3 during pod filling. Although more flowers and pods were produced at the highest density, there was a 34 per cent wastage by abscission such that no yield difference was obtained from a four-fold difference in seed density. They concluded pea yields depended more on the post-flowering ability to produce and distribute photosynthates to the economic product rather than the stand's ability to provide reproductive nodes.

Only limited information has been gathered on growth responses of snap beans in high density other than plant height and flowering dates noted previously. Mack and Hatch (34) reported generally higher plant fresh weights from growth in square arrangements, and the leaf area for a "typical" plant in squares increased as the area per plant increased. Plant to pod (weight) ratios did not differ among the square arrangements. Crandall et al. (15) found yields and LAI to both be 64 per cent higher for beans in 12-inch rather than 36-inch rows.

Lodging may have important effects on light relations as well as affecting crop quality and harvestability. Cooper (14) notes for soybeans that the unlodged canopy forms a highly organized leaf pattern for maximum light-use efficiency. This efficiency is emphasized by having younger, more photosynthetically active leaves located in the upper canopy where light intensity is greatest. With lodging these more active leaves become shaded, and older, less active leaves are exposed with an overall disruption of normal canopy integrity. With severe lodging light may become limiting as less photosynthate production may result in reduced

seed size and pod abortion. Although severe lodging was a problem in high soybean populations, Shibles and Weber (57) considered partial lodging of wide rows somewhat favorable as these plants better covered the otherwise exposed inter-row area.

VI. HIGH CROP DENSITY MOISTURE RELATIONSHIPS

Yao and Shaw (74) reported in 1964 that increasing plant densities in row-oriented corn also increased water use by the crop, but the relative increase in water use was less than the proportionate stand increase. Fulton (20) found strong interactions among soil moisture, spacing, and population in four years of study with corn. Yields were generally increased with high populations or high levels of soil moisture, but for narrow rows both high populations and high soil moisture levels were needed for increased yields.

Rosenburg et al. (52) found water use equivalent between row-oriented snap beans grown in the open and with wind shelter protection under Nebraska conditions. Their observations concurred with an earlier inference by Rosenburg (51) that physiological control of transpiration in shelter balanced evapotranspiration in the open. In the open considerable evaporation occurred from the exposed, inter-row soil surface while near complete canopy coverage from more luxuriant growth in the shelter reduced soil evaporation to negligible levels but less restricted transpiration provided for more water loss from that route, and similar soil moisture tensions resulted.

VII. ENVIRONMENTAL INFLUENCES ON STOMATA

Stomatal Density

The occurrence and density of stomata vary with the species, leaf position, and environmental conditions. Woody plants commonly have stomata present on the abaxial (lower) leaf surface only while herbaceous plants generally have some, but generally fewer, on the adaxial surface as well (73). For snap beans Kanemasu and Tanner (27) found stomata seven times more numerous on the abaxial surface which concurs with the general densities listed by Wilson and Loomis (73) of 40 and 248/mm^2 for the adaxial and abaxial surfaces, respectively.

Light and soil moisture conditions may both alter stomatal densities. Under optimum conditions of soil moisture fewer stomata are present per unit area (48). Growing plants in heavy or light shade reduces stomatal densities as compared to plants in full sun (1, 13). In tobacco, this effect was attributed to greater leaf enlargement (1).

Effects of leaf age on lowered stomatal densities in older leaves of sugar beet were also attributed to leaf enlargement (9). Cole and Dobrenz (12) found terminal leaves of several alfalfa cultivars to have higher stomatal densities than basal leaves, and wheat had variation among various leaves and also over the length of individual leaves as well (41). However, Slavick (58) indicated samples taken near the center of a tobacco leaf are representative of an average for the entire surface.

Diffusion Resistance

Measurements of diffusion resistance vary in the methodology employed as the total resistance has components of stomatal, cuticular, and

boundary layer resistances (25) each of which has been measured directly, calculated, or estimated in a variety of ways (9, 27).

The resistance to water vapor transfer from evaporative surfaces in the leaf relates inversely to transpiration rates (25). As stomatal aperture effects major control over transpiration rates (9, 27, 73), the resistances increase with advancing stomatal closure and therefore also relate to resistances for carbon dioxide entry to photosynthetic sites. However, Miskin et al. (42) tested barley breeding lines of high and low stomatal densities which differed in diffusion resistances and transpiration rates but not in photosynthetic rates. With pretreatment to ensure fully open stomata, a 25 per cent reduction in stomatal density reduced transpiration 24 per cent, indicating that breeding for fewer stomata may be effective in improving water use efficiency without adversely affecting photosynthesis.

Testing moisture stress reactions, Boyer (7) found net photosynthesis reduced in corn beginning at leaf water potentials of only -3.5 bars as compared with soybeans which were unaffected down to -11 bars. Differences occurring with desiccation were solely attributable to differences in stomatal behavior down to -10 and -16 bars for corn and soybeans, respectively.

Leaf age is less important than microclimate for inducing greater stomatal resistances in the lower canopy of sugar beets according to Brown and Rosenburg (9). The differences between sunlit and shaded leaves suggested that greater resistances in older leaves were due either to long-term preconditioning at low illuminance or to low illuminance during or

immediately preceding sampling. Thus, with a lack of dependence on leaf age, resistance measurements might be practically made on shaded and sun-lit leaf groups in that crop for sampling moisture stress effects.

Because of preferential water flow to upper canopy leaves, diffusion resistances in the mid-portions of a soybean canopy under moisture stress were found to increase earlier in the day and to a greater extent (59). The degree to which canopy areas are out of phase was speculated to be a function of canopy density and the associated differential in microclimates.

Kanemasu and Tanner (27) found abaxial resistances in snap beans unaffected by leaf water potentials to -11 bars, but with further decrease a rapid resistance increase occurs. Stomatal closure in this crop in response to moisture stress is not fully effective nor is it beneficial. Millar and Gardner (40) noted growth rate was reduced more by stomatal closure than was transpiration.

VIII. ENVIRONMENTAL INFLUENCES ON CHLOROPHYLL CONTENT

Growth under heavy shade caused alterations from normal full-sun leaf morphology and chlorophyll contents of alfalfa and birdsfoot trefoil (13). When in full sun the leaves were thicker with greater numbers of palisade and mesophyll cells and greater cell volumes as well. Chlorophyll contents were higher on a leaf weight basis for shade leaves and on a leaf area basis for the sun leaves. These changes were directly associated with increased SLA from shading these legumes.

Gabrielson (21) noted that rates of photosynthesis are proportional to chlorophyll contents only at low light levels, and the chlorophyll factor reaches its optimum at a chlorophyll a plus b concentration of 4 to 5 mg/dm^2 of leaf. Chlorophyll increases beyond this range have no appreciable effect on photosynthesis.

IX. SNAP BEAN NUTRITION

A lack of standardization of sampled plant parts and sampling times has made direct application of reported tissue analysis data difficult. Thomas et al. (61) used the first leaf from the plant base without specifying if petioles were retained or not, and samples were collected 22 and 54 days after planting. In contrast, MacKay and Leefe (35) selected the lamina only from the uppermost mature leaf at the early bloom stage, and for lima beans Ulrich and Berry (64) used petioles only from the second lateral leaf from the top also at the early bloom stage. More recently, Lorenz and Tyler (31) used petioles from the fourth leaf from the top at either early bloom or midgrowth stages.

Thomas et al. (61) reported the following ranges and optimum levels for snap beans 54 days after planting:

Nitrogen (N)	1.50-2.37 per cent, 1.86 per cent optimum
Phosphorus (P)	0.20-0.28 per cent, 0.22 per cent optimum
Potassium (K)	1.17-2.20 per cent, 1.93 per cent optimum
Calcium (Ca)	5.38-6.39 per cent, 5.75 per cent optimum
Magnesium (Mg)	0.50-0.99 per cent, 0.66 per cent optimum

Optimum levels, i.e. those above which no further yield increase can be expected, were determined from regression analyses by MacKay and Leefe (35). From their sampled leaf, optima of 5.1, 0.40, and 2.0 per cent exist for N, P, and K, respectively. Data from Lorenz and Tyler (31) indicate sufficient petiole levels of P and K to be 0.20 and 4.0 per cent, respectively.

Although equipment for banding fertilizer applications is not yet available for all high density planting patterns, the practice is still advantageous if a relatively narrow row orientation is employed. Peck (46) cited New York data for 12 and 36-inch rows where broadcasting twice the normal rate for the 12-inch rows gave no yield increase over 36-inch rows with normal banding. However, if both spacings were banded, appreciable increases were obtained with the higher population even if the per row application was only one-third the normal rate.

Current Tennessee recommendations for snap beans are 40 kg/ha of N, 12 to 18 kg/ha of elemental P, and 11 to 22 kg/ha of elemental K for soils testing low to medium in the available nutrient (65). For soils testing high, 6 kg/ha of P may be applied, but no K need be included.

CHAPTER III

MATERIALS AND METHODS

I. FIELD TECHNIQUES

These experiments were conducted during the summer of 1974 with an early and late crop of snap beans grown at the Plant Science Farm, Knoxville, and a mid-season crop at the Plateau Experiment Station, Crossville. Hereafter, the early, middle, and late crops will be referred to as the KNX-E, CRS-M, and KNX-L crops, respectively.

The experimental design was a randomized complete block for each crop with four replications of five spacing treatments. These treatments are presented in Table 1. The Early Gallatin snap bean cultivar was used throughout.

Planting and Crop Maintenance

The KNX-E crop was for study of growth relationships of plants at the precise spacings listed in Table 1. To this end, treatments three through five had two seeds hand-dropped at each intended position in an opened furrow, and treatments one and two were heavily over-seeded. An in-furrow spray of 1.3 kg A.I./ha Terrachlor was applied prior to furrow closing. Two replicates were planted on May 8, but rain delayed planting of the other two until May 14. Thinning to one plant at the desired spacing was made on May 24 and 25.

For the CRS-M and KNX-L plantings, double-seeding and thinning were not employed in order that effects from the tested 80 per cent

Table 1. Snap Bean Spacings, Per Plant Areas, Plant Populations, and Densities Relative to Conventional Spacing.

Treatment Number	Spacing (cm)	Area/Plant (dm^2)	Population (ha^{-1})	Density (%)
1	91.4 x 3.8	3.48	287,000	100[z]
2	45.7 x 3.8	1.74	544,000	200
3	30.5 x 7.6	2.32	431,000	150
4	22.9 x 7.6	1.74	544,000	200
5	15.2 x 15.2	2.32	431,000	150

[z]Conventional spacing varies slightly about that of treatment 1.

germination rate might be observed in the context of a simulated mechanical planter capable of dropping seeds at the intended intra-row spacings. Thus eight seeds per foot of row were hand-planted for treatments one and two, and one seed per position for treatments three through five. The few seeds dropped accidentally were considered part of the normal variation from multiple drops by the simulated mechanical planter. The CRS-M planting was made on June 24 with a post-plant surface application of 1.3 kg A.I./ha each of Terrachlor and Captan on June 26. The KNX-L planting was made July 11 and 12 with the in-furrow Terrachlor spray employed as previously described.

Plot sizes were identical for both KNX-E and KNX-L. Each spacing treatment covered an area about 5.5 by 3.7 m with rows following the short dimension which was oriented nearly N-S. Thus, row numbers varied from seven in the conventional spacing to 37 in the 15.2-cm rows. Each plot was a conventional row width (0.9 m) from a neighboring plot or guard row surrounding the perimeter. The CRS-M plots differed only in their smaller size, 3.7 by 3.7 m, yielding 5 to 25 rows per plot. Row orientation was more NW-SE at this location.

The soils involved were an Etowah silt loam for both crops at Knoxville and a Hartsell sandy loam at Crossville.

Each location received a pre-plant application and incorporation of Treflan at 0.67 kg A.I./ha for weed control. One or two hand-cultivations were also made for each crop. Other pest control measures employed were Sevin (0.1 kg A.I./ha), Benlate (0.2 kg A.I./ha), and Manzate (1.4 kg A.I./ha), and Bravo (2.0 kg A.I./ha) was included with

occurrence of rust. Spray schedules and pesticide components of the tank mix varied according to conditions and other crops included in the daily operations.

Supplemental irrigations were applied when normal precipitation was deficient. Amounts applied and other climatological data for the three crops are summarized in Table A-1, Appendix A.

Fertilization

As higher than conventional plant populations were used in these experiments, it was determined that fertilization rates should be increased somewhat but not so high as to over-stimulate the conventional spacing. All fertilizer applications were based on soil tests and adjusted to provide 1.5 times the amounts recommended for the conventional spacings. Rates for KNX-E were 62, 35, and 27 kg/ha of elemental N, P, and K, respectively; 57, 19, and 18 kg/ha for CRS-M; and 62, 53, and 40 kg/ha for KNX-L. All fertilizer was applied broadcast and disked in pre-plant.

Harvesting

The crops were harvested when an estimated 30 per cent of the pods had reached sieve size 5. For KNX-E, daily estimates were made for individual plots which resulted in a spread harvest period. The first-planted replicates were harvested July 5 and 6 and the later replicates from July 13 to 17. With no consistent differences in maturity date attributable to the treatments, all treatments of subsequent crops were harvested within one day. CRS-M and KNX-L were harvested August 23 and September 2, respectively.

Harvesting procedure involved cutting all plants from a 0.84-m^2 square in the center of each plot and removing all pods of marketable size. Data on weights and numbers were collected for individual sieve size grades.

Plant Growth Sampling

Plant sampling techniques for growth analysis purposes were consistent for all crops, but relative sampling times differed. Three plants, selected at random from outside the area designated for harvest and a minimum of 0.5 m from the plot border, were cut at ground level, placed in plastic bags, and stored under shade for a minimum time before chilling to prevent excessive dehydration. These plants were later separated into leaf lamina, petiole, stem, and pod components. Subsequent processing will be described under laboratory techniques.

Because of differing planting dates for KNX-E, periods between samplings were varied such that all four replicates could be considered together on the basis of days from planting as mediated by heat unit accumulation. The earlier replicates were first sampled 29 days after planting and the later set 28 days after its planting, but for simplicity 28, 35, 43, 49, 56, and 63 days after planting will be used to indicate the "average" sampling times.

Single-day plantings for CRS-M and KNX-L allowed better sampling standardization. Seven-day intervals were utilized throughout for these crops except for a single three-day period prior to harvest for CRS-M.

Samples were collected at 23, 30, 37, 44, 51, 58, and 61 days after planting for CRS-M and at 25, 32, 39, 46, and 53 days for KNX-L.

In conjunction with collection of plant samples, photographs were made of the plant canopies for measuring relative coverage. One section from each plot was marked for exact repetition of areas photographed and to avoid plant removal. A standard camera height was maintained, and the film plane was as near as possible to parallel with the canopy surface. A point-grid was placed over black-and-white prints (unsatisfactory) or small color slide projections (preferable) for calculation of percentage of soil surface covered. Photographs were made near solar noon to decrease measuring difficulties arising from shadows.

Supplemental data were also collected on plant height and spread. Height was measured from the soil surface to the terminal leaflet pulvinule of the uppermost leaf in order to avoid effects from leaf orientation in response to light direction. Three measurements of each variable were made per plot in conjunction with plant sampling.

Microclimate Measurements

Light attenuation. A Weston 756 light meter was utilized to determine the percentage of incident light attenuated by the plant canopies. Measurements were made immediately above the plant canopy and within 2.5 cm of the soil surface midway between and along the rows. Multiple intra-row measurements were averaged to decrease variation from very low leaves and canopy discontinuity. These data were also collected as near to solar noon

as possible with the hand-held sensor carefully oriented in a vertical position. Variable cloudiness and wind restricted the number of sampling times available.

Soil moisture. Gravimetric determinations of soil moisture were made during drying periods to observe variable canopy effects on rates of water loss. Composite samples were collected from the 0 to 15-cm level for this purpose as preliminary greenhouse observations had indicated improved maintenance of surface moisture with near complete canopy coverage. Soil cores were taken midway between rows and between plants within rows with two cores bulked from each location group within a plot. The samples were dried at 105°C for 24 hours with results expressed as percentage moisture on an oven-dry basis.

Canopy air temperature. Within-canopy air temperature measurements were made with a Yellow Springs Model 47 telethermometer at KNX-E and KNX-L only. Eleven channel capacity allowed monitoring two replications and a 1.2-m high ambient air level. Each sensing probe was fitted with a white styrofoam shield to prevent direct solar exposure and was calibrated to the specific channel and extension lead used. In the plots the probes were set at 10-cm directly over the center row. Although several continuous temperature traces were desired, recorder malfunction necessitated periodic hand-operation at selected intervals during the day.

Canopy CO_2. Measurements of CO_2 concentrations within the plant canopies were made on selected days after the canopies had become extensively developed at KNX-E and KNX-L. The concentrations were measured

with a Beckman Model 215B infrared gas analyzer with output to a chart recorder. To reduce temperature variations and avoid instrument damage, all equipment remained in a small air-conditioned shed and the Tygon intake lines were shaded by foliage cover as much as possible. Two intake lines and pumps reduced analysis time as one line could be cleared while sample air from the other was passed through the analyzer. Excess pressure from the inline pump was released before passage of the sample air through 0.9 m of anhydrous $CaSO_4$ in 5-cm glass tubes, a fritted-glass filter, a flow meter adjusted to 1.5 liter/min, and the analyzer. Standard gases were dry nitrogen (0-ppm CO_2) and 160,322, and 568-ppm CO_2.

The suggestions by Livingston (29) for sampling technique were generally followed. Days selected for these measurements were clear or very uniformly cloudy with light intensities above 750 lux and no wind movement of the canopy. Dew was allowed to evaporate before commencement of sampling. The areas undisturbed for harvest were sampled, and glass tubing on a pole was carefully passed into the canopy with the port at a height of 15 cm, about one-third of total plant height, located in the row center.

Diffusion resistance and leaf temperature. Terminal leaflets of fully exposed mature leaves in the upper canopy and shaded leaves near the canopy base were measured for diffusion resistance of the abaxial surface. A Lambda Instrument Company Diffusion Resistance Meter, Model Li-60 was used (27, 28, 68), equipped with the sensing unit described by Kanemasu et al. (28). Leaf temperature measurements are needed for resistance

determination and are made by means of a thermistor within the sensor cup. Duplicate measurements were made for each leaf group.

Stomata and chlorophyll samples. Abaxial surfaces of terminal leaflets from exposed upper and shaded basal mature leaves were sprayed with a rapid-drying acrylic resin dissolved in toluenemethylene chloride which Brown and Rosenburg (9) described for obtaining stomatal impressions from sugar beet leaves. The leaves to be sprayed were slowly and gently raised, and after the resin had dried, the sprayed leaflets were separated at the pulvinule and bagged. During the same day, impression strips were removed from the basal portion adjacent to the midrib, as suggested by Slavick (58), with Scotch No. 600 tape. Two strips from duplicate leaves in each group were placed on glass slides in hopes that at least one would be of satisfactory quality, a problem with densely pubescent leaves.

Exposed and shaded leaves were also sampled for chlorophyll contents. Sufficient terminal leaflets to provide a minimum of one gram dry tissue, generally seven to ten leaflets, were collected, bagged in plastic, and chilled for laboratory analysis .

II. LABORATORY TECHNIQUES

Growth Analysis

Sampled plants which had been separated into components were measured for total leaf areas and dry weights. Petioles and petiolules were separated from the lamina with the latter measured with a Hayashi Denko

Model AAM-5 automatic area meter. Immature leaves having leaflets less than one centimeter wide were considered photosynthate sinks only and bulked with stems. All the component parts were subsequently dried at 70°C for 24 hours and weighed separately.

Growth analysis formulas used were as described by Radford (49). Components of these relationships and their abbreviations are presented in Table B-1, Appendix B, and the equations are given in Table B-2, Appendix B.

Pod Color

Samples of marketable pods were measured for color with a Hunterlab Color/Difference Meter, Model D25D2. The instrument was calibrated with a green standard, C2-141, for better accuracy with the pod samples. Sufficient pods to completely cover the sample port were used, and Hunter color values "L" (lightness), "a" (-a = green), and "b" (+b = yellow) were determined. The ratio of the "a" value to the "b" value, Hunter a/b, was calculated from the measured values.

Mineral Analysis

Petioles were selected for analysis of mineral content, but because of limited plant numbers and the need to avoid missing leaves on plants which might subsequently be utilized in growth analysis sampling, all petioles from the three plants routinely sampled were bulked. Thus, each sample consisted of petioles ranging from immature to senescing. However, if the lamina had already abscissed or the leaves were severely chlorotic such that the petioles broke from the stem with minimal pressure,

those tissues were not included in either leaf area, dry weight, or mineral content determinations. In addition, leaf, stem, and pod samples from CRS-M and KNX-L plants collected at harvest were also analyzed for comparison to the petiole levels.

After drying, the tissues were ground in a Wiley mill to pass a 2-mm screen. Samples of 200 mg were predigested with 5 ml of concentrated H_2SO_4 for a minimum of eight hours. After refluxing at over 200°C for at least two hours, 5 ml of 35 per cent H_2O_2 was added to the cooled tubes which were then reheated until the samples cleared. The lower than standard acid and peroxide volumes were satisfactory for all but about 10 per cent of the samples which required a second peroxide treatment. After sample clearing, the tubes were uncovered and heated 30 minutes more to drive off remaining peroxide and then cooled, diluted to 50 ml, and rediluted 1:2.5 for analysis.

Concentrations of protein-N, P, K, Ca, and Mg were determined on a Technicon Model III AutoAnalyzer (60). Solution concentration of protein-N was determined by the phenol-hypochlorite color reaction (69), K and Ca by flame emission photometry, and P and Mg by the molybdovanadate and magnesium blue colorimetric reactions, respectively.

Stomatal Density and Size

Preliminary studies indicated very few stomata on adaxial leaf surfaces in this snap bean cultivar, and these stomata tend to cluster along the veins making density determinations very difficult. As a result, only abaxial surfaces were studied in these experiments.

Three fields approximately 0.076 mm^2 were averaged from each slide prepared as earlier described. All stomata, including those extending over 50 per cent into the field, were counted, and lengths of 10 stomata per field were measured.

Chlorophyll Content

Preliminary studies indicated no differences between contents measured from fresh tissue extractions in acetone later diluted to 80 per cent solvent concentration and dry tissue extractions with 80 per cent acetone. Therefore, as a time-saving measure, dry leaf tissue was used in these studies.

Leaflets sampled for chlorophyll analysis were measured for total area, dried at 70°C for 24 hours, and then weighed such that the contents might be expressed on both area and weight bases. Samples of 100 mg were refluxed in a soxhlet apparatus containing 80 ml of 80 per cent acetone until the extract came off clear. The extract was diluted to 100 ml and measured for absorbance at 645 and 663 nm on a Beckman DU-2 spectrophotometer. Further dilution was often necessary to obtain mid-scale absorbance values. The component chlorophyll contents were calculated using the equations of MacKinney (36) as modified by Arnon (2).

III. DATA ANALYSIS

All data were analyzed by analysis of variance on the IBM 360/65 computer of The University of Tennessee Computing Center with the Statistical Analysis System program package (55). In certain cases to be noted

later, other analyses were applied. Where the F-statistic was significant at $P > .05$, means were separated by Duncan's New Multiple Range test at $P = .05$ within the program package.

CHAPTER IV

RESULTS AND DISCUSSION

I. GROWTH RELATIONSHIPS

Canopy Development

Only small differences in plant heights occurred during each crop's growth period as shown in Figure 1. For KNX-E and KNX-L these differences occurred only at the early sampling times. CRS-M had differences throughout, but the only consistent indications appeared to relate to emergence and lodging conditions. Early samples had taller plants directly associated with the intra-row spacing as more seeds per meter had greater capacity for readily breaking the soil surface while the 15-cm square spacing had delayed emergence. Near harvest lodging decreased the heights for all but the narrow row, 200 per cent density. There the relationship was a tendency for narrower rows to offer better support for holding a neighboring row more upright. Wider spacings between plants in the square spacing did not offer this same advantage.

Differences among the crops relate directly to general climatic conditions. KNX-E was started well with favorable temperatures and moisture supply, but a post-flowering period of drought not fully compensated by irrigation severely restricted overall growth through harvest and delayed maturation. For CRS-M irrigation was needed one week

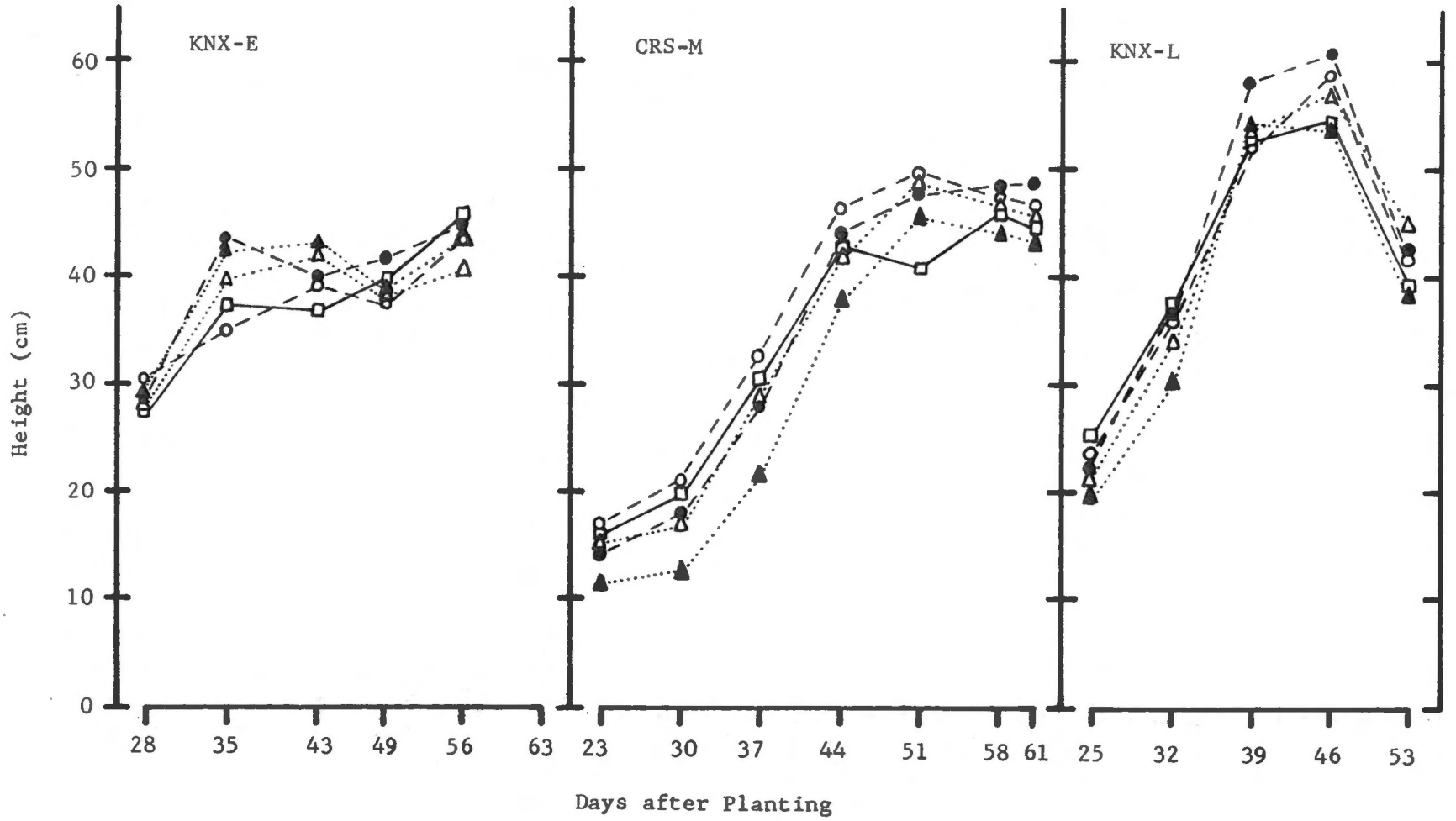


Figure 1. Spacing and Density Effects on Plant Heights.

Key: Density/Row Width = 100%/91 cm (□——□); 150%/30 cm (△·····△); 200%/46 cm (○— —○); 150%/15 cm (▲·····▲); 200%/23 cm (●— —●).

after planting as germination had not yet occurred. However, ample moisture was available later with an additional irrigation supplementing rainfall such that the longer growth period for this crop was the result of delayed germination only. The moisture distribution for KNX-L was better maintained with supplemental irrigations, even though the total was much less than provided the CRS-M crop (see Table A-1, Appendix A). Higher temperatures likely affected the greater plant heights attained with this late summer crop. This proved to be a disadvantage as indicated by the excessive height reduction the final week due to lodging.

Plant spread into the inter-row space is shown in Figure 2. As expected the extent of spread was directly related to the row width according to the distance conventionally spaced plants could extend branches and leaves and how soon plants in the higher densities became partially shaded by the neighboring rows. Utilization of the available space is further indicated in Figure 3 by the percentage of soil surface covered. In general, the conventional row spacing presented a very inefficient arrangement for space utilization and interception of solar radiation. In all three crops, 20 to 30 per cent of the incoming radiation was not intercepted by even a single leaf layer in this plant arrangement. Although canopy discontinuity caused less than full surface coverage in the higher populations (or narrower rows), full inter-row closure was attained near the time of flowering, and interception capabilities of 90 per cent or more were retained through harvest.

Plant stands determined as the percentage of the intended stands (Table 2) did not directly influence canopy relationships. However, they

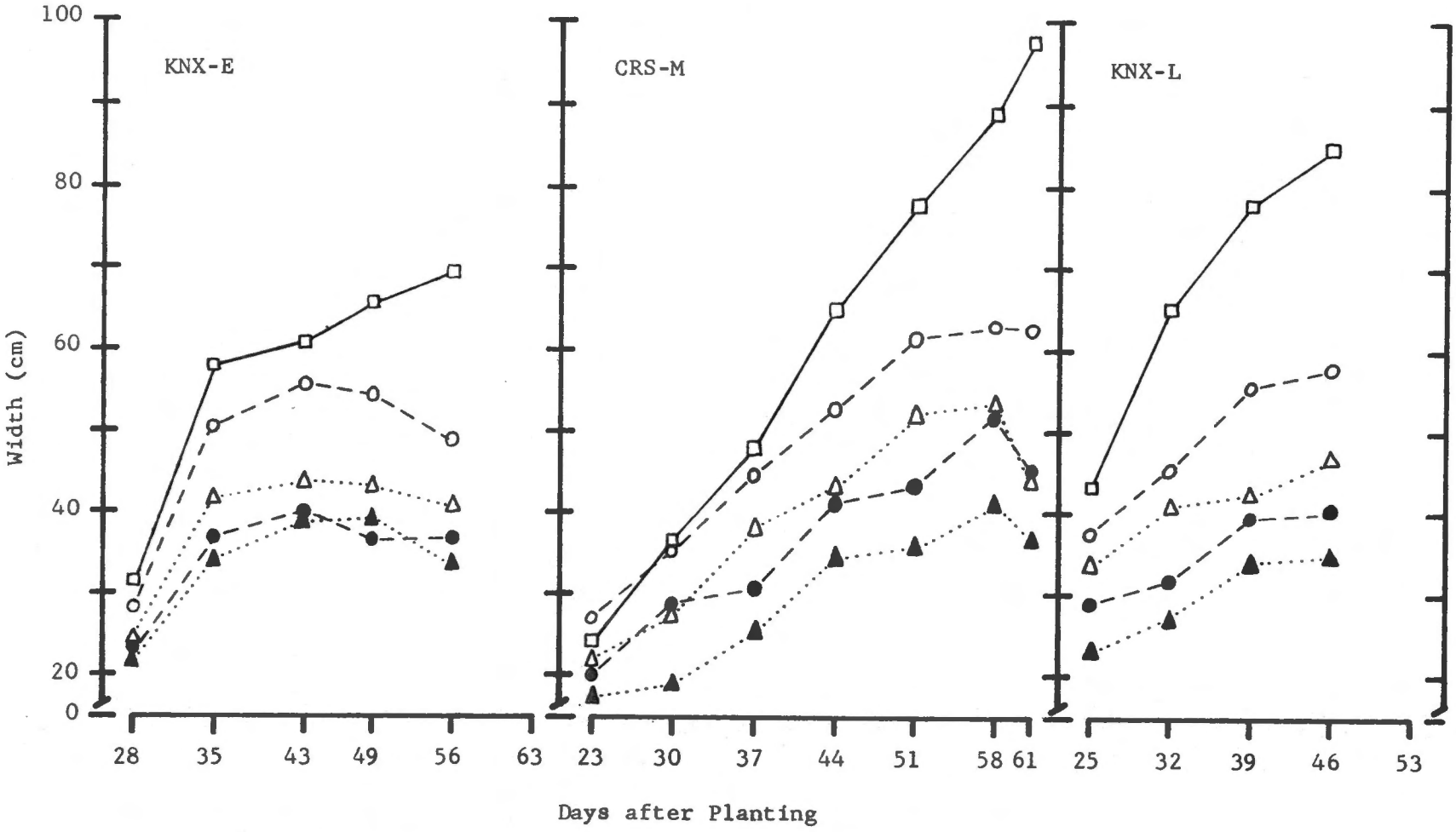


Figure 2. Spacing and Density Effects on Inter-Row Canopy Widths.

Key: Density/Row Width = 100%/91 cm (□——□); 150%/30 cm (△·····△); 200%/46 cm (○– –○);
150%/15 cm (▲·····▲); 200%/23 cm (●– –●).

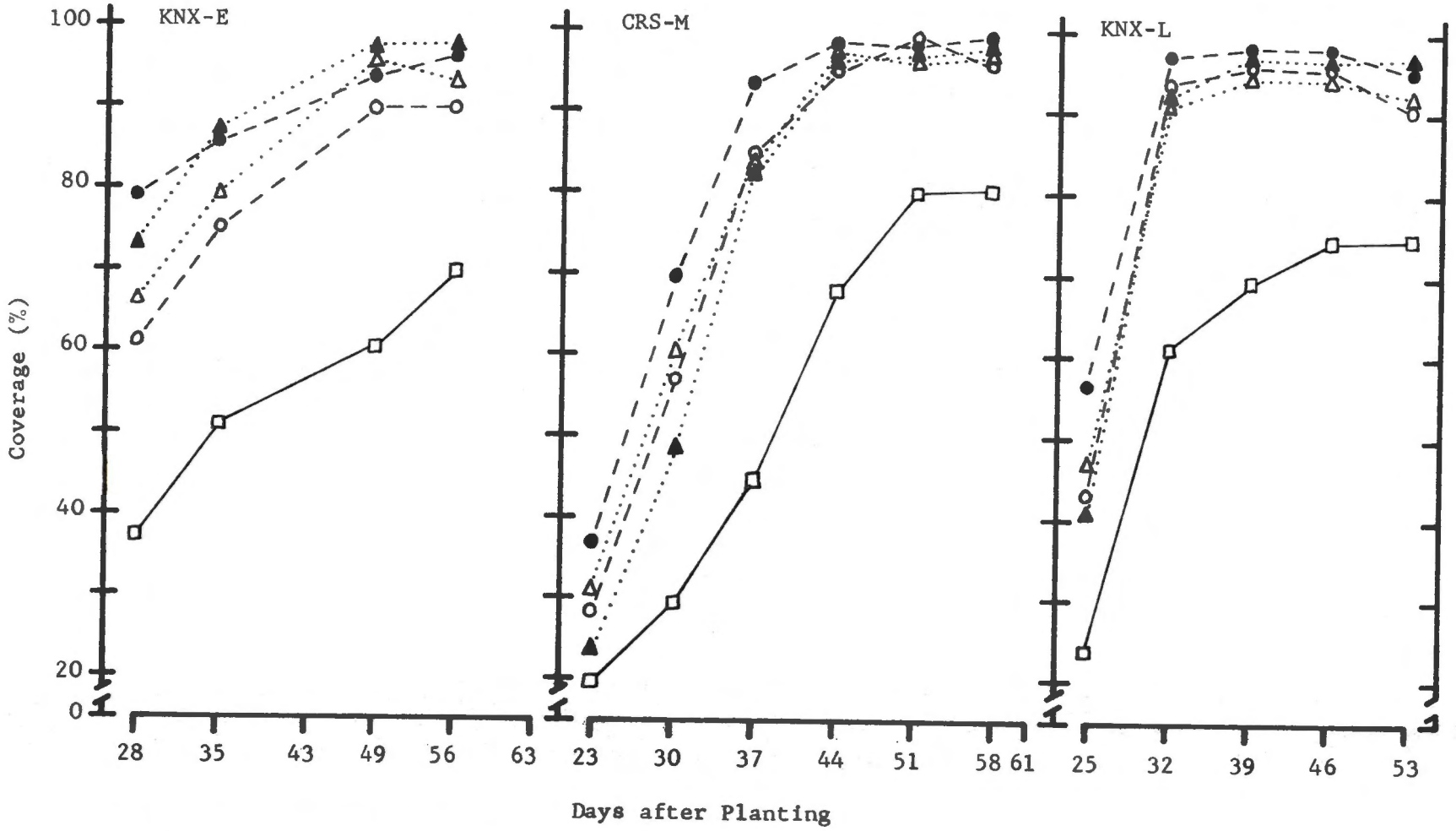


Figure 3. Spacing and Density Effects on Percentage of Canopy Coverage of Soil Surface.

Key: Density/Row Width = 100%/91 cm (□——□); 150%/30 cm (△·····△); 200%/46 cm (○— —○); 150%/15 cm (▲·····▲); 200%/23 cm (●— —●).

Table 2. Plant Stands as Percentages of the Intended Stands for the Three Snap Bean Crops.

Spacing (cm)	KNX-E	CRS-M (%)	KNX-L
91 x 4	90 a[z]	82 a	88 a
46 x 4	85 a	84 a	80 a
30 x 8	93 a	87 a	80 a
23 x 8	92 a	82 a	86 a
15 x 15	96 a	83 a	82 a

[z]Means within columns followed by a common letter do not differ at P = .05.

were necessary for adjustment of per plant measurements to a land area basis (see Table B-2, Appendix B).

Crop Productivity

Leaf numbers on a per plant basis are presented in Figure 4. Early in the growth period no differences occurred, but with the onset of inter-plant competition leaf addition was offset by abscission of older leaves to extents related more to population density than spatial arrangement. Better exposure of leaves extended into the conventional inter-row space reduced basal leaf abscission due to shading effects observed in the higher populations. Data for CRS-M illustrate this relationship best as moisture deficiency and rust infestation for KNX-E and KNX-L, respectively, accelerated rates of leaf loss. Additionally, within the CRS-M crop there was a tendency for the square spaced plants to have fewer leaves than the middle density counterpart, but this was a function of delayed emergence with the wider spaced seeds. Both middle density spacings exceeded the high density spacings in leaf numbers per plant at harvest.

Leaf areas and dry weights of lamina tissue per plant, Figures 5 and 6, respectively, also followed this population trend at CRS-M after the onset of competition. The results were less distinct at KNX-E and KNX-L where both higher densities were equivalent in the early crop and leaf areas in the middle density spacings were equivalent to the conventional at KNX-L while dry weights were intermediate.

The population trends for competition effects in these plant basis measurements are generally as would be expected (17, 34). However,

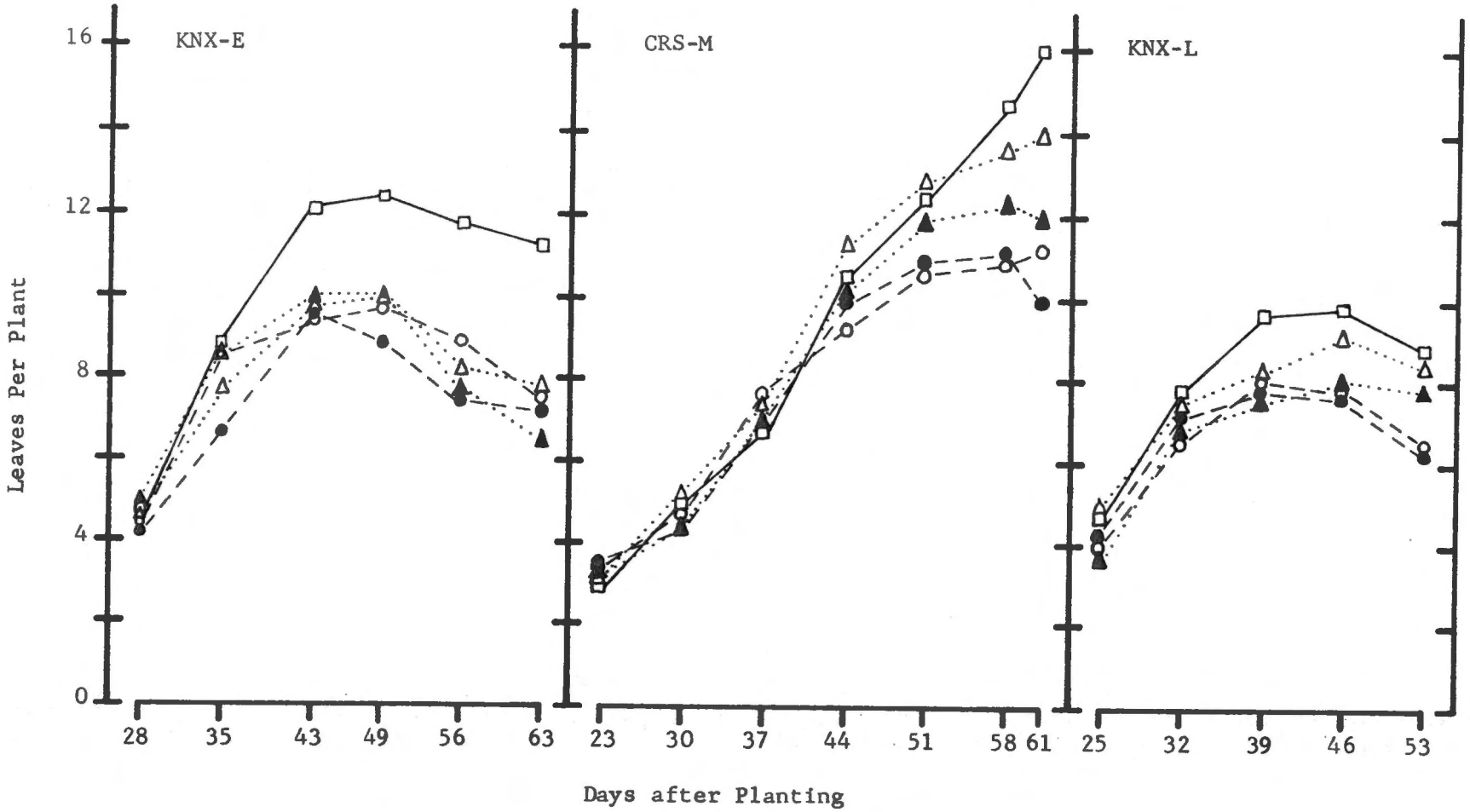


Figure 4. Spacing and Density Effects on Leaf Numbers per Plant.

Key: Density/Row Width = 100%/91 cm (□——□); 150%/30 cm (△·····△); 200%/46 cm (○— —○);
150%/15 cm (▲·····▲); 200%/23 cm (●— —●).

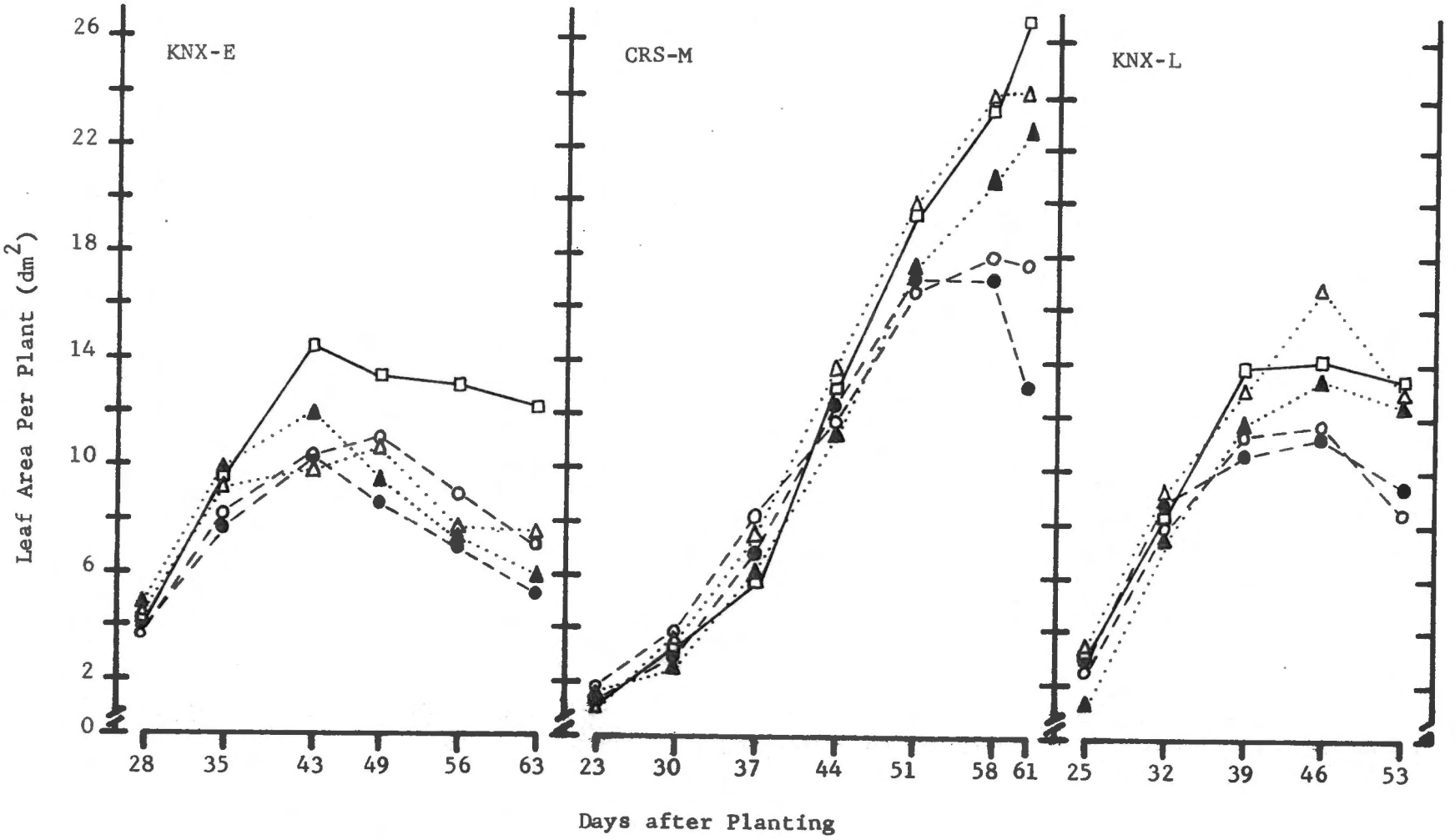


Figure 5. Spacing and Density Effects on Leaf Areas per Plant.

Key: Density/Row Width = 100%/91 cm (□——□); 150%/30 cm (△·····△); 200%/46 cm (○— —○);
150%/15 cm (▲·····▲); 200%/23 cm (●— —●).

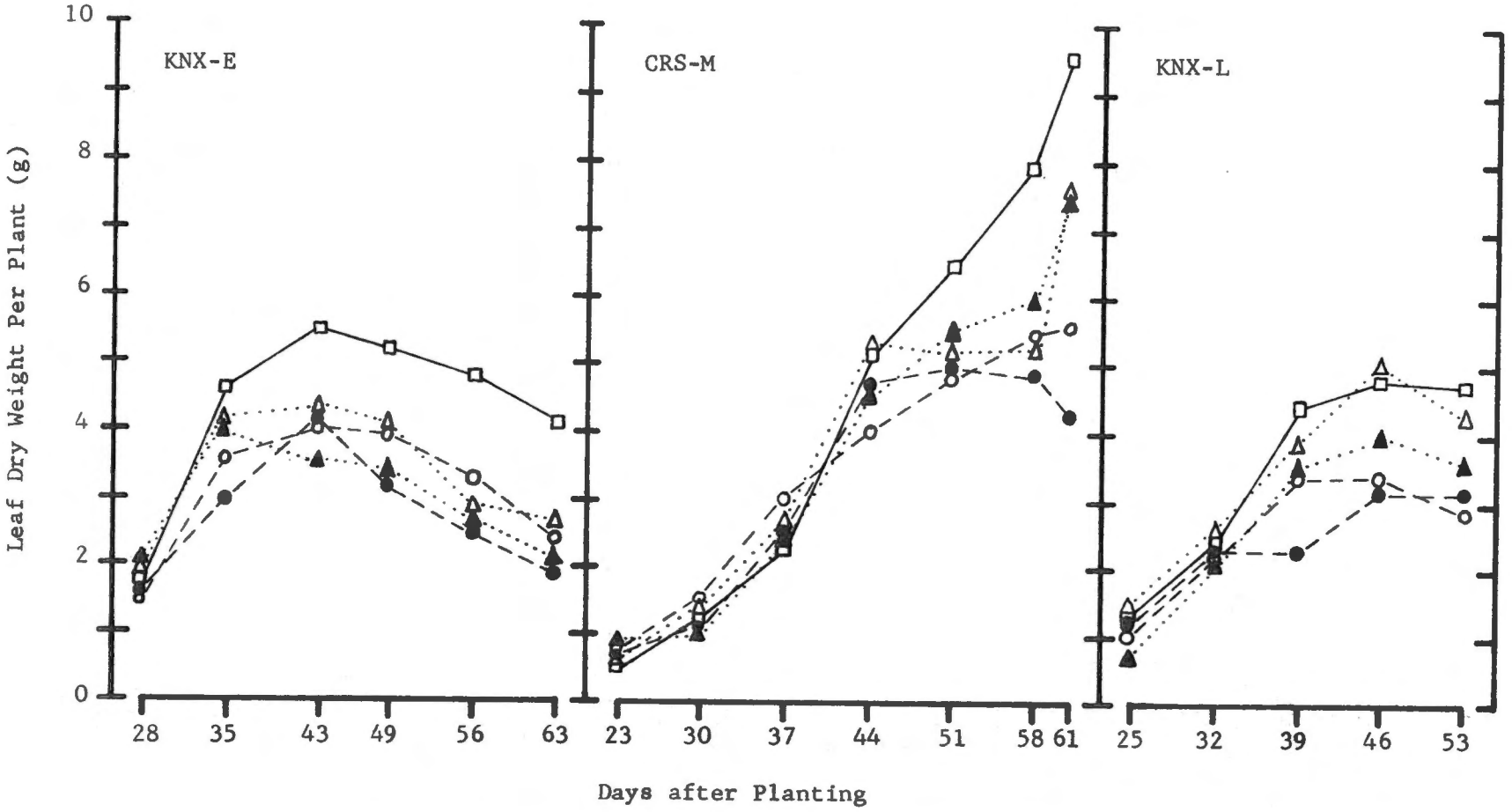


Figure 6. Spacing and Density Effects on Leaf Dry Weights per Plant.

Key: Density/Row Width = 100%/91 cm (□——□); 150%/30 cm (△·····△); 200%/46 cm (○– –○); 150%/15 cm (▲·····▲); 200%/23 cm (●– –●).

more important is the relationship to land area use efficiency. The LAI measurements presented in Figure 7 make this comparison.

Considerable variation is indicated among and within the crops as related to the climatic and disease influences in effect. Under the relatively ideal conditions at CRS-M very high values were attained by all spacings. Late season leaf losses in the other crops reduced the values at harvest which apparently had the early season potential for being comparable to the CRS-M crop had growing conditions been better. Although no data were found for snap beans, the CRS-M crop had higher maximum LAI values than generally reported for other crops (10, 18, 24, 56) but relatively equivalent to one Russian report for peas (in 18).

In each crop high levels of leaf area production in the conventional spacing did not compensate for the amount of soil surface left exposed (Figure 3, page 38). Thus, the LAI for this spacing remained lower throughout the growth periods. An exception to this is the late season values at KNX-E where this spacing had notably less reduction under conditions of moisture deficiency. It would be informative to vary spacings within the conventional density to determine if this relationship was a density or row width effect.

For CRS-M the LAI trends followed population levels until the beginning of pod filling. At that time more extensive leaf area loss in the high population not offset by new leaf expansion (Figure 5, page 42) reduced these values to or below those for the middle density spacings which maintained their rates of LAI increase. The same

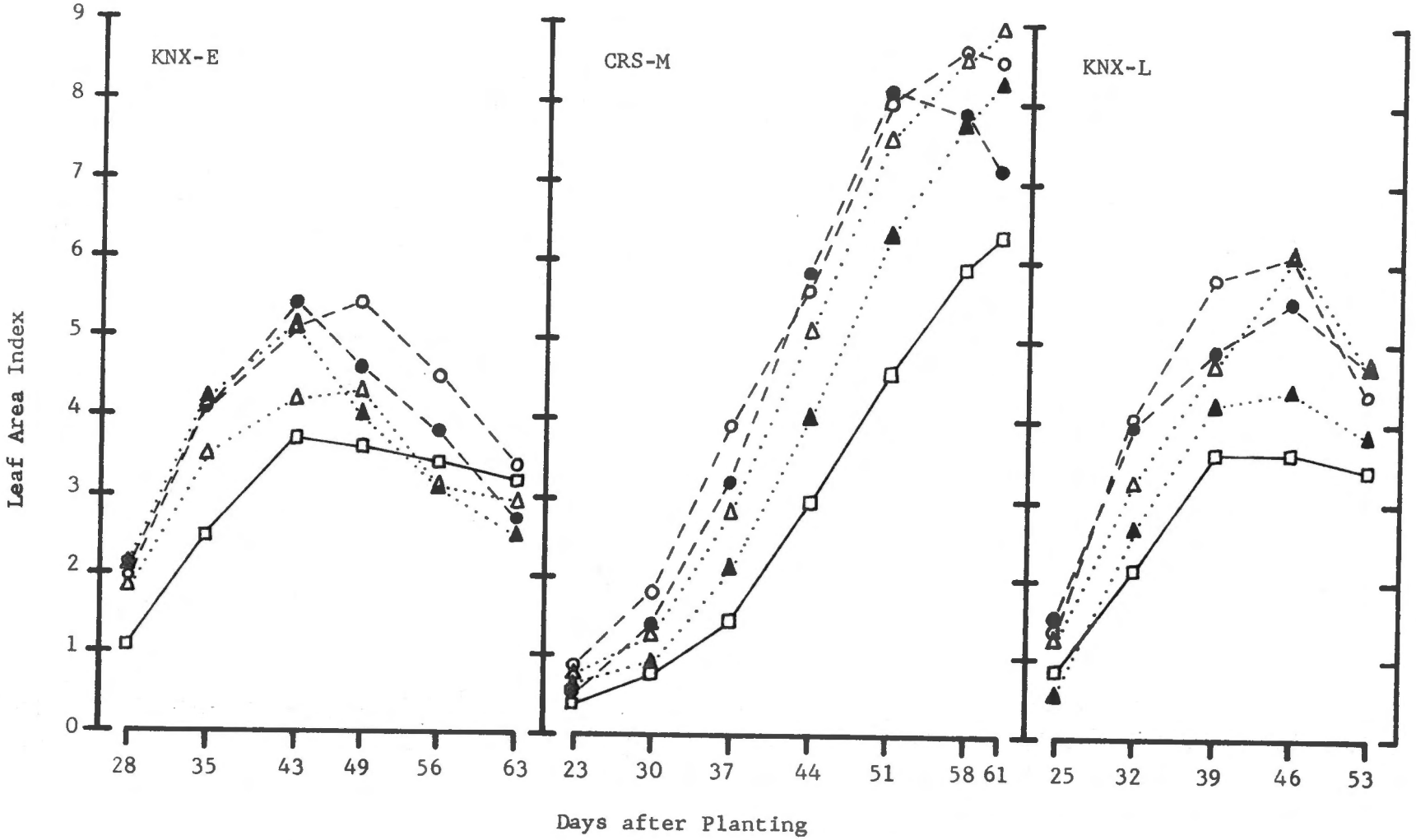


Figure 7. Spacing and Density Effects on Leaf Area Indexes.

Key: Density/Row Width = 100%/91 cm (□——□); 150%/30 cm (△·····△); 200%/46 cm (○— —○);
150%/15 cm (▲·····▲); 200%/23 cm (●— —●).

relationship occurred at KNX-L where more extensive high population leaf area loss was the result of rust infestation rather than mutual shading of leaves.

A notable relationship among the crops briefly mentioned previously is that involving establishment of seedlings in the square spacing. At KNX-E where two seedlings generally were available to break the soil surface (80 per cent seed germination rate), the seedlings became established as fast as the other spacings and had LAI development exceeding the middle density counterpart. In the later crops where only one seedling provided the emergence force, establishment was delayed slightly such that relatively lower LAI values resulted during early growth periods. However, this provided no real disadvantage as a complete canopy cover was established as fast as in the other spacings (Figure 3, page 38). This relationship may also indicate wasteful leaf area production among the other higher density spacings in regard to that needed to maximize efficiency of solar radiation interception.

Accumulation of dry matter in stem tissue (including petioles) on a per plant basis closely paralleled that for leaf lamina and is presented in Figure 8. No differences were present until the final two weeks. Extreme sampling variability at KNX-E differentiated the conventional and higher populations only. During early pod filling at CRS-M and KNX-L all spacings were equivalent, but by harvest the high density was exceeded by both lower densities.

As with the component parts the total dry weights per plant, which include pods, presented in Figure 9 follow the same trends. The

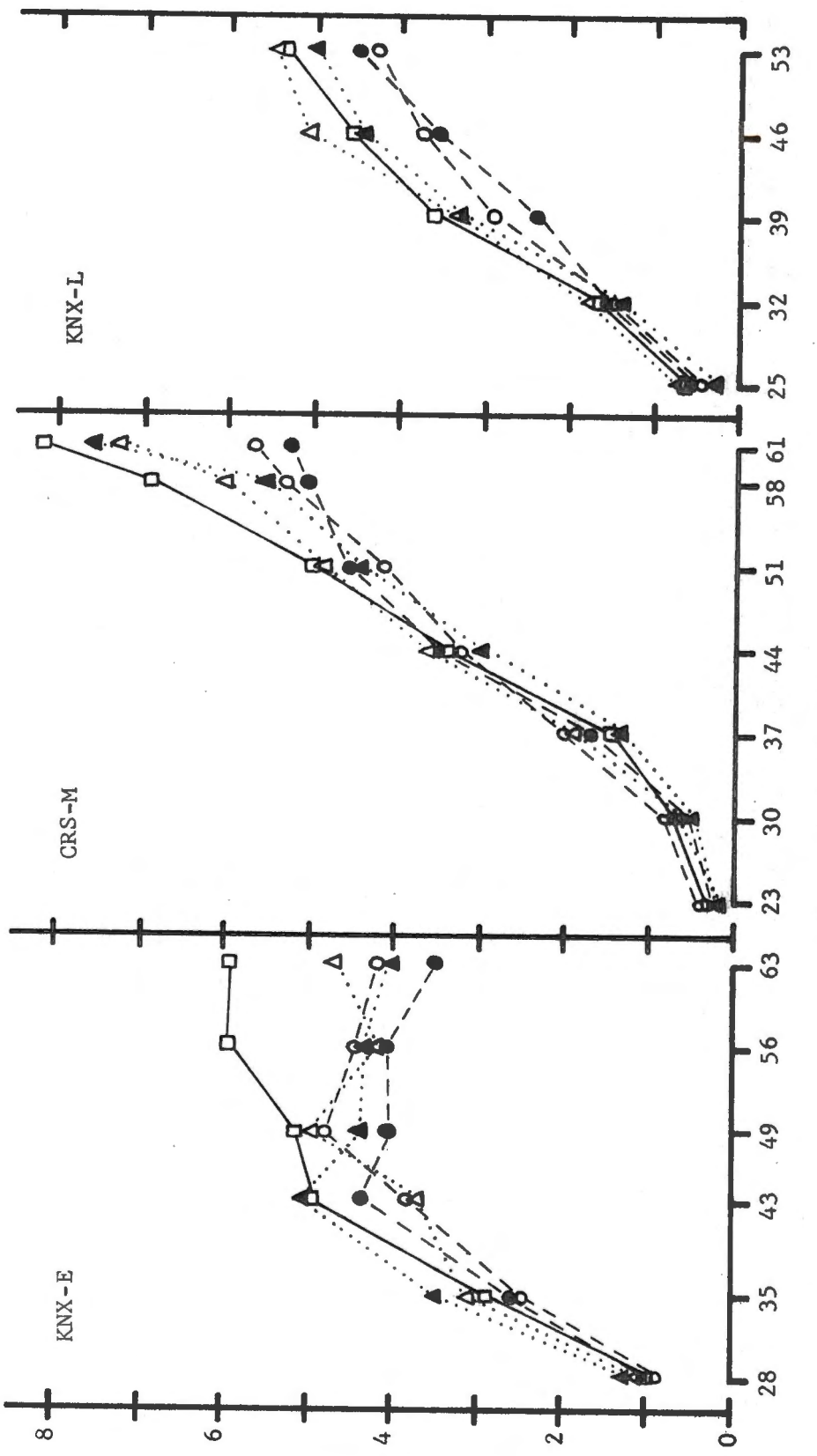


Figure 8. Spacing and Density Effects on Stem Tissue Dry Weight Accumulations per Plant.

Key: Density/Row Width = 100%/91 cm (□—□); 150%/30 cm (△····△); 200%/46 cm (○– –○);
150%/15 cm (▲····▲); 200%/23 cm (●– –●).

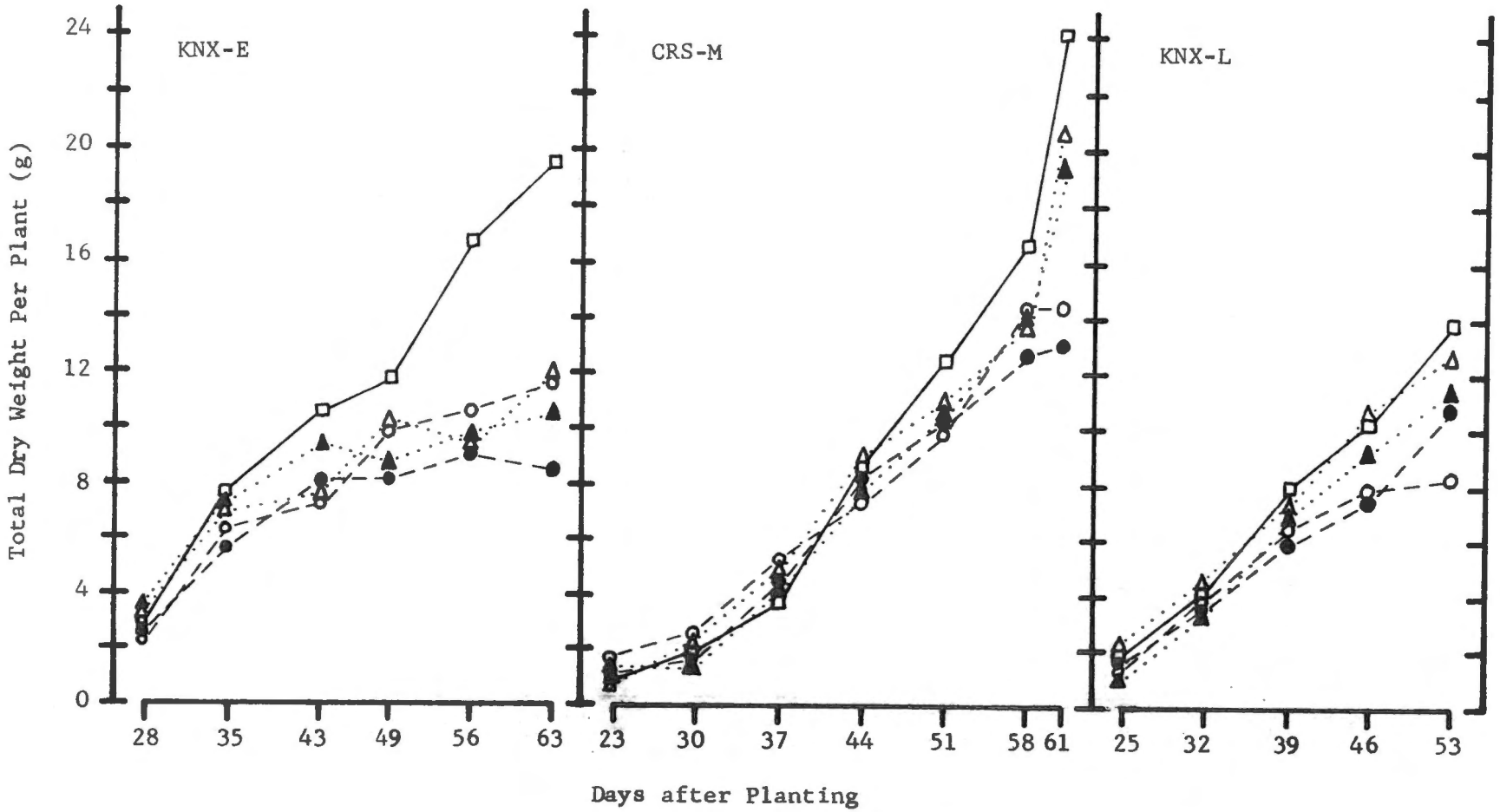


Figure 9. Spacing and Density Effects on Total per Plant Dry Weight Accumulations.

Key: Density/Row Width = 100%/91 cm (□——□); 150%/30 cm (△·····△); 200%/46 cm (○– –○); 150%/15 cm (▲·····▲); 200%/23 cm (●– –●).

significance of retained leaf productivity by the conventional spacing during the period of moisture stress at KNX-E is emphasized in these data. Less differentiation was present with the other crops. The middle and high densities at CRS-M did not differ until harvest, and at KNX-L the narrow row, high density spacing equalled the square spacing which in turn equalled the conventional.

As with leaf areas space utilization efficiency is better related on a land area basis. Total dry weights per unit area are presented in Figure 10. With the exception of the special situation in the KNX-E crop, the conventional spacing had less efficient productivity in spite of generally larger plants. At CRS-M only there was a segregation of the higher densities during the pod set and early filling stages. Leaf loss by the high density, narrow row spacing disrupted this trend during the final period, and at harvest the higher densities did not differ. The later weeks of growth at KNX-L also had no distinction among the higher density spacings.

Observations of treatment effects on LAR and its components, LWR and SLA, may provide indications of differing assimilatory capacities. LAR data (Figure 11) indicated a separation by population at the first KNX-E sampling time. Thereafter, and throughout both later crops, the highly variable data did not differentiate any effects. The single case of difference is very likely an artifact since competitional effects were not observed in the other measurements until later sampling times.

Differences in LWR values were observed until the onset of pod filling (Figure 12). At KNX-E more photosynthate was being invested in leaf tissue than other parts in a segregation by relative inter-row

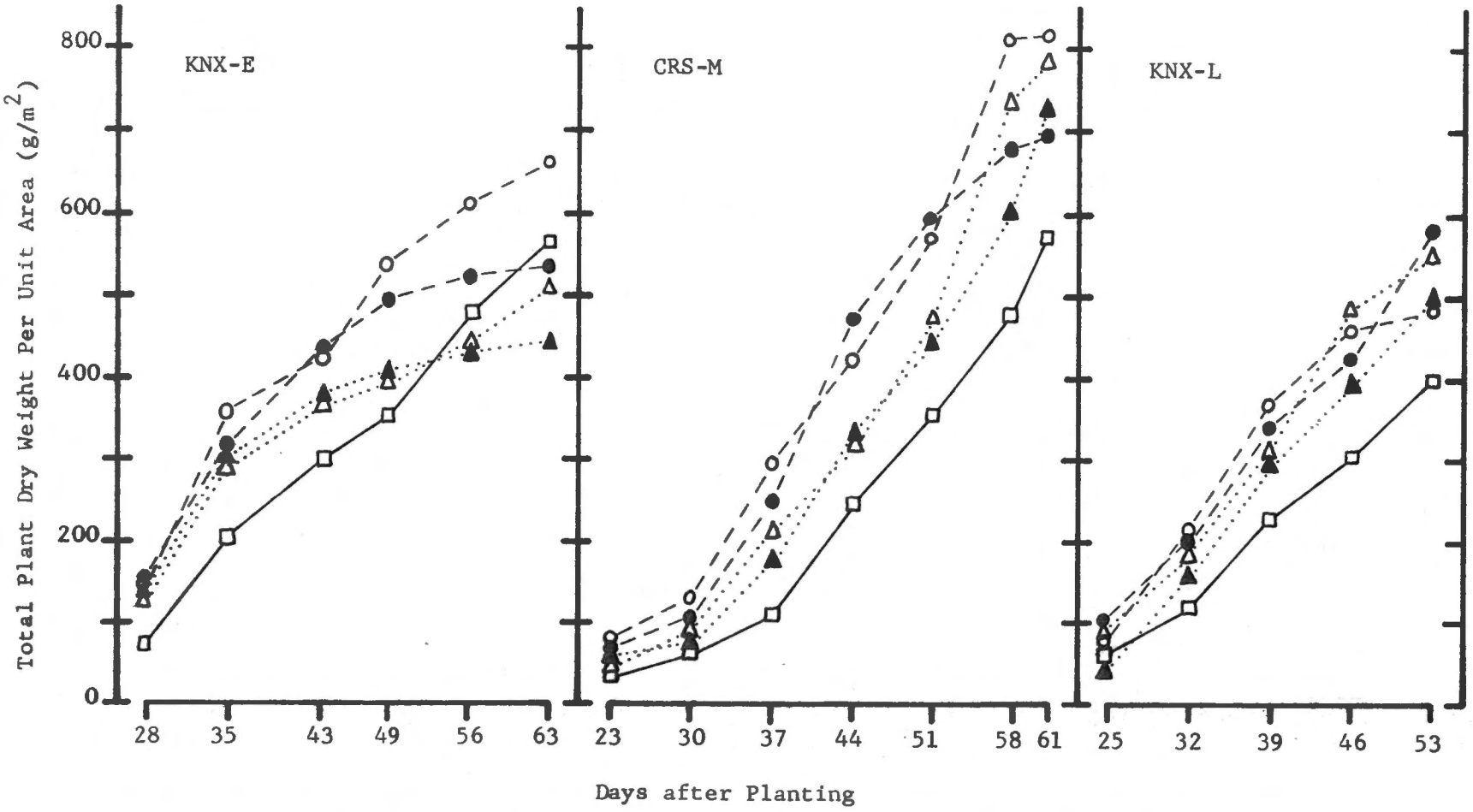


Figure 10. Spacing and Density Effects on Total Plant Dry Weights per Unit Land Area.

Key: Density/Row Width = 100%/91 cm (□——□); 150%/30 cm (△·····△); 200%/46 cm (○– –○); 150%/15 cm (▲·····▲); 200%/23 cm (●– –●).

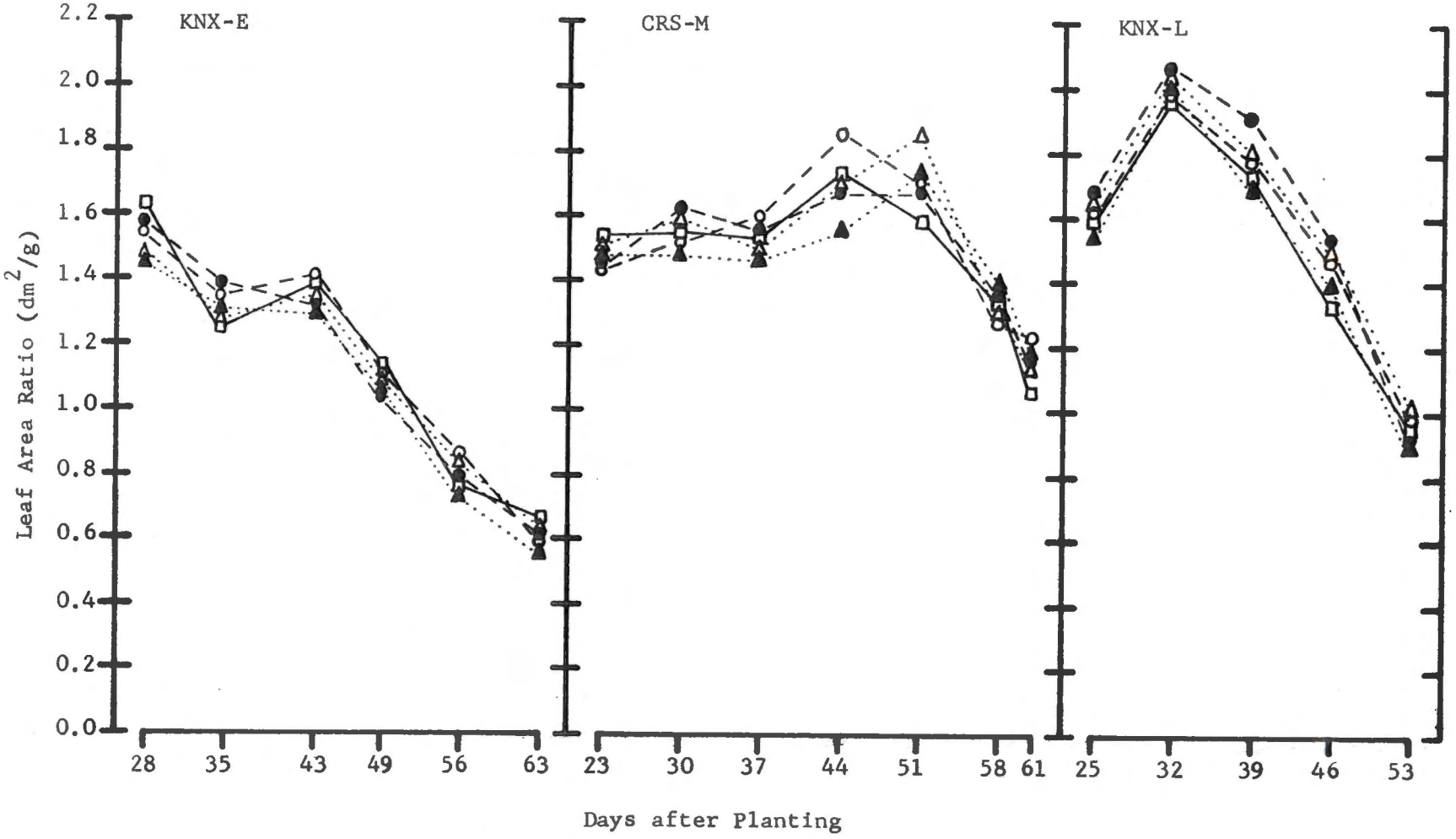


Figure 11. Spacing and Density Effects on Leaf Area Ratios.

Key: Density/Row Width = 100%/91 cm (□——□); 150%/30 cm (△·····△); 200%/46 cm (○— —○); 150%/15 cm (▲·····▲); 200%/23 cm (●— —●).

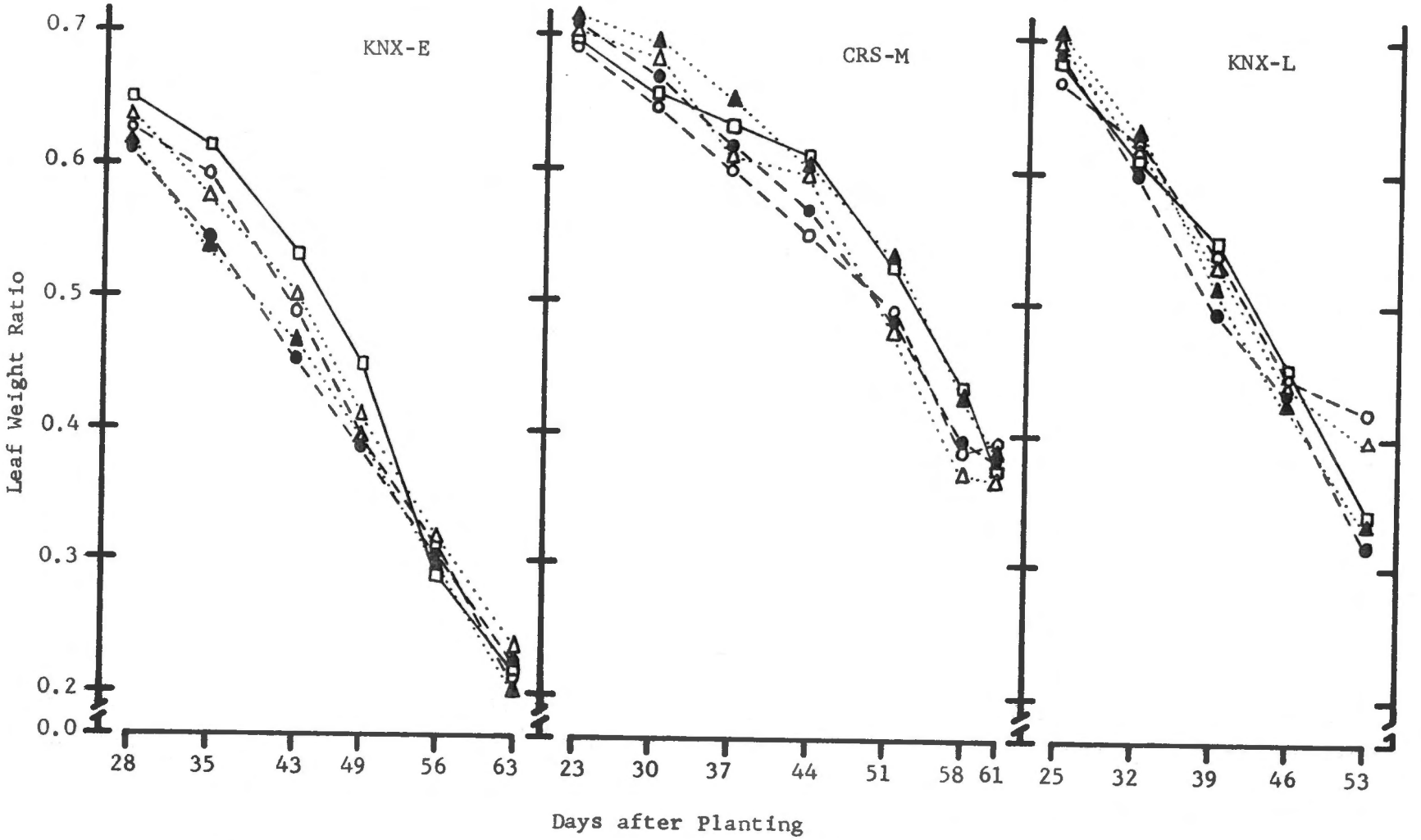


Figure 12. Spacing and Density Effects on Leaf Weight Ratios.

Key: Density/Row Width = 100%/91 cm (□——□); 150%/30 cm (△····△); 200%/46 cm (○— —○);
150%/15 cm (▲····▲); 200%/23 cm (●— —●).

space rather than density at the first three sampling times. This relationship also emerged at the third sampling at KNX-L. In contrast the fourth sampling at CRS-M did segregate by population density. In all crops the subsequent differential distribution of photosynthate was quite naturally not into leaf tissue as pods were being filled.

Values for SLA (Figure 13) exhibited more variability than any other relationship studied. No differences were found in the KNX-E crop, and differences which emerged during pod set and filling disappeared by harvest at CRS-M and KNX-L. For these two crops the only general relationship was for leaves of plants in the conventional spacing to be slightly thicker and thus have lower values for SLA. The high peaks and rapid declines only serve to indicate that the larger basal leaves were being lost.

Because random samples within individual plots may occasionally have lower plant weights than the previous sample and the resultant negative values for growth analysis relationships are not realistic, data for mean CGR, RGR, and NAR values were determined from treatment means for the growth analysis formula components in Table B-2, Appendix B. As such, these data were not subject to statistical analysis.

Mean CGR values presented in Figure 14 prohibit interpretation with the extreme vaiation present. Mean RGR and NAR values (Figures 15 and 16, respectively) are little better except that the data for CRS-M indicate that an increase in rates occurred which was then followed by a rapid decline observed in all three crops. Relatively stable rates

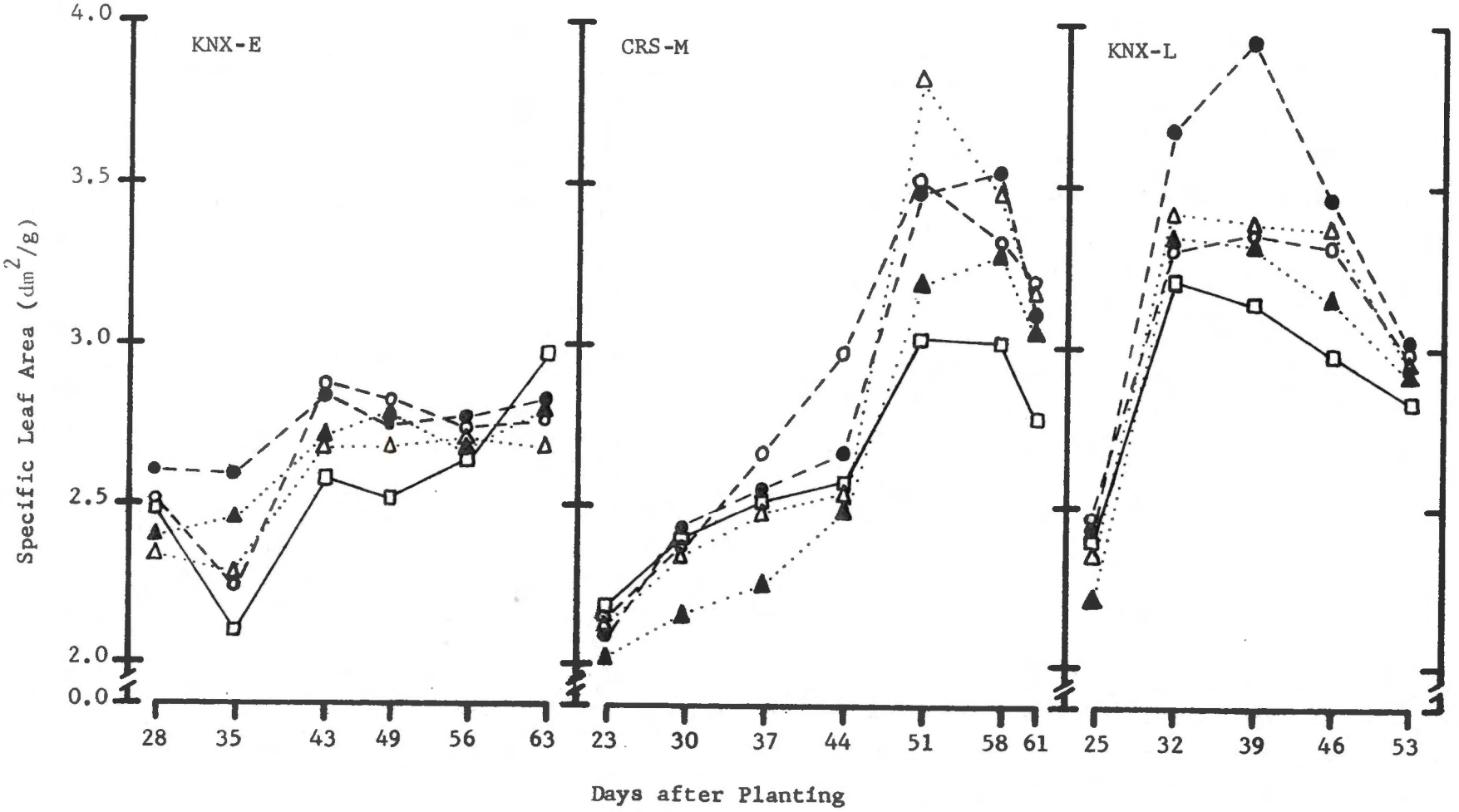


Figure 13. Spacing and Density Effects on Specific Leaf Areas.

Key: Density/Row Width = 100%/91 cm (□—□); 150%/30 cm (△···△); 200%/46 cm (○— —○); 150%/15 cm (▲···▲); 200%/23 cm (●— —●).

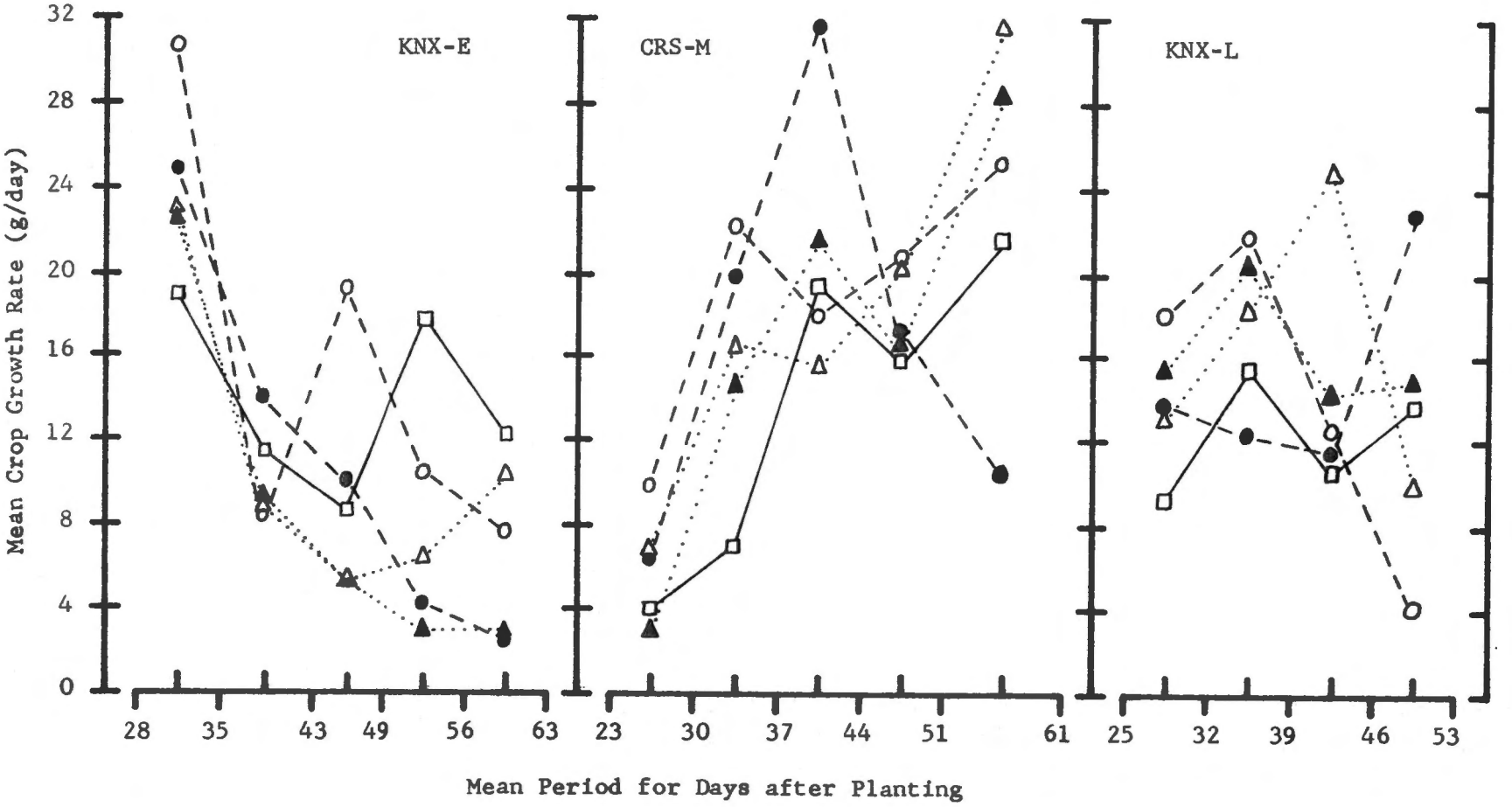


Figure 14. Spacing and Density Effects on Mean Crop Growth Rates.

Key: Density/Row Width = 100%/91 cm (□——□); 150%/30 cm (△·····△); 200%/46 cm (○— —○); 150%/15 cm (▲·····▲); 200%/23 cm (●— —●).

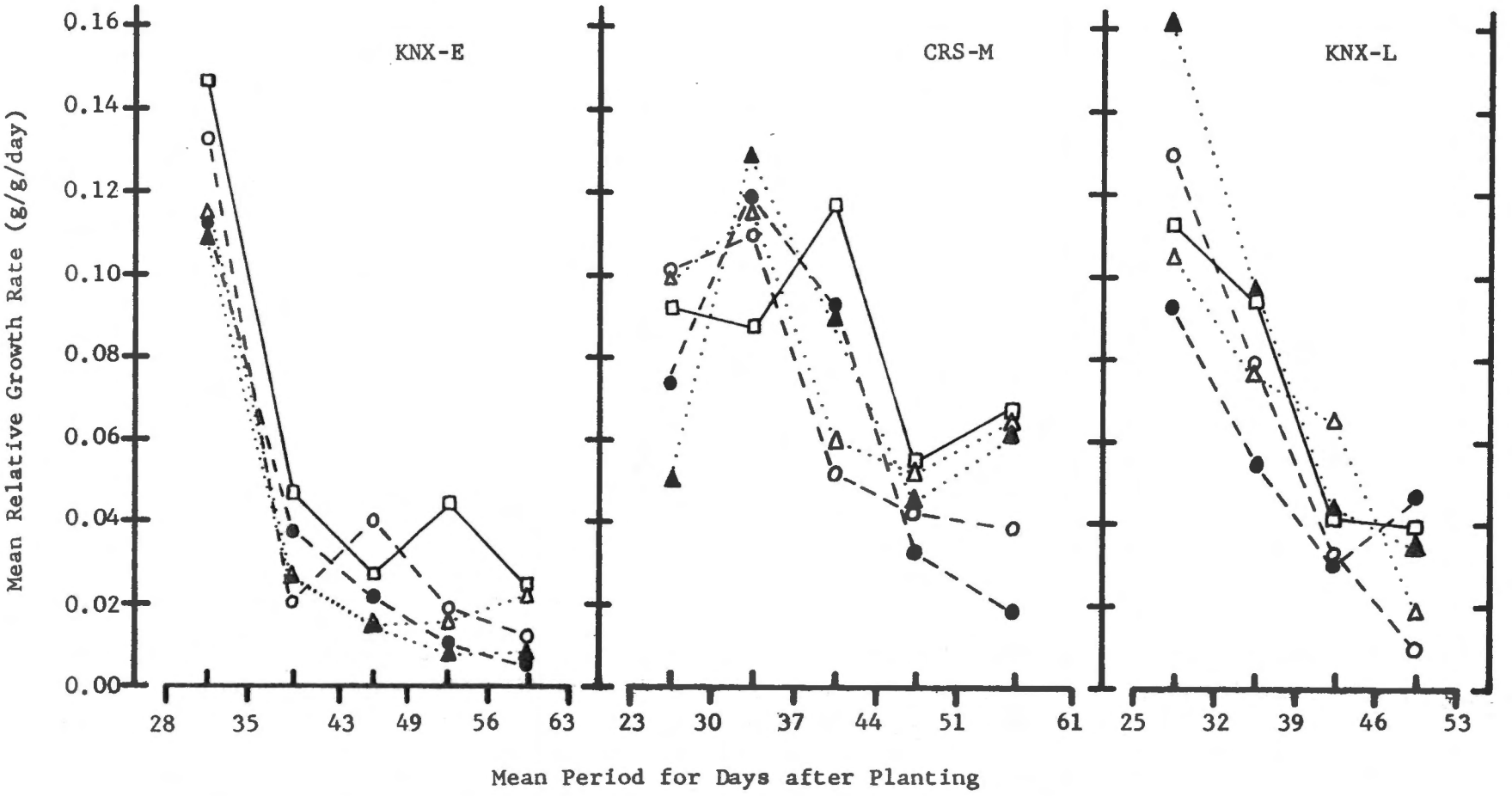


Figure 15. Spacing and Density Effects on Mean Relative Growth Rates.

Key: Density/Row Width = 100%/91 cm (□——□); 150%/30 cm (△·····△); 200%/46 cm (○——○); 150%/15 cm (▲·····▲); 200%/23 cm (●——●).

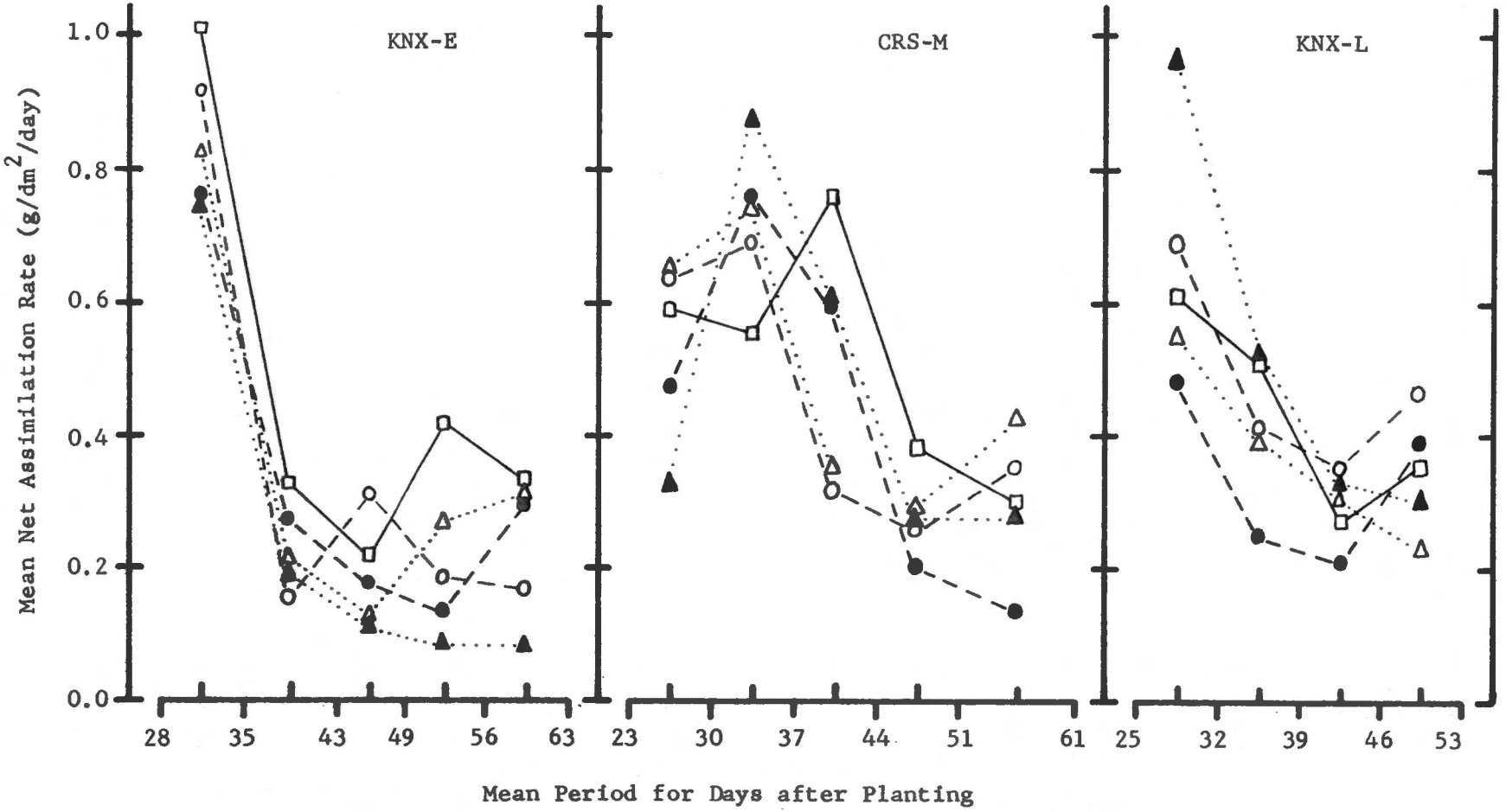


Figure 16. Spacing and Density Effects on Mean Net Assimilation Rates.

Key: Density/Row Width = 100%/91 cm (□——□); 150%/30 cm (△····△); 200%/46 cm (○— —○); 150%/15 cm (▲····▲); 200%/23 cm (●— —●).

then prevailed through harvest. No differences among spacing treatments are evident in these data presentations.

To provide a clearer view of possible relationships in these rates, the crops were separated into pre- and post-flowering periods. Mean rates for these periods are presented in Table 3.

In these analyses each crop behaved differently, and indicated differences must be taken as suggestions only. Mean CGR values in general were only slightly higher in the high density spacings until flowering, but later the suggested differences related to row width rather than density at KNX-E while only one of the two high density spacings was lower through pod filling in the other crops. Within each crop, pre-flowering RGR values did not differ appreciably, and only the KNX-E crop indicated a later trend which was identical to the CGR trend. At KNX-E mean NAR was inversely related to density prior to bloom and was later associated with the relative row widths. No pattern is evident for the other crops.

In general these data indicate the extensive variability present among plant samples in a snap bean crop. As leaf area measurement techniques have been improved the capability for handling and accurately measuring larger samples has also improved but is still dependent on the labor supply and time available for separating the plant parts and making the necessary measurements.

With the growth variability observed in these crops, generalization requires caution. For the various plant components the trends follow generally expected paths. On a per plant basis leaf areas and

Table 3. Spacing Treatment Effects on Crop Growth Rates, Relative Growth Rates, and Net Assimilation Rates Expressed as Means of Pre- and Post-Flowering Periods.

Location	Spacing (cm)	CGR (g/day)		RGR (g/g/day)		NAR (g/m^2/day)	
		I[z]	II	I	II	I	II
KNX-E	91 x 4	13.2	15.0	.074	.034	6.3	4.8
	46 x 4	18.9	9.1	.064	.015	5.6	2.3
	30 x 8	12.5	8.4	.052	.019	4.3	2.5
	23 x 8	16.5	3.2	.058	.006	5.1	0.9
	15 x 15	12.5	2.8	.050	.007	4.2	0.9
CRS-M	91 x 4	10.0	19.3	.099	.050	6.5	3.6
	46 x 4	16.7	23.4	.087	.039	5.6	2.8
	30 x 8	13.1	27.4	.092	.053	5.4	3.5
	23 x 8	19.3	13.2	.095	.023	6.3	1.8
	15 x 15	13.1	23.7	.089	.047	5.9	3.4
KNX-L	91 x 4	12.4	12.3	.102	.040	6.0	3.2
	46 x 4	20.0	8.5	.103	.020	4.8	1.5
	30 x 8	15.9	17.1	.090	.041	5.2	3.1
	23 x 8	13.0	17.1	.072	.038	3.9	3.1
	15 x 15	18.0	14.7	.138	.038	8.3	3.0

[z] I = pre-flowering period; II = post-flowering period.

component and total weights segregated primarily between conventional and higher densities. With more space available for each plant a major part of the growth was involved with filling the open area. Thus, when considering productivity per unit of land area, the conventional spacing represented inefficiency of space utilization. Although both higher densities utilized available space efficiently, it was only under the more favorable conditions at CRS-M that the high density gave better production efficiency than the middle density spacings.

Although very high values for LAI were obtained at CRS-M, no suppression of dry matter accumulation was observed except in relation to leaf losses by the high density spacings just prior to harvest. Shibles and Weber (56) noted that soybeans did not define an "optimum LAI" with populations having lower LAI values than observed with snap beans here. It is possible that an "optimum LAI" was surpassed in these two high density spacings, and an anatomical adjustment of assimilatory capacity was in effect, but more evidence is needed from a higher population to draw a conclusion. The question also arises as to whether the dry matter changes were a function of leaf mass loss or assimilatory capacity loss. Since leaf weight per plant declined in only one of these high density spacings while stem weights continued to increase, it is doubtful that the shed leaves were making a significant contribution to the plants' photosynthate supplies. This fact would indicate an "optimum LAI" of 8 to 8.5. However, equally high LAI values were also attained by the middle density spacings at harvest. Whether these would also decline is unimportant since the economic product was already obtained. Thus,

whether an "optimum LAI" is defined for snap beans is probably unimportant in terms of economic yield production in this relatively short term crop. On the other hand, difficulties with spray penetration of all canopies at CRS-M would indicate generally excessive LAI in terms of ease of cultural operations and possible adverse effects on pod quality.

When adverse growing conditions due to water stress or disease were present, leaf area losses were significant for all but the conventional spacing. This fact may present an advantage for retaining the present cultural system, but total dry matter accumulations by the higher densities were not reduced to an extent which would negate their better growth advantages had the adversity not been present.

Data in Table 3, page 59, for mean RGR and NAR values indicate a general reduction in growth rate per unit of dry matter or assimilatory area during pod set and filling. The change in rates was not associated with either spatial arrangement or population, but given similar rates the greater leaf areas and plant weights at higher than conventional densities would favor productivity in those systems. However, that the degree to which those systems were favored was proportional to the respective density was not indicated.

The conventional and wide row, middle density spacing had relatively constant mean CGR values before and after flowering. The other spacings had slightly increased or stable rates after flowering under favorable growing conditions and stable or decreased rates under less favorable conditions. Eastin and Gritton (18) had indicated increased CGR from flowering through maturity with peas as LAI and LAR decreased.

This indicated an improved efficiency in assimilate production concluded to be a function of the assimilate sink size. In these snap bean studies this relationship was not fully evident. LAR values decreased similarly for all spacings and crops during pod filling, but under favorable conditions increases in LAI continued. Changes in CGR depended more on how LAI changed between the pre- and post-flowering periods. With continued LAI increases, the CGR also increased, but LAI decreases also decreased CGR by proportions directly related to the leaf area loss. Thus, the improved efficiency during maturation observed in peas was not indicated for the snap bean crops.

Economic Yield Productivity and Quality

Harvesting at KNX-E when an estimated 30 per cent of the pods had reached sieve size 5 provided no indications of maturation differences among treatments. Also, the estimates of pod distribution made on a few plants was never very accurate when applied to the harvested area data. Thus, single day harvests were utilized for the succeeding crops.

Yield and grade data in Table 4 illustrate that the optimum harvest time was passed in all cases. Thus, the reported yields are slightly higher than if harvested at the more desirable stage of development, but it is doubtful that the treatment relationships were affected.

The numbers of marketable pods produced per unit area differed only at CRS-M. In comparison with the other crops, it is evident that adverse growing conditions did not greatly affect the number of pods reaching marketable size. Rather it appeared that more favorable conditions extended vegetative and flowering periods. General observations

Table 4. Spacing Treatment Effects on Snap Bean Pod Yields and Grade Distributions.

Location	Spacing (cm)	Marketable Pods (m^{-2})	Pod Weight >4 Sieve (%)	Adjusted Yield[z] (t/ha)	Yield Increase[y] (%)
KNX-E	91 x 4	134 a[x]	48.7 a	4.73 c	----
	46 x 4	169 a	37.0 a	6.40 ab	35.3
	30 x 8	146 a	36.7 a	6.58 a	39.1
	23 x 8	144 a	38.0 a	5.92 b	25.2
	15 x 15	161 a	39.5 a	6.89 a	45.7
CRS-M	91 x 4	97 c	37.6 a	6.57 b	----
	46 x 4	176 a	45.0 ab	8.90 a	35.5
	30 x 8	146 b	50.0 a	6.46 b	-1.7
	23 x 8	182 a	44.1 ab	9.67 a	47.2
	15 x 15	151 b	35.6 b	9.91 a	50.8
KNX-L	91 x 4	130 a	46.2 a	6.14 b	----
	46 x 4	159 a	41.2 a	7.07 a	15.1
	30 x 8	139 a	48.0 a	6.76 a	10.1
	23 x 8	125 a	38.9 a	5.86 b	-5.0
	15 x 15	147 a	37.2 a	7.14 a	16.3
KNX-E	Combined	151 a	40.0 a	6.11 b	36.3
CRS-M	Combined	151 a	42.5 a	8.30 a	33.0
KNX-L	Combined	140 a	42.3 a	6.59 b	9.1
Combined	91 x 4	120 b	44.2 a	5.81 c	----
	46 x 4	168 a	41.1 a	7.45 a	28.2
	30 x 8	144 a b	44.9 a	6.60 b	13.6
	23 x 8	151 a	40.3 a	7.15 ab	23.1
	15 x 15	153 a	37.4 a	7.98 a	37.3

[z]Yields adjusted by analysis of covariance and grade weight distribution.

[y]Percentage of yield increase over conventional spacing.

[x]Means within groups and columns followed by a common letter do not differ at P = .05.

suggested greater numbers of newly set and pin-size pods in the CRS-M crop. Encroachment of vegetative growth into the period of economic yield development has been observed in higher than conventionally spaced soybeans (57), but in these snap beans, the growing conditions affected the conventional spacing as well.

Under favorable conditions, the number of marketable pods harvested was essentially proportional to the crop density. However, if conditions were less than satisfactory, better growth relations observed in the conventional spacing produced pod numbers equivalent to the higher densities.

Only within the CRS-M crop were maturity differences indicated. There it was suggested that the wide row, middle density spacing matured earlier than its square counterpart and the conventional. As neither Knoxville crop indicated maturation rate differences, it is doubtful that the CRS-M difference was real. However, because minor differences were present, it was believed that adjusting individual plot yields for grade distribution would better reveal possible treatment effects. Analysis of covariance was used for this purpose.

These data in Table 4 indicated that within each crop the wide row, high density and square, middle density spacings were consistently superior to the conventional spacing. Reasons why the wide row, middle density spacing at CRS-M yielded low were not apparent, but at KNX-L the narrow row, high density arrangement appeared more severely affected by rust.

The low yield from the conventional spacing at KNX-E is a notable contrast to the biological productivity data. Better productivity retention under moisture stress did not provide for higher economic productivity. Pod numbers were lowest for this spacing but not significantly different which possibly indicates greater plant and pod dehydration at harvest.

Over all the crops the wide row, high density and square, middle density spacings provided 28 and 37 per cent yield improvements, respectively, over the conventional. Except for the late crop the narrow row, high density spacing also gave a satisfactory improvement. Because of more variability the wide row, middle density spacing proved only marginally satisfactory for recovery of the additional costs of the higher plant population.

No association between yield and any of the growth analyses could be found.

A component of pod quality was assessed with color measurements of pods from the CRS-M and KNX-L harvests which are summarized in Table 5. Considerable data variability produced differences between the crops only with pods from KNX-L slightly more yellow.

As mentioned previously, the canopy density can affect pod quality relative to the efficiency of spray penetration. Preliminary tests on bottom soil had incidence of white mold, but this disease was not encountered during 1974. However, the extreme canopy development at CRS-M allowed considerable insect and some disease damage of pods to occur.

Table 5. Spacing Treatment Effects on Hunter Color/Difference Measurements of Harvested Pods from CRS-M and KNX-L.

Location	Treatment	L	-a	b	a/b
Combined	91 x 4	37.7 a[z]	6.9 a	14.2 a	.485 a
	46 x 4	36.8 a	6.7 a	13.8 a	.483 a
	30 x 8	38.4 a	7.1 a	14.5 a	.485 a
	23 x 8	37.8 a	7.4 a	14.4 a	.509 a
	15 x 15	37.2 a	6.7 a	13.8 a	.481 a
CRS-M	Combined	36.6 a	6.6 a	13.1 b	.499 a
KNX-L	Combined	38.6 a	7.5 a	15.2 a	.492 a

[z]Means within groups and columns followed by a common letter do not differ at P = .05.

Under conditions of high moisture and excessive growth, provisions for access by pest control equipment will be necessary for high density production.

Nutritional Status

Plant nutrient analyses were made to assess differences in plant uptake of broadcast fertilizer applied at recommended rates adjusted to the middle population density.

Data for petiole levels of protein-N, P, K, Ca, and Mg are presented in Table 6. The primary concern in these analyses was that macronutrient contents of the high density plants would not lower their productivity. Equivalent contents among the higher density spacings indicate that this goal was achieved for all five elements. Thus, it is not necessary to make fertilizer applications which are fully proportional to the density increase, but the economical proportionality for banded applications, when feasible, does need study.

Levels of protein-N at KNX-E were somewhat lower than with the other crops. This is likely a result of turning under the vegetative cover on this plot area less than a month before planting while three months elapsed before the later crop was planted in the neighboring area. No real indications of N deficiency were noted with the higher densities, but plants were darker green in the conventional spacing and along the periphery of each higher density plot. This color difference was assessed to luxury consumption rather than a deficiency condition. Neither of the later crops exhibited this color difference.

Table 6. Spacing Treatment Effects on Petiole Contents of Five Elements Averaged Across Individual Sampling Dates.

Crop	Spacing (cm)	N	P	K	Ca	Mg
				(%)		
KNX-E	91 x 4	1.54 a[z]	0.28 a	3.91 a	1.80 a	0.61 a
	46 x 4	1.41 b	0.28 a	2.81 b	1.86 a	0.67 a
	30 x 8	1.33 b	0.29 a	2.92 b	1.86 a	0.63 a
	23 x 8	1.29 b	0.30 a	2.99 b	1.79 a	0.60 a
	15 x 15	1.32 b	0.31 a	3.18 b	1.75 a	0.56 a
CRS-M	91 x 4	2.47 a	0.27 a	3.97 a	2.71 a	0.48 a
	46 x 4	2.18 b	0.28 a	3.17 b	2.73 a	0.46 a
	30 x 8	2.32 b	0.27 a	3.41 b	2.81 a	0.46 a
	23 x 8	2.20 b	0.29 a	3.52 b	2.74 a	0.43 a
	15 x 15	2.47 a	0.30 a	3.45 b	2.90 a	0.48 a
KNX-L	91 x 4	2.15 a	0.22 a	3.44 a	2.32 a	0.88 a
	46 x 4	2.12 a	0.23 a	3.43 a	2.25 a	0.74 b
	30 x 8	2.19 a	0.24 a	3.29 a	2.13 a	0.83 a
	23 x 8	2.15 a	0.26 a	3.82 a	2.10 a	0.73 b
	15 x 15	2.22 a	0.26 a	3.70 a	2.19 a	0.77 b

[z]Means within groups and columns followed by a common letter do not differ at P = .05.

No differences among crops or spacing treatments were observed for the other plant parts sampled at harvest. As a result, only the combined data are presented in Table 7. Only relative comparisons may be made to the published optimum levels for leaves (35, 61) as samples utilized here involved composites of each part. However, in general the leaf levels of N and K were high while the other elements were near the optimum.

II. ENVIRONMENTAL RELATIONSHIPS

Light Attenuation

Data on the percentage of incident light intensity reaching the soil surface are presented in Table 8. KNX-E data are not included as the differing stages of canopy development on a given day precluded meaningful interpretation.

For all treatments canopy densities directly above the row were equivalent in light interception. In contrast the inter-row measurements revealed the extent of canopy closure with attentuation an inverse function of the row width effect on closure rather than density. At CRS-M closure was incomplete in the three widest rows at the 37 day measurement, but only the conventional density canopy remained open two weeks later. After 47 days at KNX-L the wide row, high density plots had a closed canopy and high LAI, but midway between rows the peripheral canopy density was insufficient to reduce light penetration by half.

With canopy closure in soybeans Sakamoto and Shaw (53) found light interception limited to the top of the canopy. This might also apply to

Table 7. Contents of Five Elements of Plant Parts at Harvest Averaged Across Locations and Spacing Treatments.

Tissue	N	P	K	Ca	Mg
			(%)		
Petioles	1.73	0.24	2.77	2.53	0.76
Leaves	3.77	0.42	1.98	3.92	0.91
Stems	2.26	0.31	1.97	0.72	0.48
Pods	3.41	0.48	2.77	0.80	0.37

Table 8. Spacing Treatment Effects on Plant Canopy Attenuation of Light Reaching the Soil Surface.[z]

Position	Spacing (cm)	CRS-M 37 Days[y]	CRS-M 51 Days	KNX-L 47 Days
		(%)		
Intra-Row	91 x 4	1.8 a[x]	1.3 a	2.0 a
	46 x 4	2.9 a	1.9 a	4.0 a
	30 x 8	2.8 a	2.2 a	3.2 a
	23 x 8	2.1 a	1.0 a	3.4 a
	15 x 15	3.8 a	1.9 a	3.8 a
Inter-Row	91 x 4	98.1 a	99.0 a	98.4 a
	46 x 4	84.6 a	4.2 b	58.4 b
	30 x 8	36.1 b	2.3 b	16.5 c
	23 x 8	5.9 c	1.3 b	6.6 c
	15 x 15	12.4 c	3.6 b	4.0 c

[z]Expressed as percentage of light intensity above the canopy reaching the soil surface.

[y]Days after planting.

[x]Means within groups and columns followed by a common letter do not differ at P = .05.

snap beans, especially with the relatively high LAI values observed in these crops. In this situation, the light environment of the conventional row having incomplete canopy closure might enhance productivity as was found for skip-row planted soybeans (45). This was observed on a per plant basis (Figure 9, page 48) but not on a unit area basis (Figure 10, page 50).

Because the snap bean canopy is rather low and dense, intra-canopy light measurements would require a much smaller sensor than used here. Although these measurements were not made, it is speculated that light penetration at all but the very high LAI levels was sufficient for most of the lower leaves to contribute photosynthates. This would result from the extensive phototropic response of bean leaflets which Wien and Wallace (72) have characterized. Under high light intensities, the leaflets tend to rotate to an orientation which decreases their exposure. At the same time, the less exposed lower leaves would be oriented for maximum exposure. Although soybean leaflets also orient themselves in response to light direction and intensity (29), the benefits from opening the canopy surface of this large-leaved snap bean cultivar would likely be greater. Thus, while soil level intensities were low under the dense canopies, intra-canopy light relations in the higher densities could partially offset the better peripheral exposure of the conventional spacing with this snap bean cultivar.

Leaflet orientation to light may also suggest that a direct determination of LAI does not present a clear indication of interception capabilities in crops expressing this phenomenon.

Canopy CO_2

One measurement of canopy CO_2 concentrations at KNX-E and two at KNX-L are presented in Table 9. Although differences in mean CO_2 levels were observed, they were not significant. This lack of difference probably occurred because CO_2 depletions are readily restored from soil respiration and from equilibration with the ambient air at these relatively low plant heights. Also, these measurements were made in less dense canopies than were present at CRS-M, but sampling was not possible for that crop.

Soil Moisture

Although snap bean roots penetrate beyond 60-cm depths (51), most water absorption occurs in the upper zones. As preliminary studies indicated better maintenance of surface moisture under the denser canopies, only the top 15-cm were sampled. These data are presented in Table 10.

Initial observations at KNX-E of intra- and inter-row samples revealed no differences among treatments or positions. Subsequent inter-row samples in the other crops also did not differ.

As suggested for wind-sheltered snap beans (51, 52) it is possible that transpiration losses from the fuller canopies with little soil surface evaporation balanced the total evapotranspiration of the open, conventional canopies. This is especially true with these crops since higher populations were involved with the closed canopies thereby creating greater moisture demands even if less than proportional to the population increase (74). If upper level soil moisture was retained by the closed canopy, a varied spacing of the conventional density capable of canopy closure would be needed for verification.

Table 9. Spacing Treatment Effects on Canopy CO_2 Levels.

Spacing (cm)	CO_2 (ppm) KNX-E[z] 44 Days[y]	KNX-L 40 Days	KNX-L 46 Days
91 x 4	290 a[x]	294 a	290 a
46 x 4	303 a	304 a	300 a
30 x 8	296 a	298 a	293 a
23 x 8	300 a	300 a	298 a
15 x 15	301 a	299 a	296 a
Ambient[w]	291	294	288

[z]Two stages of canopy development present.

[y]Days after planting; from first planting date for KNX-E.

[x]Means within columns followed by a common letter do not differ at P = .05.

[w]Measured at 1.2-m height.

Table 10. Spacing Treatment Effects on Surface Level Soil Moisture[z].

Position	Spacing (cm)	KNX-E[y] 42 Days[x]	KNX-E[y] 49 Days	CRS-M 44 Days	CRS-M 58 Days	KNX-L 42 Days
		(%)				
Inter-Row	91 x 4	19.1 a[w]	9.0 a	18.8 a	17.5 a	14.3 a
	46 x 4	15.8 a	9.6 a	20.2 a	17.3 a	13.3 a
	30 x 8	17.7 a	10.0 a	19.1 a	16.8 a	12.7 a
	23 x 8	15.9 a	10.6 a	18.6 a	16.6 a	13.0 a
	15 x 15	18.1 a	9.4 a	17.9 a	16.7 a	13.2 a
Intra-Row	91 x 4	16.7 a	9.7 a			
	46 x 4	18.2 a	10.1 a			
	30 x 8	17.3 a	9.9 a			
	23 x 8	15.7 a	10.2 a			
	15 x 15	17.3 a	10.2 a			
Inter-Row	Combined	17.3 a	9.7 a			
Intra-Row	Combined	17.0 a	10.0 a			

[z]Composite samples from 0-15 cm expressed as weight percentage on oven-dry basis.

[y]First planted replicates only.

[x]Days from planting.

[w]Means within groups and columns followed by a common letter do not differ at P = .05.

Air Temperatures

As only two replications could be monitored for intra-canopy air temperatures and since differences among sampling hours or adjacent days were not significant, various measurement periods were combined to present a better view of possible relative differences. These data are summarized in Table 11.

Different relationships prevailed among the measurement periods. For KNX-E the afternoon temperature relationship followed the treatment separation by canopy coverage and LAI (Figures 3 and 7, pages 38 and 45, respectively). The early KNX-L measurements for five afternoon hours were very erratic and did not follow a pattern which would relate to canopy structure. However, just prior to harvest the treatments were again distinguished on the basis of relative canopy coverage.

In no case did temperatures differ more than 1 to 2^{o}C. Also, depending on the day, the canopy air might be warmer, cooler, or the same as ambient air.

Leaf Temperatures

As measurements were made of diffusion resistance, leaf temperatures were also recorded, and these means are presented in Table 12. No differences were observed between exposed upper and shaded basal leaves across treatments. Apparently latent heat of exposed leaves was rapidly dissipated into the surrounding air. Where differences occurred among spacings, they were usually very small. Reasons why the exposed leaves occasionally differed or shaded leaves sometimes differed in a manner opposite to the canopy relationship are unknown.

Table 11. Spacing Treatment Effects on Intra-Canopy Air Temperatures.

Location	Days After Planting	Hours Each Day	Spacing (cm)	Temperature (°C) Canopy	Ambient
KNX-E	37-39[z]	2	91 x 4	33.2 ab[y]	31.4[x]
			46 x 4	33.5 a	
			30 x 8	32.8 b	
			23 x 8	32.0 c	
			15 x 15	31.9 c	
KNX-L	39	5	91 x 4	28.7 c	31.1
			46 x 4	30.6 a	
			30 x 8	29.9 b	
			23 x 8	29.0 c	
			15 x 15	30.7 a	
KNX-L	50	8	91 x 4	25.7 a	25.4
			46 x 4	25.2 ab	
			30 x 8	25.2 ab	
			23 x 8	25.3 ab	
			15 x 15	24.9 b	

[z]First planted replicates only.

[y]Means within groups followed by a common letter do not differ at P = .05.

[x]Measured at 1.2-m height.

Table 12. Spacing Treatment Effects on Abaxially Measured Leaf Temperatures of Exposed Upper and Shaded Basal Snap Bean Leaves.

Leaf Position	Spacing (cm)	KNX-E[z] 45 Days[x]	CRS-M 37 Days	CRS-M 44 Days	CRS-M 51 Days	KNX-L[y] 50 Days
				(°C)		
Upper	91 x 4	39.2 a[w]	34.4 a	37.7 a	39.4 a	26.4 a
	46 x 4	38.8 a	35.9 a	33.5 bc	34.4 c	25.5 b
	30 x 8	38.4 a	34.8 a	36.0 ab	35.5 b	25.1 b
	23 x 8	39.7 a	35.5 a	34.6 bc	34.6 bc	25.6 b
	15 x 15	39.8 a	35.2 a	32.6 c	29.8 d	25.1 b
Basal	91 x 4	38.2 b	34.4 a	34.2 a	34.2 b	26.3 a
	46 x 4	39.9 ab	35.2 a	31.3 b	33.4 c	25.6 b
	30 x 8	38.8 b	35.2 a	34.0 a	36.0 a	25.4 b
	23 x 8	40.6 a	35.3 a	34.2 a	36.0 a	25.5 b
	15 x 15	38.8 b	35.1 a	32.4 ab	32.8 c	25.2 b
Upper	Combined	39.6 a	35.1 a	34.9 a	34.8 a	25.5 a
Basal	Combined	39.3 a	35.0 a	33.2 a	33.2 a	25.6 a

[z]First planted replicates only.

[y]Averaged over eight hourly measurements.

[x]Days after planting.

[w]Means within groups and columns followed by a common letter do not differ at P = .05.

Diffusion Resistance

These data relating physiological reactions to moisture conditions are presented in Table 13. Each of these measurements was made one to three days after a rain or irrigation to indicate transpiration interactions with soil moisture loss.

Where differences occurred between exposed and shaded leaves, the latter group always had higher resistances, i.e. lower transpiration rates, as would be anticipated. Within each leaf group only two of the dates indicated differences due to treatment spacings.

Only in the combined resistances from eight hourly measurements before harvest at KNX-L were the differences related to canopy structure. Considerably more transpiration was occurring in the conventional spacing plants on that day which was three days after a 15-mm irrigation. With the full canopies of the higher densities, higher basal leaf resistances would be expected, but the lower resistances of exposed and shaded leaves in the conventional spacing seem contrary to the theory of Rosenburg et al. (51, 52) on soil moisture depletion under closed versus open canopies. However, as previously mentioned, higher populations with the closed canopies create a different demand on the soil moisture supply such that moisture depletion at greater depths than measured was less with the low population, and transpiration would be favored.

Another possible factor for the greater transpiration by basal leaves of plants in the conventional spacing relates to the hours over which measurements were made. Lower solar aspect during the morning hours would result in some basal leaves being exposed for a part of the

Table 13. Spacing Treatment Effects on Abaxial Surface Diffusion Resistance of Exposed Upper and Shaded Basal Snap Bean Leaves.

Leaf Position	Spacing (cm)	KNX-E[z] 45 Days[x]	CRS-M 37 Days	CRS-M 44 Days	CRS-M 51 Days	KNX-L[y] 50 Days
			(sec/cm)			
Upper	91 x 4	6.9 a[w]	4.9 a	6.2 a	4.1 a	1.0 b
	46 x 4	8.2 a	4.3 a	5.3 a	2.8 a	3.6 a
	30 x 8	6.0 a	5.9 a	5.8 a	4.0 a	3.4 a
	23 x 8	7.3 a	5.5 a	3.4 a	3.0 a	3.0 a
	15 x 15	8.1 a	6.6 a	3.1 a	1.1 a	3.3 a
Basal	91 x 4	10.6 a	5.6 a	5.7 a	4.6 b	2.7 b
	46 x 4	14.4 a	6.0 a	5.9 a	4.6 b	11.8 a
	30 x 8	14.7 a	7.9 a	7.7 a	6.9 a	11.4 a
	23 x 8	17.2 a	8.8 a	6.6 a	6.3 a	9.8 a
	15 x 15	19.0 a	8.0 a	5.9 a	4.2 b	10.8 a
Upper	Combined	7.3 a	5.4 a	4.8 a	3.0 b	2.9 b
Basal	Combined	15.2 a	7.3 a	6.4 a	5.3 a	9.3 a

[z]First planted replicates only.

[y]Averaged over eight hourly measurements.

[x]Days after planting.

[w]Means within groups and columns followed by a common letter do not differ at P = .05.

time. This would stimulate stomatal opening and increased transpiration as compared to the more continuously shaded basal leaves under closed canopies. It is notable in the temperature and diffusion resistance data (Tables 12 and 13, respectively) that both upper and basal leaves of conventionally spaced plants had higher leaf temperatures associated with the higher transpiration rates, and these leaf temperatures exceeded ambient air temperatures (Table 11, page 77) while leaves in the higher densities did not. It might be speculated from this that a better moisture supply to the conventional spacing disposed the leaflets to orient themselves for better radiation interception. No observations were made on this possibility, however.

Stomatal and Chlorophyll Relationships

Plants grown under shade have been observed to differ from fully exposed plants in stomatal densities and chlorophyll contents (1, 13). The possibility of these results from mutual shading of leaves within a canopy was investigated.

Abaxial surface stomatal densities and sizes were not significantly affected by sampling time or crop, and only the overall means are presented in Table 14. The lack of spacing or density effects on either measurement would indicate that short term shading influences do not greatly alter leaf development. Basal leaves did have a lower density, probably due to leaf expansion (1, 9). However, in the case of shade-grown plants, the influence is present from the time of leaf emergence while shaded leaves in the normal field crop were exposed during part of their maturation periods.

Table 14. Spacing Treatment Effects on Abaxial Stomatal Density and Size of Exposed Upper and Shaded Basal Snap Bean Leaves.[z]

Position	Spacing (cm)	Stomatal Density (mm^{-2})	Stomatal Size (u)
Upper	91 x 4	345 a[y]	26 a
	46 x 4	329 a	21 a
	30 x 8	331 a	18 a
	23 x 8	350 a	20 a
	15 x 15	338 a	19 a
Basal	9o x 4	265 a	24 a
	46 x 4	278 a	22 a
	30 x 8	291 a	23 a
	23 x 8	261 a	19 a
	15 x 15	283 a	21 a
Upper	Combined	339 a	21 a
Basal	Combined	276 b	21 a

[z]Averaged over four sampling dates.

[y]Means within groups and columns followed by a common letter do not differ at P - .05.

The total and component chlorophyll contents presented in Table 15 were also averaged over all sampling times. Only within the exposed leaf group were differences present. On a leaf weight basis the higher densities had lower total and component levels which probably is directly attributable to the better N status of plants in the conventional spacing (Table 6, page 68). On a leaf area basis only chlorophyll b levels differed, and these followed the same relationship.

Table 15. Spacing Treatment Effects on Chlorophyll Contents of Exposed Upper and Shaded Basal Snap Bean Leaves.[z]

Position	Treatment (cm)	Total (mg/g)	Total (mg/dm^2)	a (mg/g)	a (mg/dm^2)	b (mg/g)	b (mg/dm^2)	a:b
Upper	91 x 4	7.0 a[y]	2.4 a	5.2 a	1.8 a	1.8 a	.69 a	2.7 a
	46 x 4	5.8 b	2.3 a	4.4 b	1.8 a	1.3 b	.52 bc	3.4 a
	30 x 8	5.0 b	2.0 a	3.8 b	1.5 a	1.2 b	.47 bc	3.2 a
	23 x 8	5.1 b	1.9 a	3.9 b	1.4 a	1.2 b	.42 c	3.3 a
	15 x 15	5.9 b	2.3 a	4.4 b	1.7 a	1.6 ab	.58 b	2.8 a
Basal	91 x 4	5.9 a	2.3 a	4.5 a	1.8 a	1.4 a	.53 a	3.3 a
	46 x 4	6.0 a	2.2 a	4.6 a	1.6 a	1.4 a	.51 a	3.2 a
	30 x 8	6.4 a	2.2 a	5.0 a	1.7 a	1.4 a	.47 a	3.6 a
	23 x 8	5.9 a	2.1 a	4.6 a	1.6 a	1.3 a	.48 a	3.4 a
	15 x 15	6.2 a	2.1 a	4.4 a	1.5 a	1.5 a	.49 a	3.0 a
Upper	Combined	5.8 a	2.2 a	4.3 a	1.6 a	1.4 a	.54 a	3.1 a
Basal	Combined	6.1 a	2.2 a	4.6 a	1.6 a	1.4 a	.50 a	3.3 a

[z]Averaged over four sampling dates.

[y]Means within groups and columns followed by a common letter do not differ at P = .05.

CHAPTER V

SUMMARY AND CONCLUSIONS

As technological improvements are made available for crop production, it is important for the options present to be studied such that growers might have the best system available to remain competitive. Introduction of a mechanical harvester capable of handling any snap bean planting arrangement has made serious consideration of high density potentials possible for this crop.

These studies were initiated to investigate biological and economic productivity modifications of snap beans planted in five spatial arrangements. These represented three populations in 50 per cent increments from conventional to double. Three crops were grown during 1974, and supplemental measurements were made on environmental factors as affected by the populations and canopy structures.

General growth relationships indicated the production of leaf numbers and area and of leaf, stem, and total dry weights on a per plant basis were greater as the space available per plant increased. On a land area basis both higher populations were similar in exceeding the conventional spacing in efficiency of space utilization and productivity of leaf area and economic yield. That the highest population differed in productivity from the middle density only under very favorable moisture conditions suggested that competition becomes very strong as the population is raised to double the conventional.

Competition generally became influential shortly before flowering which corresponded roughly to the time of canopy closure in the higher densities. Competitional effects on biological productivities were not modified by spatial arrangement differences within populations.

Highly variable data in the analyses of mean CGR, RGR, and NAR generally concealed trends which might have been present.

To adjust for the higher populations, fertilizer rates were broadcast at 1.5 times the conventional recommendations. Nutrient contents of petiole samples averaged over each crop's growth period indicated this rate was sufficient for both higher densities. More luxuriant feeding of N and K by the conventional spacing plants may have exaggerated their biological productivities somewhat in the first two crops. No differences were observed among spacing treatments in petiole contents of P, Ca, or Mg, nor were treatment differences found among nutrient contents of leaves, stems, or pods sampled at harvest.

Canopy closure was related to row widths with coverage virtually complete in the higher densities by the time pods were set. Conventional rows left 20 to 30 per cent of the soil surface exposed through harvest.

Light attenuation by the canopies was a direct function of the LAI and coverage percentage. CO_2 concentrations were not affected by canopy structure, however, and any effects on upper level soil moisture were likely offset by greater moisture demands with the higher populations.

Only in limited cases were air and leaf temperatures and diffusion resistances associated with the populations and corresponding canopies. Intra-canopy air temperatures were usually lowered 1 to 2°C by increasing canopy densities, but in one case they were raised. Resistances to transpiration water loss were increased by raising the population level under lower soil moisture conditions, but seldom were the resistance differences very dramatic.

Although biological yields generally divided into conventional and higher density groups, economic yields differed slightly. Averaged over the three crops, yields were improved by any density higher than the conventional. However, the square, middle density spacing was equivalent to both higher density spacings. This further indicates that severe competitional influences were present in the high density spacings.

Yield improvements and growth relationships varied with the growing conditions. When the conditions were relatively ideal, growth may have been excessive, but yield returns were more than sufficient to offset added costs for high density planting. If conditions were less satisfactory, especially relating to severe rust infestations of a late crop, yields were still better with higher populations but only marginally.

The square planting pattern consistently yielded best in these crops along with the wide row, high density spacing. Variability among yields for the other higher densities reduced their overall yield improvements. Thus, as planting technology has not yet reached this square spacing capability on a commercial basis, the higher density, row-oriented

system appears best for conversion to high density systems. However, the prospects for equally high yields with a fourth less investment in seed are such that this square planting system should be retained as an option for future consideration.

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APPENDIXES

APPENDIX A

Table A-1. Summarized Climatological Data for Three Snap Bean Crops, Summer 1974.

Crop	Crop Period	Precipitation			Average Temperatures			Heat Units Accumulated
		Natural	Irrigation[z]	Total	Minimum	Maximum	Mean	
		(mm)			(°C)			
KNX-E[y]	5/8-7/17	75	76	151	13.9	27.8	21.1	775
CRS-M	6/24-8/23	187	76	263	15.0	26.7	21.1	673
KNX-L	7/11-9/2	138	25	163	17.8	30.6	24.4	746

[z]Approximation only.

[y]Total data for overlapping growth periods.

APPENDIX B

Table B-1. Abbreviations and Definitions of Growth Analysis Components Used for Calculations in Table B-2.

Abbreviation	Definition
P_i/A	Intended plants per unit land area
P_a/P_i	Proportion of intended plants present
P_a/A	Actual plants per unit land area
LA/P	Total leaf area per plant
A (or LAI)	Leaf area per unit land area
W/P	Total dry weight per plant
W	Plant dry weight per unit land area
LW/P	Leaf dry weight per plant
LW	Leaf dry weight per unit land area
t	Time of sampling
CGR	Crop growth rate
RGR	Relative growth rate
NAR	Net assimilation rate
LAR	Leaf area ratio
LWR	Leaf weight ratio
SLA	Specific leaf area

Table B-2. Growth Analysis Formulas Used.

Abbreviation	Formula	Calculation From	Example Units
P_a/A^z		$P_i/A \times P_a/P_i$	
A^z (or LAI)		$LA/P \times P_a/A$	
W^z		$W/P \times P_a/A$	g/dm^2
LW^z		$LW/P \times P_a/A$	g/dm^2
CGR^y	$\frac{dW}{dt}$	$\frac{W_2 - W_1}{t_2 - t_1}$	g/day
RGR^y	$\frac{1}{W} \times \frac{dW}{dt}$	$\frac{\log_e W_2 - \log_e W_1}{t_2 - t_1}$	g/g/day
NAR^y	$\frac{1}{A} \times \frac{dW}{dt}$	$\frac{\log_e A_2 - \log_e A_1}{A_2 - A_1} \times \frac{W_2 - W_1}{t_2 - t_1}$	$g/dm^2/day$
LAR^x	$\frac{A}{W}$		dm^2/g
LWR^x	$\frac{LW}{W}$		
SLA^x	$\frac{A}{LW}$		dm^2/g

[z] Population and area adjustments for deviations from intended spacings.

[y] Calculation form is for mean value during period from t_2 to t_1.

[x] Function appropriately integrated to obtain mean only under limited conditions (49).

VITA

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