1977

Row width and growth habit influence on light interception and leaf area development in beans.

Thomas Robert Gardiner
University of Massachusetts Amherst

100

ROW WIDTH AND GROWTH HABIT
INFLUENCE ON LIGHT INTERCEPTION
AND LEAF AREA DEVELOPMENT IN BEANS

A Thesis Presented

By

THOMAS ROBERT GARDINER

Submitted to the Graduate School of the
University of Massachusetts
in partial fulfillment of the requirements for the degree of
MASTER OF SCIENCE
September 1977
Major Subject Plant Science

ROW WIDTH AND GROWTH HABIT

INFLUENCE ON LIGHT INTERCEPTION

AND LEAF AREA DEVELOPMENT IN BEANS

A Thesis

By

Thomas Robert Gardiner

Approved as to style and content by:

(Chairman of Committee)

(Head of Department)

(Member)

(Member)

September 1977

ACKNOWLEDGEMENTS

I would like to thank my major advisor, Dr. Lyle E. Craker, for his interest and guidance concerning the execution of this project.

For their expert council and patience, gratitude is extended to Professors William Roseneau and Martin Weeks.

Special thanks are due to Dr. Donald M. Vietor, my former advisor, without whose personal expertise and commitment this work would have been especially difficult.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

The demonstrated yield potential of dry benas (Phaseolus vulgaris L.) is 2,500 kg ha^{-1} for bush cultivars and 4,000-5,000 kg ha^{-1} for climbing varieties under optimum growing conditions in the tropics (18). Presently, average yields of dry beans are 1,360 kg ha^{-1} in the U.S. and only 620 kg ha^{-1} in Latin America (3). Limited information concerning light interception, leaf area development, canopy structure and efficiency of determinate and indeterminate bean cultivars is available to determine if these factors are responsible for suboptimal yields. Improvement in dry bean productivity is desirable and perhaps could be accomplished by better management techniques developed through a more complete understanding of leaf area development and canopy light relations.

The objective of this research was to determine how row width, growth habit, and stage of maturity affect light interception, leaf area development, canopy structure, and efficiency of crop growth in Phaseolus vulgaris.

CHAPTER II

LITERATURE REVIEW

Light Interception

Productivity of any particular crop plant genotype is related to the quantity and quality of solar radiation intercepted by its photosynthetic tissues (14, 27, 30, 47). The principal determinants of crop canopy light interception are the total leaf area produced (36, 48) and the length of time the leaf area is functional (leaf area duration [LAD]) (55, 58). The rapidity of leaf area expansion (57), plant height (64), vertical distribution of leaves (26, 46), and leaf size, shape, angle and reflectivity, (20, 31, 49) are other genotypic characteristics that influence light interception by plant communities.

Watson (52) noted that light interception at early growth stages is sub-optimal because initial canopy development tends to be slow and he considered this to be a major source of inefficiency in crop production systems. Any practice which accelerates leaf area development should increase light interception efficiency.

Almost no information is available on light interception by *Phaseolus vulgaris* canopies. However, Williams *et al*. (62) found that the quantity of solar radiation intercepted by corn foliage is a major determinant of crop growth rate (CGR) during the vegetative state. Shibles and Weber (47) concluded that for maximum soybean yields complete light interception must be reached before the period of pod formation and filling.

Leaf Area Development

Leaf Area Index. Solar radiation interception is closely linked to leaf area development since increasing light interception is dependent upon concomitant leaf expansion. Evans (16) observed that light interception usually approaches high values (90-95%) only when leaf area index (LAI) exceeds 3-4. In temperate latitudes LAI values greater than 3 exist for only 2-3 months in many annual crops and often occur when daily totals of solar radiation are actually decreasing (16). Although low temperatures limit early planting in northern latitudes, solar radiation interception could be increased in both temperate and tropical climates by reducing the initial lag in leaf area development upon seedling emergence. Leaf area cannot be increased indefinitely, but its expansion is usually accelerated by planting in narrower rows (12, 47), employing equidistant spacings (28), increasing plant density (27), and applying fertilizers (54).

Larger LAI is usually associated with higher economic yield (2, 37, 51). Watson (53) suggested that ideal foliar development would be the attainment of L_{95} (LAI required to intercept 95% of the incident photosynthetically active radiation (PAR) at solar noon) upon seedling emergence, since rapid attainment of high LAI gives greatest total dry matter (TDM) accumulation.

L_{95} is important in crop management because it indicates the LAI required for maximum measurable crop canopy light interception. For soybeans planted at a constant population (258,000 plants ha^{-1}) the LAI for L_{95} is 3.6 and 4.2 in 25 cm and 100 cm row width spacings, respectively (47).

As foliage density increases beyond the LAI value required for L_{95}, crop growth rate (CGR) responds in one of two ways. "Critical" LAI implies that a further increase in LAI after L_{95} results in no decline in CGR, but rather in an asymptotic increase to a maximum (9). Ryegrass-clover mixtures (8), corn (63), and soybeans (48) are crops which exhibit a "critical" LAI. An "optimum" LAI (CGR maximum at a particular LAI and less at LAI values below or exceeding the optimum) has been reported for subterranean clover, kale, rice and beans (30, 51, 53). Early investigators who reported an "optimum" (parabolic) response were concerned that peak LAI values could be excessive, with net photosynthesis being reduced because respiration of lower shaded leaves exceeded photosynthesis (16, 49). It is now known that shaded leaves have low respiration rates, are not parasitic to the plant, and soon die if respiration rate exceeds their photosynthetic rate (23). As a result, net photosynthetic rates of a combination of sunlit and shaded leaves tend to plateau at a high LAI (16, 48, 64).

Leaf Area Duration. Maintenance of leaf longevity or leaf area duration (LAD) so as to maximize the time period over which L_{95} endures is also an important yield determinant (6). In fact, total dry matter (TDM) productivity is often more closely related to LAD than to LAI (50). Watson (56) showed that TDM production of wheat, barley, potatoes, and sugar beets increases steadily with increasing LAD. Montojos and Magalhaes (33) concluded that maintenance of LAI at about 3.0 during the post flowering period is an important factor in determining *Phaseolus vulgaris* seed yields.

LAD is influenced by several factors, including date of planting, genotype, spacing, and plant population. Highest yields are obtained when maximum LAI is attained early in the growing season (38). Genotypes of early maturity have a shorter LAD, and thus lower yields (50). During seed filling soybeans in narrow rows have more leaf abscission as compared to those in wide rows (57) and in high density stands one half of the leaves may abscise by mid bean filling (46).

Row Width. Theoretically, crops should give highest yields in equidistant spacings (38) since uniform arrangement would minimize inter and intra-row competition, maximize solar radiation interception and reduce the number of days required to reach L_{95} (28, 30). Work with bush beans (4, 28), lima beans (24), and soybeans (57, 60) indicates that at constant plant populations higher yields are produced by narrowing row width so as to approach equidistant plant arrangement. Soybeans planted at constant densities reach greater LAI in narrow rows as compared to wide rows because more uniform distribution in the former enables the plants to more quickly occupy the aerial environment (47). At constant plant populations LAI of soybeans decreases as row width increases and seed yields are lowest in the widest rows tested (1 m) because of greater intra-row and less inter-row plant competition (57).

Narrowing row width does not always increase grain yield. At constant seeding rates soybeans yielded no better in 25 cm row widths than in 76 cm rows (20) and *Vicia faba* yields were no different in 18, 36, or 54 cm row widths (21).

Plant Density. Since seedling stands increase LAI slowly (and consequently a large proportion of incident radiation is not intercepted by the crop) the period of low LAI can be shortened by increasing plant density (27, 35, 47). With 4 cm between plants bush snap beans had 64% more LAI and yielded 64% more crop in rows spaced 30 cm apart as compared to beans in rows 90 cm apart (12). For both soybeans and beans increasing plant density results in increased LAI and fewer days to L_{95} (2, 29, 47).

Leaf area development and grain yield are controlled by plant density only up to a certain point. Dry beans adjust to various densities by producing more seeds per plant in thin populations and fewer seeds per plant in thick populations (40). Crothers and Westermann (13) found that seed yields are greater at higher populations and with equidistant plant arrangements for bush bean cultivars, but not for semivining cultivars because of the ability of the latter to compensate for increased area per plant at lower populations.

Efficiency of Crop Growth

<u>Crop Growth Rate</u>. Crop growth rate (CGR), the rate of dry matter production per unit land area, is the most meaningful measurement of photosynthetic efficiency for comparing species, varieties, or the effect of environment (65). Early in the season CGR is a linear function of intercepted irradiance (25, 46, 48). CGR approaches a

maximum value at L_{95} and thereafter the response is either critical or optimum. At L_{95} continued high CGR depends on uniform distribution of light within the canopy (61). Shaded, lower leaves, though not parasitic, contribute little photosynthate (48). At LAI less than 3 or 4 highest CGR is associated with canopies having horizontal leaf arrangement because foliage at or near right angles to incident light intercepts and absorbs more solar energy (61). At LAI greater than 4 plants with vertical leaf orientation have superior CGR because vertical leaves allow for better light penetration to lower canopy levels (25, 26, 64). The highest CGR (50 g m^{-2} day^{-1}) have generally been observed for low photorespiration, monocotyledenous communities at high LAI and with tendencies toward erect leaves and low extinction coefficients (26, 65). The maximum CGR of soybeans and beans is estimated to be 17-18 g $m^{-2}day^{-1}$ (10, 44).

<u>Total Dry Matter Production</u>. Total dry matter (TDM) production is the most completely integrated and easily attained measure of overall photosynthetic efficiency (37). LAI is the main determinant of TDM productivity (35, 36, 48, 54), but it is also influenced by the length of the growing season and LAD (6, 53). Shibles and Weber (48) found that the rate of soybean dry matter production was a linear function of percent solar radiation interception.

More equidistant plant spacing and/or higher seeding rates generally have a positive effect on LAI which, in turn, increases TDM productivity (2, 47, 57). However, increasing LAI does not raise TDM production indefinitely because mutual shading of lower leaves eventually causes a decrease in the photosynthetic rate of the shaded part of the foliage (54, 64). Nor does it necessarily follow that maximizing TDM production results in maximum grain yield (36, 54, 57). Weber et al. (57) working with soybeans, found that plant population arrangements favoring rapid attainment of high LAI (i.e., high plant populations and narrow row spacings) are those also having the greatest TDM accumulation, but maximum seed yields occur at less than maximum LAI and TDM. They observed that plants grown at the highest density (516,500 plants ha^{-1}) are taller, more sparsely branched, lodge more, and set fewer pods due to severe plant competition (57). Beyond an optimum population of 48,700 plants ha^{-1} grain yields of corn are also negatively correlated with population density because the percentage of barren stalks increases with higher rates of seeding (62). As a result, TDM production increases asymptotically with increasing plant population and LAI, but grain yield reaches a maximum at a finite population level (17, 57).

Canopy Structure

Growth Habit. Although research comparing determinate plant types is limited, differences in growth habit can affect canopy development, light interception, and yield. Egli _et al_. (15) noted that in indeterminate soybeans competition between vegetative and reproductive growth for assimilates could be detrimental to yield but that longer periods of flowering and pod set could compensate for this competition. They found that at commencement of pod and seed development, pods were the primary sink for photosynthate with only limited competition from the vegetative portion of the plant regardless of growth habit (15).

Chapman and Cowling (11) hypothesized that reduction in overlapping by wider spacing of leaves might be an important factor in determining foliage efficiency since Nitrogen (which increases LAI) actually depressed sweet potato yields in the absence of wire supports, but when light penetration was improved by providing trellises for plants to climb up, N increased yield. Donald (14) and Yoshida (64) concluded that tall stature is advantageous because greater vertical spacing of leaves permits increased downward penetration of light whereas very short plants with leaves too closely spaced on the stem suffer from self shading. Shibles _et al_. (46) observed that indeterminate soybeans have the largest leaflets and largest petioles in mid plant with gradations in size towards each end of the stem, while determinate types have very large upper leaves which cause poorer canopy light distribution. CIAT workers concluded that light distribution within pole bean canopies grown at high densities (100 plants m^{-2}) is adequate since LAI of 9.0 was attained without premature leaf drop in the lower canopy (2). Also, Phaseolus grain yield is directly related to LAI and TDM production, and thus greater LAI and TDM of pole beans over bush beans partially account for their increased yield performance (2).

Light Extinction Coefficient. In contrast to C-4 plants, individual leaves of C-3 plants reach light saturation (photosynthesis ceases to respond to increasing light intensity) at approximately one quarter full sunlight (30, 34, 65). However, competition for light amongst the leaves of plants grown in stands is often so acute that lower shaded leaves fix carbon dioxide more slowly than adequately illuminated leaves (49). Crop stands respond to light intensities in excess of the saturation values of isolated leaves because more light reaches leaves at lower canopy levels. Carbon dioxide uptake in single alfalfa leaves is saturated at 0.12 cal cm^{-2} min^{-1}, but a canopy is not saturated until 0.45 cal cm^{-2} min^{-1} of incident radiation reaches the crop surface (19). For soybeans, a single leaf is light saturated at one quarter full sunlight (7), but a stand of plants does not light saturate until greater than 50% of full sunlight intensity (43). Since photosynthesis in individual leaves of C-3 species does not increase linearly with increases in light intensity, and since saturation of fully exposed leaves occurs well below full sunlight, maximum photosynthetic efficiency would be obtained by a crop canopy which absorbs less light in the upper layers and transmits more light to lower layers (46, 49, 61).

The extinction of light intensity as it penetrates a crop canopy is approximately exponential with increasing LAI (14, 49). When crop foliage presents surfaces at or near right angles to the incident light, absorption is exponential, but departure from the relationship occurs as the foliage becomes more acutely inclined to the incoming light (61). Brougham (8) showed that ryegrass with vertically inclined leaves transmits 74% of the light per unit LAI, while clover, with more horizontal leaves, transmits 50% per unit LAI.

The extinction coefficient (α_L) decreases as more light penetrates the canopy (65). Most grass communities (with vertically inclined leaves) have $_L$ values of 0.3 to 0.5 (26, 63). Planophile leaf orientation (a high percentage of leaves at low angles of inclination) is characteristic of dicotyledonous communities, and their α_L value is generally between 0.7 and 1.0 (26, 32, 65).

In addition to total leaf area displayed and leaf angle, vertical leaf area distribution also affects light attenuation in crop communities. Grass plants are characterized by maximum leaf area in the middle of the canopy, whereas in forbs maximum leaf area density occurs in the upper 7th and 8th tenths of the canopy (31). Maximum leaf area density within soybean canopies occurs in the upper 8th and 9th tenths of the canopy (22). Broad, planophile leaves and concentration of leaf area in the upper canopy result in inefficient light use by soybean stands. Consequently, 90% of the incident light is captured by the outer 15-30 cm of the soybean canopy (42, 45). Narrow leaf soybean cultivars have been used to allow more light penetration into the canopy but they have not provided a yield advantage (20).

Limited work with Phaseolus vulgaris indicates that the extinction coefficient for bush beans is 0.86 at L_{95} and a LAI value of 3.8. (32). The geometry of bean foliage is invariant with age because daily mean light transmission decreases linearly with increasing LAI (32).

It has been argued that diurnal variation of α_L can occur because light interception by a leaf layer depends on the incident angle of radiation (65). However, direct measurements of radiation in crops with a wide range of leaf sizes and angles do not support this view (32). Diurnal changes of α_L in mature corn canopies is minimal within $\pm$ 4 hours of noon (1). Monteith (32) concluded that variation of α_L is small enough to neglect over the central

8 hours of the day when most assimilation takes place provided there is a preponderance of leaf angles at less than 30°.

Summary

Work with corn and soybeans has provided substantial information on how LAI and light interception influence canopy development and vice versa. However, knowledge of canopy structure, leaf area development and light in Phaseolus vulgaris is limited and almost no work exists which compares differences in these factors due to determinate and indeterminate growth habit.

CHAPTER III

MATERIALS AND METHODS

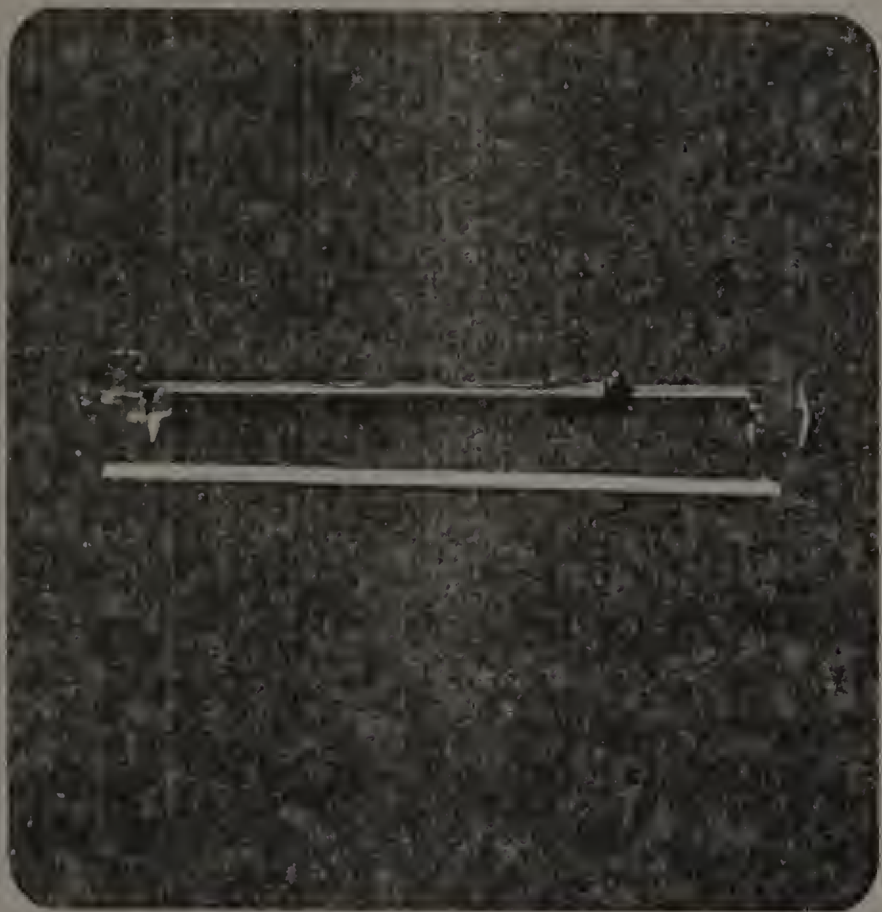
Two types of beans (Phaseolus vulgaris L.), one a determinate (bush) variety (Bush Blue Lake 290), and the other an indeterminate (pole) variety (Stringless Blue Lake Pole S-7) were planted June 4, 1976 at the rate of 247,000 plants ha^{-1} to a previously fallowed Hadley silt loam (mesic Typic Udifluvents) at the University of Massachusetts Experimental Farm, South Deerfield. Fertilizer and dolomitic lime applications previous to planting brought pH to 6.5 and P and K levels to 225 kg ha^{-1} and 561 kg ha^{-1}, respectively. N fertilizer was not applied, and initial levels of NO_3 and NH_4 were 22 and 27 kg ha^{-1}, respectively. Plots 6 m x 6 m had rows oriented in a North-South direction. Spacings were: 1) 45.5 cm between rows and 9 cm between plants, and 2) 91 cm between rows and 4.5 cm between plants. Seeds of both varieties were pretreated with Captan fungicide and were inoculated prior to planting with R. phaseoli to provide for N fixation. Pole beans were supported on wire and string trellises 1.75 m high. Weeds were controlled by hand cultivation, and irrigation was provided as needed with an overhead sprinkler system. An aphid infestation 2 weeks after emergence required 1 spraying with Guthion insecticide for control.

Photosynthetically active radiation (PAR) was measured above and below the plant canopy with a LI 190-S quantum sensor (Lambda Inst. Co.). Both short term and instantaneous sampling errors, as well as border effects, were avoided by integrating PAR over time within inner plot rows, using the LI 190-S quantum sensor with a LI 500 Integrator (Lambda Inst. Co.).

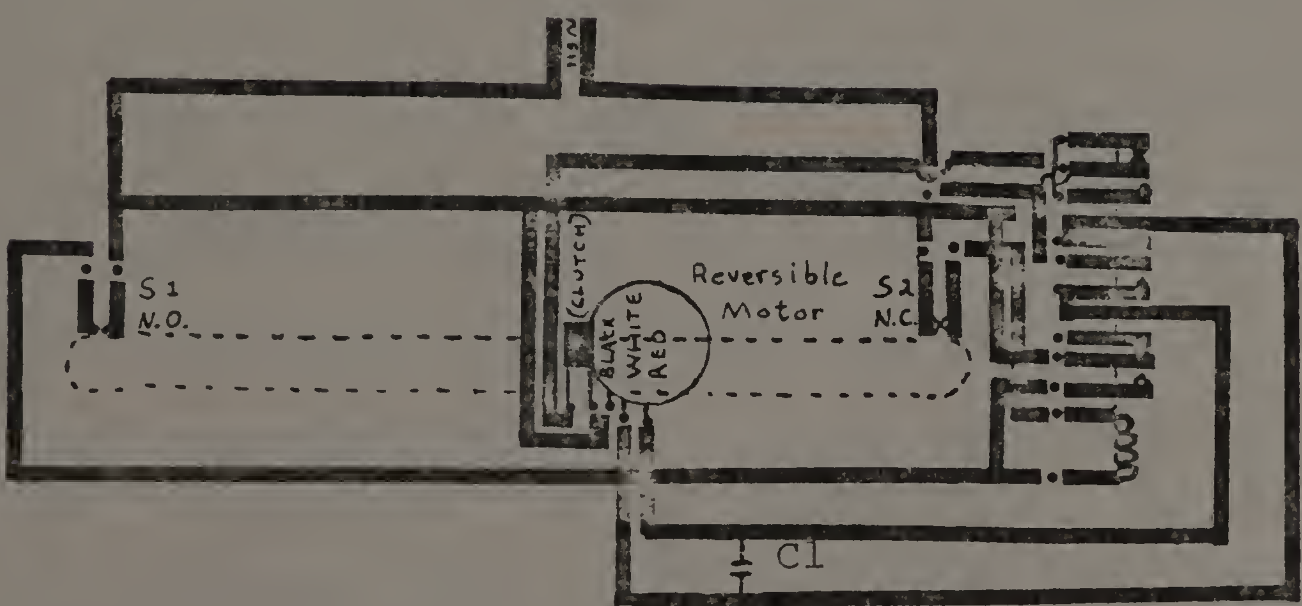
A representative subsample of light penetrating to the soil surface was obtained by constructing a trolley system (fig. 1) which carried a light sensor 5 cm above ground level, at a speed of 1.95 cm sec^{-1} over a distance of 91 cm. Integration of light levels transverse to the row were obtained by placing the trolley system perpendicular to row direction so that it straddled 2 rows at the narrow spacing and 1 row at the wide spacing treatment.

Incident light, reflected light, and light penetrating to ground level were integrated for 1 minute, 4 minutes, and 1 minute 34 seconds (time required for 1 round trip of trolley system), respectively. Light measurements were replicated (except for reflected light) on each sampling date. All light measurements were made between 10 a.m. and 3:30 p.m. (Eastern Daylight Savings time) in order to avoid large variation in irradiance within the time period required to sample all 4 treatment combinations of a replication. The effect of solar angle on

Figure 1



A) Light sensor and trolley system for measuring canopy light penetration



.5 Mfd
400 V

B) Circuit diagram of trolley system

light measurements was determined by monitoring canopy light interception and light penetration to ground level throughout the course of a day in a fixed subplot. Bean canopy development was studied by randomly recording light profiles within each treatment at successive dates during the growing season. Profile peaks indicated light penetration to ground level and profile troughs indicated light interception by the crop canopy. It was assumed that near midday the effect of solar angle on light interception is minimal, and thus trough widths of profiles measured within ± 1-1/2 hours of solar noon were used to estimate canopy width.

Light extinction coefficients (α_L) were calculated for all treatments by plotting solar radiation transmission to ground level as a function of increasing LAI over time until maximum canopy LAI was attained;

$$\log_e (I/I_o) = (\alpha_L) \text{ LAI}$$

where I, I_o and α_L are the light intensities measured inside the canopy, at the surface of the top of the plant community and the extinction coefficient, respectively (41, 65).

Vertical leaf area distributions were determined at 5 developmental stages by harvesting leaves within a 1 m x 0.91 m unit of land area from canopy top to bottom using 8 divisions (above 150, 125-150, 100-125, 75-100 50-75, 30-50, 15-30, and 0-15 cm). At each harvest date plants within a subsample were separated into leaves, stems, and pods. Leaf area measurements were made with a L I 3000 portable leaf area meter (Lambda Inst. Co.) and a 3050 A accessory transparent belt conveyor (Lambda Inst. Co.). Parts were oven dried to a constant weight at 70°C and weighed to determine dry matter accumulation. Seed yields were obtained on the last harvest date.

Estimates of various growth variables were determined by the following methods:

leaf area index (56)

'total leaf area per unit ground area'

crop growth rate (39, 53)

'change in dry weight per unit land area per unit of time'

$$CGR = (W_2 - W_1)/(t_2 - t_1)$$

leaf area duration (58)

'green leaf area per unit land area integrated over time'

$$LAD = \sum 1/2(L_n + L_{n+1})(t_{n+1} - t_n)$$

where W = total above ground dry weight, L = leaf area index and t = time.

The experimental design was a randomized complete block replicated 3 times. Standard analysis of variance procedures were used separately on the data of each sampling date.

CHAPTER IV

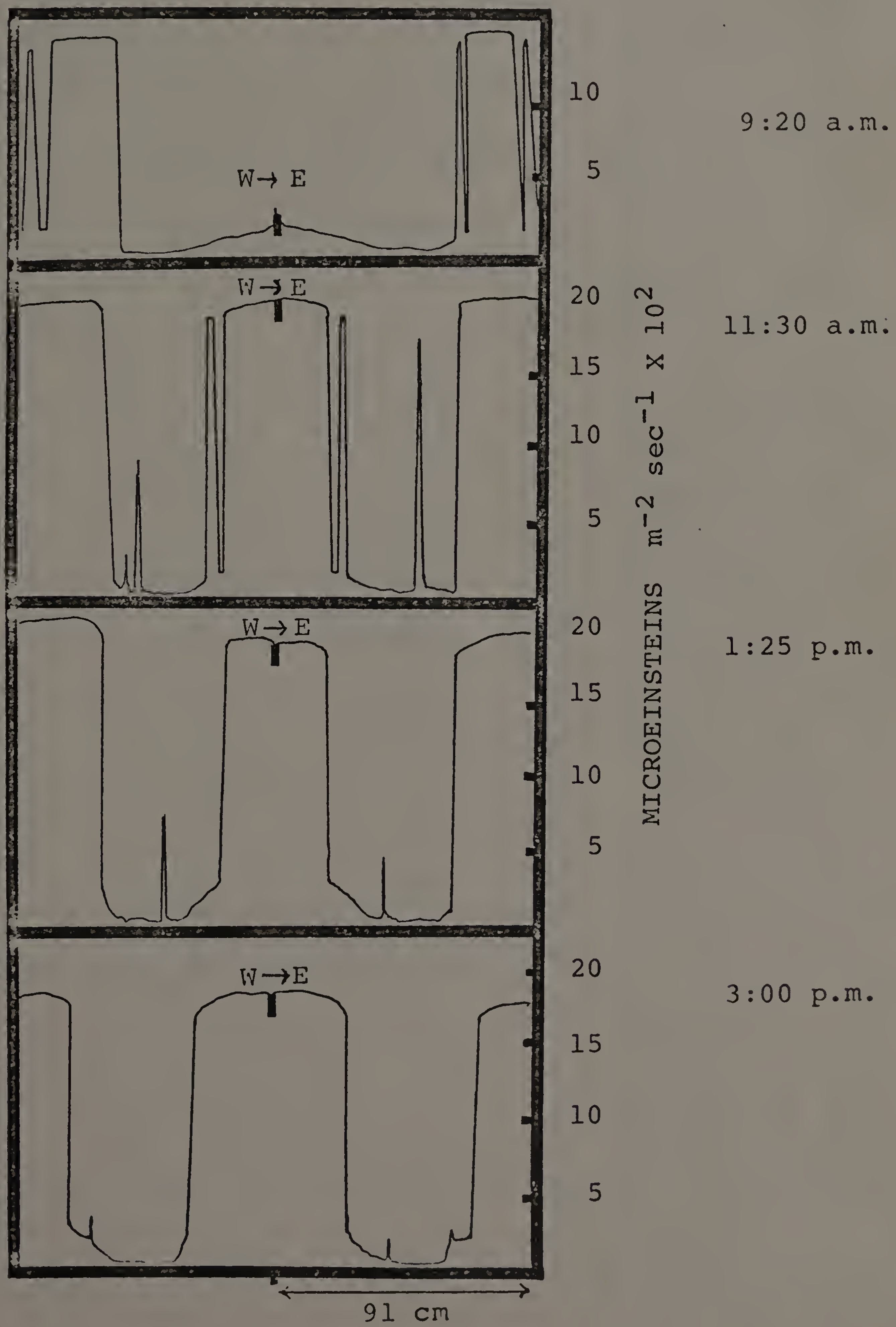
RESULTS

Solar Angle

The light profiles for the 91 cm row width bush bean canopy recorded at 36 days after planting are indicated in figure 2. Profile peaks indicate maximum light penetration to ground level and troughs indicate canopy light interception. Solar irradiance levels ($\mu E\ m^{-2}\ sec^{-1}$) increased as solar elevation increased, reached a maximum of 2,137 $\mu E\ m^{-2} sec^{-1}$ at approximately solar noon (1.25 p.m. E.D.S.T.) and then began to decline by 3:00 p.m. Irradiance was nearly constant between 11:30 a.m. and 1:25 p.m. However, early in the morning irradiance increased by 38% in only 40 minutes from a value of 1,080 $\mu E\ m^{-2} sec^{-1}$ at 8:40 a.m. (profile not shown) to 1,490 $\mu E\ m^{-2} sec^{-1}$ by 9:20 a.m. Irradiance also diminished rapidly after 3 p.m., declining from 1885 $\mu E\ m^{-2} sec^{-1}$ to 1488 $\mu E\ m^{-2} sec^{-1}$ (profile not included) by 3:30 p.m.

The light penetration profiles of figure 2 also indicated how solar angle affected canopy light interception. The direction of movement of the light sensor from west to east (as indicated by the W → E symbol on the graph) is plotted on the right side of each individual

Figure 2. LIGHT PENETRATION INTO CANOPY AT 36 DAYS FROM PLANTING IN 91 cm BUSH BEAN



profile. The left side of the profile is the mirror image of the right side and indicates the consistency of the data.

At 9:20 a.m. light penetrated to the east side of the row (profile peak) and was of low intensity on the west side of the row (profile trough). In the 11:30 a.m. profile the sun was more directly overhead and so light penetrated to the inter-row spaces on both sides of the canopy. The two narrow peaks (sunflecks) which appeared within the large trough area of the 11:30 a.m. profile indicated that canopy light interception within the row was incomplete. The 1:25 p.m. profile demonstrated that maximum canopy light interception (trough at maximum width and sunflecks less pronounced) occurred simultaneously with maximum recorded light intensity for the day. The last profile indicated that an opposite effect from the early morning was beginning by 3:00 p.m. The west side of the row was now more exposed to light (west peak beginning to widen) as the sun moved toward the western horizon while the east side began to be shaded (east peak beginning to narrow).

Light Profiles and Canopy Development

91 cm Row Width Bush Beans. Light profiles complimented the quantitative light interception data. Development of the wide row bush bean treatment canopy is

presented in figure 3. At 32 days after planting the canopy was not well developed, being 40 cm wide and intercepting only 42% of the incident solar radiation. At 45 days canopy development was more complete - canopy width being 50 cm and light interception having increased to 62%. Maximum measured light interception (82%) and maximum canopy width (72 cm) occurred 52 days after planting, but the canopy had also begun to lodge. Lodging had the effect of widening row width appearance and of creating more sunflecks within the canopy. The profile recorded at 76 days indicated that the wide row bush bean canopy structure had disintegrated due to severe lodging observed in the test plots.

45.5 cm Row Width Bush Beans. Light penetration profiles recorded for the narrow row bush bean treatment are presented in figure 4. Moving from west to east (W→E) 32 days after planting an inter-row space, then an incompletely developed row, another inter-row space, a more fully developed row, and finally another inter-row space are observed. Light interception at this date was 50% and the combined canopy width of the two narrow rows (50 cm) already equalled that of the wide row bush bean treatment at 45 days. The second profile (45 days) indicates that the first inter-row space had been filled and that the second was in the process of being filled. The

Figure 3. BUSH BEAN CANOPY DEVELOPMENT MEASURED BY LIGHT PENETRATION PROFILES AT 91 cm ROW WIDTH

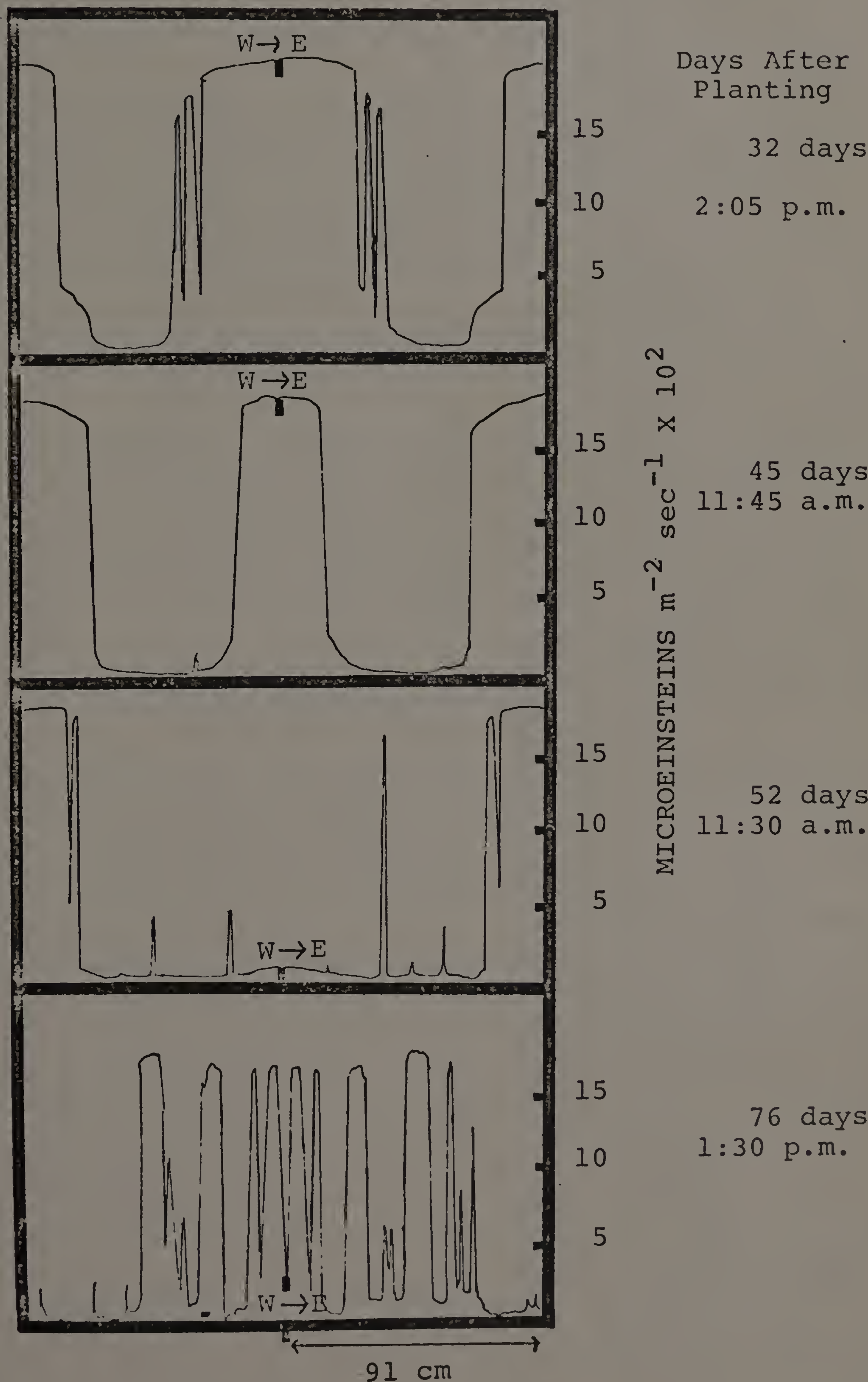
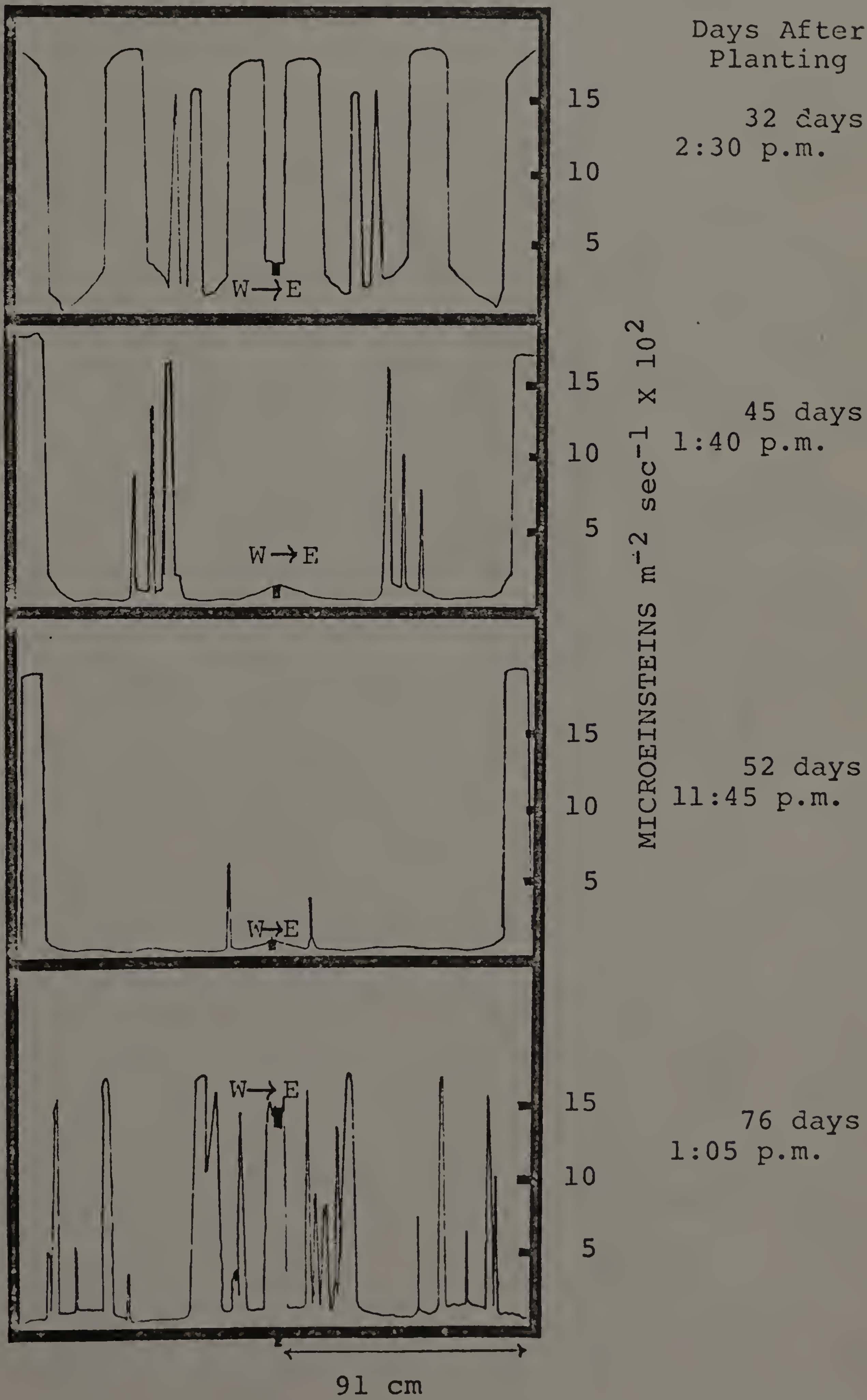


Figure 4. BUSH BEAN CANOPY DEVELOPMENT MEASURED BY LIGHT PENETRATION PROFILES AT 45.5 cm ROW WIDTH



combined row widths for this date were 78 cm and light interception was 77%. The profile recorded at 52 days indicates that canopy development was almost complete, which coincided with maximum light interception (90%) and maximum LAI (3.72) recorded on this date. The profile at 76 days indicates that disintegration of canopy structure had occurred.

91 cm Row Width Pole Beans. Canopy development of the 91 cm row width pole bean treatment is shown in figure 5. At 32 days the canopy was in an early developmental stage, being only 34 cm wide and intercepting only 45% of the available solar radiation. At 45 days canopy width was increasing (46 cm) and where the canopy covered the ground it was better developed than at the first date (sunflecks less pronounced). Irregularities in the profile recorded at 52 days were caused by wind turbulence. However, the profile does indicate that canopy width continued to expand (63 cm wide). The profile recorded at 76 days contrasts sharply with the profiles of the bush bean treatments because canopy light interception of the wide row pole bean is essentially complete.

45.5 cm Row Width Pole Beans. The canopy development profiles of the narrow row pole bean treatment are presented in figure 6. The second profile (45 days) indicated that canopy development and light interception occurred

Figure 5. CANOPY DEVELOPMENT MEASURED BY LIGHT PENETRATION PROFILES AT 91 cm ROW WIDTH IN POLE BEANS

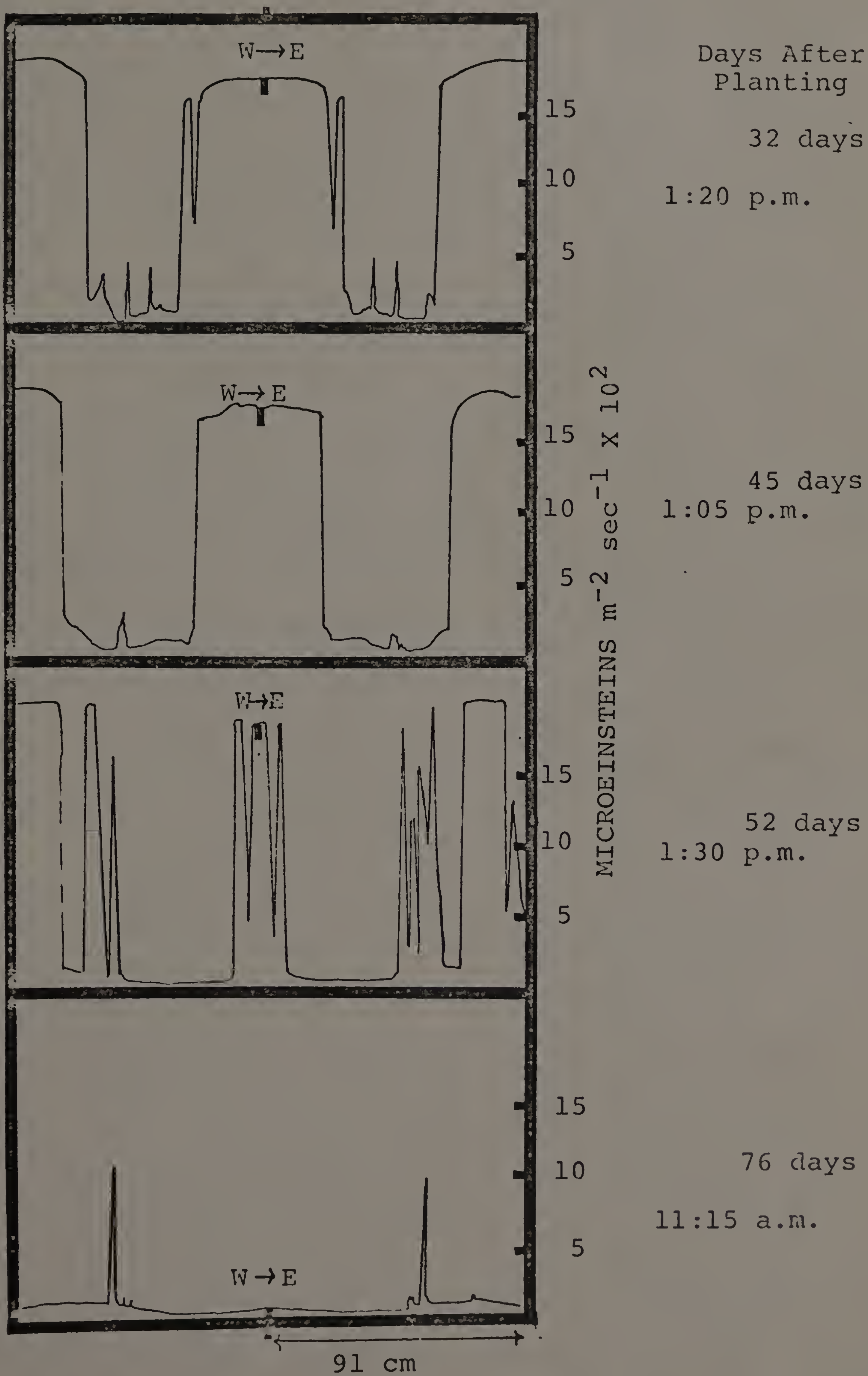
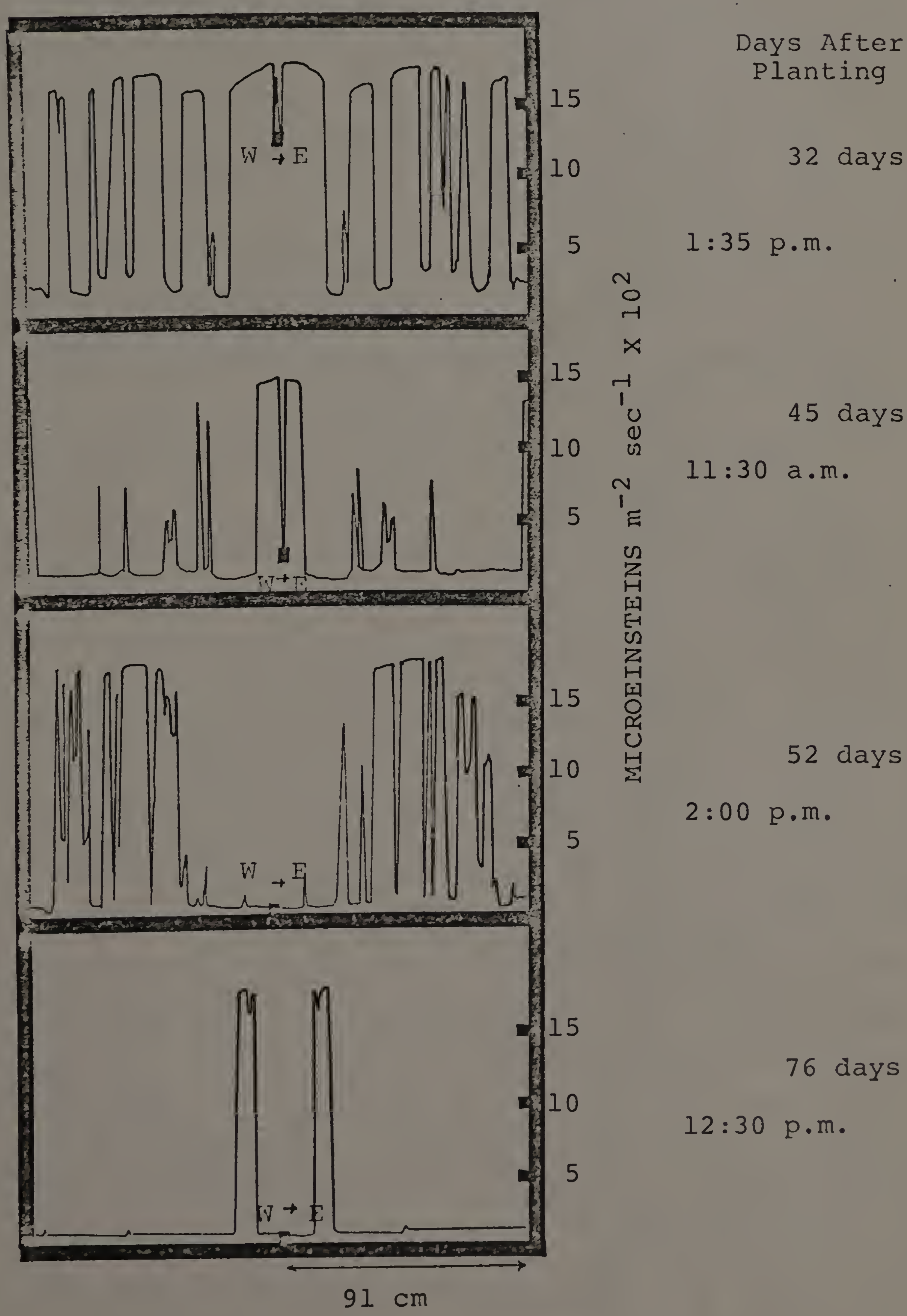


Figure 6. POLE BEAN CANOPY DEVELOPMENT MEASURED BY LIGHT PENETRATION PROFILES AT 45.5 cm ROW WIDTH



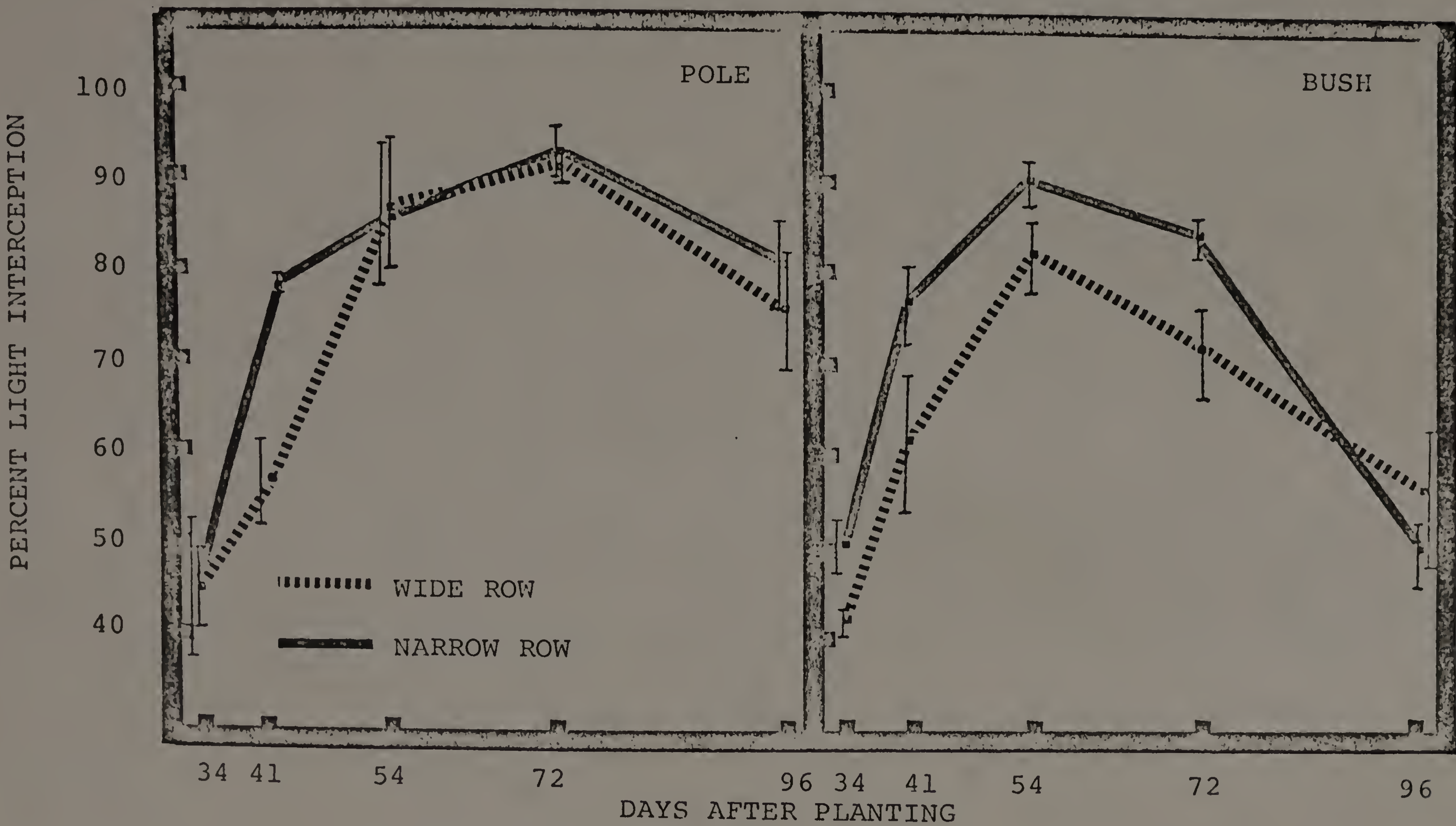
earlier for the narrow row pole bean treatment as compared to the wide row pole treatment. Light interception was 57% vs. 78% and canopy width was 46 cm vs. 76 cm at 45 days for the wide row pole and narrow row pole bean treatments, respectively. The profile recorded at 52 days was indiscernible due to excessive wind turbulence. At 76 days the narrow row pole exhibited the same response as the wide row pole bean treatment - nearly complete light interception.

Light Interception

The time course of percent light interception for the 4 treatments is presented in figure 7. A statistically significant difference ($p = 0.05$) in light interception due to row width occurred at 41 days after planting. The effect of growth habit on light interception was significant at 72 days ($p = 0.05$) and at 96 days ($p = 0.01$). Maximum observed light interception for the bush bean treatments occurred at 54 days and thereafter declined, while for pole beans maximum light interception was observed at 72 days. Maximum light interception by the narrow row bush bean treatment (90%) was nearly equivalent to that of the wide and narrow pole bean treatments (92% and 93%, respectively), while maximum light interception for the wide row bush bean treatment was only 82%.

Figure 7

TIME COURSE OF PERCENT LIGHT INTERCEPTION



VERTICAL BARS INDICATE THE STANDARD ERROR OF THE MEAN

Leaf Area Development

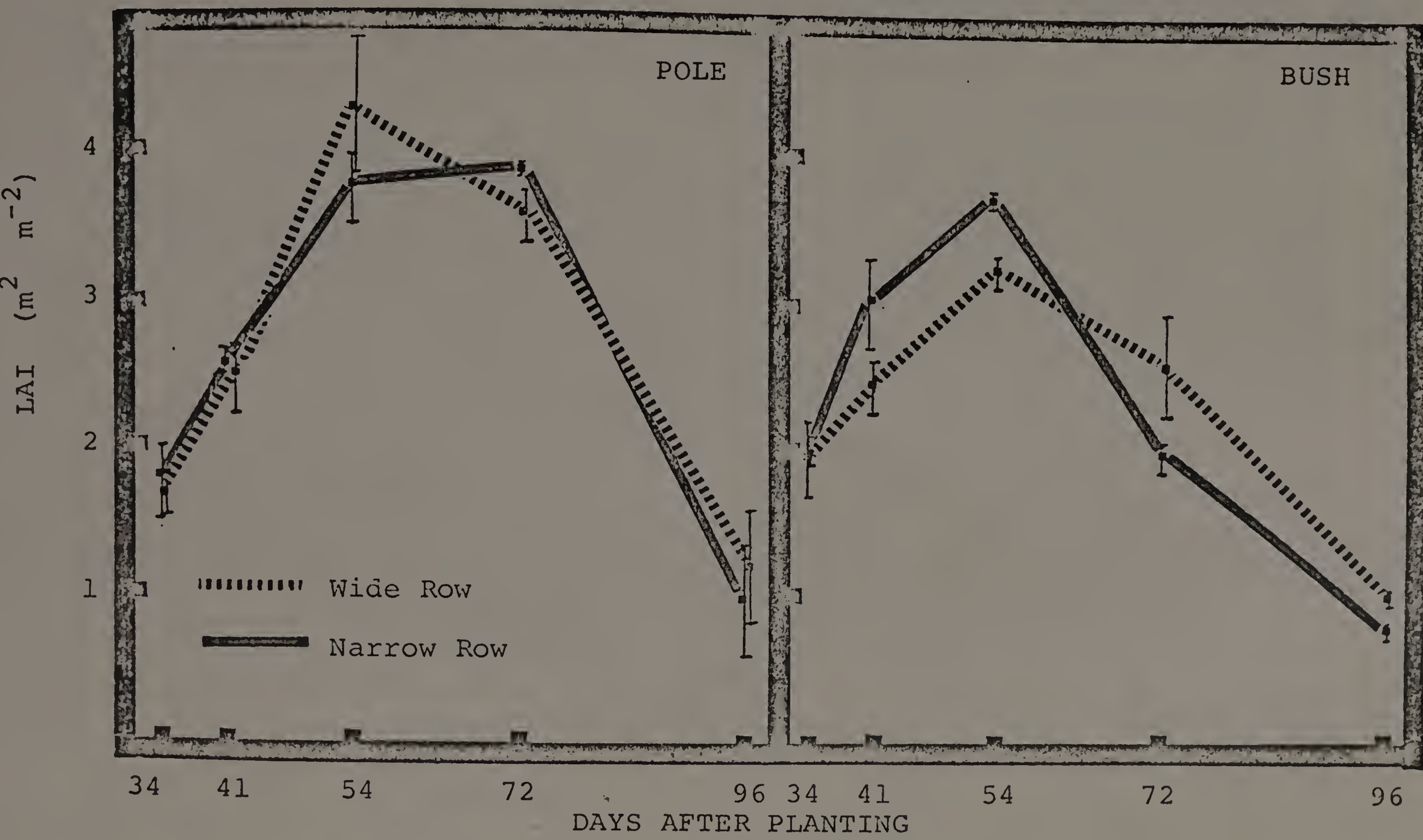
Leaf Area Index. The within-sampling-date analyses of variance indicated that row width had no significant effect on LAI. A highly significant difference ($p = 0.01$) in LAI due to growth habit occurred at 72 days.

The distribution of LAI with stage of development for the 4 treatments is presented in figure 8. LAI increased nearly linearly with time up to a maximum value observed at 54 days after planting in all treatments except the narrow row pole bean. Between day 54 and day 72 LAI increased slightly (from 3.8 to 3.9) for the narrow row pole treatment, while for all other treatments LAI declined during this period. At 54 days the narrow row bush treatment and the narrow row pole treatment had similar LAI (3.7 and 3.8, respectively). However, the difference in leaf area between the wide row pole (LAI = 4.3) and the wide row bush (LAI = 3.2) was substantial. Once maximum LAI was attained, the narrow row bush and pole treatments appeared to shed leaves more rapidly than the wide row treatments.

The inverse relationship between increasing LAI and decreasing light penetration to ground level is indicated by the data of figure 9. More light penetrated to ground level in bush beans because they produced less total LAI and their LAI declined more rapidly than that of the pole

Figure 8

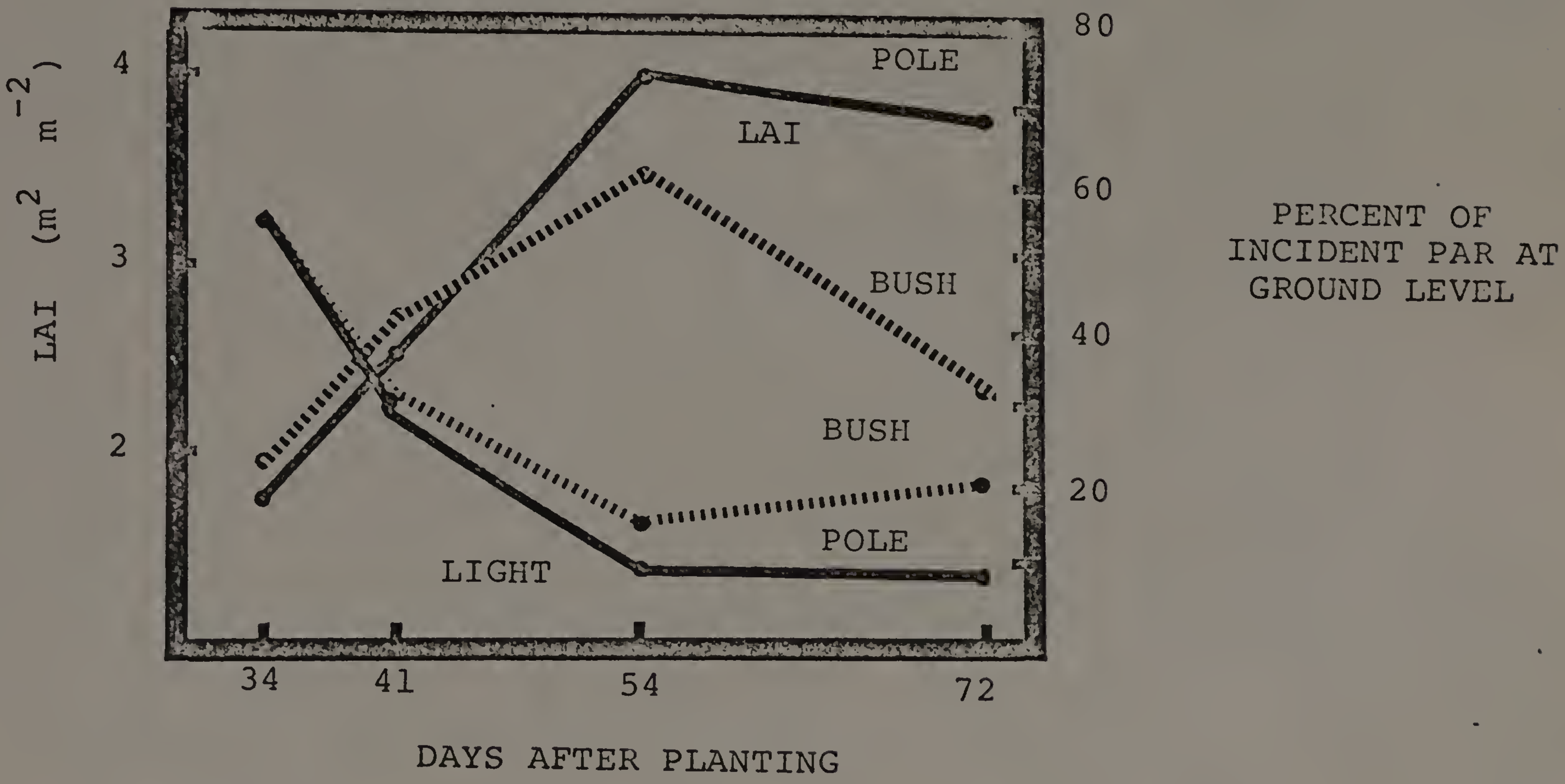
TIME COURSE OF LAI DEVELOPMENT



VERTICAL BARS INDICATE THE STANDARD ERROR OF THE MEAN

Figure 9

LEAF AREA DEVELOPMENT AND LIGHT PENETRATION



beans. In contrast, LAI declined only slightly for the pole beans between day 54 and day 72 and consequently, percent light intensity at ground level did not change.

Leaf Area Duration. Treatment means of LAD are given in Table 1 together with dry seed yeilds m^{-2}. An analysis of variance calculated at the termination of growth indicated that the indeterminate growth habit conferred significantly longer LAD than the determinate type, but row width was shown to have no effect on LAD. Although seed yields were not significantly different in the 4 treatments, higher yields of pole beans were positively associated with longer LAD.

Efficiency

Crop Growth Rate. Statistically significant differences in Crop Growth Rate (CGR) due to growth habit were observed at only one sampling date in the experiment. At 54 days after planting bush beans exhibited a significantly higher CGR than pole beans. Row width had no significant effect on CGR in any of the 4 treatments.

The relationship between LAI and CGR presented in figure 10 indicated that changes in CGR paralleled changes in LAI. In both bush and pole bean treatments CGR increased as LAI increased, reached a maximum at 54 days, and thereafter declined as LAI declined. Maximum CGR was

TABLE 1

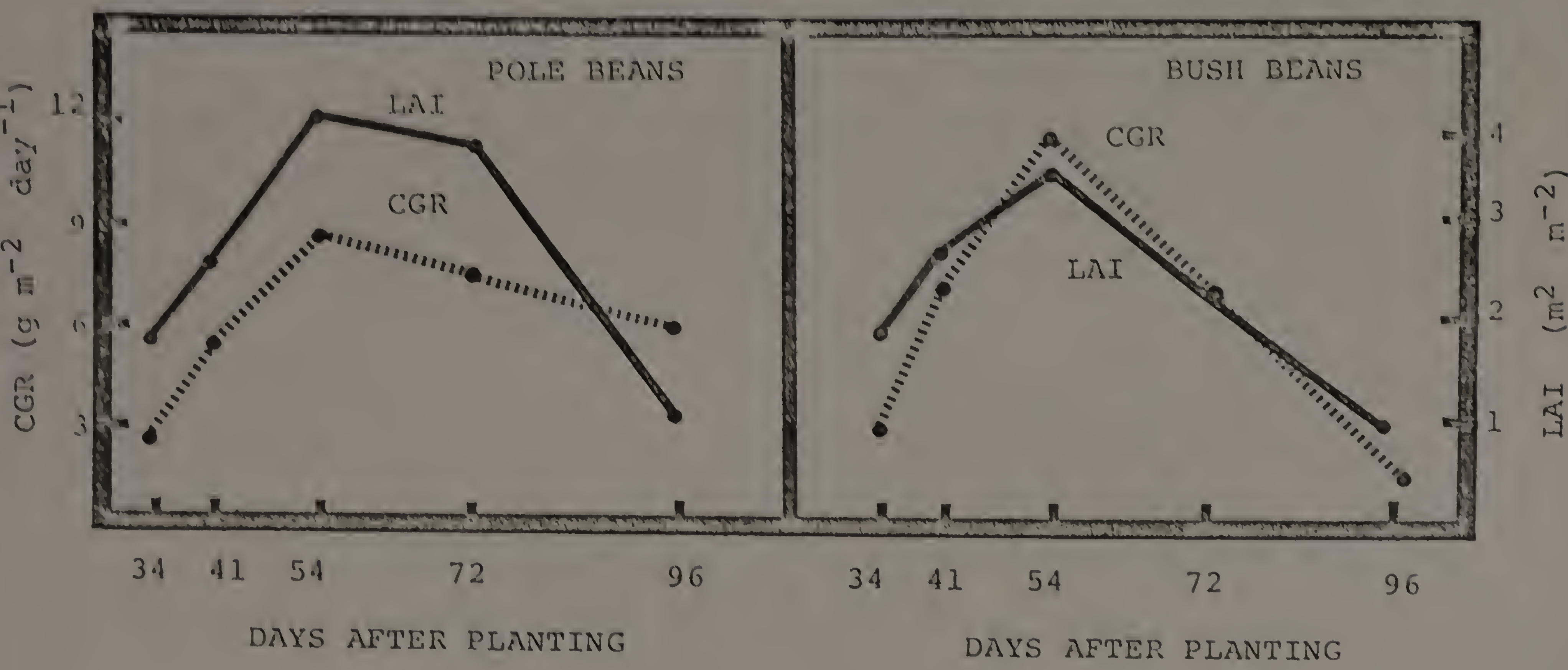
Treatment	Leaf Area Duration (Weeks)		Yield of Dry Seed ($g\ m^{-2}$)	
91 cm row width pole bean	28.7*	a	258.0*	a
45.5 cm row width pole bean	28.4	a	264.5	a
91 cm row width bush bean	23.9	b	203.6	a
45.5 cm row width bush bean	23.4	b	230.6	a

* Each value represents the mean of 3 replicates.

Means in the same column not followed by the same letter are significantly different at $p = 0.05$.

Figure 10

TIME COURSE DEVELOPMENT OF CROP GROWTH RATE AND LEAF AREA INDEX



higher for bush beans as compared to pole beans but CGR also decreased more rapidly in the former due to a rapid decline in LAI after day 54. Both LAI and CGR declined more slowly in pole beans as compared with bush beans.

In figure 11 CGR is plotted as a function of increasing LAI. The data indicate a positive correlation between CGR and LAI. For the wide versus narrow spacing treatments there were no observed differences. Data comparing bush versus pole treatments indicated that bush beans produced a higher CGR and that pole beans attained a higher maximum LAI (4.0 versus 3.5 for pole beans and bush beans, respectively). The high LAI of the pole beans was not associated with as high CGR as that produced by the bush beans at a lower LAI.

Total Dry Matter Production. Total dry weights of the aerial shoots for all sampling dates are presented in figure 12. TDM production of bush beans was significantly higher than that of pole beans at 54 days. Analysis of variance at 96 days did not indicate significance at the 0.05 level for pole bean TDM production over that of the bush bean cultivar.

Dry matter accumulation patterns (fig. 13) indicated that TDM, total vegetative growth, and reproductive growth, were all higher for pole beans than for bush beans. In bush beans there was little increase in TDM after 72 days.

Figure 11

CROP GROWTH RATE AS A FUNCTION OF LEAF AREA INDEX

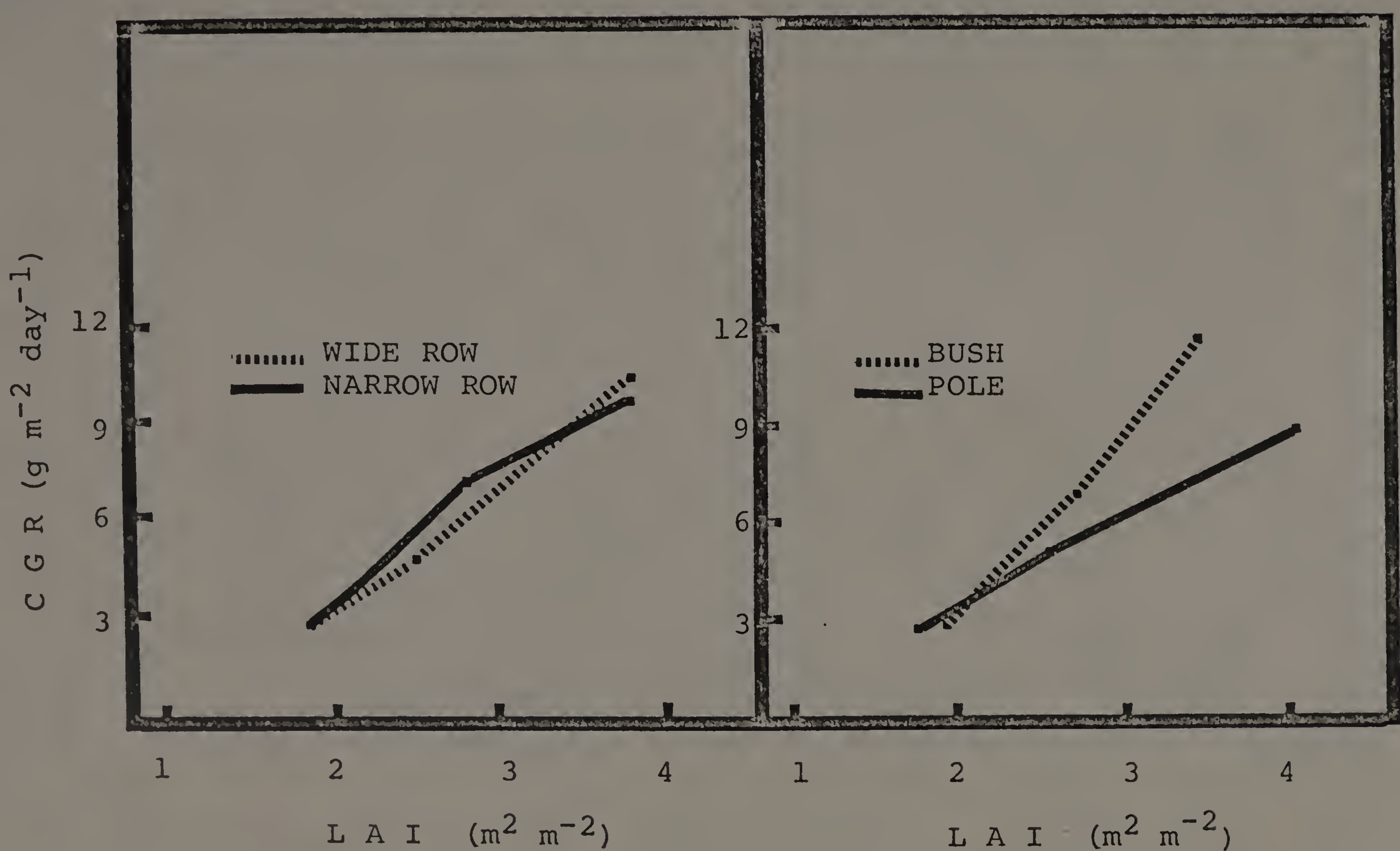
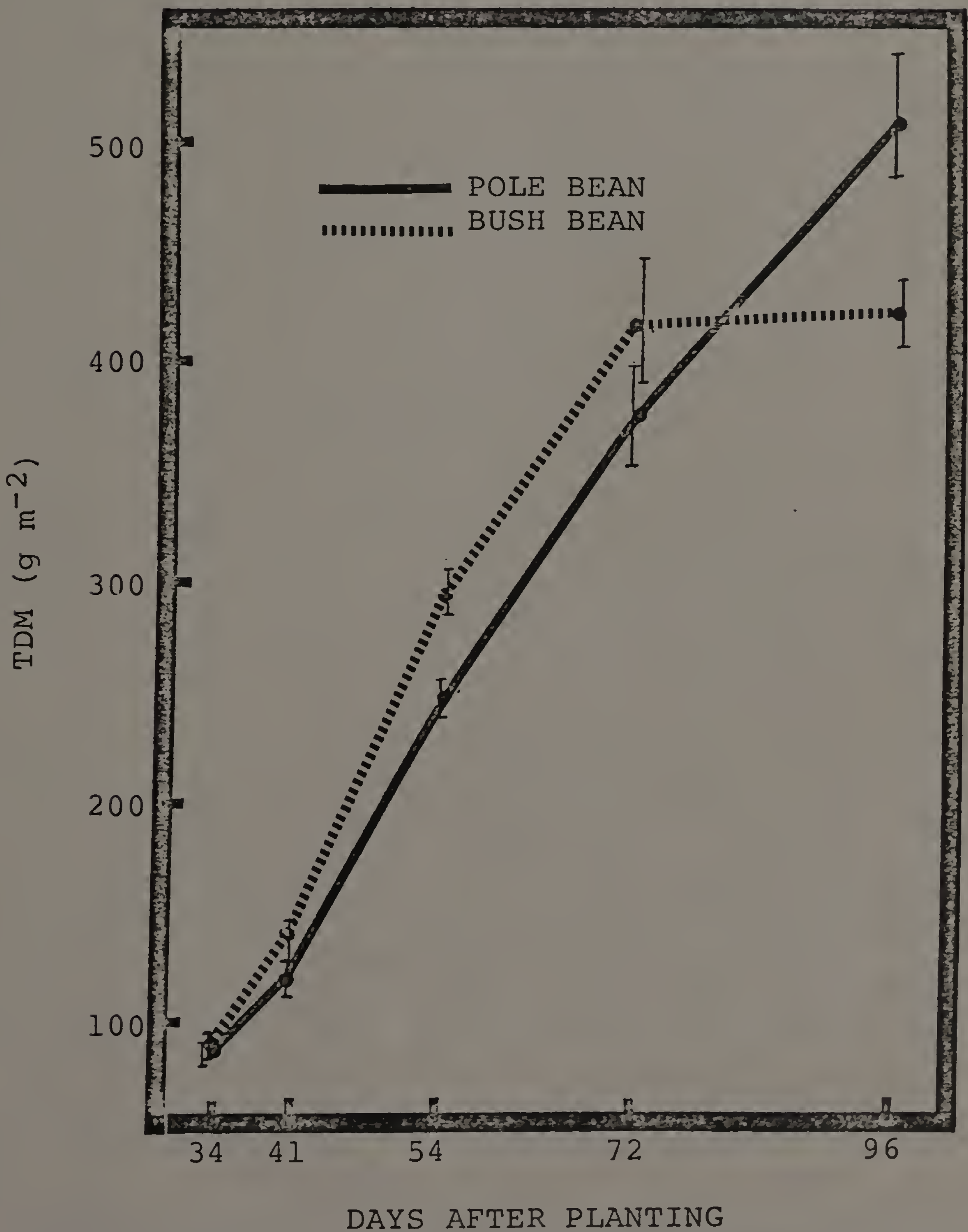


Figure 12

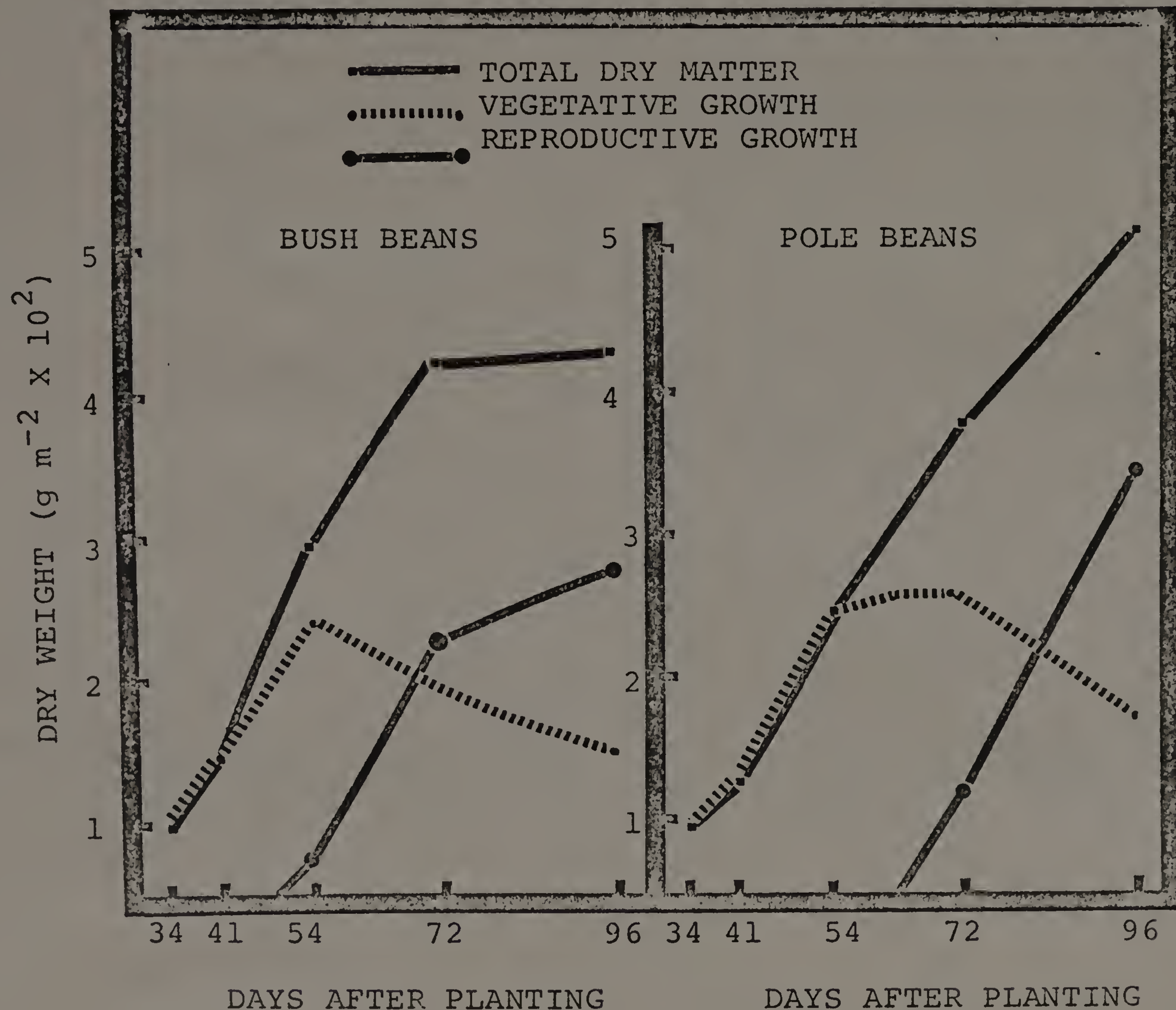
TIME COURSE OF TDM ACCUMULATION



VERTICAL BARS INDICATE THE STANDARD ERROR OF THE MEAN

Figure 13

DRY MATTER ACCUMULATION PATTERNS



Maximum observed vegetative growth of bush beans occurred at 54 days but vegetative growth of pole beans did not attain a maximum until 72 days. Pod formation and filling began at an earlier date for bush beans, but the rate of pod filling declined concomitantly with the decrease in the rate of TDM production observed between 72 days and 92 days after planting. In pole beans pod filling began at a later date (about 60 days) but showed no decrease in its rate during late growth stages.

Canopy Structure

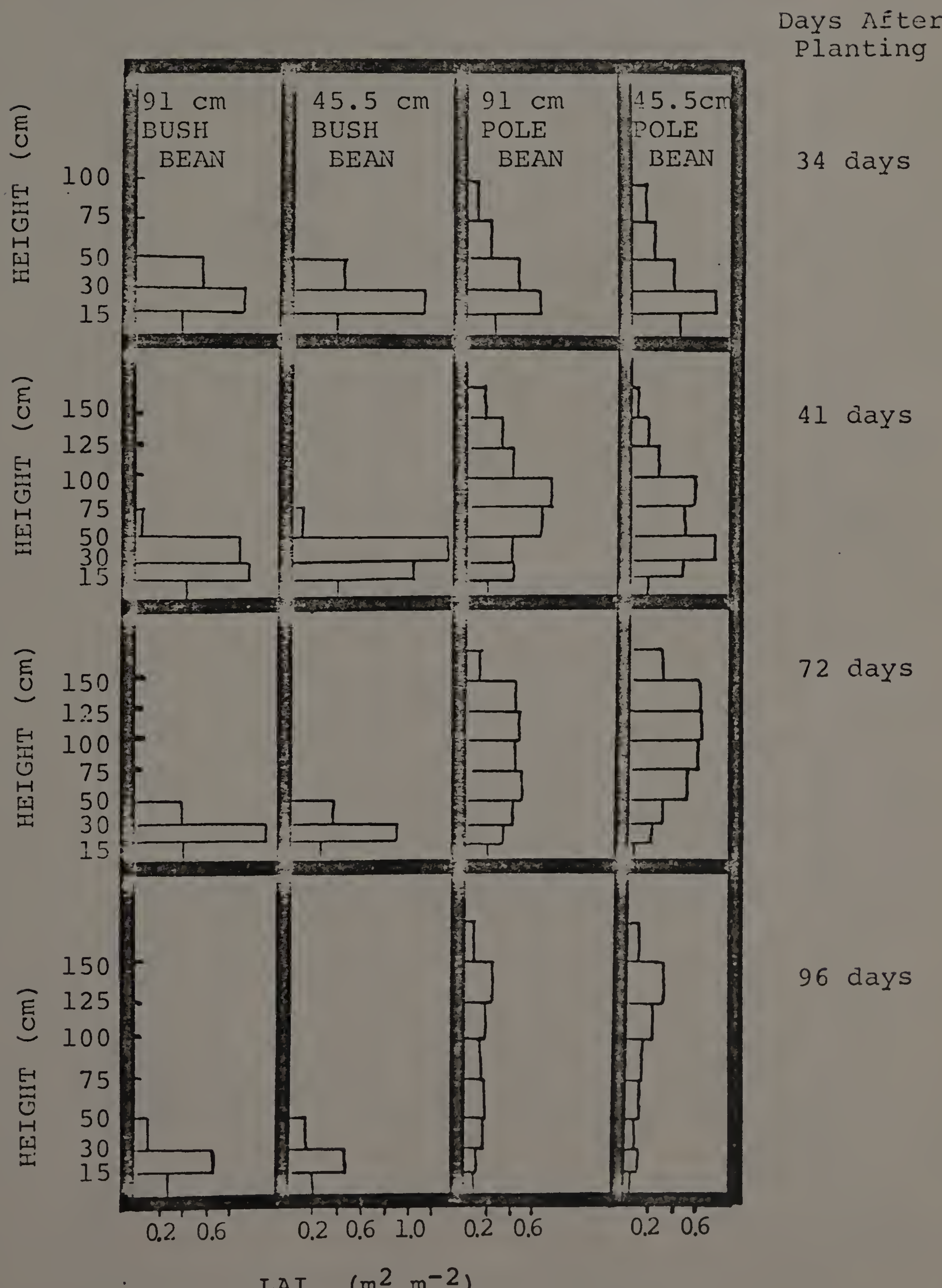
Vertical Distribution of Leaf Area Index. The vertical distribution of LAI versus height in the canopy for the 4 treatments over the course of the growing season is presented in figure 14. Differences in growth habit profoundly affected canopy structure. For the bush bean treatments total LAI was concentrated within a canopy height of approximately 50 cm, while for pole beans total leaf area was distributed over a vertical distance of 1.75 m.

Data at 34 days after planting indicated that row width initially had no effect on vertical leaf area distribution in either bush or pole beans. At 54 days all canopies had attained maximum height and all showed a general upward shift in vertical leaf area distribution.

Figure 14

VERTICAL DISTRIBUTION OF LAI VS. HEIGHT

IN THE CANOPY

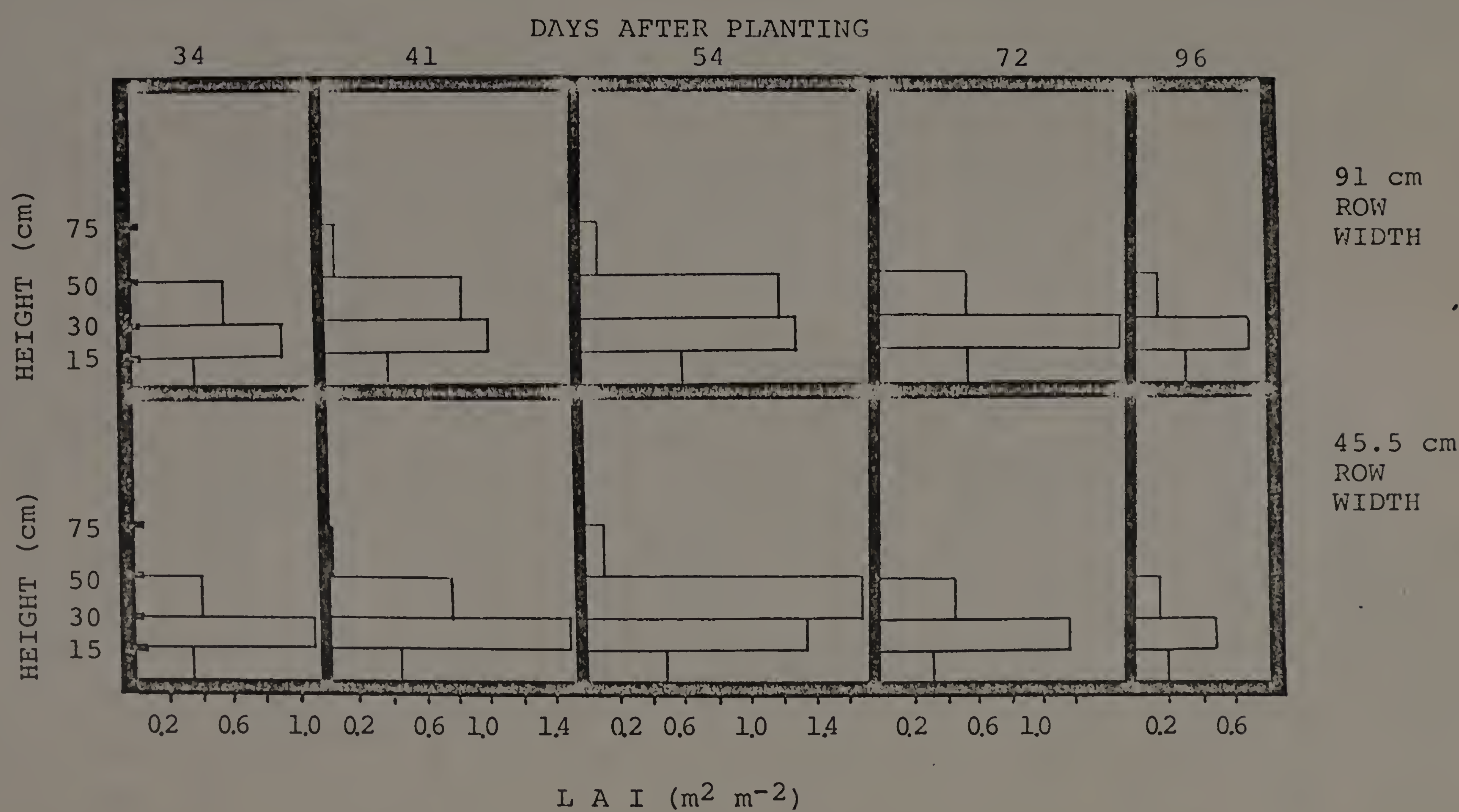


However, the pole bean treatments appeared to maintain a more symmetrical vertical leaf area distribution while the bush bean canopies concentrated their leaf area in the upper canopy levels (excluding the 50-75 cm zone which was minimal and measurable only on July 28). At 72 days the determinant beans had actually decreased in height since the 50-75 cm zone was no longer present in either bush bean treatment. The concentration of leaf area in the 15-30 cm zone of the bush beans at 72 days was due to lodging and pod weight which lowered canopy height. Total LAI also declined in the bush beans at 72 days. In contrast, pole beans continued the upward shift in vertical leaf area distribution, and loss in total LAI was inconsequential for these treatments until the last sampling interval. Data at 96 days after planting indicated the similarity of vertical leaf area distribution within bush and pole treatments for the row width factor.

The vertical distribution of leaf area in bush beans at wide and narrow row spacings is presented in figure 15. Only minor differences in the vertical leaf area distribution were observed at the first, fourth and last sampling dates (34, 41, and 96 days). At 41 days differences in canopy structure were accounted for by the 15-30 cm zone, with the narrow row treatment having 50% more LAI in this vertical interval as compared to the wide row treatment. At 54

Figure 15

VERTICAL DISTRIBUTION OF L A I IN THE CANOPY - BUSH BEANS

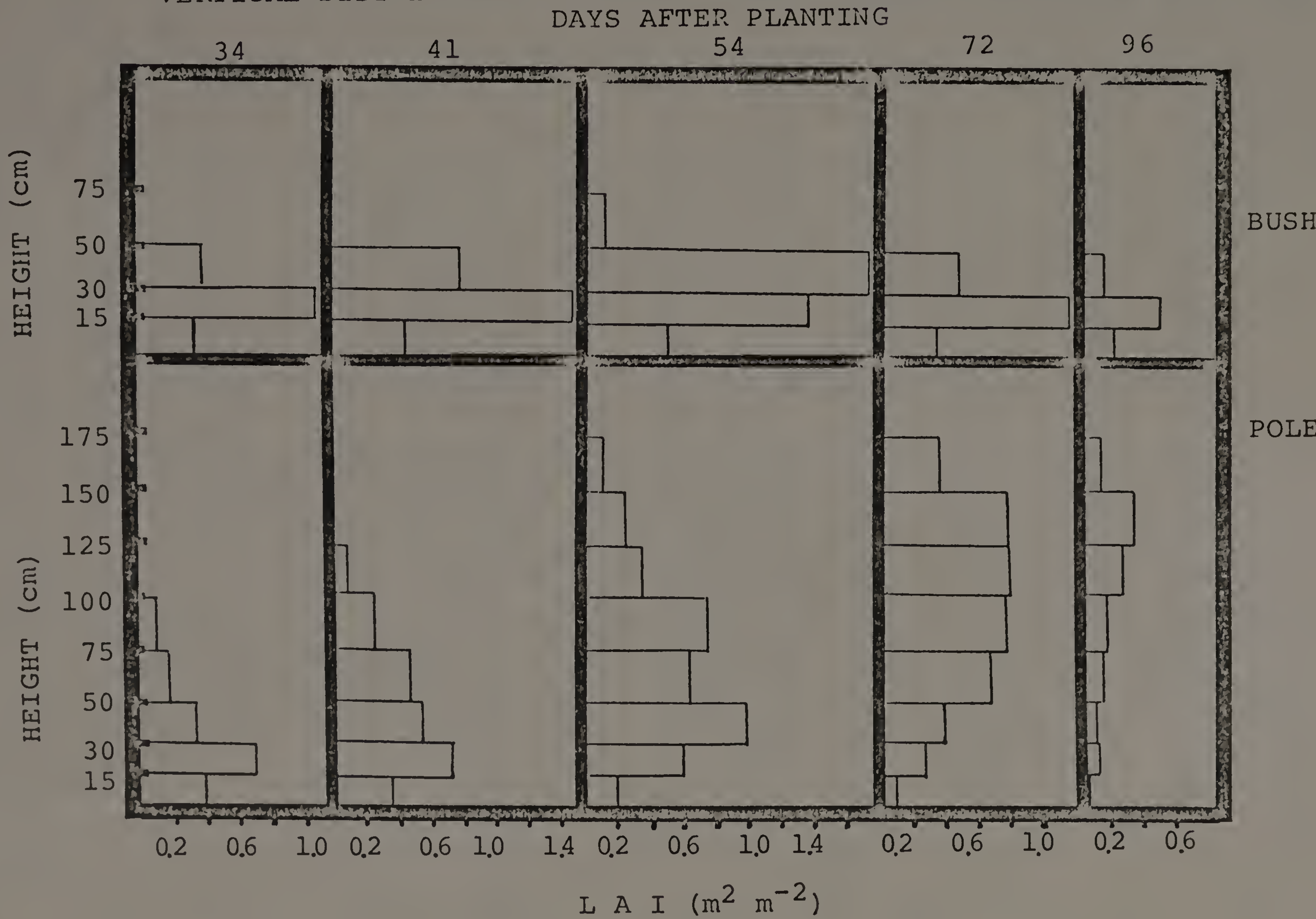


days after planting both canopies attained maximum observed LAI. At this date differences between treatments in total LAI and in canopy structure were accounted for by the 30-50 cm zone, with the narrow row treatment having a LAI of 1.78 in this zone as compared to a LAI of 1.21 for the wide row treatment in this same interval. Between 41 days and 54 days the narrow row treatment more than doubled its LAI (from 0.8 to 1.78) in this zone. Although LAI increased for the wide row treatment, its vertical distribution of leaf area remained almost unchanged over the same time period. At 72 days after planting the canopy structure of the two treatments was similar, however, between 54 days and 72 days leaf abscission proceeded at a faster rate in the narrow row treatment.

Comparisons of leaf area distributions between bush and pole beans over time at the narrow row spacing are presented in figure 16. Both canopies displayed a dramatic upward shift in vertical leaf area distribution over the time interval preceding maximum observed LAI (54 days and 72 days for narrow row bush bean and narrow row pole bean treatments, respectively.) The vertical leaf area distributions of both treatments were asymmetrical at maximum observed LAI. After maximum LAI was attained, rapid rates of leaf abscission occurred in both treatments.

Figure 16

VERTICAL DISTRIBUTION OF L A I IN THE CANOPY - NARROW ROW SPACING



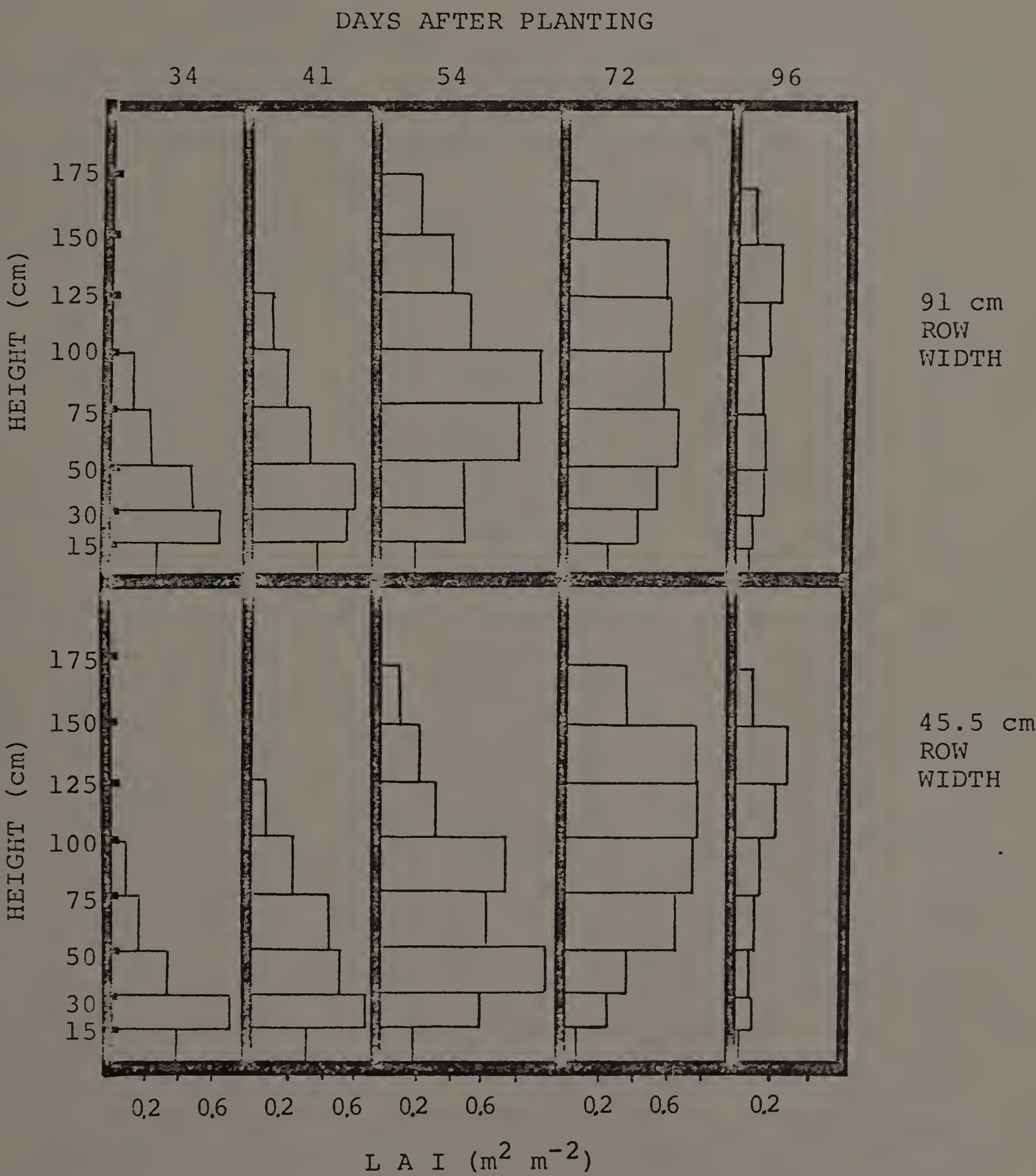
Leaf abscission in the narrow row pole bean treatment appeared to be more pronounced in the lower canopy levels as compared to the narrow row bush bean treatment.

Vertical leaf area distribution comparisons between pole bean treatments are given in figure 17. There were essentially no differences in vertical leaf area distribution at the first, second and last sampling dates (34, 41 and 96 days after planting). Comparison of the data at 54 days and at 72 days suggested that the wide row pole bean maintained a symmetrical leaf area distribution while in the narrow row pole bean canopy structure became asymmetrical due to leaf abscission in the lower levels and rapid leaf area accumulation in the upper levels.

Trends in leaf area accumulation over time indicated that in the wide row pole bean treatment the vertical LAI distribution from 0-50 cm remained almost constant through sampling at 72 days and declined thereafter. The middle two zones (50-100 cm) attained maximum LAI at 54 days and then gradually declined. The top three zones (100 cm) increased until 72 days after planting. In contrast, the lowest zone (0-15 cm) of the narrow row pole treatment declined from the first sample date on, the second zone (15-30 cm) decreased after the second sample date, and the third zone (30-50 cm) decreased after the third sample date. However, the upper zones of this treatment (50-150+ cm) all increased in LAI until 72 days after planting.

Figure 17

VERTICAL DISTRIBUTION OF L A I IN THE CANOPY - POLE BEANS



Light Extinction Coefficients. The light extinction coefficients and the corresponding coefficients of correlation are presented in Table 2.

TABLE 2

LIGHT EXTINCTION COEFFICIENTS (α_L) AND

COEFFICIENTS OF CORRELATION (r)

Treatment	Row Width	α_L	r
BUSH BLUE LAKE 290	91	0.94	-0.87
	45.5	0.86	-0.91
STRINGLESS BLUE LAKE POLE S-7	91	0.69	-0.74
	45.5	0.97	-0.80

CHAPTER V

DISCUSSION

Solar Angle and Light Profiles

A comparison of light profiles for the bush beans indicated that light interception and canopy development occurred earlier and were more complete in the narrow row treatment. Wien (59) also demonstrated that complete canopy development of determinate beans planted in rows 25, 50 and 75 cm wide occurs earliest at the narrowest spacing.

The duration of uniform canopy structure over time varied considerably between the bush bean and pole bean treatments. The canopy structure of both bush bean treatments (fig. 3 and 4) deteriorated rapidly after 52 days (due to lodging in the wide row bush bean and leaf abscission in the narrow row bush bean) so that at 76 days from planting the light profiles of both treatments were indiscernible. In contrast to this, the light profiles of both pole bean treatments (fig. 5 and 6) indicated almost complete light interception at 76 days after planting. The height advantage, trellis supports (which stabilized canopy integrity) and longer LAD enabled the pole bean canopies to intercept most of the available light late in the season.

Light Interception

In general the narrow row bush bean treatment intercepted more light at a given sampling date than the wide row bush bean spacing (fig. 7), but light interception in the pole bean treatments was similar at all dates except 41 days after planting. The significantly higher percent light interception of the narrow row treatments at 41 days was not correlated with a significantly higher LAI and so was probably due to the more nearly equidistant plant arrangement which minimized the inter-row spaces.

Complete light interception (90%) was attained earliest by the narrow row bush bean treatment and later by the pole bean treatments at both row spacings. Bush beans planted at the wide row spacing did not reach complete light interception. Wien (59) has also shown that Red Kidney bush beans planted 10 cm apart in rows 25, 50, and 75 cm apart do not achieve complete light interception at the widest row spacing (75 cm). The results of this experiment and Wien's data (59) suggest that complete light interception by bush bean canopies occurs at row width spacings of 50 cm or less and at a minimum population of 200,000 plants ha^{-1}.

After 54 days from planting light interception was maintained at a high level in the pole bean treatments but declined rapidly in the bush beans. The decline in light interception by the bush beans between 54 days and 72 days was accounted for by 47% and 19% leaf abscission in the narrow and wide row treatments, respectively. In addition, the wide row bush bean treatment, which began to lodge at 54 days after planting, was severely lodged at 72 days and thus allowed greater light penetration to ground level. The higher light interception observed in the pole bean treatments during later growth stages was accounted for by their indeterminate growth habit which permitted better vertical distribution of leaves and longer LAD.

Leaf Area Development

Leaf Area Index. The data of figure 8 indicated that the more nearly equidistant spacing arrangement of the narrow row treatment neither accelerated leaf area development nor resulted in a higher total LAI in pole beans. However, narrowing row width in the bush bean cultivar hastened leaf area expansion and resulted in higher total LAI.

In this experiment it was not possible to determine whether bush and pole beans exhibit a "critical" or "optimum" LAI response since plant density was not varied, L_{95} was not attained in any of the treatments, and no further increases in LAI were observed after approximately 90% light interception. The data did indicate that L_{90-95}

of bean canopies occurs at a LAI value between 3.7 and 4.3, and this compares favorably with the L_{95}= 3.8 value reported for beans by Monteith (32). From 54 days to 72 days after planting the rate of leaf abscission for the narrow row bush bean treatment exceeded that of the wide row treatment. (Fig. 8) However, rapid leaf abscission in the narrow row bush bean canopy was offset by the fact that it produced a higher total LAI.

Leaf Area Duration. Within both pole and bush bean treatments differences in LAD due to the row width factor were minimal (Table 1) suggesting that spacing had little effect on the rate of leaf abscission. The significantly higher LAD of pole beans over bush beans was accounted for in part by the rapid decline in total LAI for the latter after 54 days from planting. The indeterminate growth habit of the pole beans permitted both leaf expansion (in the upper canopy) and leaf abscission (in the lower canopy) to occur simultaneously, resulting in maintenance of a high LAI up to 72 days after planting.

Efficiency of Crop Growth

The higher CGR of bush beans over pole beans (fig. 10) was accounted for by the fact that maximum LAI and rapid pod filling were occurring simultaneously at day 54 while for the pole beans initiation of pod development did not commence until about day 60 (fig. 13). Although CGR was less for the pole beans it also decreased at a slower rate than the CGR of bush beans due to the indeterminate growth habit which extended LAD and the length of the pod filling period. Figure 11 indicated that bush beans had a higher maximum crop growth efficiency over pole beans at the plant population employed in this experiment since the former produced a higher CGR and at a lower LAI. The significantly higher CGR and TDM of bush beans over pole beans recorded at 54 days after planting also suggested that bush beans were more efficient earlier in the growing season when the daily totals of solar radiation were higher. Mitchell (30) has noted that a crop should be producing its economic yield at the peak of its radiation curve and that in temperate latitudes more solar energy is available to drive photosynthesis during the long, high irradiance days of June than of August. Total solar radiation data collected at Blue Hill, Milton, Massachusetts (Table 3) indicated that for both the 27 year average and the 1976 data the mean daily totals of solar radiation decreased as the growing season progressed.

Canopy Structure

The indeterminate growth habit and height advantage of pole beans (175 cm) over bush beans (50 cm) (fig. 14)

TABLE 3

MEAN DAILY SOLAR RADIATION

LANGLEYS (1 LY = 1 gm. cal. cm^{-2})

BLUE HILL, MILTON, MASS.   Latitude 42°N

1976 MONTH		27 YEAR AVERAGE (data up to 1964)
June	476.7	510
July	457.6	502
August	413.0	449
Sept.	346.75	354

Source:

1976 Data: U. S. Dept. of Commerce, National Climatic Center, Asheville, N.C.

27 Year Avg.: U. S. Dept. of Commerce (1964) Mean Daily Solar Radiation, Monthly and Annual, Superintendent of Documents, U. S. Government Printing Office, Washington, D.C.

permitted better vertical distribution of leaf area in the former and this was related to their high percent light interception at late growth stages.

With the exception of the wide row pole bean which maintained symmetry of vertical leaf area distribution throughout the growing season, all treatments displayed a dramatic upward shift in vertical leaf area distribution over the time interval preceding maximum LAI (fig. 14). As a result canopy structure was asymmetrical in both bush bean treatments and the narrow row pole bean treatment at maximum observed LAI. The vertical leaf area distributions indicated that lack of symmetry was more pronounced in the narrow row spacing. The disproportionately high leaf area accumulation in the upper canopy of the narrow treatments caused shading of lower leaves which may have accelerated the rate of leaf abscission in the lower canopy. From the time of maximum observed LAI to the next sampling date the decrease in total leaf area was 47% and 75% for the narrow row bush bean and narrow row pole beans, respectively. However, rapid leaf abscission in the narrow row pole bean could also be accounted for by the fact that it attained maximum observed LAI late in the growing season. Also, the similarity in LAD for the row width factor within bush and pole bean treatments indicated that rapid leaf abscission was not a problem at the narrow row spacing.

The differences in canopy structure noted between narrow and wide bush bean treatments (fig. 15) could have been caused by more inter-row competition in the former which caused the plants to produce more leaf area in the upper canopy levels, or by excessive intra-row competition in the latter which caused the plants to droop into the inter-row spaces. Shibles and Weber (47) noted that 1 m wide soybean rows presented a spatial barrier to the formation of a complete canopy of leaves and that the filling-in of this large space caused petioles to droop and main stems to partially lodge into the inter-row space. Visual inspection of the plants as early as 54 days after planting confirmed that lodging affected canopy structure in the wide row bush bean treatment.

Row width greatly influenced canopy structure in the pole bean treatments (fig. 17). Pole beans planted at the wide row spacing maintained a symmetrical vertical leaf area distribution throughout the growing season because of better light penetration into the canopy. At the narrow row spacing leaf area distribution became asymmetrical after 54 days due to inter-row competition. As more leaf area accumulated at the top of the canopy less light would presumably reach the lower leaves and they abscised.

Light Extinction Coefficients. Light extinction coefficients for the bush bean treatments were similar and they were comparable with the α_L of 0.86 reported for beans by Monteith (32).

The high α_L (0.97) of the narrow row pole bean treatment could be accounted for by the asymmetrical leaf area distribution observed at 72 days (fig. 17) which closed the top of the canopy and prevented adequate light penetration to lower leaves. Poor light penetration was probably responsible for the more rapid leaf abscission observed in the lower canopy of the narrow row pole bean as compared with the wide row pole bean treatment. The lower α_L (0.69) of the latter indicated that less light was absorbed in the upper canopy, and consequently light was more evenly distributed to lower leaves. For pole beans planted in wide rows the rate of leaf abscission was slower (16% from 54 days to 72 days) as compared to those planted in narrow rows due to improved canopy light relations. Photographs taken at 72 days from planting (fig. 18) revealed the qualitative differences in light penetration and canopy symmetry between the wide and narrow pole bean treatments. However, the similarity of final seed yields in both pole bean treatments indicated that rapid leaf abscission in the narrow row pole bean had no detrimental effect. Since measurements of canopy photosynthesis were not made, it can only be hypothesized that lower, older leaves, remote from the sinks, made little

Fig. 18 Differences in Canopy Structure and Light Penetration in Pole Beans at 72 Days from Planting.

91 cm row width

45.5 cm row width

contribution to net photosynthesis and that the photosynthetic rate of active leaves near the canopy top was sufficient to maintain economic yield in the narrow row pole bean treatment.

Economic Yields. A comparison of seed yields (as a percentage of the 91 cm row width bush beans) (Table 4) indicated that differences in light interception were related to differences in yield. The wide row bush bean treatment attained a maximum light interception of only 82% of the total incident solar radiation and consequently had the lowest LAI and economic yield.

Although this study was limited to a single growing season and one location, the data indicated that bush beans planted at a population density of 247,000 plants ha^{-1} in rows 45.5 cm apart might produce economic yields comparable to those of pole beans under short season temperate zone conditions. The similarity in percent light interception, LAI, and seed yield (Table 4) among the narrow row bush treatment and the two pole bean treatments also supported this hypothesis.

The experiment did show that the 91 cm row spacing for the Bush Blue Lake 290 variety was not suitable because of the severe lodging which occurred in this treatment. Excessive intra-row competition (plants spaced too close together within the row) caused the plants to lodge into

TABLE 4

INFLUENCE OF ROW WIDTH AND GROWTH HABIT ON LIGHT INTERCEPTION, LAI, AND SEED YIELD OF BEANS

TREATMENT	MAXIMUM LIGHT INTERCEPTION	LAI AT MAXIMUM Ll	SEED YIELD (% OF 91 CM BUSH)
BUSH - 91 CM ROW	82%	3.2	100
BUSH - 45.5 CM ROW	90%	3.7	113
POLE - 91 CM ROW	92%	4.3	127
POLE - 45.5 CM ROW	93%	3.9	130

the inter-row spaces and soon resulted in complete dis-integration of canopy structure. Lodging associated with this treatment greatly increased the incidence of white mold disease, Sclerotinia sclerotiorum, (because pods were in direct contact with the soil). Yields would have been further reduced by lodging in this treatment had the beans been mechanically harvested. Clearly, the ability to better withstand lodging and the higher light interception, LAI and seed yield of the narrow row treatment indicated that this spacing was the more appropriate plant arrangement for Bush Blue Lake 290 bean production.

For pole beans the wide row spacing appeared to be preferable. Since light interception, LAI, TDM yields and seed yields were almost identical for the 2 treatments and since the wide row treatment required only half as much labor and materials for trellis construction, the savings in production costs favor this spacing.

CHAPTER VI

CONCLUSION

Light Interception

In both bush and pole beans the narrow row treatment intercepted more light earlier in the season as compared with the wide row treatment. The higher percentage light interception by the narrow row treatment over the wide row treatment was maintained in the bush beans until late in the season, but for the pole beans no differences in light interception due to row width occurred after 41 days. The higher maximum light interception of the narrow row bush bean treatment and the pole beans (≥ 90%) over the wide row bush bean treatment (82%) was associated with a higher LAI and seed yield.

Leaf Area Development

Narrowing row width accelerated the rate of leaf area development and produced a higher maximum LAI in the bush bean cultivar. Conversely, for the pole bean variety the wide row treatment produced a higher maximum LAI and at an earlier date as compared with the narrow row treatment.

The indeterminate growth habit of the pole beans conferred no significant yield advantage over the bush beans probably because the quantity of solar radiation available for photosynthesis was declining throughout the growing season. When the pole beans finally demonstrated a light interception advantage (due to significantly longer LAD), there was less solar energy to exploit. These results contrasted with work in the tropics during the dry season (when mean monthly totals of solar radiation are increasing) which has shown that at high planting densities (one million plants ha^{-1}) pole beans accumulate 3 times more LAI and produce twice the seed yield of bush beans (2).

Canopy Structure

Canopy development varied according to spacing arrangement and growth habit. More light penetrated to ground level in the wide row treatment canopies than in the narrow row treatments, because in the former, canopy development into the inter-row spaces was incomplete.

A large proportion of the total LAI was concentrated in the upper canopy of the narrow row treatments of both bush and pole beans at the time of maximum observed LAI. The asymmetrical leaf area distribution of the narrow row treatments was accompanied by rapid leaf abscission once maximum LAI was attained. The symmetrical vertical leaf area distribution of the wide row pole bean canopy probably accounted for the low α_L of this treatment. Excessive intra-row competition in the wide row bush bean treatment caused lodging which hastened disintegration of canopy structure.

Efficiency of Crop Growth

Bush beans had a significantly higher maximum CGR and significantly higher TDM productivity in mid-season over the pole beans. This was probably due to reproductive growth occurring simultaneously with maximum observed LAI. The data indicated that a determinate (bush) bean which initiates pod formation and filling early in the temperate zone growing season will yeild about as well as an indeterminate (pole) type having longer LAD.

LITERATURE CITED

1. Allen, L. H., C. S. Yocum and E. R. Lemon. (1964) Photosynthesis under field conditions: VII. Radiant energy exchange. Agron. J. 56:253-259.

2. Anon. (1975) Bean production systems. International Center for Tropical Agriculture (CIAT). Cali, Columbia, pp. 130-138.

3. Anon. (1975) Bean production systems program. CIAT. Cali, Columbia. Series F.E. No. 5, 38 pp.

4. Atkin, J. D. (1961) Row spacing influences yield of snap and dry beans. N. Y. Agr. Exp. Sta. Farm. Res. 27(3):13.

5. Baker, D. N. and R. B. Musgrave. (1964) Photosynthesis under field conditions. V. Further plant chamber studies of the effects of light on corn. Crop Sci. 4:127-131.

6. Blackman, G. E., and J. N. Black. (1959) Physiological and ecological studies in the analysis of plant environment. Ann. Bot. N. S. 23:131-145.

7. Bohning, R. H., and C. A. Burnside. (1956) The effect of light intensity on apparent photosynthesis in leaves of sun and shade plants. Amer. J. Bot. 43:557-561.

8. Brougham, R. W. (1960) The relationship between critical leaf area, chlorophyll content and maximum growth rate of some pasture and crop plants. Ann. Bot. N. S. 24:463-474.

9. Brougham, R. W. (1956) Effect of intensity of defoliation on regrowth of pasture. Aust. J. Agr. Res. 7:377-387.

10. Buttery, B. R. (1970) Effects of variation in leaf area index on the growth of maize and soybeans. Crop Sci. 10:9-13.

11. Chapman, T. and D. J. Cowling. (1965) A preliminary investigation into the effects of leaf distribution on the yields of sweet potato. Trop. Agr. Trinidad. 42:199-203.

12. Crandall, P. C., M. C. Jensen, J. D. Chamberlain, and L. G. Jones. (1971) Effect of row width and direction of mist irrigation on the microclimate of beans. Hort. Sci. 4:345-347.

13. Crothers, S. E., and D. T. Westermann. (1976) Plant population effects on seed yield of Phaseolus vulgaris L. Ag. Jour. 68:958-960.

14. Donald, C. M. (1963) Competition among crop and pasture plants. Adv. in Agron. 15:1-118.

15. Egli, D. B. and J. E. Leggett (1973) Dry matter accumulation patterns in determinate and indeterminate soybeans. Crop Sci. 13:220-222.

16. Evans, L. T. (ed.) (1975) Crop physiology: Some case histories. Camb. Univ. Press, Cambridge, pp. 327-355.

17. Fery, R. L. and J. Janick (1971) Response of corn (Zea Mays L.) to population pressure. Crop Sci. 11:220-224.

18. Francis, C. A., C. A. Flor, and S. R. Temple (1976) Adapting varieties for intercropping systems in the tropics; in R. I. Papendick, P. A. Sanchez and G. B. Triplett (eds.) Multiple Cropping. Proc. ASA symp. on multiple cropping. Knoxville, Tenn. Aug. 1975. ASA spec. pub. No. 27, pp. 235-253.

19. Gaastra, P. (1962) Photosynthesis of leaves and field crops. Neth. J. Agr. Sci. 10:311-324.

20. Hicks, D. R., J. W. Pendleton, R. L. Bernard, and T. J. Johnson (1969) Response of soybean plant types to planting patterns. Ag. Jour. 61:290-293.

21. Hodgson, G. L. and G. E. Blackman (1956) An analysis of the influence of plant density on the Growth of Vica faba. J. of Exp. Bot. 7:147-165.

22. Ito, A., and J. Udagawa (1971) Phytometrical studies of crop canopies. I. Geometrical structure of soybean canopy and sun light penetration. J. Agr. Meteorol. 26:187-195.

23. Jeffers, D. L. and R. M. Shibles (1969) Some effects of leaf area, solar radiation, air temperature and variety on net photosynthesis in field grown soybeans. Crop. Sci. 9:762-764.

24. Larson, R. E. and Li Peng Fi (1948) The influence of various row and plant spacings on yield of lima beans. Proc. Amer. Soc. Hort. Sci. 51:479-485.

25. Loomis, R. S. and P. A. Gerakis (1975) Productivity of agricultural ecosystems. In J. P. Cooper (ed.) Photosynthesis and productivity in different environments. Camb. Univ. Press, Cambridge, pp. 145-173.

26. Loomis, R. S., W. A. Williams, and W. G. Duncan (1967) Photosynthetic limits on crop yields. In A. San Pietro, F. A. Greer, and T. J. Army (eds.) Harvesting the sun. Academic Press, New York, pp. 291-308.

27. Loomis, R. S., and W. A. Williams (1963) Maximum crop productivity: an estimate, Crop. Sci. 3:67-72.

28. Mack, H. J., and D. L. Hatch (1968) Effects of plant arrangement and population density on yield of bush snap beans. Proc. Am. Soc. Hort. Sci. 92:418-425.

29. McDaniel, A. R. and H. D. Swingle (1975) Population and spacing effects on the growth of snap beans. Ann. Rep. Bean Imp. Coop. 18:42-43.

30. Mitchell, R. L. (1970) Crop growth and culture, Iowa State Univ. Press, Ames, chapter II and Chapter VI.

31. Monsi, M., Z. Uchijima and T. Oikawa (1973) Structure of foliage canopies and photosynthesis. Ann. Rev. Ecol. and Systematics. 4:301-328.

32. Monteith, J. L. (1969) Light interception and radiative exchange in crop stands. In J. D. Eastin, F. A. Haskins, C. Y. Sullivan, and C. H. M. van Bavel. Physiological aspects of crop yield. Amer. Soc. Agron. Madison, Wisc. p. 80-111.

33. Montojos, J. C., and A. C. Magalhaes (1971) Growth analysis of dry beans (Phaseolus vulgaris L. var Pintado) under varying conditions of solar radiation and nitrogen application. Pl. and Soil 35:217-223.

34. Moss, D. N. and R. B. Musgrave (1971) Photosynthesis and crop production. Adv. in Agron. 23:317-336.

35. Nassar, H. N. and E. J. Kinbacher (1975) Growth characteristics in relation to productivity of snap beans. Ann. Rep. Bean Imp. Coop. 18:55-56.

36. Nichiporovich, A. A. (1960) Photosynthesis and the theory of obtaining high crop yields. Field Crop. Abs. 13:169-175.

37. Ozbun, J. L. (1976) Potential increases in food supply through research in agriculture. Researchable areas which have potential for increasing crop production. Cornell Univ., Ithaca, N. Y. pp. 5-14.

38. Pendleton, J. J., and E. E. Hartwig (1973) Management. In B. E. Caldwell (ed.) Soybeans, improvement, production and uses. Amer. Soc. Agron. Madison, Wisc., p. 215-216.

39. Radford, P. J. (1967) Growth analysis formulae - their use and abuse. Crop. Sci. 7:171-175.

40. Robinson, R. G., D. D. Warnes, W. W. Nelson, J. H. Ford, and L. J. Smith (1974) Field beans - rates of planting, width of row and effects of irrigation and Nitrogen on yield and seed quality. Ag. Exp. Sta. Univ. of Minn. Misc. Report 124. 8 p.

41. Saeki, T. (1963) Light relations in plant communities In L. T. Evans (ed.) Environmental control of plant growth. Academic Press, N. Y. pp. 79-94.

42. Sakamoto, C. M., and R. M. Shaw (1967) Light distribution in field soybean canopies. Agron. J. 59: 7-9.

43. Sakamoto, C. M. and R. H. Shaw (1967) Apparent photosynthesis in field soybean communities. Agron. J. 59:73-75

44. Sale, P. J. M. (1975) Productivity of vegetable crops in a region of high solar input. IV. Field chamber measurements on french beans (*Phaseolus vulgaris* L.) and cabbages (*Brassica oleracea* L.) Aust. J. Pl. Phys. 2(4) 461-470.

45. Shaw, R. H. and C. R. Weber (1967) Effects of canopy arrangements on light interception and yield of soybeans. Agron. J. 59:155-159.

46. Shibles, R. M., I. C. Anderson and A. H. Gibson (1975) Soybeans. In L. T. Evans (ed.) Crop physiology - some case histories. Camb. Univ. Press, Cambridge, pp. 157-168.

47. Shibles, R. M. and C. R. Weber (1966) Interception of solar radiation and dry matter production by various soybean planting patterns. Crop Sci. 6:55-59.

48. Shibles, R. M. and C. R. Weber (1965) Leaf area, solar radiation interception and dry matter production by soybeans. Crop Sci. 5:575-577.

49. Verhagen, A. M., J. H. Wilson, and E. J. Britten (1963) Plant production in relation to foliage illumination. Ann. of Bot. N. S. 27:627-640.

50. Wallace, D. H., J. L. Ozbun and H. M. Munger (1972) Physiological genetics of crop yield. Adv. in Agron. 24:97-146.

51. Wallace, D. H., and H. M. Munger (1965) Studies of the physiological basis for yield difference. I. Growth analysis of six dry bean varieties. Crop Sci. 5:343-348.

52. Watson, D. J. (1971) Size, structure and activity of productive systems of crops. In P. F. Wareing and J. P. Cooper (eds.) Potential crop production. Heinemann, London, pp. 76-88.

53. Watson, D. J. (1958) The dependence of net assimilation rate on leaf area index Ann. Bot. N. S. 22:37-55.

54. Watson, D. J. (1956) Leaf growth in relation to crop yield. In F. L. Milthorpe (ed.) The growth of leaves. Proc. of 3rd Easter School in Ag. Sci. Butterworths Sci. Pub., London, pp. 178-191.

55. Watson, D. J. (1952) The physiological basis of variation in yield, Adv. in Agron. 4:101-145.

56. Watson, D. J. (1947) Comparative physiological studies on the growth of field crops. I. Variation in net assimilation rate and leaf area between species and varieties and within the between years. Ann. Bot. N. S. 11:41-76.

57. Weber, C. R., R. M. Shibles and D. E. Byth (1966) Effect of plant population and row spacing on soybean development and production. Ag. Jour. 58:99-102.

58. Welbank, P. J., S. A. W. French and K. J. Witts (1966) Dependence of yields of wheat varieties on their leaf area duration. Ann. Bot. N. S. 30:291-299.

59. Wien, H. C. (1971) The influence of spacing on light interception, growth and seed yield of *Phaseolus vulgaris* L. under temperate and tropical conditions. Ph. D. thesis Cornell Univ. Diss. Abstr. 32B:4965-4966.

60. Wiggins, R. G. (1939) The influence of space and arrangement on the production of soybean plants. J. Am. Soc. Agron. 31:314-321.

61. Williams, C. N., and K. T. Joseph (1973) Climate, soil and crop production in the humid tropics. Oxford Univ. Press, Kuala Lumpur., pp. 59-97.

62. Williams, W. A., R. S. Loomis, W. G. Duncan, A. Dovrat and F. Nunez A. (1968) Canopy architecture at various population densities and the growth and grain yield of corn. Crop Sci. 8:303-308.

63. Williams, W. A., R. J. Loomis and C. R. Lepley (1965) Vegetative growth of corn as affected by population density. I. Components of growth, net assimilation rate and leaf area index. Crop Sci. 5:215-219.

64. Yoshida, S. (1972) Physiological aspects of grain yield. Ann. Rev. Pl. Physiol. 23:437-464.

65. Zelitch, I. (1971) Photosynthesis, photorespiration and plant productivity. Academic Press, N. Y. pp. 267-299.

APPENDIX A

ANALYSES OF VARIANCE

ANALYSIS OF VARIANCE - LIGHT INTERCEPTION

Days after planting	Source	df	M.S.	F
34	Rep.	2	18.65	N.S.
	Growth	1	6.02	N.S.
	Width	1	41.44	N.S.
	GW	1	50.02	N.S.
	Error RG RW RGW	6	101.01	
41	Rep.	2	135.23	N.S.
	Growth	1	16.56	N.S.
	Width	1	984.64	12.36*
	GW	1	25.52	N.S.
	Error RG RW RGW	6	79.626	
54	Rep.	2	369.83	16.169**
	Growth	1	2.08	N.S.
	Width	1	41.07	N.S.
	GW	1	56.33	N.S.
	Error RG RW RGW	6	22.87	
72	Rep.	2	28.62	N.S.
	Growth	1	614.90	12.44*
	Width	1	126.10	N.S.
	GW	1	90.20	N.S.
	Error RG RW RGW	6	49.43	
96	Rep.	2	249.99	N.S.
	Growth	1	1,968.64	21.82**
	Width	1	.44	N.S.
	GW	1	98.04	N.S.
	Error RG RW RGW	6	90.23	

ANALYSIS OF VARIANCE - LAI

(Calculated in cm^2)

Days After Planting	Source	df	MS	F
34	Rep.	2	2,248,876.58	N.S.
	Growth	1	8,551,408.33	N.S.
	Width	1	445,445.33	N.S.
	GW	1	1,809,633.3	N.S.
	Error RG RW RGW	6	12,687,707.93	
41	Rep.	2	21,947,063.25	N.S.
	Growth	1	10,414,170.08	N.S.
	Width	1	25,763,490.25	N.S.
	GW	1	14,491,414.08	N.S.
	Error RG RW RGW	6	16,421,967.82	
54	Rep.	2	19,970,970.08	N.S.
	Growth	1	88,449,270.08	N.S.
	Width	1	365,752.08	N.S.
	GW	1	67,265,410.08	N.S.
	Error RG RW RGW	6	20,976,399.77	
72	Rep.	2	22,344,158.08	N.S.
	Growth	1	553,887,644.08	73.59**
	Width	1	8,421,900.75	N.S.
	GW	1	51,738,074.08	6.87*
	Error RG RW RGW	6	7,526,160.98	
96	Rep.	2	1,062,449.08	N.S.
	Growth	1	9,703,806.75	N.S.
	Width	1	14,614,754.08	N.S.
	GW	1	2,976.75	N.S.
	Error RG RW RGW	6	25,576,306.86	

ANALYSIS OF VARIANCE CGR

Days After Planting	Source	df	MS	F
34	Rep.	2	0.044	N.S.
	Growth	1	0.057	N.S.
	Width	1	0.156	N.S.
	GW	1	0.022	N.S.
	Error RG RW RGW	6	0.342	
41	Rep.	2	24.44	N.S.
	Growth	1	8.3	N.S.
	Width	1	16.94	N.S.
	GW	1	5.90	N.S.
	Error RG RW RGW	6	8.29	
54	Rep.	2	2.05	N.S.
	Growth	1	16.78	7.399*
	Width	1	2.77	N.S.
	GW	1	7.98	N.S.
	Error RG RW RGW	6	2.27	
72	Rep.	2	16.33	N.S.
	Growth	1	.15	N.S.
	Width	1	3.60	N.S.
	GW	1	97.30	8.26*
	Error RG RW RGW	6	11.77	
96	Rep.	2	8.13	N.S.
	Growth	1	51.70	N.S.
	Width	1	1.14	N.S.
	GW	1	9.31	N.S.
	Error RG RW RGW	6	11.43	

ANALYSIS OF VARIANCE - TDM

Days After Planting	Source	df	MS	F
34	Rep.	2	53.08	N.S.
	Growth	1	65.33	N.S.
	Width	1	176.33	N.S.
	GW	1	27.00	N.S.
	Error RG RW RGW	6	394.30	
41	Rep.	2	1,621.75	N.S.
	Growth	1	800.33	N.S.
	Width	1	1,776.33	N.S.
	GW	1	481.33	N.S.
	Error RG RW RGW	6	42.42	
54	Rep.	2	696.08	N.S.
	Growth	1	6,627.00	21.77**
	Width	1	432.00	N.S.
	GW	1	3,675.00	12.07*
	Error RG RW RGW	6	304.42	
72	Rep.	2	9,601.00	N.S.
	Growth	1	4,920.75	N.S.
	Width	1	102.08	N.S.
	GW	1	12,740.08	N.S.
	Error RG RW RGW	6	2,356.88	
96	Rep.	2	673.25	N.S.
	Growth	1	27,075.00	N.S.
	Width	1	208.33	N.S.
	GW	1	1,728.00	N.S.
	Error RG RW RGW	6	5,125.69	

ANALYSIS OF VARIANCE - LAD

Days After Planting	Source	df	MS	F
96	Rep.	2	3 394.83	N.S.
	Growth	1	3,593.21	12.00*
	Width	1	26.37	N.S.
	GW	1	1.22	N.S.
	Error RG			
	RW	6	299.26	
	RGW			

ANALYSIS OF VARIANCE - DRY SEED YIELDS

Days After Planting	Source	df	MS	F
96	Rep.	2	611.27	N.S.
	Growth	1	4,860.18	N.S.
	Width	1	713.02	N.S.
	GW	1	256.68	N.S.
	Error RG			
	RW	6	1,397.05	
	RGW			