THESIS

DROUGHT STRESS BY GROWTH STAGE AND ONION PLANT GROWTH

Submitted by

Paul Allen Richwine

Horticulture Department

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WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION BY PAUL ALLEN RICHWINE ENTITLED DROUGHT STRESS BY GROWTH STAGE AND ONION PLANT GROWTH BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

Committee on Graduate Work

Robert E. Danielson

Stephen J. Wallner

Frank D. Moore III

Adviser

K. M. Brink

Department Head

ABSTRACT OF THESIS

DROUGHT STRESS BY GROWTH STAGE AND
ONION PLANT GROWTH

Three distinct growth stages of the onion's vegetative development have been defined: early (73-101 days), mid (102-122 days), and late season (123-143 days). Two years of field experiments and a greenhouse study with onions examined the effects of drought stress applied during these stages. Influence of excessive nitrate salts was also investigated.

Rootview boxes submerged in a furrow-irrigated onion field allowed for a continuous study of root, leaf, and bulb development. A drought stress of -100 kPa soil matric potential was imposed for three weeks during each growth stage. Soil matric potential of -55 kPa was used as a standard.

Onion plants located in the greenhouse were hydroponically grown in cans containing half-strength Hoagland's solution. Polyethylene glycol (PEG 3500) was used as the osmotic potential modifier creating drought stresses of -100 kPa and -200 kPa which were applied for 3 weeks during each growth stage. Ammonium nitrate (NH4NO3) at levels of 153 and 202 ppm NO3-N provided the high nitrate source.

Both field and greenhouse studies identified the mid-season growth stage as the most sensitive to drought stress equal to or

greater than -100 kPa. Bulb, root, and top components were significantly reduced as compared with the no stress treatment. Drought stress of -100 kPa during the early season growth stage had no significant negative effect on onion growth, however, a drought stress of -200 kPa applied during the early season growth stage caused growth to be suppressed. Drought stress had no significant effect on onion growth when applied during the late season growth stage.

There was no significant influence of high nitrate levels on onion top, bulb, or root growth.

Paul Allen Richwine
Horticulture Department
Colorado State University
Fort Collins, Colorado 80523
Summer 1984

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INTRODUCTION

Onion production has been steadily rising in Colorado over the past few years. Favorable onion prices have intensified interests in onions resulting in more acreage being devoted to their production. In 1981 for example, production had jumped 19% and value of sales increased 37% compared to 1980 (47). In 1982, the General Farm Business Summary of Northern Colorado reported that the percentage of profit which was returned to management was highest for onions (31).

Expanding onion production in Colorado also means increased use of irrigation water and therefore the increased energy utilization for pumping. Irrigation water is a major limiting factor in Colorado and other semi-arid regions. Growers often irrigate too frequently and apply more water than needed by the crop. Since one result of persistent misuse and waste of water is high cost, attention has been focused on various water conserving measures.

One possible approach to water savings would be applying irrigation water only when the crop needs it the most (2). To evaluate an approach such as this requires imporved understanding of the response to drought stress at specific growth stages. Such information may provide evidence that irrigation(s) can be withheld during certain developmental stages.

The objective of this research was to determine the effect of drought stress during different vegetative growth stages.

LITERATURE REVIEW

The improvement of irrigation technology through time brought more semi-arid and arid land into irrigated crop production. The rapid expansion of irrigable lands in these areas, however, causes new problems. One of these is water availability. Today, due to dwindling water supplies and pumping costs, attention has been turned to water conserving measures.

Farmers in Colorado often encounter the problem of how much and when to irrigate a crop using minimum amounts of water. Since water resources must be conserved, a question often asked is what yield losses could be expected by withholding one or more irrigations? The farmer needs to know if profitable yields can be maintained when normally applied irrigations are eliminated. The most promising possibility is that irrigation(s) could be eliminated during growth stages which are least affected.

The development of the onion plant following emergence occurs in three distinct growth stages: early, mid, and late season vegetative (5, 26, 29, 38, 42). The early season vegetative growth stage or "seedling" stage is initially a period of slow growth, a lag phase, characterized by minimal leaf bud differentiation, leaf emergence, and some increase in fresh weight (17, 29, 53). The number of active adventitious roots increases proportionally with top weight during this period (29). This period also includes the transition from lag to log phase of leaf growth as reported by Bosley (2). The mid-season vegetative growth stage or "late green onion" stage is a period of exponential growth or log phase of bulb development, characterized by prolific scale bud initiation and differentiation, root initiation and elongation (17, 29, 50). This stage of growth has also been reported as the bulbing phase of growth (2).

Finally, the late season vegetative growth stage is a period during which bulb growth, maturation, and sizing occurs. The bulb exhibits a rapid increase in the accumulation of fresh and dry weight (53). Overall, the whole plant shows a decline in its growth rate leading toward senescence (29). Leaf emergence decreases and eventually ceases approximatley two weeks after scale bud initiation (29). Root elongation is inhibited from time of visible bulbing although rooting will begin again if there is adequate soil moisture during this last stage (50).

Many plants exhibit different levels of tolerance to drought stress throughout their life cycle (13, 19, 30, 38). In some species (e.g. the tomato), one response to drought stress is delayed stimulation of the growth of young plants (4, 10). The most sensitive stage during the development of corn, snapbeans, cereal, and certain other crops grown for their reproductive structures is the flowering and fruiting period. However, cabbage, potato, and turnip yields were reduced most by drought stress during initiation and development of vegetative structures (4, 21, 38, 40, 49). With regard to soybeans, Sutherland found that drought stress during the flowering period actually increased yield and the pod and bean stages were the most sensitive to drought (43).

Apparently, it has been difficult to identify a single most critical growth stage of onion since there are conflicting reports in the literature. Some researchers found that drought stress at the beginning of bulb initiation and formation, i.e. during development of vegetative structures, caused a significant final yield loss. These findings are comparable to those mentioned previously which involved species other than onion which were stressed during development of vegetative structures (5, 19, 38, 48). Other researchers, however, have shown that drought stress has a greater effect in suppressing yield when applied during the early vegetative growth stage (42).

Numerous experiments have been conducted to evaluate the effects of drought stress on onion top and yield components, but few have simultaneously evaluated root growth (44). Root studies are important since root depth and distribution combined with evapotranspiration and available soil moisture measurements give better estimates of water requirements than the individual components for a particular crop species (27). In addition, there may be a direct relationship between root growth and top growth of onion thereby allowing accurate predictions of root depth from top size to be made for use in estimating irrigation requirements. Mayaki (27) was able to correlate root depth and distribution in the field with above-ground parameters at specific physiological stages of soybean.

Root studies have been limited due to difficulty in sampling and in making periodic observations. Many root evaluation methods are available, but, most are time consuming, tedious, and the variability in measurements is high (1, 28, 44). Examples of these methods are: excavation method, monolith method, profile wall method, and various container methods (1). Most methods require separation of roots from the soil. Although these methods provide quantitative data on studies of root length, size, shape, and distribution, they do not allow for continuous measurement of root growth (1, 18). Transparent container methods and profile wall methods allow progressive study of root development throughout the crop's life cycle. Root growth is observed or recorded through a rigid inclined transparent material against a soil profile and semi-quantitative data is usually obtained by visual estimations of rooting intensities. Disadvantages include limited observation surface of the container (usually a single plane), possible algal growth, moisture condensation, root growth restriction by the container and an unnatural environment at the root-glass panel interface (1). However, the latter is not as serious as it was once thought since the glass can be considered as a barrier similar to a large stone or a grain of sand (35). Furthermore, all disadvantages are outweighed by the fact that continuous semi-quantitative observation of root development may be made.

There is no general agreement among results pertaining to the effects of drought stress on root development and distribution. Sharp (37) indicated that root growth in corn and wheat increases in response to a mild degree of stress. However, others (12, 23, 44) have shown a negative correlation between soil moisture stress and root growth in crops such as cotton, corn, and wheat. Plants exposed to a drought stress also exhibit different rooting patterns when compared to plants which are well-watered (9, 22). Roots subjected to a drought stress are usually distributed uniformly throughout the profile while roots which are well-watered may be confined to the upper half of the soil profile (22).

Excess NO3

The effect of nitrate, positive or negative, on onion yield is determined by the relative amount of soil moisture and nitrogen fertilizer received by the crop. Utilization of nitrogen by the onion fluctuates greatly according to moisture supply (34). Increasing amounts of nitrogen are necessary for optimum growth and maturity under conditions of adequate moisture. Above a certain requirement, however, no direct relationship has been shown between quantity of dry matter produced and quantity of nitrogen available in the medium, probably due to luxury consumption by the crop (52). Under dry conditions, high rates of nitrogen application depress yields due to high concentrations of salts which accumulate in the soil (33).

Many vegetable growers are indiscriminate in the amount of fertilizer they use, therefore, most fields receive too much. Due to progressive fertilizer accumulation, little precipitation, minimum percolation, and high rates of evaporation, many arid region soils contain excess soluble salts. The chief anion contributing to the salt problem is nitrate (14). Toxicity from an excess of nitrate usually occurs as a result of overfertilization (11). Onion fields in Colorado often contain high residual soil NO3-N (51).

Irrigation water contributes far more soluble salts to the soil than initial soluble salts in the soil (11). Colorado irrigation water varies from excellent to poor and some irrigation waters may contain up to 0.09 kg NO3-N per cubic meter (25,51). Furrow irrigation together with bed culture results in excessive salt accumulation in the tops of the beds due to evaporative deposit.

Nitrate salts can injure plants quite severely. Onions are moderately sensitive to moderately tolerant to salts, with this varying according to growth stage (14, 26). A soil with an ECe of 1.8 mmhos/cm reduced onion yield by 10% (7). The seedling stage of the onion is the most sensitive stage and general symptoms of salt damage include: burning and discoloration of roots, decreased branching of roots, and burning of leaf tips and margins (6, 15, 24, 33).

Once salts have been identified as a problem, more frequent irrigations with greater volumes of water may be necessary.

MATERIALS AND METHODS

Three separate experiments were conducted: two field experiments and a greenhouse experiment. The procedures for the field experiments during the summers of 1982 and 1983 were identical and some of the results were averaged over 2 years. Allium cepa L., cv. Brown Beauty, the principal cultivar grown in northeastern Colorado, was used in all experiments. Three distinct growth stages and a control with no stress were employed in all experiments. The 3 growth stages are:

Early season: Seedling stage; 5 leaves

Mid-season: Late green onion stage; 7-8 leaves

Late season: 2.5-3.8 cm bulb stage; 8-10 leaves

FIELD EXPERIMENTS - Summer 1982 and Summer 1983

The purpose of these experiments was to determine the response of onion tops and roots to soil moisture stress during different growth stages. Both experiments were conducted at the Northern Colorado Research and Demonstration Center, northeast of Greeley, Colorado. The plots were situated in a furrow-irrigated onion field located in the northeast corner of the Center in 1982 and southwest corner of the Center in 1983.

Rootview Box Preparation

Twenty rootview boxes[1] were used in 1982 and 1983. Each box as illustrated in Figure 1 contains two removable plexiglass side panels supported by plastic end panels and bracing rods. The dimensions of the box are 50.8 cm length x 25.4 cm width tapering down to 2.0 cm width. Depth of the box is 43.2 cm. Link chains were secured on both end panels and functioned as handles. Black polyethylene, removed for observation of roots, was used to protect the roots from light and to minimize algal growth.

Soil used in the boxes in 1982 was classified as a sandy loam and originated from the surface 30.5 cm of the onion field. Peat-lite (1 part peat; 1 part vermiculite) was mixed into the soil at a rate of 0.4 kg/19.6 kg soil to increase the organic matter to 2%. No fertilizer was incorporated into the soil mix since the field had been previously fertilized. The soil mix was sifted through a 1.3 cm mesh screen and 20 kg of the mixture was added to each box. Figure 2 shows soil moisture content by volume and depletion curves for the sandy loam soil mix used in 1982.

Soil in 1983 was a sandy clay loam. Neither fertilizer nor organic matter was added due to sufficient amounts already present in the sandy clay loam. Soil was screened and 20 kg of the sandy clay loam was used for each box. Soil moisture content and depletion curves are shown in Figure 3.

Electrical resistance blocks and a Delmhorst model KS-2 moisture tester were used to determine soil matric potential. Four of the

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[1]Olson Manufacturing Co., P. O. Box 109, Ames, Iowa.

Figure 1. Rootview box used in 1982 and 1983 field experiments. Box consisted of 2 removable plexiglass side panels supported by 2 end panels and 4 bracing rods. Link chains on either end panel functioned as handles.

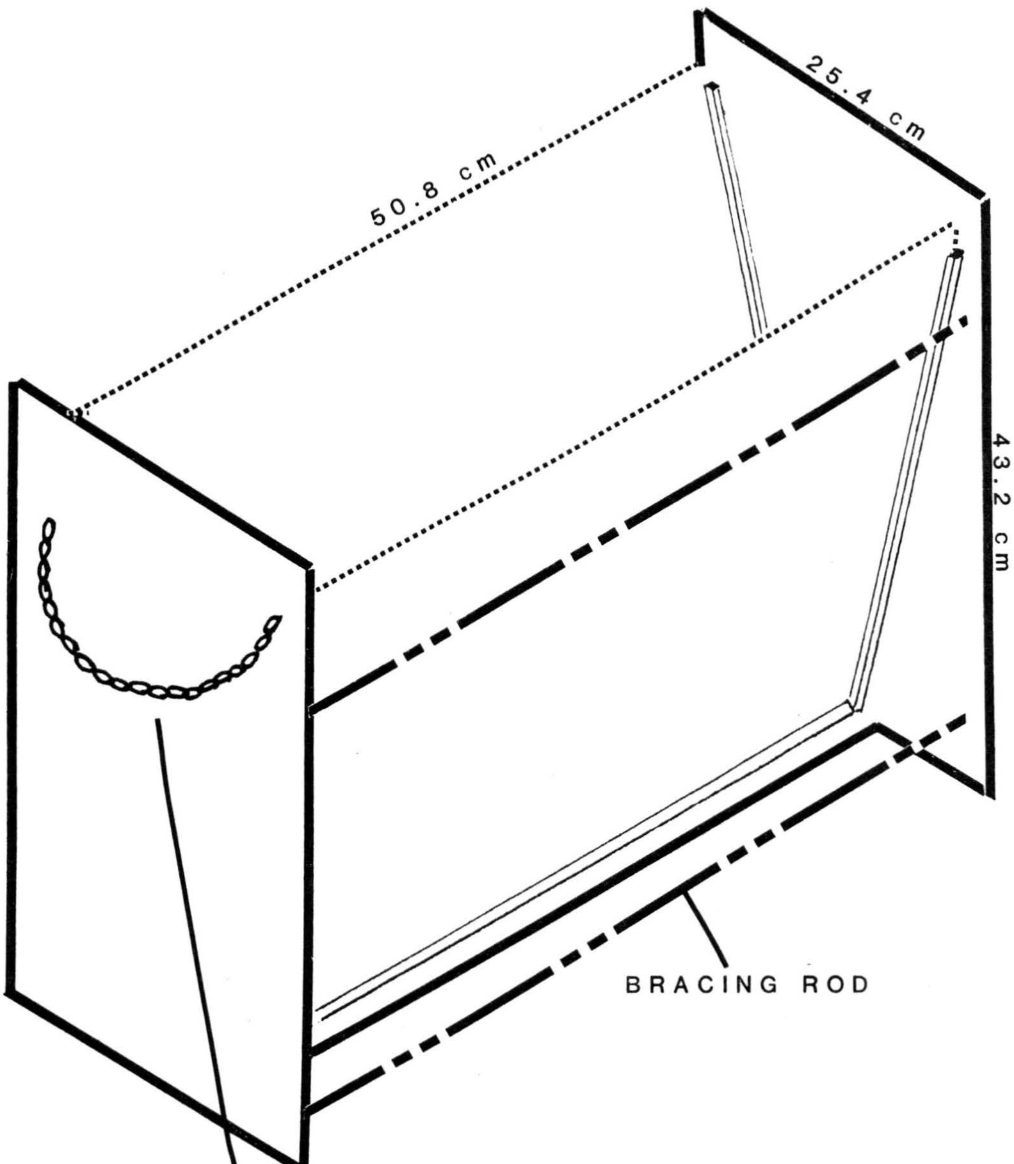
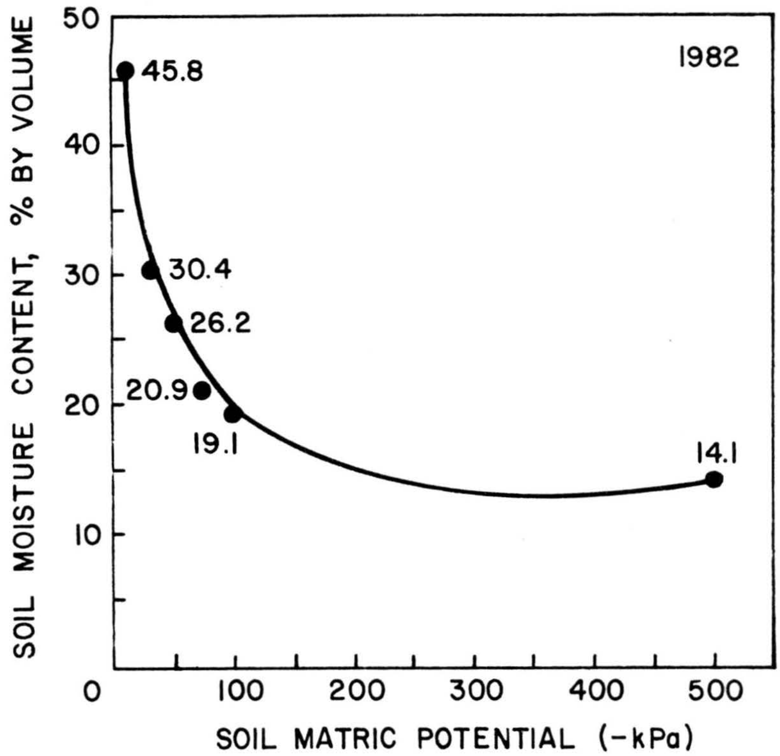

25.4 cm
50.8 cm
43.2 cm
BRACING ROD
LINK CHAIN HANDLES

Figure 2. Desorption and depletion curve for the sandy loam soil mix used in the 1982 field experiment. Sample of soil from surface, 0-30 cm and mixed with peat-lite.


1982
45.8
30.4
26.2
20.9
19.1
14.1
SOIL MOISTURE CONTENT, % BY VOLUME
0
10
20
30
40
50
100
200
300
400
500
SOIL MATRIC POTENTIAL (-kPa)

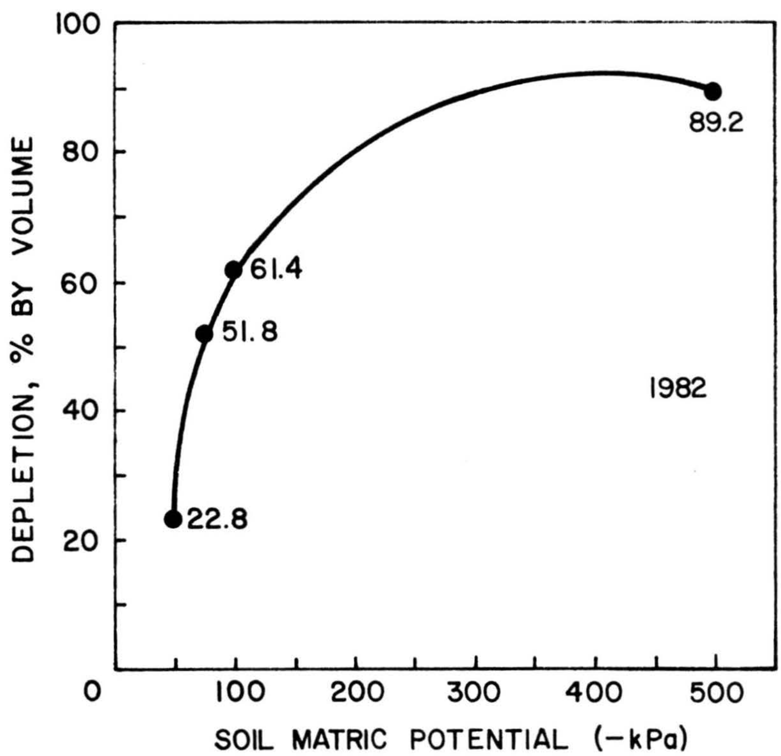
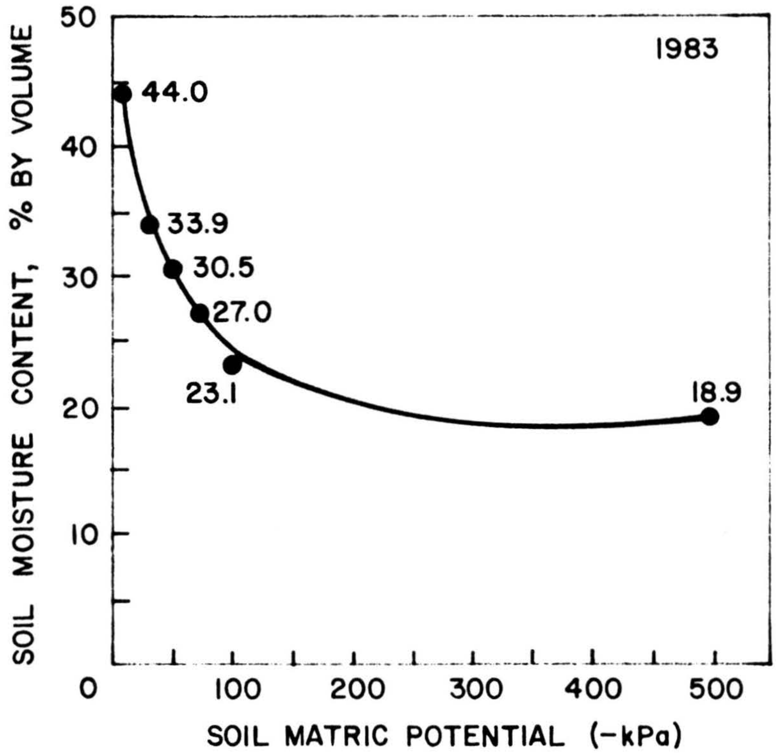
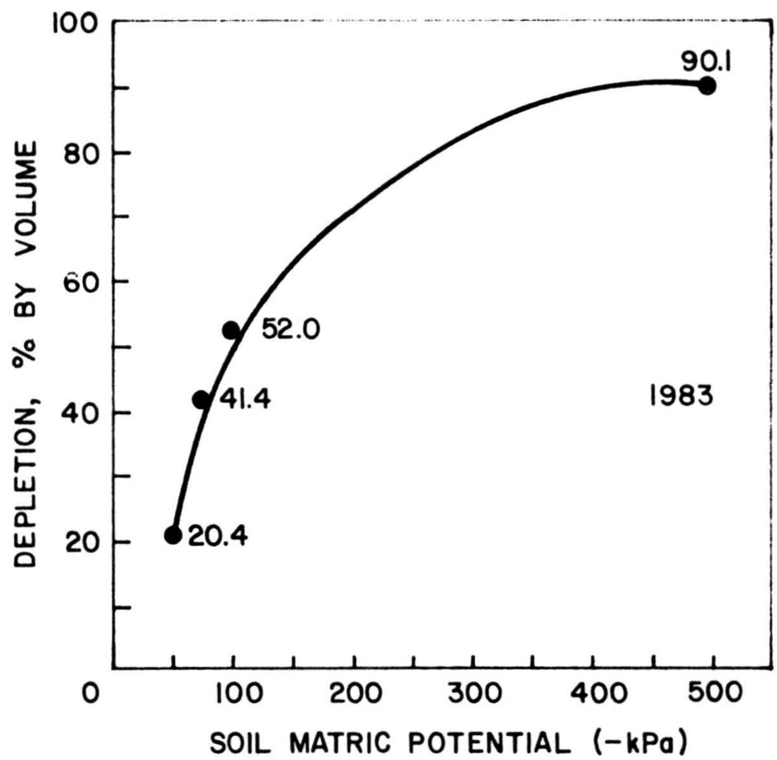

89.2
61.4
51.8
22.8
1982
DEPLETION, % BY VOLUME
0
20
40
60
80
100
200
300
400
500
SOIL MATRIC POTENTIAL (-kPa)

Figure 3. Desorption and depletion curve for the sandy clay loam soil used in the 1983 field experiment. Sample taken from surface, 0-30 cm.


1983
44.0
33.9
30.5
27.0
23.1
18.9
SOIL MOISTURE CONTENT, % BY VOLUME
50
40
30
20
10
0
100
200
300
400
500
SOIL MATRIC POTENTIAL (-kPa)


90.1
52.0
41.4
20.4
1983
DEPLETION, % BY VOLUME
100
80
60
40
20
0
100
200
300
400
500
SOIL MATRIC POTENTIAL (-kPa)

cylindrical resistance blocks were placed in the center of each box. They were submerged at depths of 5.1 cm, 10.2 cm, 20.3 cm, and 40.7 cm with color coded leads extending above ground.

Site Preparation

The furrow-irrigated onion fields were planted using current commercial practices - double row beds 96.5 cm wide were seeded with rows 61.0 cm apart. Site preparation for the research plots began after field planting. Research plots included 4 double row beds 15.2 m long with border rows of field-planted onions in between and surrounding the rootview boxes. Twenty rectangular excavations, 5 per bed spaced 3.1 m apart along the bed, were centered within the bed between the 2 commercial onion rows. Galvanized metal sleeves 55.9 cm x 20.5 cm x 45.7 cm were submerged into the holes first to prevent soil from collapsing. A 0.6-1.3 cm lip of the metal sleeve was above ground to avoid flooding from furrow irrigation. Removable transparent shelters prevented precipitation during the stress period. The shelter consisted of a mylar covered frame attached to 4 posts.

Planting Dates

Onions were sown April 9, 1982 in the rootview boxes with each row approximately 3.8 cm from the edge of the plexiglass. Onion seed was planted 1.3-2.5 cm deep at a rate of 20 seeds per row. The rootview boxes were hand-watered using approximately 3 liters of water and allowed to drain to field capacity (-33 kPa).

The seedlings were eventually thinned to 8 plants per box (4 plants/side).

The above was repeated in 1983, but, the onions were sown May 16 due to unfavorable field conditions at the beginning of the 1983 growing season.

Weed control throughout the growing seasons involved hand cultivation. Insect pest control, primarily for onion thrips, was accomplished using applications of Diazinon®.

Experimental Design

The experimental design was a randomized complete block with 4 treatments replicated 5 times. Water was applied to the control boxes when a threshold value of -55 kPa soil matric potential was reached throughout the soil profile (32). The rootview boxes during the early, mid, and late season stress treatments were allowed to lose water and no water was added to the soil until mean moisture content corresponded to -100 kPa. This stress level of -100 kPa was maintained for approximately 3 weeks. If soil moisture content was less than -100 kPa, the appropriate volume of water was added to the rootview boxes to bring the water potential back to the desired level of -100 kPa. The soil matric potential of -55 kPa was also a standard during the time the growth stages were not exposed to a drought stress. Soil matric potential was estimated by averaging the readings of the 4 resistance blocks placed at various depths in the rootview box. Measurements were made two to three times a week.

Onion Growth Measurements

Onion growth parameters were measured nondestructively each week throughout the field experiments. These were number of readily visible leaves without dissection, plant height, and relative root length. Plant height (cm) was measured from the tip of the longest leaf to the soil level. Root length was estimated using a modified line intersect method (1, 45). Equipment consisted of a hand tally counter and mylar sheet printed with a 2 cm x 2 cm grid. The sheet was cut to fit the plexiglass side of the box. Initially, 50 squares out of 378 squares were designated on the mylar sheet with a grease pencil. These squares were selected by a MINITAB program which randomizes without replacement. The same 50 squares were used throughout the 1982 growing season. A different set of 50 squares were randomly selected in 1983. The grid was placed on top of the plexiglass and secured with tape and clips. Counts were made of the roots intersecting any side of the marked squares. Guidelines for counting have been formulated in order to maintain a uniform procedure (45). A count of one was given when a root crossed a line, a root end touched the line, or a curved portion of the root touched a line. A count of two was given for curved root portions which lay on or along a side of the square. Counts of root intersections were accumulated on the hand tally counter and totaled. Total counts were done for each side of the rootview box.

Total counts were converted to length measurements using the Modified Newman's Line Intersect Equation (45):

R = N(Length Conversion)(Sample Conversion)

where:

R = Root Length, cm

N = Total number of intersects

Length Conversion = 1.5714 for a 2 cm grid

Sample Conversion = Total squares/counted squares

Total root length was determined for each side of the rootview box and then averaged over the two sides. The average was then divided by the number of plants per side and expressed as relative root length per plant. Root length in this case was relative since the roots were measured on only one plane. Onion plants were harvested from rootview boxes at the end of the growing season.

Measurements taken at harvest for statistical analysis included: bulb fresh and dry weight (g), bulb length (cm), bulb diameter (cm), bulb length/bulb diameter, top fresh and dry weight (g), number of leaves, and plant height (cm). Bulb and top components were oven dried using a forced air oven at 70 C until sample dry weights became constant. Bulb diameter and length were measured using a vernier caliper. Root weights were not taken due to difficulty in washing and separating roots from the soil. USDAOV computer program (46) analyzed the randomized complete block design and automatically applied Duncan's New Multiple Range Test to the ranked means. Mean separation test for fresh bulb weight was determined by the least significant difference (LSD) procedure at the 5% level of probability.

GREENHOUSE EXPERIMENT - Spring 1983

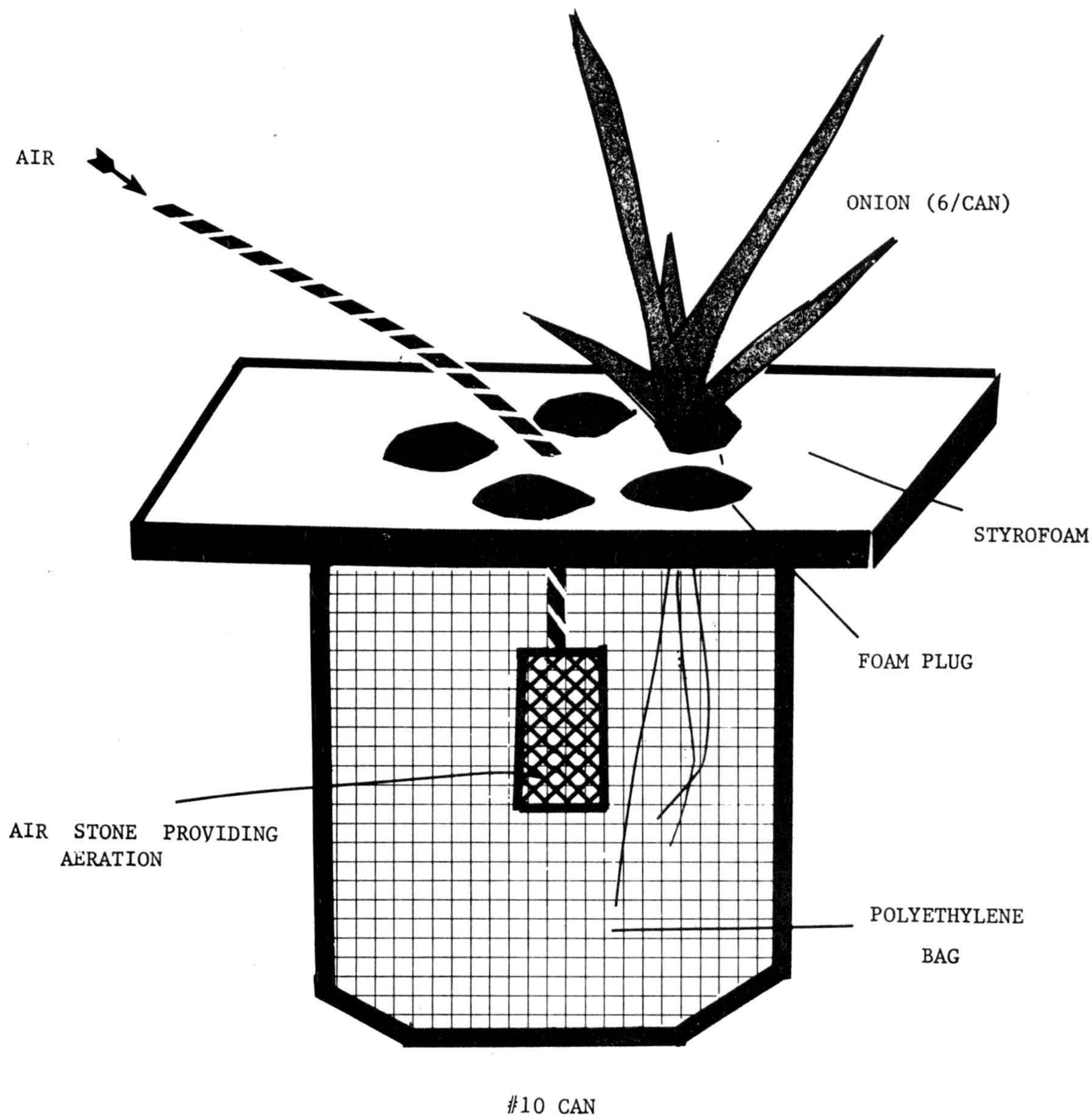
This experiment was designed to examine the effects of drought stress using polyethylene glycol (PEG) and excessive nitrate salts during different growth stages of onions. Effects of high nitrates were included in the investigation since nitrates have been found in high concentrations in northeastern Colorado soils and irrigation water (51).

Onion seeds cv. Brown Beauty were sown 1.3-2.5 cm deep in flats containing perlite, placed in plastic bags to retain moisture, and put in a 25 C growth chamber with a 16 hr photoperiod, provided by a combination of fluorescent and incandescent lights. Seedlings were grown to the hook stage after which flats were moved to the greenhouse (28 C - 19 C) where they were watered daily with 1/4 strength Modified Hoagland's nutrient solution (16). Upon reaching the 1 leaf stage (17 days from planting), uniform plants were transferred to containers of 1/2 strength Hoagland's solution with each can containing 6 plants (Fig. 4). The solution was aerated using commercial aquarium pumps and air stones. Solutions were changed every other day to prevent nutrient deficiencies or toxicities. The experiment was performed on 2 benches oriented in an east-west direction.

Experimental Design

A split plot with a randomized complete block was the design. There were 3 blocks, each having 4 times of stress as the main plots. The subplot portion was 3 PEG concentrations divided further by 3 levels of nitrates. Randomization was a two-stage process.

Figure 4. Polyethylene bags were placed in number 10 cans and 1/2 strength Hoagland's solution was added. Styrofoam lid, 30.5 x 30.5 cm and foam plugs placed on top of the container provided support. An air stone was placed at a depth of 7.6 cm.


AIR
ONION (6/CAN)
STYROFOAM
FOAM PLUG
AIR STONE PROVIDING AERATION
POLYETHYLENE BAG
#10 CAN

First, times of stress were randomized for each block. Next, the 9 possible combinations of PEG x NO3 concentrations were randomized within each main plot. Times of stress refers to the growth stage at which the drought stress was applied. The growth stages were the same as the field experiment (early, mid, late, control) and as in the field experiments, each treatment was stressed only once for a 3 week duration during the season at each growth stage (Table 1). Due to the balanced design of the experiment, 1/3 of the population did not receive PEG.

Drought stress treatments were comprised of 3 levels of osmotic stress in the hydroponic solution: - 40 kPa, -100 kPa, and -200 kPa osmotic potential. Levels of nitrate-nitrogen were: 105 ppm, 153 ppm, and 202 ppm. Control values of -40 kPa and 105 ppm NO3-N correspond to the osmotic potential and nitrate level of 1/2 strength Hoagland's solution. Polyethylene glycol 3500[2] (PEG 3500) was combined at various rates with 1/2 strength Hoagland's solution to achieve the desired level of osmotic stress (Table 7, Appendix). The quantity of PEG 3500 required in solution to obtain a specific osmotic potential was calculated from equations of Steuter (41) (see Table 7, Appendix).

Ammonium nitrate, added to the 1/2 strength Hoagland's solution 56 days after planting was the principle source of nitrogen for the 153 ppm and 202 ppm NO3-N level treatments. Due to the decrease in osmotic potential resulting from the addition of NH4-NO3, the two treatments, -40 kPa/153 ppm NO3-N and -40 kPa/202 ppm

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[2]Formerly listed as PEG 4000, Sigma Chemical Co., St. Louis, Mo.

Table 1. Stress periods for field and greenhouse experiments in terms of days from planting.

Stress Period	Field - 1982	Field - 1983	Greenhouse - 1983
Early Season	Day 73 - 108 (06/21-07/26)	Day 74 - 95 (07/29-08/19)	Day 59 - 80 (04/30-05/21)
Mid-Season	Day 102 - 122 (07/20-08/09)	Day 103 - 124 (08/27-09/17)	Day 77 - 98 (05/18-06/08)
Late Season	Day 126 - 144 (08/13-08/31)	Day 116 - 133 (09/09-09/26)	Day 111 - 132 (06/21-07/12)

NO3-N were found to match the actual values of -58 kPa/153 ppm NO3-N and -77 kPa/202 ppm NO3-N, respectively. Osmotic potential of the solution was calculated by determingin ECe and using the formula ECE x 0.36 = osmotic potential (39). The quantity of PEG required for the NH4NO3 treatments at -100 kPa and 200 kPa therefore, also changed (Tables 6 and 7, Appendix). Ammonium nitrate treatments continued throughout the growing season after day 56.

Onion Growth Measurements

Three of the 6 onion plants were randomly chosen from each container for measuring. Root length, number of leaves, plant height, and bulb diameter were nondestructive parameters measured once a week throughout the experiment. Root length (cm/plant) was measured from the basal plate of the bulb to the longest root tip while holding the styrofoam support above the can. Plant height (cm) was measured from the tip of the longest leaf to the base of the bulb.

Parameters taken at final harvest for statistical analysis included: bulb fresh and dry weights (g), bulb length and diameter (cm), bulb length/diameter, top fresh and dry weights (g), number of leaves, plant height (cm), and root dry weight (g). In addition, temperature data were recorded throughout the experiment using a hydrothermograph.

Statistical package for the social sciences (SPSS) subprogram MANOVA was the computer program used to determine analysis of variance (ANOVA) tests of all plant parameters. Least significant difference (LSD) for mean separation was applied to those components which exhibited ANOVA tests significant at the 5% level of probability.

RESULTS

FIELD EXPERIMENT 1982 AND 1983

Table 2 and Figures 5-9 summarize the results of this investigation. Analysis of variance (ANOVA) tests indicated that there were differences among treatment means for some of the plant components taken at harvest for 1982 and 1983. Drought stress applied during the mid-season growth stage reduced fresh and dry bulb weight in 1982. Drought during the early season and late season growth stage did not affect fresh and dry weights of the bulb. In 1983, results were similar to 1982, i.e. plants in the mid-season stress treatment were the most sensitive to drought. However, drought stress applied at the early season also brought about a decline in bulb fresh weight (Fig. 6). Bulb length and therefore shape, was also affected most by drought stress during the mid-season and the bulbs were smaller in diameter when stress occurred during the mid-season. Mid-season and late season stress treatments reduced plant height in 1983.

Data for the field experiments were combined by years. Plant height as a function of time (days from planting) was fitted using 3rd degree polynomials merely as a data smoothing procedure. The fitted curves for plant height are presented in Fig. 7. Plant height was reduced most when drought was applied during mid-season growth stage. Early season stress caused a slight suppression of plant height during the stress period (day 73-101); however, as the

Table 2. Field experiments 1982 and 1983. Means of above-ground parameters. Means within rows followed by different letters are significantly different at the 5% level as determined by Duncan's New Multiple Range Test.

		Growth Stage			
		Early	Mid	Late	Control
Plant height (cm)	1982	26.35a	14.08b	20.82ab	23.78ab
	1983	26.98a	21.67b	21.01b	25.05a
Leaves/plant	1982	7.36	4.22	6.75	6.58
	1983	5.39a	4.47b	5.22a	5.13a
Top fresh weight (g/plant)	1982	17.28	4.38	10.80	14.23
	1983	7.32a	4.26b	5.21b	6.70a
Top dry weight (g/plant)	1982	1.73a	0.435b	1.21ab	1.42ab
	1983	0.995	0.496	1.11	0.864
Bulb fresh weight (g/plant)	1982	41.33a	15.16b	41.76a	37.25a
	1983	22.08b	8.40c	33.49a	30.54a
Bulb dry weight (g/plant)	1982	3.39a	1.34b	3.89a	3.22a
	1983	2.36a	0.915b	3.04a	3.39a
Bulb length (cm)	1982	5.00a	3.84c	4.80b	4.68b
	1983	5.12b	4.25c	5.31b	5.63a
Bulb diameter (cm)	1982	3.98ab	3.24b	4.55a	3.87ab
	1983	2.82b	2.11b	3.60a	3.37a
Bulb length/ diameter	1982	1.26ab	1.39a	1.17b	1.17b
	1983	1.83ab	2.09a	1.48b	1.71ab

Figure 5. Field experiment 1982. Mean fresh bulb weight (g) taken at harvest, 148 days from planting. A drought stress level of -100 kPa was applied during the early season, mid-season, and late season growth stages. Control treatment was not stressed. Probability level = 5%.

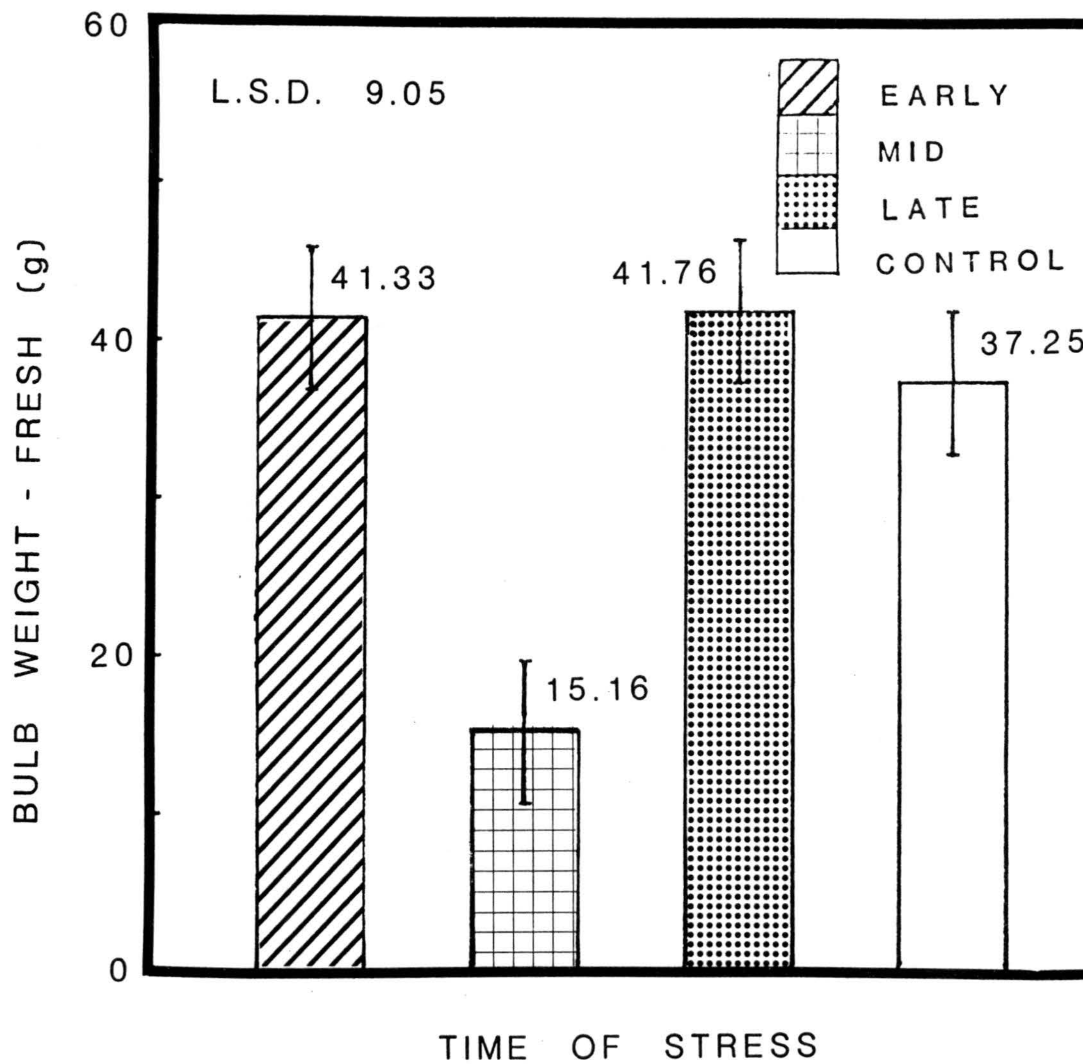
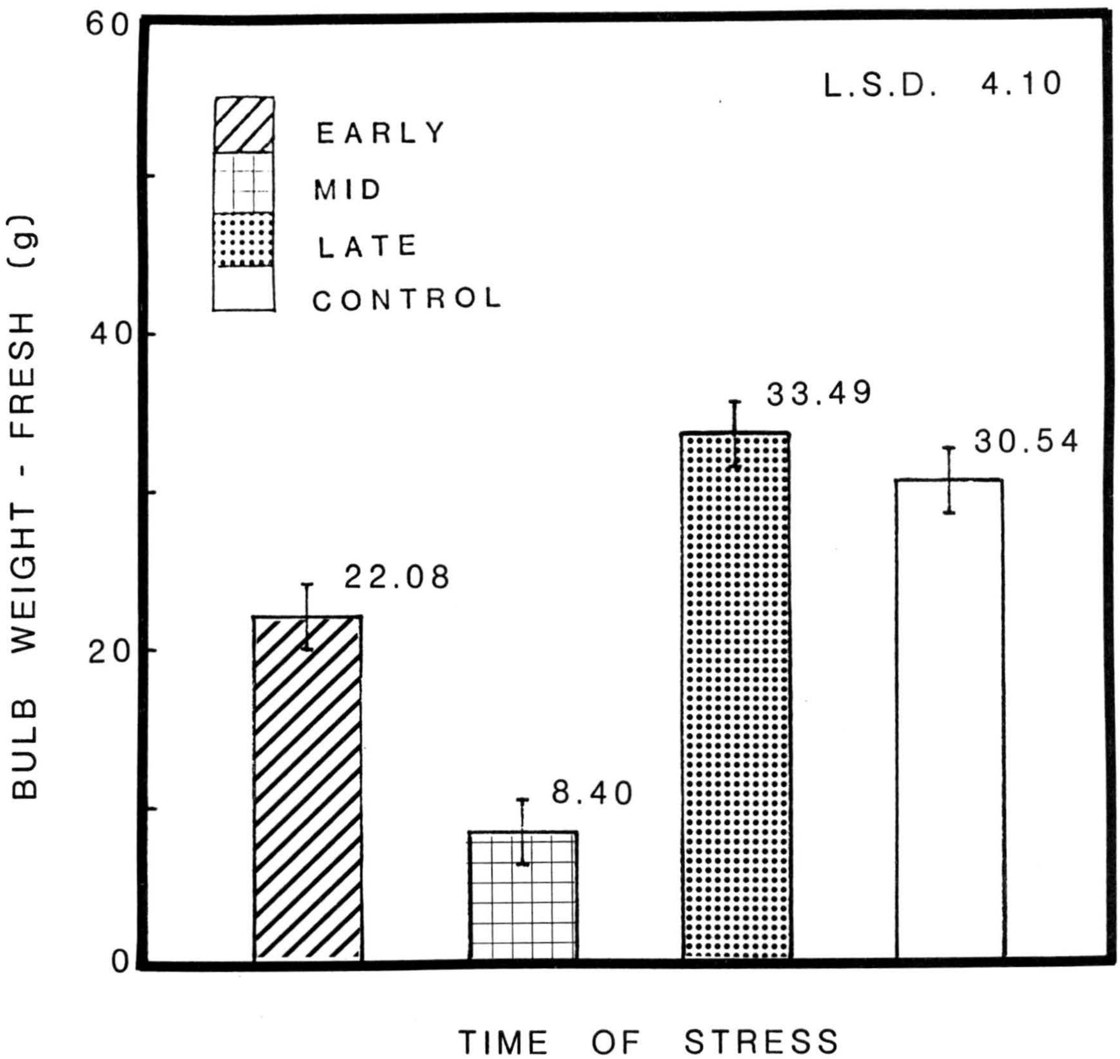
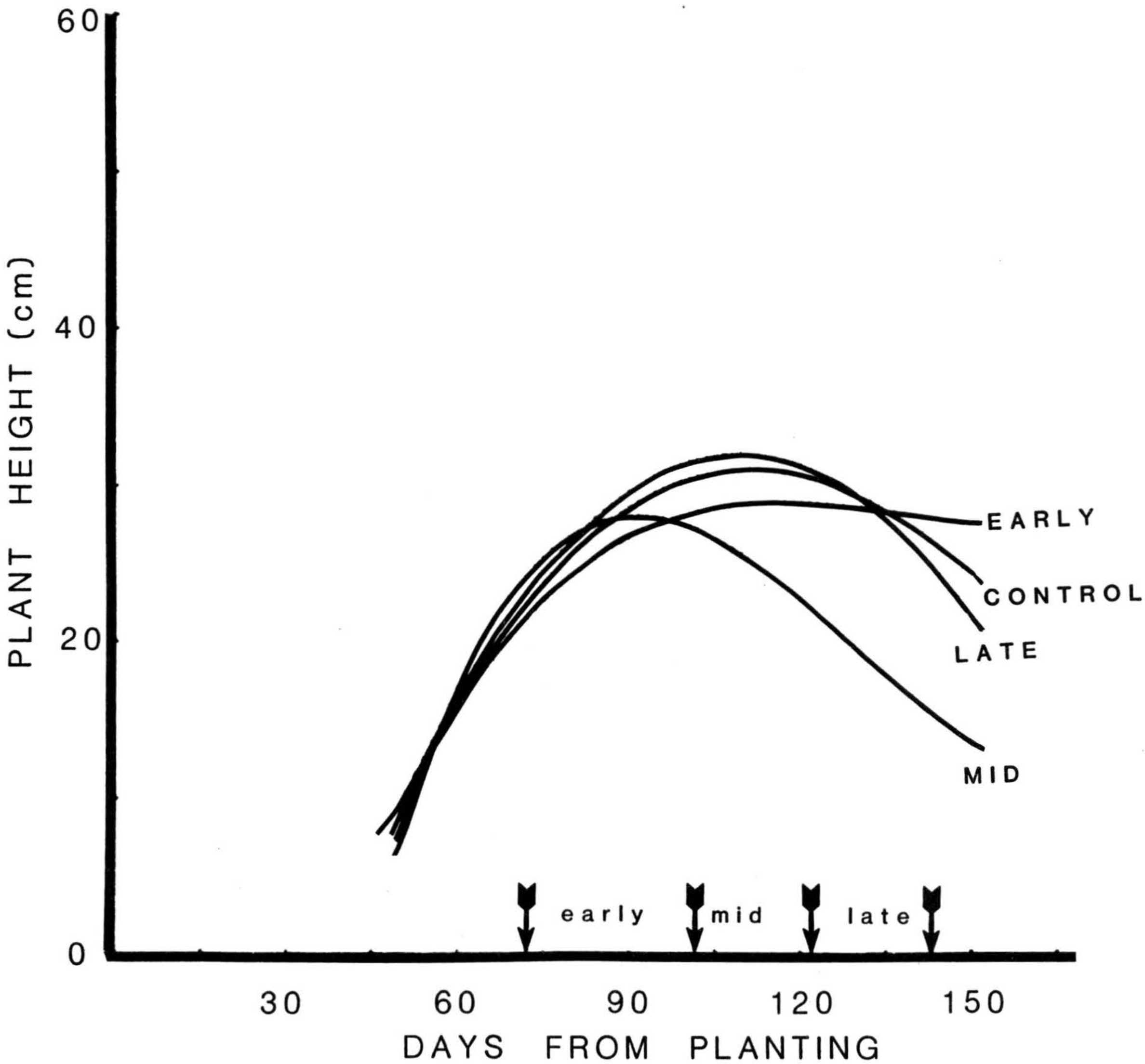

60
40
20
0
BULB WEIGHT - FRESH (g)
L.S.D. 9.05
EARLY
MID
LATE
CONTROL
41.33
15.16
41.76
37.25
TIME OF STRESS

Figure 6. Field experiment 1983. Mean fresh bulb weight (g) taken at harvest, 133 days from planting. A drought stress level of -100 kPa was applied during the early season, mid-season, and late season growth stages. Control treatment was not stressed. Probability level = 5%.



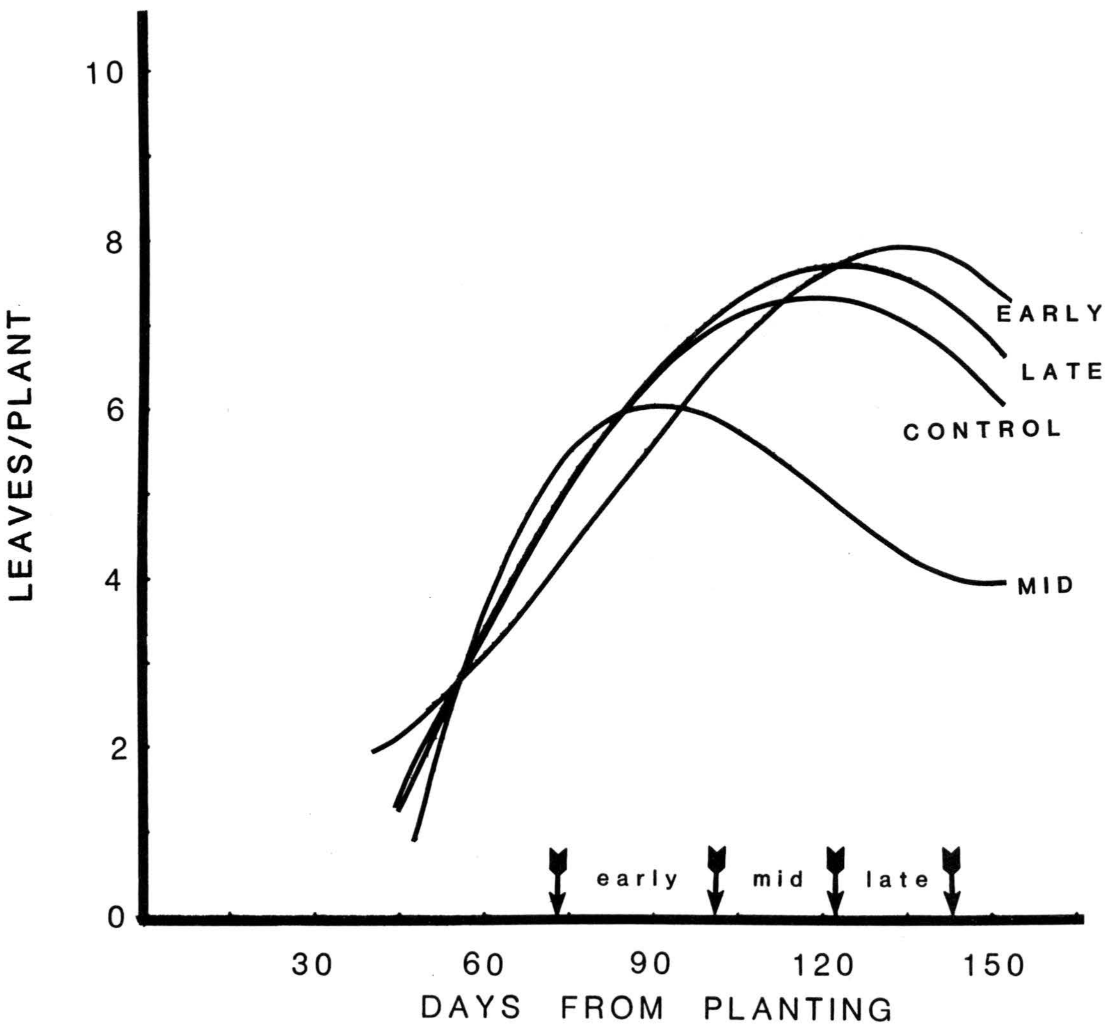
60
40
20
0
BULB WEIGHT - FRESH (g)
L.S.D. 4.10
EARLY
MID
LATE
CONTROL
22.08
8.40
33.49
30.54
TIME OF STRESS

Figure 7. Field experiments 1982 and 1983. Combined 1982 and 1983 data for plant height (cm/plant) was fitted using 3rd degree polynomials and plotted as a function of time. Arrows indicate time of stress periods.



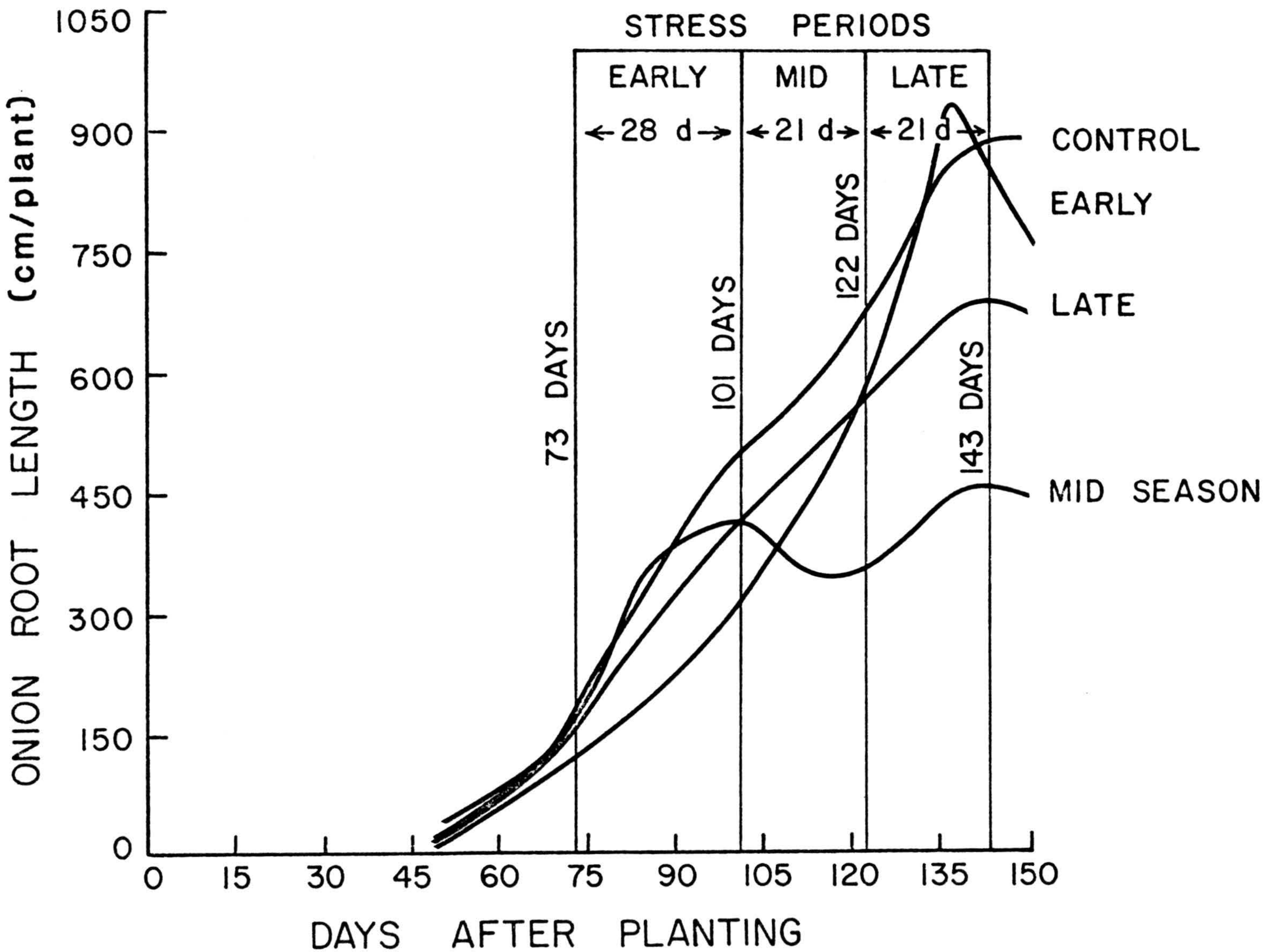
60
40
20
0
PLANT HEIGHT (cm)
EARLY
CONTROL
LATE
MID
early
mid
late
30
60
90
120
150
DAYS FROM PLANTING

Figure 8. Field experiments 1982 and 1983. Combined 1982 and 1983 data for number of leaves was fitted using 3rd degree polynomials and plotted as a function of time. Arrows indicate time of stress periods.



10
8
6
4
2
0
LEAVES/PLANT
EARLY
LATE
CONTROL
MID
early
mid
late
30
60
90
120
150
DAYS FROM PLANTING

Figure 9. Field experiments 1982 and 1983. Onion root length (cm/plant) data for 1982 and 1983 were combined and plotted as a function of time. Connecting lines for each growth stage were drawn by eye. Control was not stressed.


STRESS PERIODS
EARLY
MID
LATE
←28 d→
←21 d→
←21 d→
73 DAYS
101 DAYS
122 DAYS
143 DAYS
CONTROL
EARLY
LATE
MID SEASON
ONION ROOT LENGTH (cm/plant)
1050
900
750
600
450
300
150
0
0
15
30
45
60
75
90
105
120
135
150
DAYS AFTER PLANTING

graph indicates, the plants were able to recover later in the season. Late season stress caused a slight reduction in plant growth during and after the stress period.

Numbers of leaves were not significantly different for the treatments in 1982. However, in 1983, plants exposed to a mid-season stress treatment had fewer leaves than the other treatments. This trend can also be seen in the 1982 and 1983 combined data presented in Fig. 8 in which the number of leaves versus days from planting was fitted by 3rd degree polynomials.

Onion root length for combined 1982 and 1983 data is shown in Fig. 9 as a function of time (days from planting). Since none of the available functions fit the data patterns well, connecting lines were drawn by eye. Root length was determined weekly and calculated using the Modified Newman's Line Intersect Equation as described earlier (45). Stress periods shown in Fig. 9 are averaged over 1982 and 1983 (refer to Table 1).

Drought stress had the greatest effect on root growth when applied during the mid-season growth stage. Once stressed, roots of the mid-season treatment were not able to fully recover, thus resulting in decreased root growth. Root growth during the early season stress period was retarded but recovered by the end of the season. The late stress treatment had no effect on root growth.

GREENHOUSE EXPERIMENT 1983

Analysis of variance tests shown in Table 8 (Appendix) indicate that the interaction between time of stress and PEG level was significant at the 5% level of probability for bulb weight (fresh, dry), bulb length, bulb diameter, plant height, top dry weight, and root dry weight. Interactions for the above components were considered an artifact due to variability of the control created from the balanced design. Response to applied nitrogen was not significant at the 5% level.

Drought stress had its greatest effect on bulb parameters when it was applied in the mid-season stage of growth. Figures 10, 11, 12, and 15 provide evidence that there was a reduction of fresh and dry bulb weight, bulb diameter, and bulb length caused by the mid-season/-100 kPa treatment. Bulb weights and diameter in the early season/-100 kPa treatment were not affected by drought stress; however, bulb length was negatively influenced. Bulb parameters for late season/-100 kPa were not different from the control. At -200 kPa, there was a reduction in bulb fresh weight, dry weight, length, and diameter in both early season and mid-season treatments when compared to the control. Late season stress had no effect on the bulb. The general trend as explained above can also be seen in Figure 13 and 14 which shows bulb diameter over time at -100 kPa and -200 kPa.

Final plant height was reduced when -100 kPa osmotic stress was applied during the early, mid, and late season growth stages. Plant elongation was suppressed the most at -100 kPa and -200 kPa during the late season treatment. Plant height over time at -100 kPa and -200 kPa is presented in Figures 17 and 18. Drought during the early season caused a reduction of plant height in time, but plants showed a slight recovery once watering was resumed. Plant

Figure 10. Greenhouse study 1983. Mean fresh bulb weight (g) collected at harvest, 140 days from planting. Plants were subjected to -100 and -200 kPa osmotic stresses applied during the early, mid, and late season growth stages. Desired levels of osmotic stress were achieved by using combinations of PEG 3500 and 1/2 strength Hoagland's solution. Control treatment used only 1/2 strength Hoagland's solution (osmotic potential = -40 kPa). Probability level = 5%.

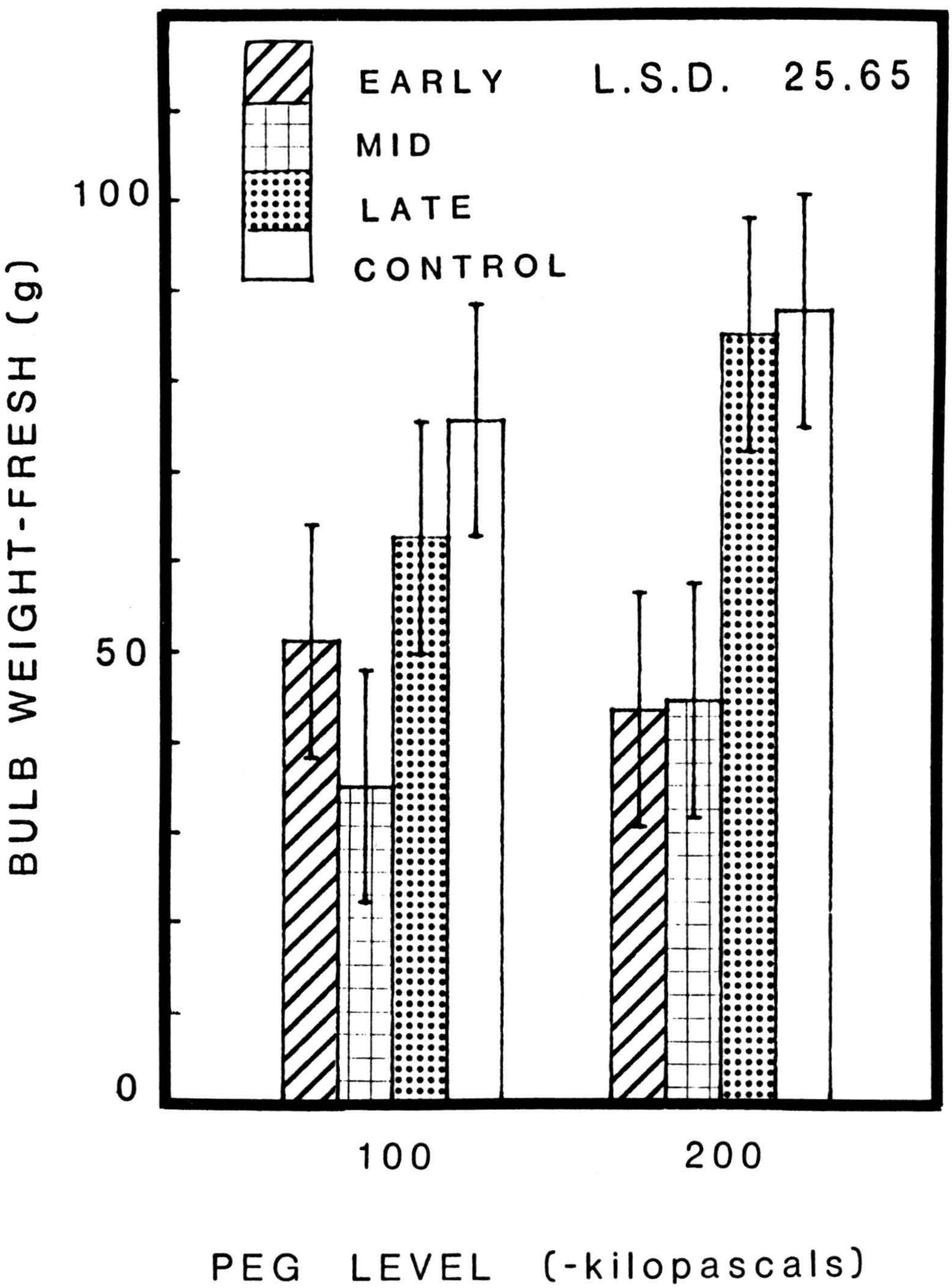

EARLY
MID
LATE
CONTROL
L.S.D. 25.65
100
50
0
BULB WEIGHT-FRESH (g)
100
200
PEG LEVEL (-kilopascals)

Figure 11. Greenhouse study 1983. Mean dry bulb weight (g) collected at harvest, 140 days from planting. Plants were subjected to -100 and -200 kPa osmotic stresses applied during the early, mid, and late season growth stages. Desired levels of osmotic stress were achieved by using combinations of PEG 3500 and 1/2 strength Hoagland's solution. Control treatment used only 1/2 strength Hoagland's solution (osmotic potential = -40 kPa). Probability level = 5%.

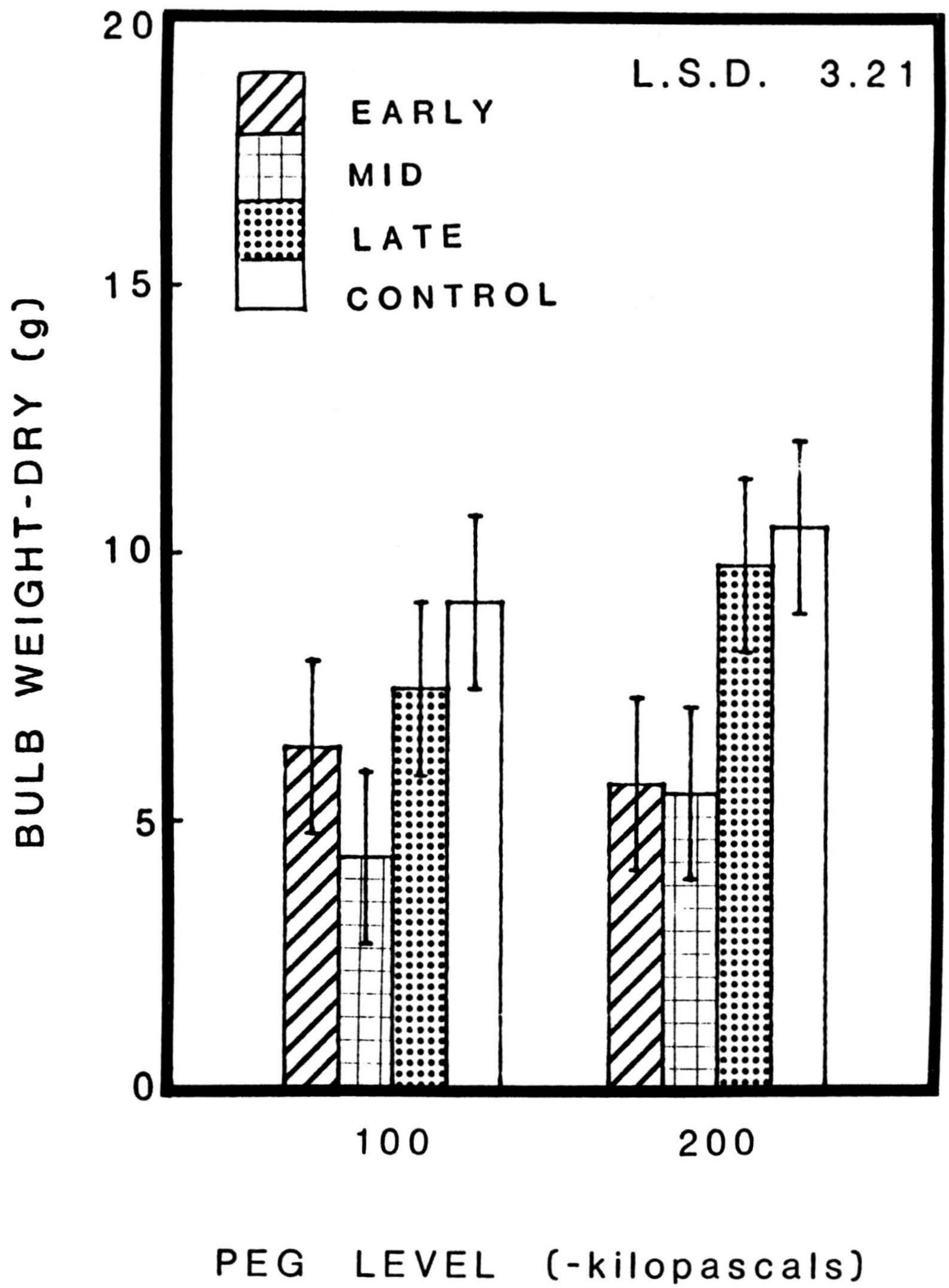

L.S.D. 3.21
EARLY
MID
LATE
CONTROL
BULB WEIGHT-DRY (g)
20
15
10
5
0
100
200
PEG LEVEL (-kilopascals)

Figure 12. Greenhouse study 1983. Mean bulb diameter (cm) collected at harvest, 140 days from planting. Plants were subjected to -100 and -200 kPa osmotic stresses applied during the early, mid, and late season growth stages. Desired levels of osmotic stress were achieved by using combinations of PEG 3500 and 1/2 strength Hoagland's solution. Control treatment used only 1/2 strength Hoagland's solution (osmotic potential = -40 kPa). Probability level = 5%.

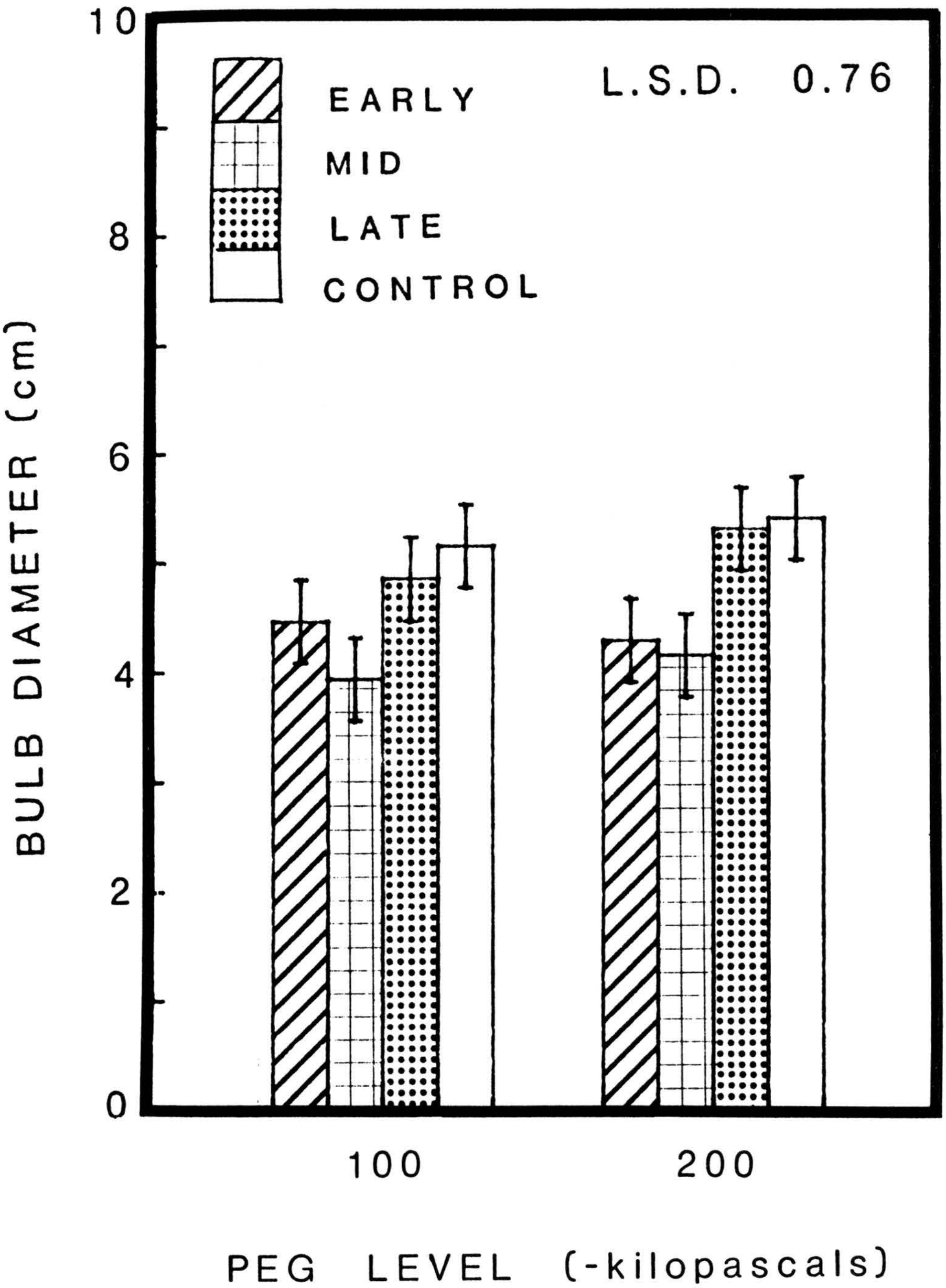
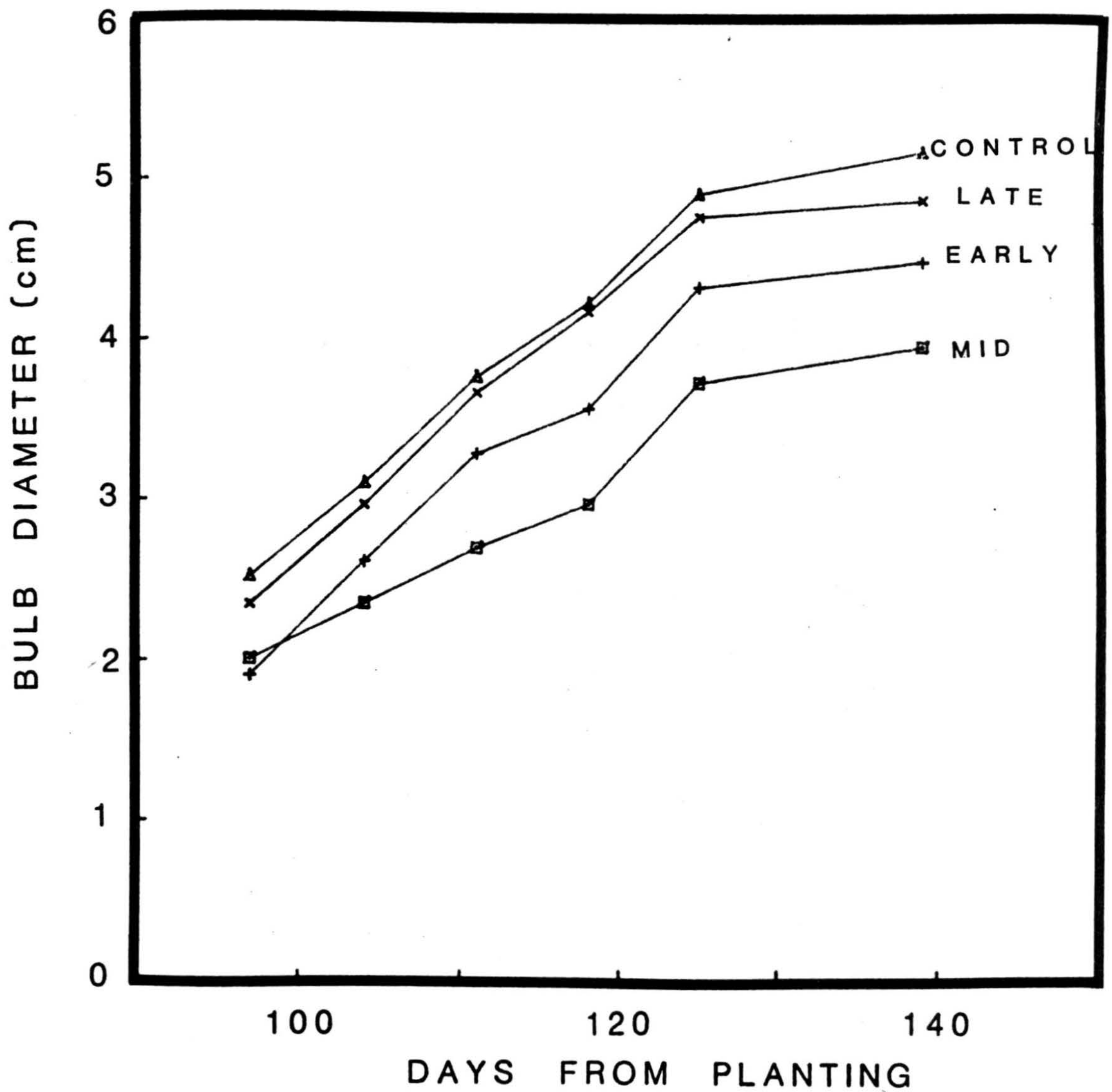

10
8
6
4
2
0
BULB DIAMETER (cm)
EARLY
MID
LATE
CONTROL
L.S.D. 0.76
100
200
PEG LEVEL (-kilopascals)

Figure 13. Greenhouse study 1983. Bulb diameter (cm) versus days from planting. Stress treatment was at -100 kPa; control was at -40 kPa. Stress period at -100 kPa was for a 3 week duration.



BULB DIAMETER (cm)
0
1
2
3
4
5
6
100
120
140
DAYS FROM PLANTING
CONTROL
LATE
EARLY
MID

Figure 14. Greenhouse study 1983. Bulb diameter (cm) versus days from planting. Stress treatment was at -200 kPa; control was at -40 kPa. Stress period at -200 kPa was for a 3 week duration.

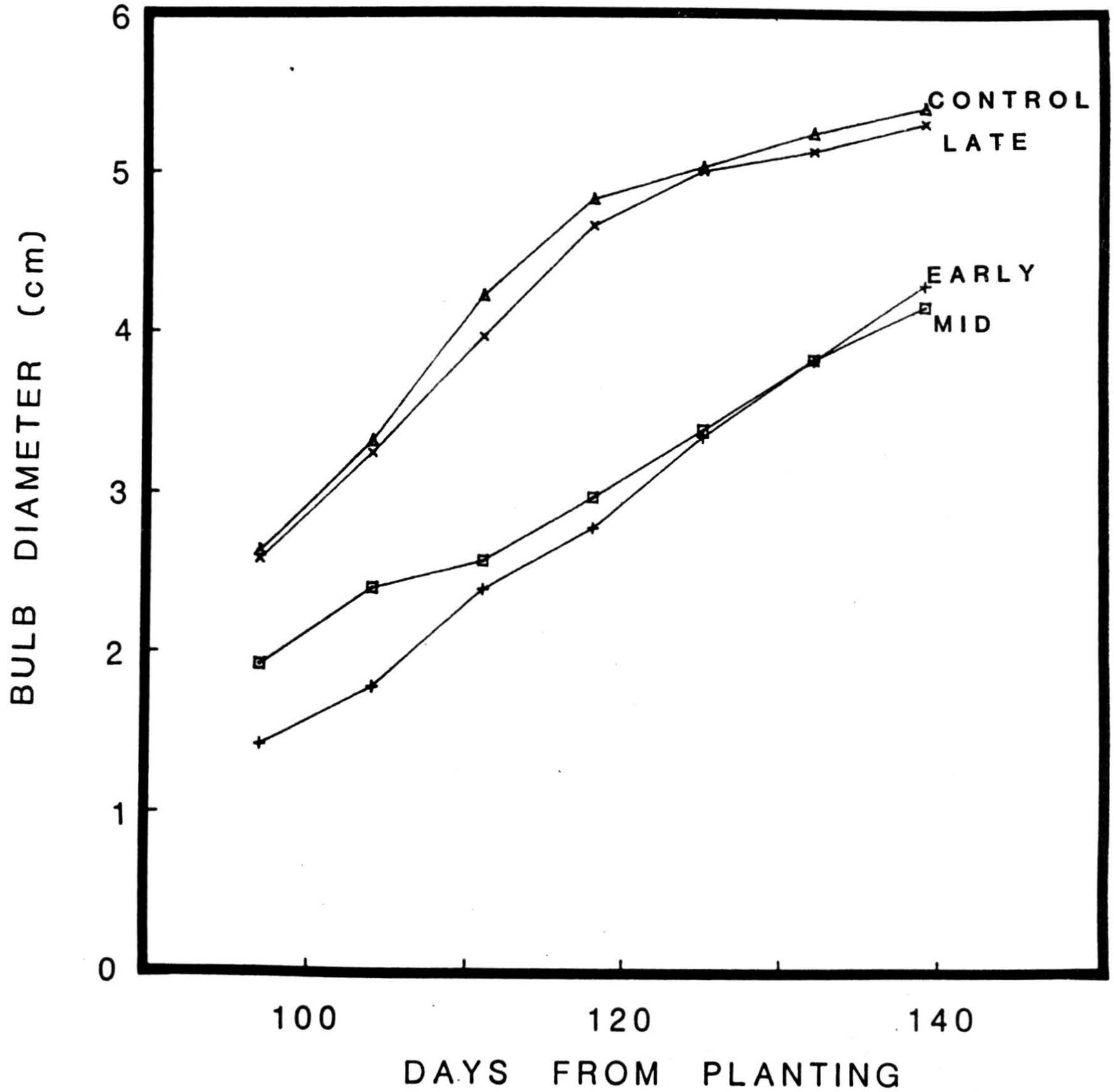
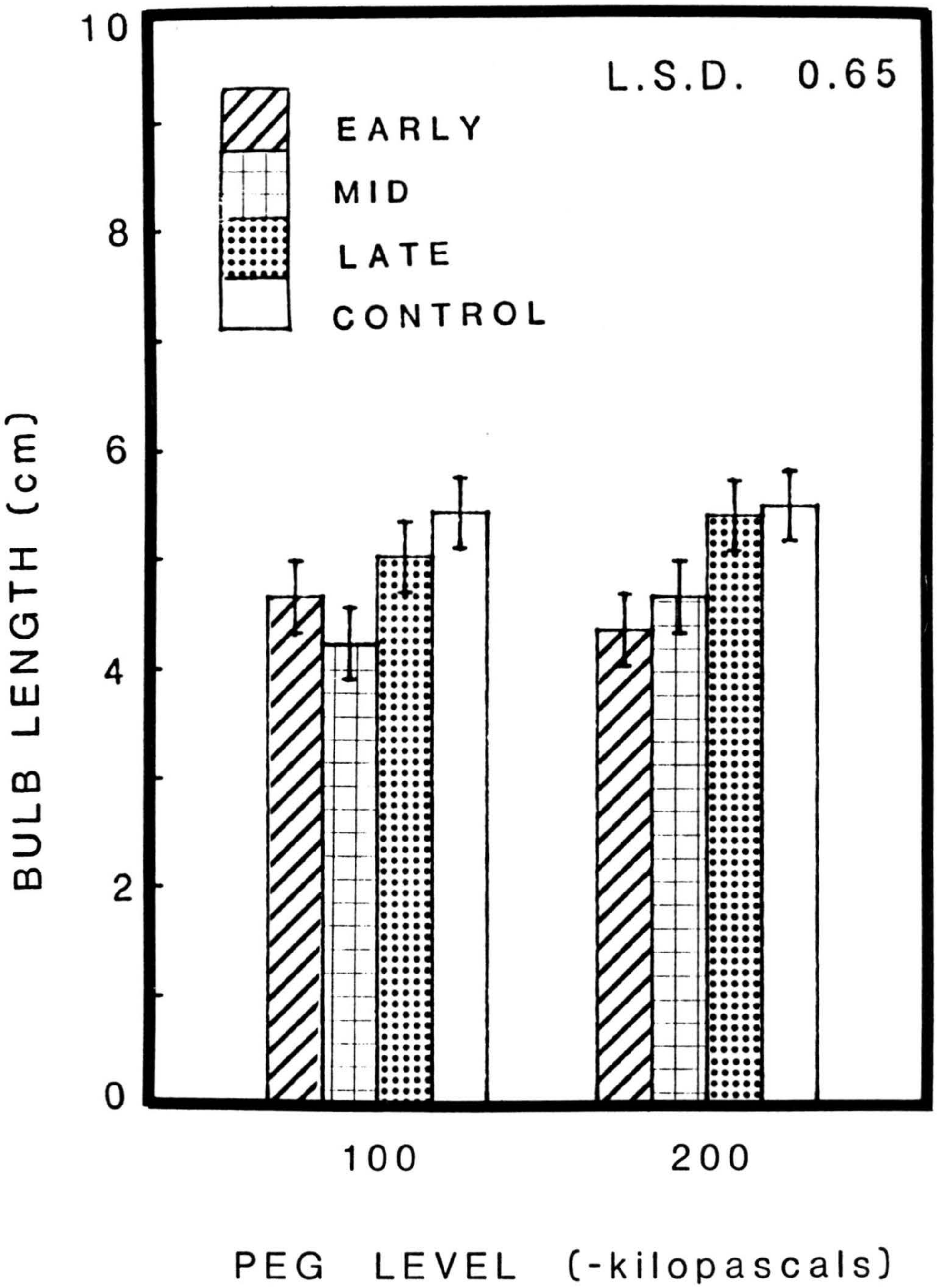
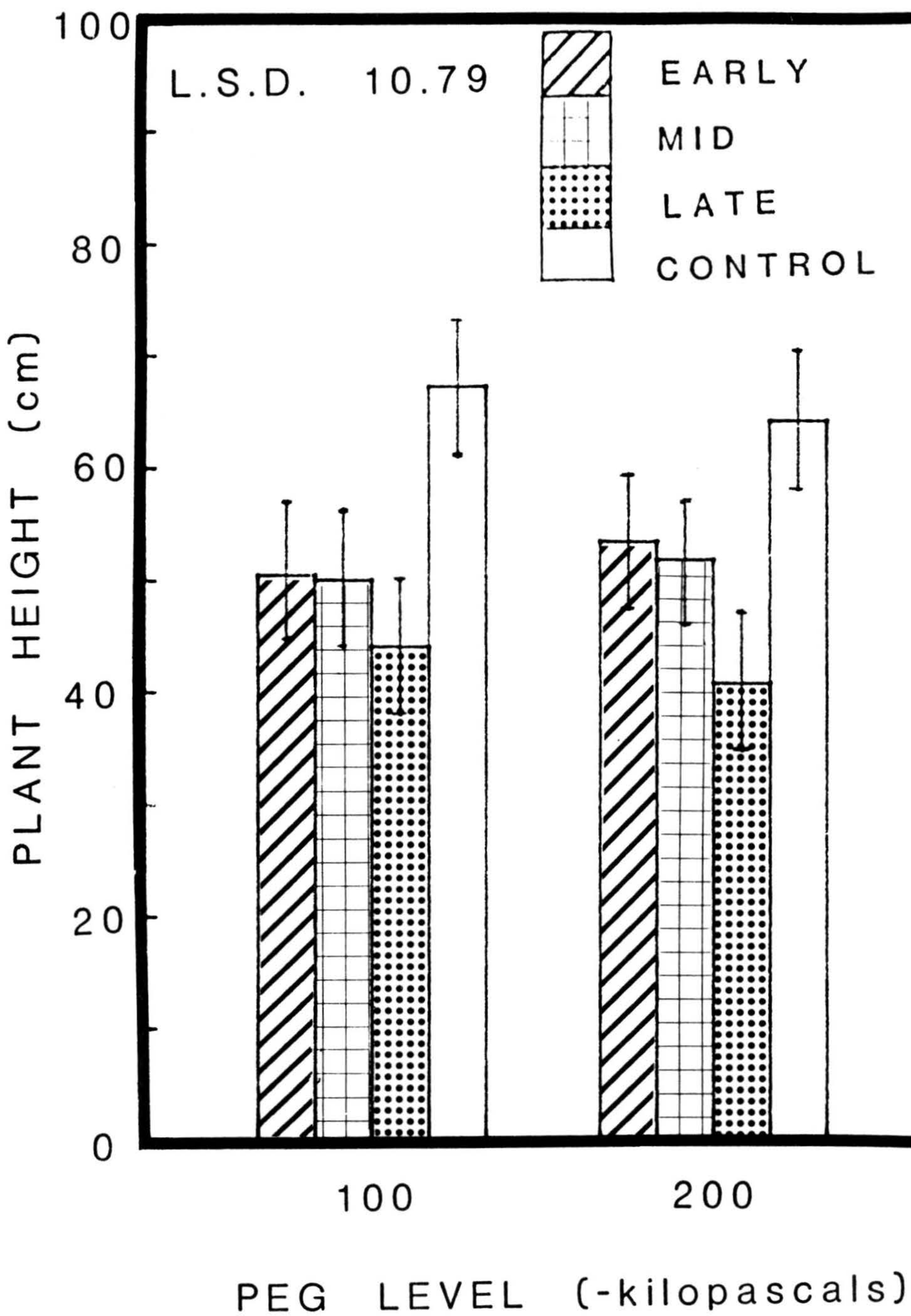

CONTROL
LATE
EARLY
MID
BULB DIAMETER (cm)
0
1
2
3
4
5
6
100
120
140
DAYS FROM PLANTING

Figure 15. Greenhouse study 1983. Mean bulb length (cm) collected at harvest, 140 days from planting. Plants were subjected to -100 and -200 kPa osmotic stresses applied during the early, mid, and late season growth stages. Desired levels of osmotic stress were achieved by using combinations of PEG 3500 and 1/2 strength Hoagland's solution. Control treatment used only 1/2 strength Hoagland's solution (osmotic potential = -40 kPa). Probability level = 5%.



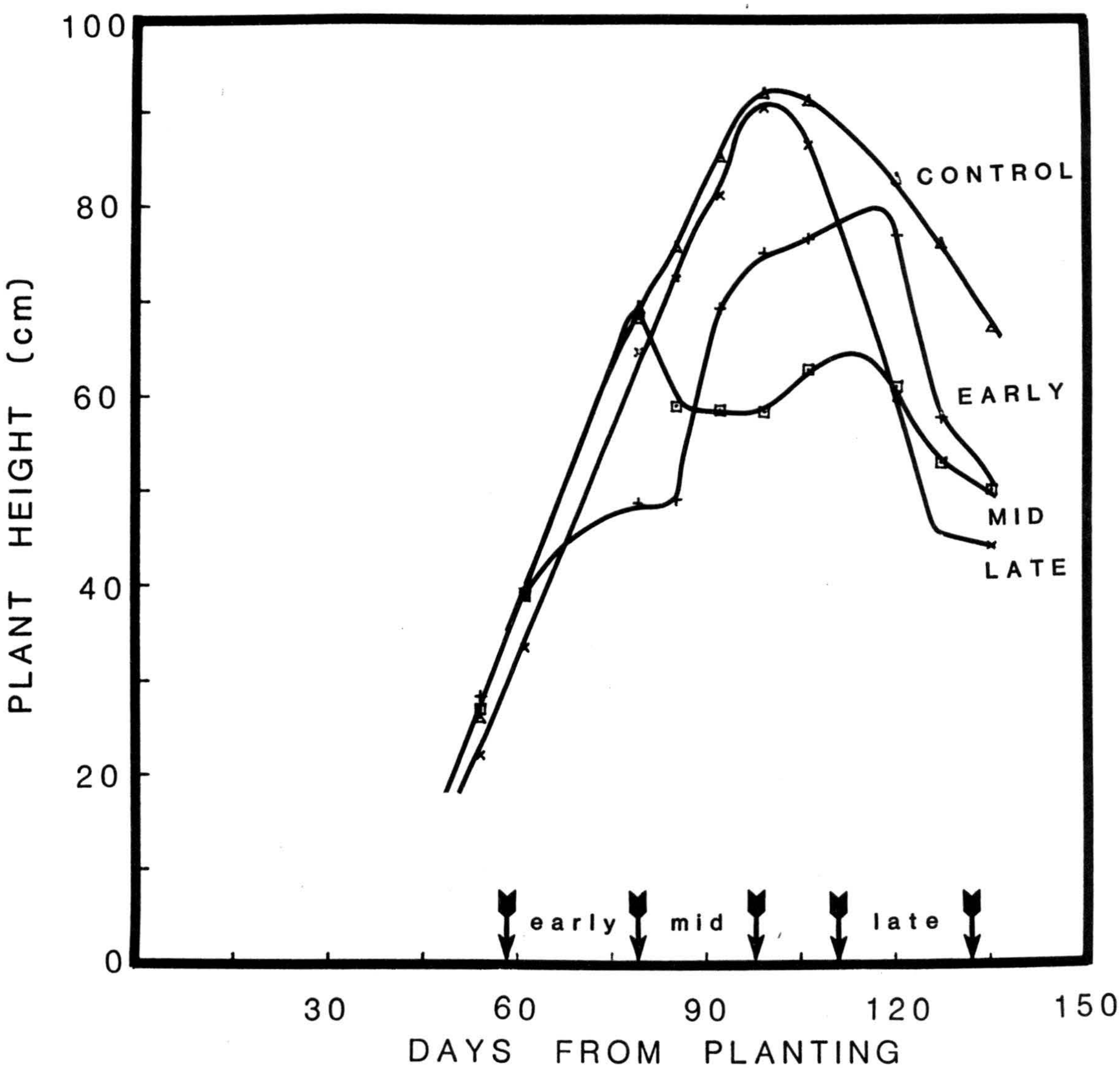
10
8
6
4
2
0
L.S.D. 0.65
EARLY
MID
LATE
CONTROL
BULB LENGTH (cm)
100
200
PEG LEVEL (-kilopascals)

Figure 16. Greenhouse study 1983. Mean plant height (cm) collected at harvest, 140 days from planting. Plants were subjected to -100 and -200 kPa osmotic stresses applied during the early, mid, and late season growth stages. Desired levels of osmotic stress were achieved by using combinations of PEG 3500 and 1/2 strength Hoagland's solution. Control treatment used only 1/2 strength Hoagland's solution (osmotic potential = -40 kPa). Probability level = 5%.



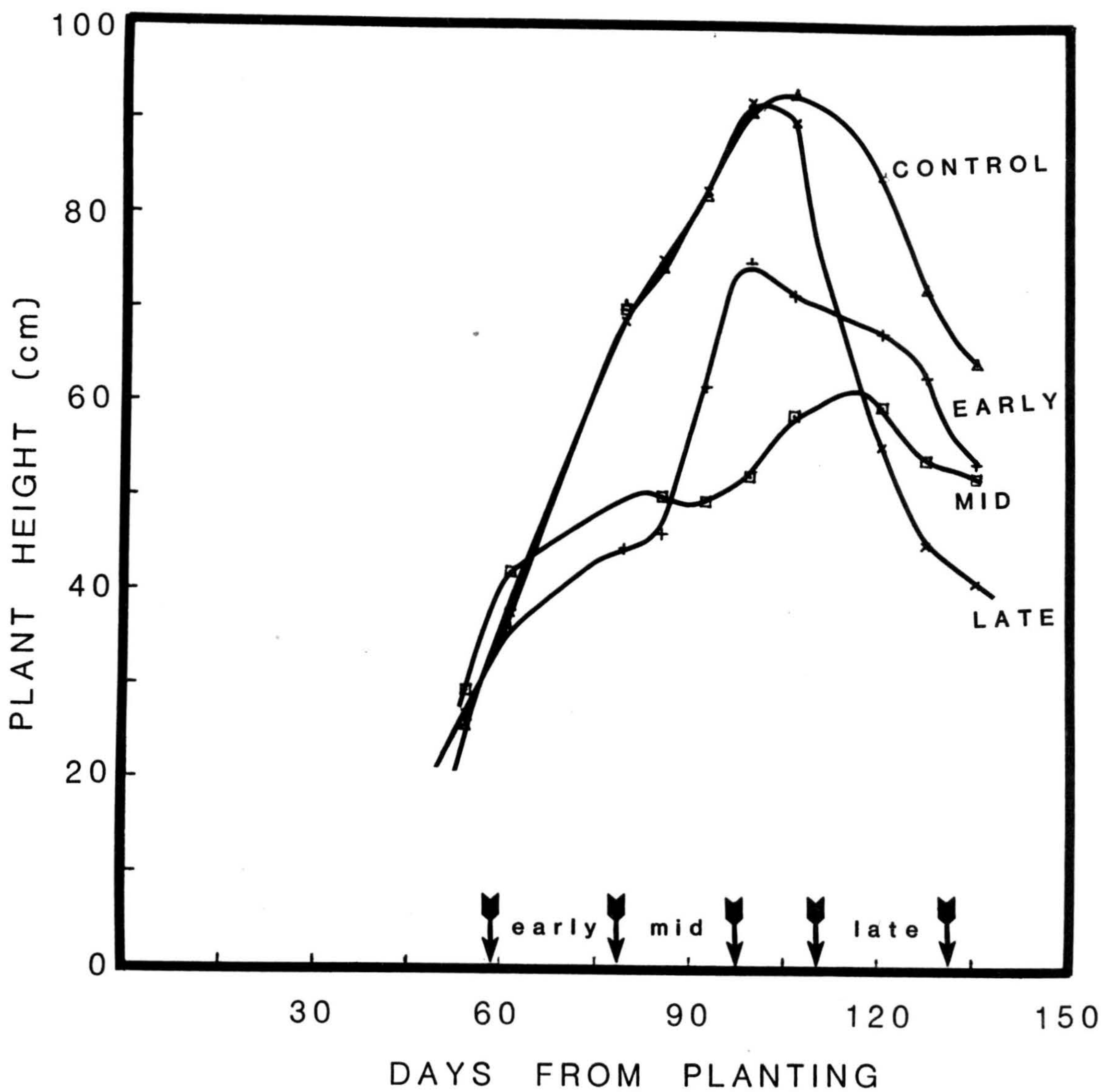
100
80
60
40
20
0
PLANT HEIGHT (cm)
L.S.D. 10.79
EARLY
MID
LATE
CONTROL
100
200
PEG LEVEL (-kilopascals)

Figure 17. Greenhouse study 1983. Plant height (cm) versus days from planting. Early, mid, and late season stress treatments were at -100 kPa; control was at -40 kPa. Stress periods were 3 weeks duration and are indicated by arrows. Connecting lines were drawn by eye.



100
80
60
40
20
0
PLANT HEIGHT (cm)
CONTROL
EARLY
MID
LATE
early
mid
late
30
60
90
120
150
DAYS FROM PLANTING

Figure 18. Greenhouse study 1983. Plant height (cm) versus days from planting. Early, mid, and late season stress treatments were at -200 kPa; control was at -40 kPa. Stress periods were 3 weeks duration and are indicated by arrows. Connecting lines were drawn by eye.


100
80
60
40
20
0
PLANT HEIGHT (cm)
CONTROL
EARLY
MID
LATE
early
mid
late
30
60
90
120
150
DAYS FROM PLANTING

growth was unable to recover as a result of the mid-season treatment. Plant height decreased rapidly subsequent to the late season treatment.

Plants in the early season and mid-season treatments had fewer leaves when compared to the control (Fig. 19). Number of leaves in the late season treatment were no different from the control. Figure 20 shows decreasing the water potential to less than -40 kPa significantly reduced the final number of leaves. Drought at all stages of growth delayed the emergence of leaves at both -100 kPa and -200 kPa (Figs. 21 and 22). After the drought periods, the plants did not recover to the rate of the control, resulting in less leaves. Figure 19, however, shows that there was no difference in final number of leaves between the late season treatment and control. This can be explained by the fact that times of stress were averaged over all levels of PEG, therefore, the graph does not show individual effects of the 3 PEG levels.

Top growth, measured at 140 days from planting was retarded when the plants were subjected to a stress during the early, mid, and late season growth stages as shown in Fig. 23. Replications were also found to be different from one another.

Root dry weight, measured at 140 days from planting, was less than for the control when drought was simulated during the early season as well as during the mid-season (Fig. 24). Drought stress applied during the late season growth stage had no negative effect on root dry weight.

Figure 19. Greenhouse study 1983. Mean leaves/plant over 4 times of stress, significant at the 5% level of probability.

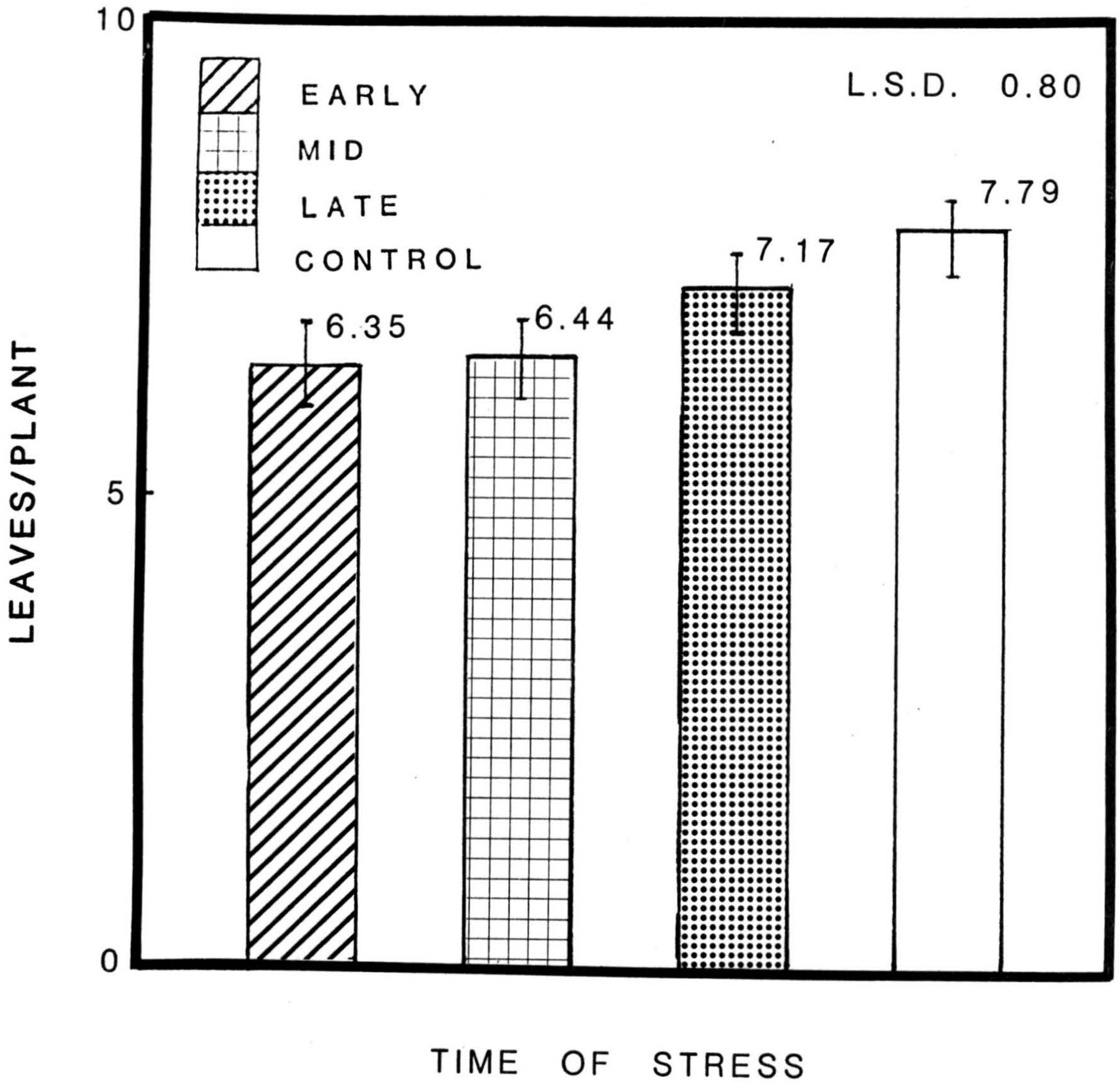
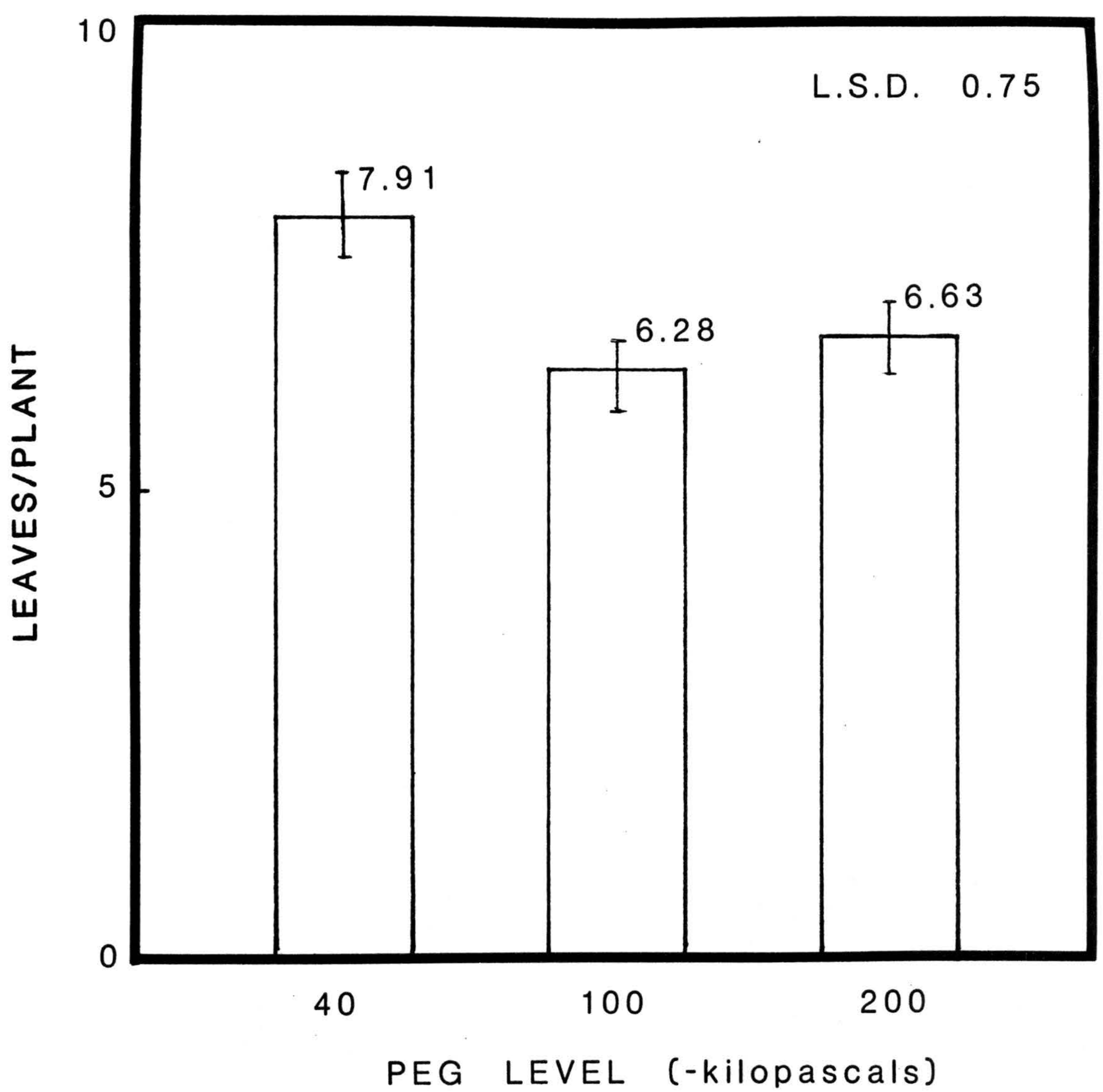
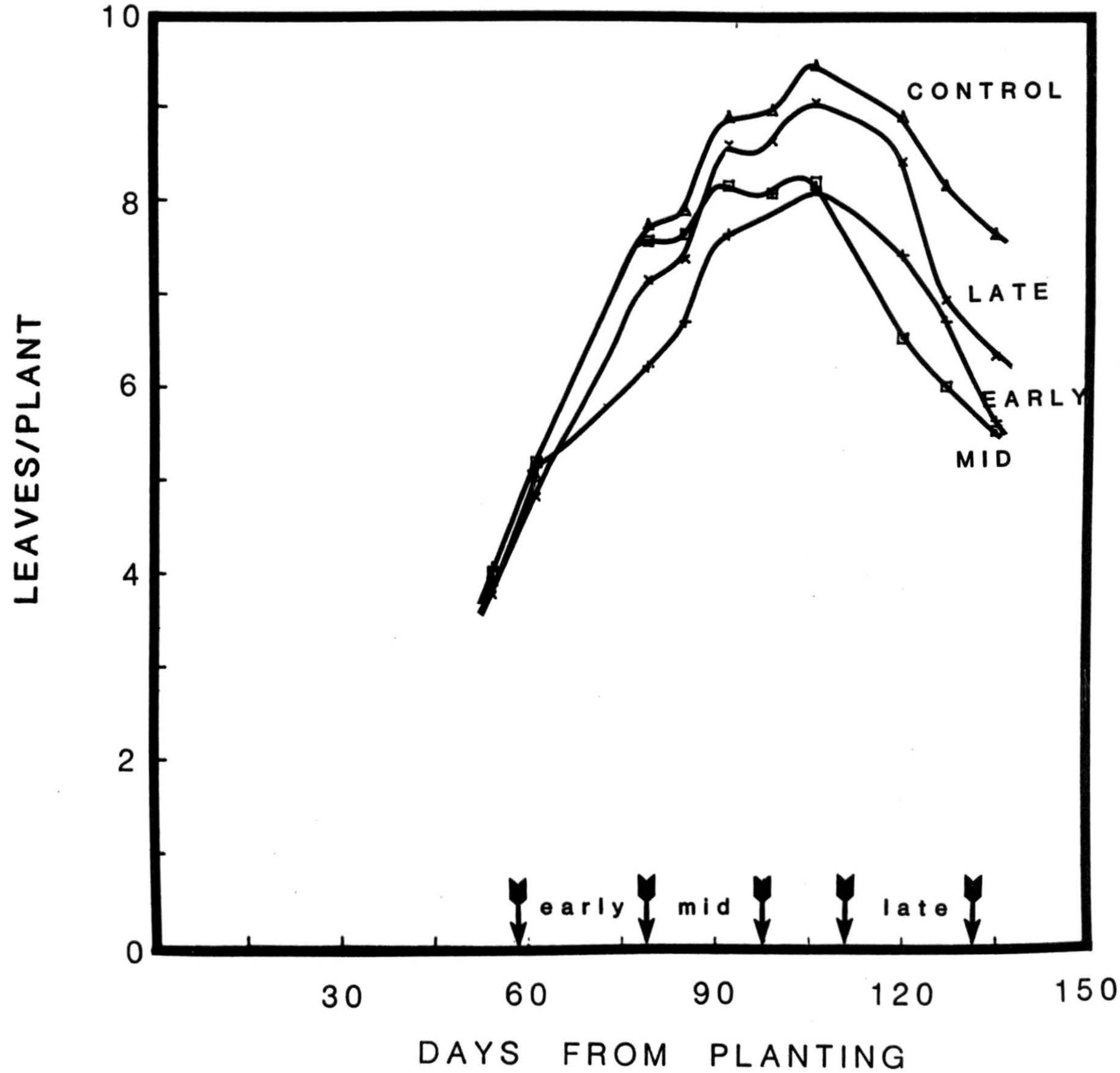

10
5
0
LEAVES/PLANT
EARLY
MID
LATE
CONTROL
L.S.D. 0.80
6.35
6.44
7.17
7.79
TIME OF STRESS

Figure 20. Greenhouse study 1983. Mean leaves/plant over 3 PEG levels, -40 kPa, -100 kPa, and -200 kPa. Significant at the 5% level of probability.



10
5
0
L.S.D. 0.75
7.91
6.28
6.63
LEAVES/PLANT
40
100
200
PEG LEVEL (-kilopascals)

Figure 21. Greenhouse study 1983. Leaves/plant versus days from planting. Early, mid, and late season stress treatments were at -100 kPa; control was at -40 kPa. Stress periods were 3 weeks duration and are indicated by arrows. Connecting lines were drawn by eye.



10
8
6
4
2
0
LEAVES/PLANT
CONTROL
LATE
EARLY
MID
early
mid
late
30
60
90
120
150
DAYS FROM PLANTING

Figure 22. Greenhouse study 1983. Leaves/plant versus days from planting. Early, mid, and late season stress treatments were at -200 kPa; control was at -40 kPa. Stress periods were 3 weeks duration and are indicated by arrows. Connecting lines were drawn by eye.

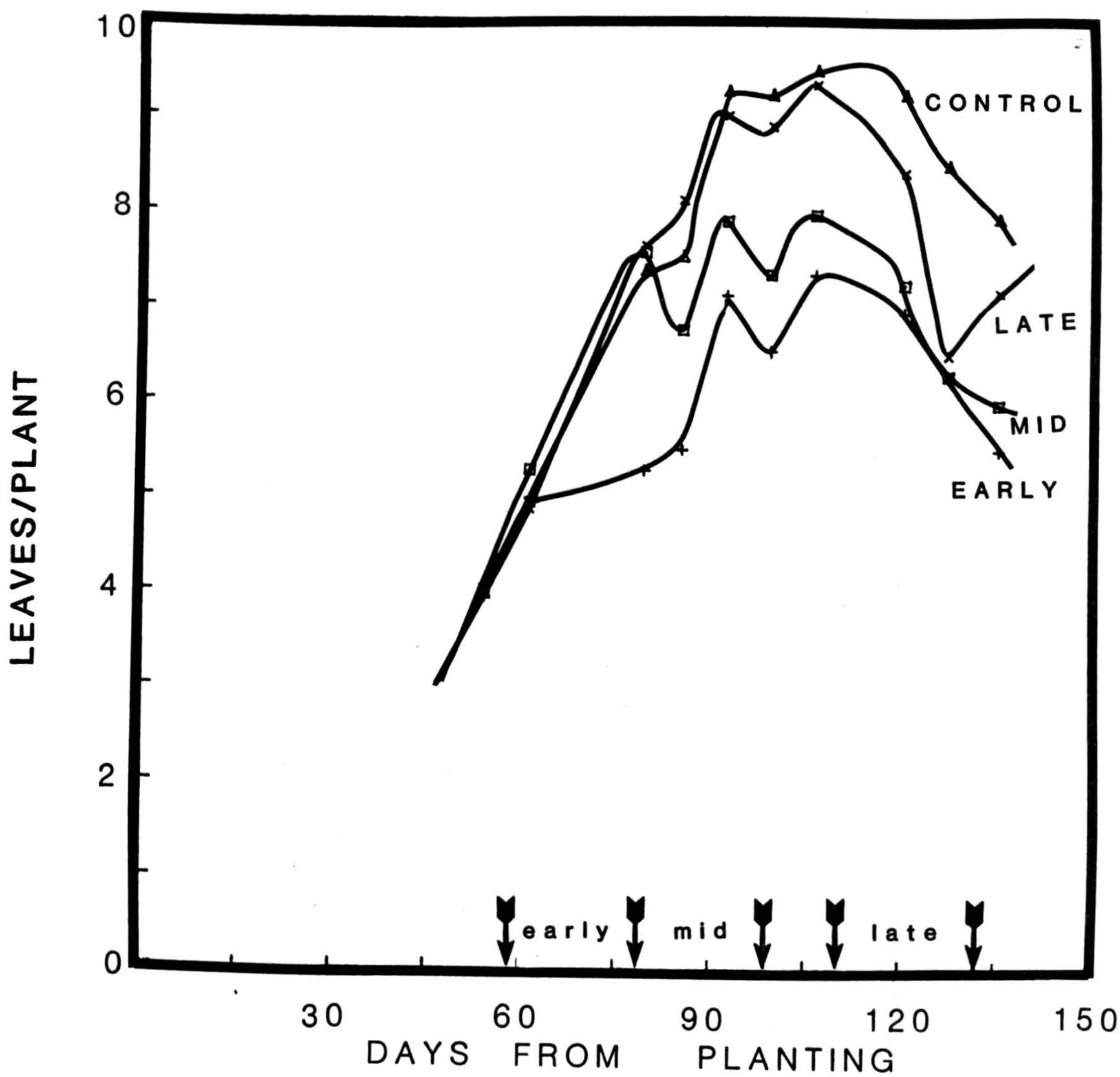
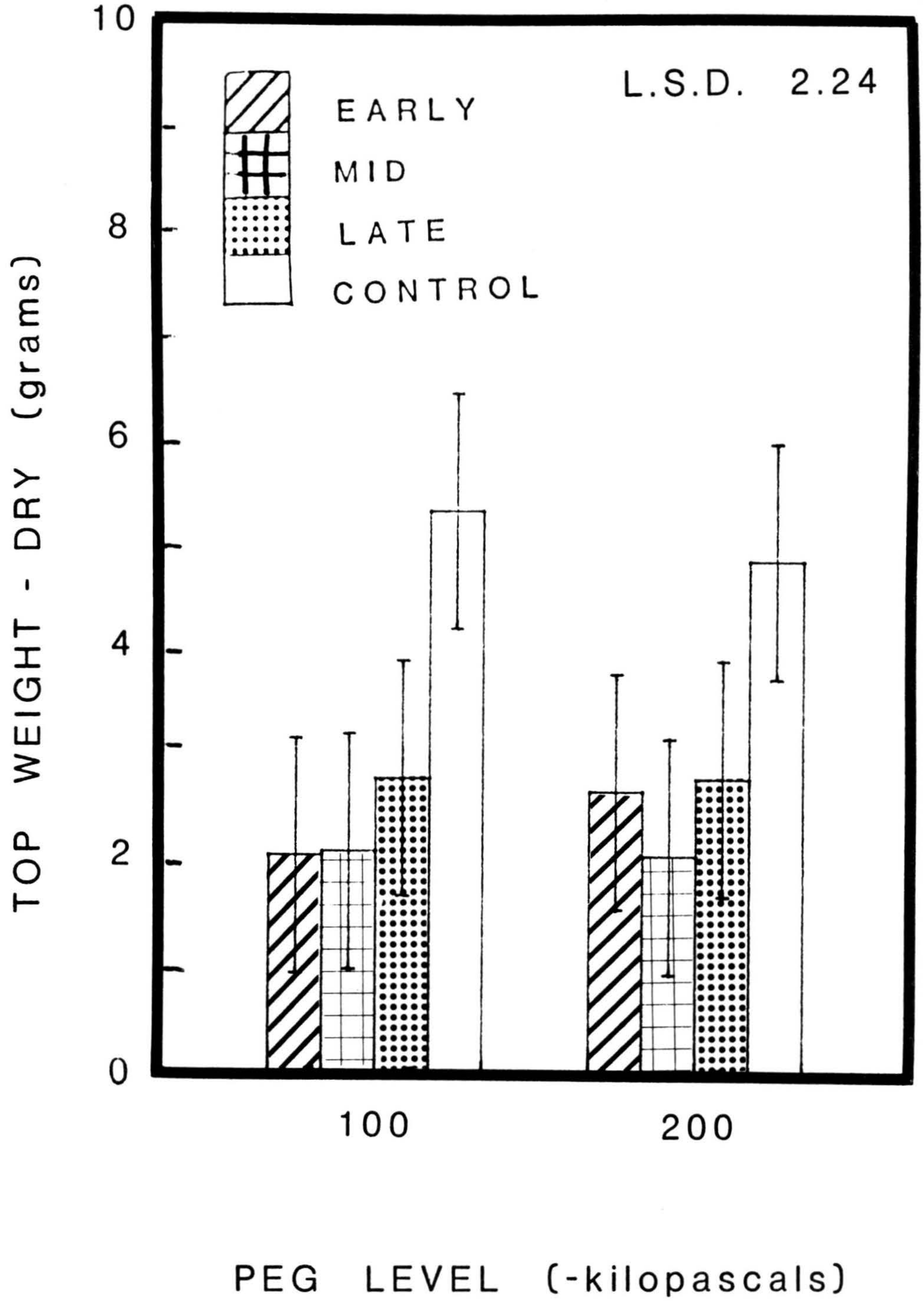
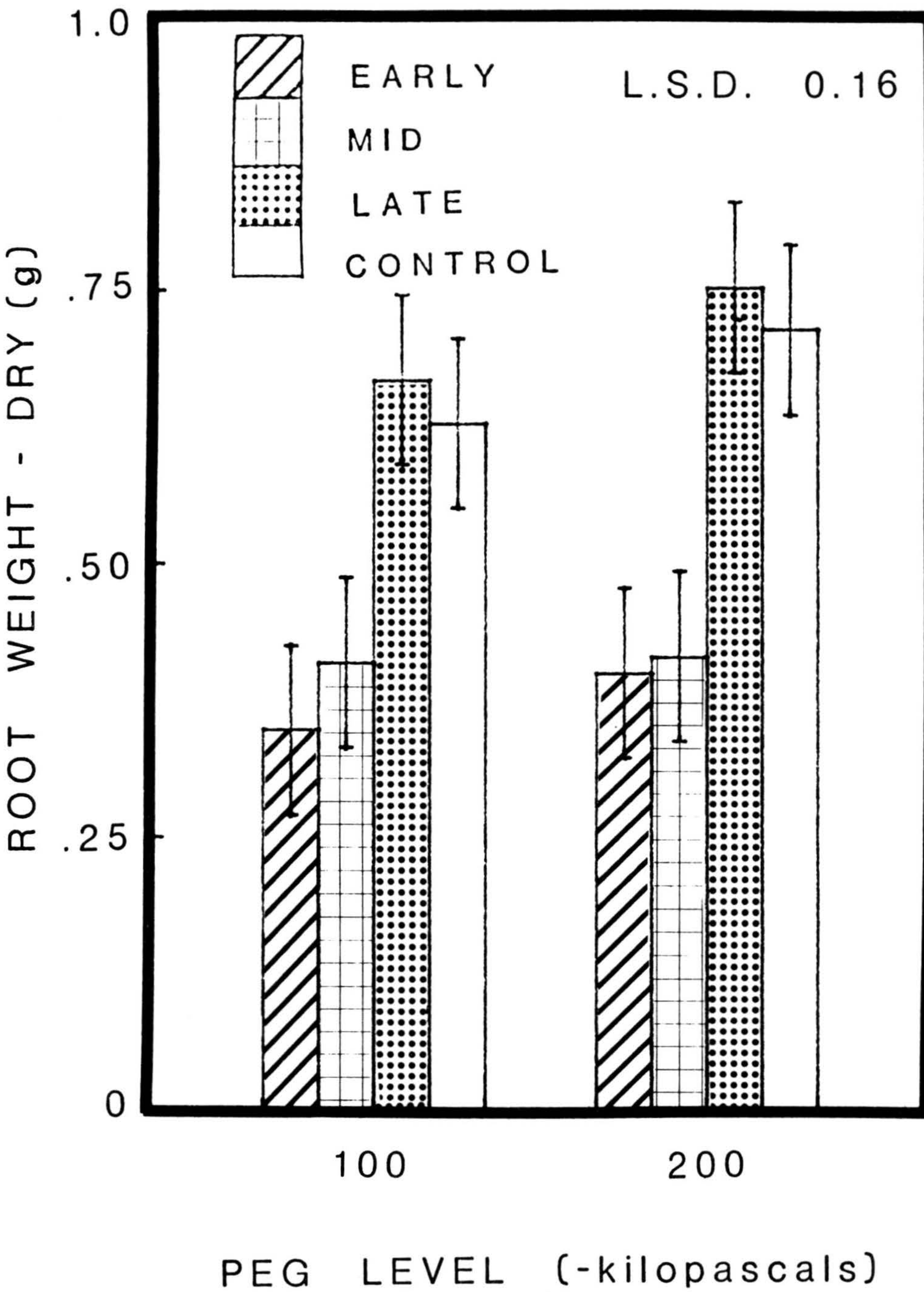

10
8
6
4
2
0
LEAVES/PLANT
30
60
90
120
150
DAYS FROM PLANTING
CONTROL
LATE
MID
EARLY
early
mid
late

Figure 23. Greenhouse study 1983. Mean top dry weight (g) collected at harvest, 140 days from planting. Plants were subjected to -100 and -200 kPa osmotic stresses applied during the early, mid, and late season growth stages. Desired levels of osmotic stress were achieved by using combinations of PEG 3500 and 1/2 strength Hoagland's solution. Control treatment used only 1/2 strength Hoagland's solution (osmotic potential = -40 kPa). Probability level = 5%.



10
8
6
4
2
0
TOP WEIGHT - DRY (grams)
EARLY
MID
LATE
CONTROL
L.S.D. 2.24
100
200
PEG LEVEL (-kilopascals)

Figure 24. Greenhouse study 1983. Mean dry root weight (g) collected at harvest, 140 days from planting. Plants were subjected to -100 and -200 kPa osmotic stresses applied during the early, mid, and late season growth stages. Desired levels of osmotic stress were achieved by using combinations of PEG 3500 and 1/2 strength Hoagland's solution. Control treatment used only 1/2 strength Hoagland's solution (osmotic potential = -40 kPa). Probability level = 5%.


1.0
.75
.50
.25
0
ROOT WEIGHT - DRY (g)
EARLY
MID
LATE
CONTROL
L.S.D. 0.16
100
200
PEG LEVEL (-kilopascals)

DISCUSSION

FIELD EXPERIMENTS 1982 AND 1983

Drought during the early season growth stage had no appreciable effect on the growth of the onion plant. Bulb fresh and dry weights observed during 1982 were not affected by drought stress.

Hail damage in 1983 resulted in smaller bulbs during that season. The plants were not able to fully recover from the hail damage and in addition to being water stressed so early in the season, experienced a significant setback in growth and ultimately reducing yield as compared to 1982.

Growth curves showing plant height and number of leaves indicate that drought during the early season (seedling stage) initially suppressed plant height and leaf emergence. Once the stress period ended, growth eventually resumed. DeLis (5) observed an accelerated rate of foliar emergence greater than that of the control 30 days after a drought stress of -1500 kPa during the seedling stage.

Onion plant growth after germination depends entirely upon production of new adventitious roots from the stem plate since older roots are continually dying and must be replaced. Root growth is most prolific from the flag stage (early season) until the bulbing or mid-season growth stage (50). The root system at this time is quite shallow with the majority of roots confined to the top 20-30 cm (2, 8, 19, 42, 48, 50). Due to limited root mass and continual production of adventitious roots from the stem plate, soil moisture must reach the bulb base during the early and mid-season growth stages to provide enough water and nutrients to the growing top (48, 50).

Results of root studies which have been done with various crop species show that root length and initiation ceases when water potential of the soil drops to -100 kPa (12, 23, 42). Figure 9 shows that a drought (-100 kPa) during the early season temporarily reduced root elongation. However, some time after the stress period, root elongation resumed at approximately its previous rate.

Results for 1982 and 1983 field experiments indicate that drought stress applied during the mid-season growth stage caused a significant decline in plant growth and development including reduction in bulb fresh weight, bulb dry weight, and length. Bulb diameter also tended to be lower. It seems logical that drought at this time would influence bulb growth the most since this is the log stage of bulb development when rapid scale bud initiation and formation occurs, placing demands on the roots for uptake of water and nutrients (2, 17, 29, 50).

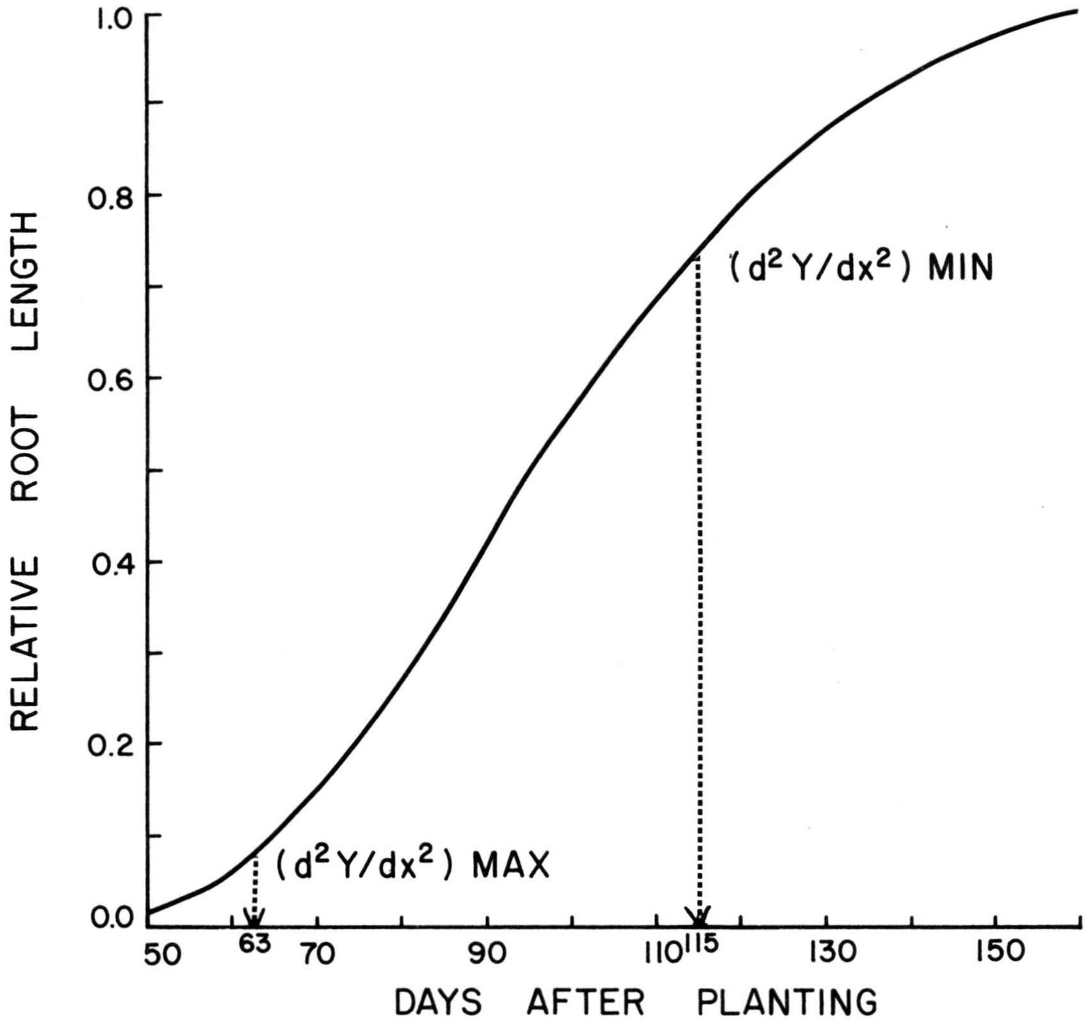
Bulb length/diameter is a relative term describing the overall shape of the bulb. The closer the ratio is to 1, the more spherical the bulb. Ratios less than 1 would result in a somewhat flattened bulb while ratios greater than 1 would tend to be elongated, torpedo-shaped bulb. Since there are many onion bulb shapes fixed genetically by plant breeders, the desired ratio varies with cultivar. 'Brown Beauty' exhibits a globe-shaped bulb (50). The mid-season soil moisture stress resulted in a malformed, elongated bulb. This was particularly evident in 1983 when the ratio averaged 2.1.

The mid-season stress also affected plant height and foliar emergence. Once experiencing a period of drought, the plants did not recover. The end result was a smaller plant with probably smaller amounts of photosynthates being produced and thus available for the developing bulb.

Root growth was suppressed after the mid-season drought treatment (Fig. 9). Figure 25 shows the relative growth of the control. The graph points out that 65% of total growth occurs within a span of 52 days with the maximum root growth rate 90 days from planting. This period in the growing season corresponds to early and mid-season growth stages with root growth rate reaching its maximum just before bulbing. Since maximum root growth rate was attained at 90 days, a drought stress after this time would result in an accelerated decrease in root growth with an accelerated increase in root senescence. The bulbing stage is a critical period and any alteration in root growth rate would ultimately negatively affect bulb development. Maintaining a continuous supply of new roots is essential in order to provide water and nutrients to the developing bulb.

Drought had no major influence on onion growth parameters when applied during the late season. Mean values for bulb weights tended to be greater than the control. Rapid decline in plant height at the end of the growing season was probably due to drought accelerating senescence (Fig. 7).

Figure 25. Field experiments 1982 and 1983 combined data. The Richards function was fitted to relative root length (cm) of the control (no stress). Maximum root growth rate, obtained from the Richards parameter values, occurred 90 days from planting.



1.0
0.8
0.6
0.4
0.2
0.0
RELATIVE ROOT LENGTH
(d2 Y/dx2) MIN
(d2 Y/dx2) MAX
50
63
70
90
110
115
130
150
DAYS AFTER PLANTING

Root growth was not significantly affected by a late season drought. However, root growth is shown to be less than the control throughout the season (Fig. 9). This trend was primarily due random error in measuring root length. Onion growers usually cause a drought stress by terminating irrigation to stop root growth and allow the bulb to mature otherwise, a late irrigation would delay maturity. Immature onions do not ship or store well (50).

GREENHOUSE EXPERIMENT 1983

This experiment using controlled greenhouse conditions provided additional evidence that drought stress applied at a specific growth stage affects onion growth and yield more than stress applied at other growth stages. The experiment included the same growth stages, stress duration and -100 kPa water potential as the field experiments. In addition, the influence of drought stress at -200 kPa was tested, all concomitant with high nitrate levels in the medium.

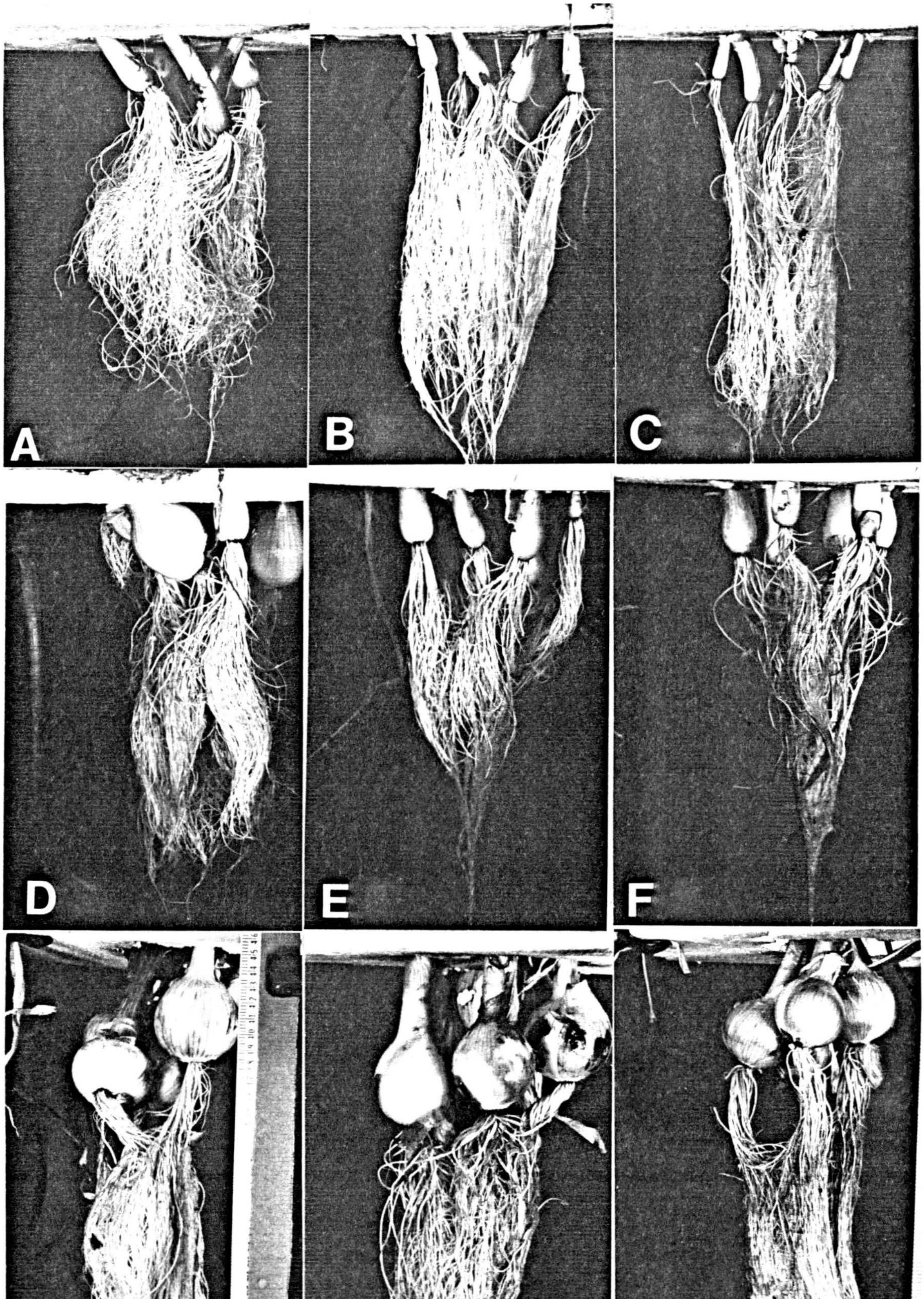
Results indicated that high nitrate levels had no major effect on onion top or root growth. Therefore, nitrate level will not be discussed any further.

Figure 26 shows the influence of drought stress at -100 kPa and -200 kPa on bulb and root growth applied during the three growth stages. The pictures were taken immediately after the 3 weeks of drought stress and the roots were the same distance from the camera during each of the three photo sessions.

Bulb growth was unaffected immediately following the early season simulated drought at -100 kPa (Fig. 26 B) compared to the

Figure 26. Greenhouse experiment 1983. Influence of drought stress at -100 kPa and -200 kPa on bulb and root growth applied during early, mid, and late season growth stages. Pictures were taken immediately after the 3 weeks of drought stress and were taken the same distance away from the camera.

A. Early season stress; -40 kPa
B. Early season stress; -100 kPa
C. Early season stress; -200 kPa
D. Mid-season stress; -40 kPa
E. Mid-season stress; -100 kPa
F. Mid-season stress; -200 kPa
G. Late season stress; -40 kPa
H. Late season stress; -100 kPa
I. Late season stress; -200 kPa


A
B
C
D
E
F
G
H
I

control of -40 kPa (Fig. 26 A). Early stress had no influence on bulb fresh weight, dry weight, or bulb diameter (Figs. 10, 11, and 12), however, bulbs were less elongated.

Unlike -100 kPa, a drought stress level of -200 kPa applied during the early season growth stage reduced all bulb parameters (Figs. 10, 11, and 12). This can also be seen in the bulb diameter growth curve (Fig. 14). Stressed plants apparently do not regain normal bulb expansion rate as the season progresses.

Top growth was reduced by the early season treatment as drought stress increased, resulting in a shorter plant with fewer leaves. The inhibition of growth was released at -100 kPa and -200 kPa after the stress period. Leaf emergence was affected at both PEG levels but was especially reduced at -200 kPa. Plants were only able to obtain an average maximum of 7 leaves as compared to over 9 leaves for the non-stressed control (Fig. 22).

During the early season period, aboveground structures exhibited visual symptoms of drought stress. The most noticeable symptom was the darkening of the leaves. Drying and dieback of leaf tips as well as wilting occurred as the stress period continued.

Fig. 26 A,B,C shows that more severe drought treatment in the early season decreased relative volume of roots somewhat. Quantitative measurements of root length gave no indication of this difference. Instead of measuring root length, a possible alternative in finding differences might be measuring root volume by water displacement. The difficulty is in finding a good non-destructive evaluation method.

Greenhouse conditions were not favorable during the early season period. Temperatures in the greenhouse were much higher during the early season than during other treatments (Table 3). The cooling and ventilation system was not functioning properly and unseasonably warm days caused the temperature inside the greenhouse to rise sharply. In addition to an osmotic stress in the solution, the plants were also exposed to higher temperatures which probably caused an aerial stress which could have caused a significant setback in onion growth, therefore yield reduction.

Drought stress had the greatest influence on bulb growth when applied during the mid-season growth stage in the greenhouse study just as it did in the field study. Bulb growth diminished a great deal after a stress of -100 kPa or -200 kPa (Fig. 26 D,E,F). A drought threshold for yield reduction was -100 kPa which reduced bulb fresh weight 55% compared to the control.

After mid-season treatment, plant height continued to increase but at a slow rate. Reduction in plant height was particularly evident beginning with the -100 kPa treatment (Fig. 17) where elongation decreased rapidly during the stress period and showed little recovery after the stress. Number of leaves was also negatively influenced by mid-season drought and drought during this period resulted in the plant having fewer leaves. However, at -200 kPa, leaf emergence was affected most when the stress was applied during the early season growth stage. Plants also showed visual stress symptoms similar to those caused by the early season stress.

Table 3. Average greenhouse temperatures during the solution culture study, °C.

Time of Stress	Max	Min
Early Season Day 59-80	30	20
Mid-season Day 77-98	24	16
Late Season Day 111-132	27	18
Control[1]	27	17

[1]Temperature averaged for day 59-132.

Applying a drought stress during the mid-season growth stage caused a tremendous setback in root growth. Number of roots in the stressed treatments appeared to be less with much dieback compared to the healthy white root mass of the control (Fig. 26 D,E,F). There was greater root senescence after the stress period in the -200 kPa treatment. Final root weight was 38% less than the control with little difference due to stress levels.

Results for the late season stress treatment in this experiment are similar to those reported in the field experiments which indicated drought during this time had no major affect on plant growth or yield. Figure 26 G,H,I provides further evidence. Plant growth at this time is characterized by bulb sizing, root inhibition, and collapse of the leaf bundle (2, 29, 50).

ANOVA tables indicated that replications for top dry weight were significantly different from one another with replication 2 having the highest mean dry weight. The explanation for this difference was the location of replications on the benches. Due to confined space in the greenhouse, the experiment was limited to two benches, therefore, replication 2 was randomly split. Both halves of replication 2 were closest to the cooling pads where the temperature was cooler, thus less transpiration by the plants. A temperature gradient occurred becuase of heating elements at one end of the greenhouse.

CONCLUSION

Similar results were obtained even though environmental conditions were different in the field and greenhouse experiments. Yield expressed as fresh bulb weight is summarized in Table 4. Both studies identified the mid-season (bulbing) stage as the most critical period where soil moisture stress should not be permitted. Level of drought stress is also an important factor to consider and should not be overlooked. A stress greater than -100 kPa in addition to causing a decrease in growth at the mid-season also significantly suppressed growth when applied at the early season (seedling) growth stage.

Based on this research, water conservation could be incorporated into the onion irrigation scheduling model. However, it would be well to determine the threshold stress level for the late season period first.

Table 4. Bulb fresh weight (g/plant) for field and greenhouse experiments.

Experiment	Stress[1] Periods			
	Control[2]	Early	Mid	Late
Field rootview[3]	34 a	32 a	12 b	38 a
Greenhouse solution	76 a	51 a	35 b	63 a

[1]-100 kPa field and greenhouse.

[2]-55 kPa field, -40 kPa greenhouse.

[3]Average of 2 experiments.

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APPENDIX

Table 5. Field soil characteristics for 1982 and 1983.

	Soil Analysis	
	1982	1983
pH	7.2	7.7
E.C. (mmhos/cm)	3.4	2.6
Lime	low	high
% O.M.	1.6	2.0
NO3-N (ppm)	94	96
P	43	40
K	262	454
Zn	3.8	2.9
Fe	29.2	14.5
Mn	14.3	4.6
Cu	4.7	3.3
% Sand	58	46
% Silt	23	24
% Clay	19	30
Texture	SL	SCL

Table 6. Nitrate solutions employed in the greenhouse study. X symbolizes nitrate concentration.

Stock Solution*	ml/liter H2O	N	NO3-N	NH4-N	P	K	Ca	Mg	SO4
		(ppm)							
				1X					
KH_2PO4	0.5	-	-	-	15.5	19.5	-	-	-
KNO3	2.5	35.0	35.0	-	-	97.8	-	-	-
$Ca(NO3)_2$	2.5	70.0	70.0	-	-	-	100.2	-	-
MgSO4	1.0	-	-	-	-	-	-	24.3	96.1
NH4NO3	0.0	-	-	-	-	-	-	-	-
Total ppm		105.0	105.0	-	15.5	117.3	100.2	24.3	96.1
				2X					
KH2PO4	0.5	-	-	-	15.5	19.5	-	-	-
KNO3	2.5	35.0	35.0	-	-	97.8	-	-	-
$Ca(NO3)_2$	2.5	70.0	70.0	-	-	-	100.2	-	-
MgSO4	1.0	-	-	-	-	-	-	24.3	96.1
NH4NO3	3.4	95.2	47.6	47.6	-	-	-	-	-
Total ppm		200.2	152.5	47.6	15.5	117.3	100.2	24.3	96.1
				3X					
KH2PO4	0.5	-	-	-	15.5	19.5	-	-	-
KNO3	2.5	35.0	35.0	-	-	97.8	-	-	-
$Ca(NO3)_2$	2.5	70.0	70.0	-	-	-	100.2	-	-
MgSO4	1.0	-	-	-	-	-	-	24.3	96.1
NH4NO3	7.0	195.0	97.4	97.4	-	-	-	-	-
Total ppm		300.0	202.4	97.4	15.5	117.3	100.2	24.3	96.1

*Micronutrient solution (0.5 ml/liter) was also added giving 2.50 ppm Fe, 0.25 ppm B, 0.26 ppm Mn, 0.025 ppm Zn, 0.010 ppm Cu, and 0.005 ppm Mo.

Table 7. PEG used in nitrate solutions.

Treatment[y] (-kPa/ppm NO3-N)	PEG 3500[z] (g/liter H2O)
-40/105	0.00
-100/105	61.99
-200/105	102.78
-58/153	0.00
-100/153	51.39
-200/153	96.54
-77/202	0.00
-100/202	37.48
-200/202	89.60

[y]Using 1/2 strength Modified Hoagland's Solution and NH4NO3 as the excess NO3-N source.

[z]Using Steuter's formula (40): $Y = 0.00002X^{1.94}$
where: Y = osmotic potential, MPa
X = PEG 3500, g PEG/liter H2O

Table 8. Analysis of variance for onion plant components, greenhouse experiment 1983.

Source of Variation	df	Mean Source	F	Probability of F (* 5%; ** 1%)
A. Bulb fresh weight (grams)				
Time	3	9939.1122	6.1854	*
Error (a)	6	1606.8808	--	
PEG	2	24293.7311	14.7553	**
TimexPEG	6	8425.5457	5.1175	**
N	2	285.1994	0.1732	NS
TimexN	6	456.8952	0.2775	NS
PEGxN	4	1610.8362	0.9784	NS
TimexPEGxN	12	1328.5111	0.8069	NS
Error (b)	280	2311.4410	--	
B. Bulb dry weight (grams)				
Time	3	127.0917	5.1719	*
Error (a)	6	24.5737	--	
PEG	2	296.0688	11.4599	**
TimexPEG	6	111.7708	4.3263	**
N	2	4.4412	0.1719	NS
TimexN	6	12.3901	0.4796	NS
PEGxN	4	24.1558	0.9350	NS
TimexPEGxN	12	29.1349	1.1277	NS
Error (b)	280	36.1908	--	
C. Bulb length (cm)				
Time	3	6.0464	10.9466	**
Error (a)	6	0.5524	--	
PEG	2	13.4396	13.3767	**
TimexPEG	6	5.5036	5.4779	**
N	2	0.0228	0.2272	NS
TimexN	6	0.2208	0.2197	NS
PEGxN	4	1.4151	1.4085	NS
TimexPEGxN	12	0.8686	0.8646	NS
Error (b)	280	1.4888	--	
D. Bulb diameter (cm)				
Time	3	9.0463	5.1034	*
Error (a)	6	1.7726	--	
PEG	2	20.9217	15.4893	**
TimexPEG	6	6.0882	4.5074	**
N	2	0.1850	0.1370	NS
TimexN	6	0.3966	0.2936	NS
PEGxN	4	0.9132	0.6761	NS
TimexPEGxN	12	1.1006	0.8148	NS
Error (b)	280	2.0120	--	

Table 8. Continued.

Source of Variation	df	Mean Source	F	Probability of F (* 5%; ** 1%)
E. Bulb length/diameter				
Time	3	0.0444	1.3307	NS
Error (a)	6	0.0333	--	
PEG	2	0.0494	3.3673	*
TimexPEG	6	0.0221	1.5134	NS
N	2	0.0079	0.5362	NS
TimexN	6	0.0064	0.4367	NS
PEGxN	4	0.0027	0.1866	NS
TimexPEGxN	12	0.0149	1.0158	NS
Error (b)	280	0.0147	--	
F. Top dry weight (grams)				
Time	3	52.5168	7.0610	*
Error (a)	6	7.4376	--	
PEG	2	110.4556	10.7534	**
TimexPEG	6	29.6900	2.8905	*
N	2	14.2964	1.3918	NS
TimexN	6	11.1913	1.0895	NS
PEGxN	4	2.3350	0.2273	NS
TimexPEGxN	12	4.8600	0.4731	NS
Blk	2	47.5223	6.3895	*
Error (b)	280	17.6982	-	
G. Number of leaves				
Time	3	12.3813	5.4711	*
Error (a)	6	2.2630	--	
PEG	2	26.4733	10.0305	**
TimexPEG	6	3.6612	1.3872	NS
N	2	5.5998	2.1217	NS
TimexN	6	2.4832	0.9409	NS
PEGxN	4	1.0273	0.3892	NS
TimexPEGxN	12	2.6967	1.0218	NS
Error (b)	64	2.6393	--	
H. Plant height (cm)				
Time	3	1116.9146	5.3757	*
Error (a)	6	207.7696	--	
PEG	2	1872.5401	13.7367	**
TimexPEG	6	315.7459	2.3163	*
N	2	225.5957	1.6549	NS
TimexN	6	249.0772	1.8272	NS
PEGxN	4	45.5062	0.3338	NS
TimexPEGxN	12	89.5165	0.6567	NS
Error (b)	64	136.3167	--	

Table 8. Continued.

Source of Variation	df	Mean Source	F	Probability of F (* 5%; ** 1%)
I. Root length (cm)				
Time	3	6.9997	0.2517	NS
Error (a)	6	27.8052	--	
PEG	2	6.9763	0.9012	NS
TimexPEG	6	5.3495	0.6910	NS
N	2	2.3405	0.3024	NS
TimexN	6	5.3309	0.6887	NS
PEGxN	4	10.4794	1.3537	NS
TimexPEGxN	12	11.1159	1.4360	NS
Error (b)	64	7.7411	--	
J. Root dry weight (grams)				
Time	3	0.3698	8.8095	*
Error (a)	6	0.0420	--	
PEG	2	0.1468	5.1829	**
TimexPEG	6	0.0915	3.2295	**
N	2	0.0325	1.1464	NS
TimexN	6	0.0273	0.9638	NS
PEGxN	4	0.0154	0.5437	NS
TimexPEGxN	12	0.0358	1.2650	NS
Error (b)	64	0.0283	--	