THESIS

ONION GROWTH AND WATER USE PATTERNS IN RELATION TO DROUGHT STRESS

Submitted by
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Horticulture

In partial fulfillment of the requirements
for the Degree of Master of Science
Colorado State University
Fort Collins, Colorado

Fall, 1983

COLORADO STATE UNIVERSITY

Fall 1983

WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION BY DONALD BRUCE BOSLEY ENTITLED ONION GROWTH AND WATER USE PATTERNS IN RELATION TO DROUGHT STRESS BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

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ABSTRACT OF THESIS

ONION GROWTH AND WATER USE PATTERNS IN RELATION TO DROUGHT STRESS

Four distinct growth stages of storage onions were established using growth analysis techniques; stand establishment (0 - 4 leaves), leafing (4 - 8 leaves), bulbing (8 - 10 leaves), and sizing (less than 10 leaves. Visible developmental observations such as number of functional leaves were determined to be the best indicator of crop growth stage. Linear relationships between soil matric potential (SMP) and evaporative demand (ED) were developed for each of the latter three growth stages in order to determine proper irrigation timing. It was assumed that SMP i.e. soil moisture "need" is a function of stage of growth, EPA, soil texture and root zone recharge. It was determined that to limit SMP to no greater than -40 kilopascals (kPa), irrigation or a significant rainfall should occur at or before 789 ml of water are evaporated from a black Bellani plate atmometer during the leafing growth stage. In a like manner, soil recharge should occur at or before 340 ml are evaporated during the bulbing and sizing growth stages.

Onions were stressed during the leafing, bulbing, and sizing growth stages by withholding irrigation until a soil matric potential of -70 kilopascals was reached. No significant differences were observed in either the growth pattern or final yield between each stress treatment and the unstressed control.

Hydroponically grown onions were transplanted into containers located in a greenhouse so that roots were subjected to six different levels of polyethylene glycol (PEG) 3500 osmotic solutions for five weeks. Leaf, bulb, and root dry weights were found to be significantly reduced in the treatment of -274 kPa or more negative osmotic potential than treatments of -147 kPa or less negative potential. Root:shoot ratio was found to be significantly greater in only one instance. After three weeks of growth the highest stress level (-622 kPa) resulted in the largest root:shoot ratio. This observation was believed to result from a proportionately greater leaf tissue decline than root tissue decline in response to high osmotic stress.

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Fall 1983

ACKNOWLEDGMENTS

I would like to thank the Northern Colorado Onion Growers Association for their interest and support for this research.

Appreciation is extended to Dave Monson and Bill Monson for their assistance and for the use of their onion fields for the research sites. And to Chuck Urono who helped establish the Greeley research.

I would especially like to thank Ann McSay for her assistance and advice on all aspects of this work.

Much appreciation is extended to members of my committee, Drs. Robert Danielson and Pat Ried for their time and constructive criticisms. I sincerely express my gratitude and appreciation of the assistance received by my advisers, Drs. Frank Moore and Steve Wallner, especially for their patience throughout the long period this thesis required.

Finally, I would like to thank my wife, Cathy, for her continued encouragement and patience.

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INTRODUCTION

Irrigation consumes 13% of all energy used in agriculture throughout the United States. The corresponding percentage of irrigation energy from farms in the arid west is much higher. Agricultural irrigation uses 79% of Colorado's annual 650,000 hectare meter (5.3 million acre feet) water budget. The greatest potential for water savings appears to be improvements in the science of farm irrigation efficiency (36,38). To accomplish this savings, efforts must be made to help growers become aware of optimal irrigation through additional research on irrigation practices. All application methods are characterized by certain inefficiencies but applying irrigation water only when the crop requires it usually results in a water savings and therefore an energy savings. Such an approach to water savings must be based on a thorough understanding of the nature and consequences of plant water stress. Detailed information on plant responses at various stages of development may provide a basis for establishing times when irrigation(s) may be withheld. Eliminating an irrigation would conserve not only water but also the energy required to pump it through the system. With a declining aquifer in parts of the irrigated west the energy may be the greatest cost of production in the future.

In Colorado and elsewhere, some current irrigation practices waste energy in two ways; the energy required to pump excess water and that required to produce the nitrogen fertilizer which may be leached from the soil by deep percolation of the excess water. Since over-irrigation is common, improvements in efficiency represent an excellent opportunity for energy conservation. Well planned irrigation scheduling facilitates correct timing and amount of water applications, thus reducing production costs, enough to maintain profitable yields.

Recent research and field observations strongly endorse the concept and feasibility of irrigation scheduling (25,31,41,42,44,46). A computer model developed by the USDA has been successfully used to schedule irrigation of agronomic crops in Nebraska and Colorado with 35% and 25% reduction (4), respectively, in water applied. These and other results, plus the increased cost of energy, have stimulated greater interest in scheduling methods and repeated urging that farmers improve water management.

However, irrigation scheduling models have generally not been accepted at the farm management level. One obstacle to widespread use has been the complexity of current models. Many irrigation scheduling programs require numerous inputs from the farmer for maximum benefit

(9,19,45). The opinion of many farmers is that they are unwilling to be "bothered" with these complex programs and the many environmental factors which need to be measured. The belief is held that experience does as well, considering the limitations of the water delivery systems (7). Simpler programs utilizing fewer imputs need to be developed before farm managers will be willing to adopt a more systematic method for scheduling irrigation.

Crop stage of growth and soil type are both important factors in determining when to irrigate a crop (8,29,35, 44). These two variables must be combined with an index for environmental conditions in making up a model which predicts evapotranspiration (ET) on a daily basis for irrigation scheduling purposes.

A less complex model utilizing black Bellani plate atmometers as the primary instrument for assessing environmental conditions has recently been developed for lettuce (26). Studies have demonstrated that atmometers can be accurate and reliable in determining evaporative demand when predicting crop water use (13,16,19,22,25,34). Atmometers have the added advantage that they are convenient to use and are relatively inexpensive when compared to the equipment required for most other irrigation scheduling programs (16). Uncomplicated irrigation scheduling models utilizing the Bellani plate should be constructed for many crops grown in the arid and semi-arid areas of the U.S. in order that farmers will more readily adopt them.

Accurate determination of crop water use is dependent upon crop stage of growth as well as soil and environmental factors (8,35). Most temperate zone crops exhibit three or four distinct stages of growth: a lag stage, or slow growth seedling stage, a log stage in which the rate of growth increases rapidly and vegetative growth predominates, a third stage in which the rate of growth declines and reproductive and/or storage organ growth predominates and, finally, a maturation or senescence stage (14,33). Onion studies have also allowed the description of four growth stages, although many researchers have combined two stages into one in their analysis (1,24,31,38,42). The aspects of all four growth stages are described in the aforementioned studies but definitive criteria for demarcation of one stage from another is lacking.

The irrigation of an onion crop is especially inefficient due to the plant's shallow rooting habit and low tolerance of drought stress. In well drained soils, onions may have roots extending to as deep as 60 cm, but most of the root mass and the primary zone of water extraction is in the top 20 - 30 cm of the soil profile (2,7,18,41,46,48). Previous research has demonstrated that onions grow poorly in response to moderate or severe drought stress (2,5,18,20,21,32). From these studies it has been consistently found that the greatest yield in marketable onions is obtained when relatively high soil moisture content is maintained, concomitant with adequate soil aeration (2,3,11,20,21,33). Recommendations for maintaining soil moisture potentials in the 30 to 60 kilopascal range are common (9,18,27). Frequent, light irrigations are needed to maintain these values in the top 20 - 25 cm of the soil profile without excessive leaching below the root zone.

Investigations have been made into the ability of the onion plant to adapt to a decreased osmotic potential in the rooting medium relative to responses found in other crop species (5,11,24). Results indicated that onions do not fully adjust to moderate and high levels of salinity in the rooting medium. When transpiration and photosynthesis were reduced, some osmotic adjustment was noted, although not sufficient to allow for resumption of normal growth and physiological processes (5). Field investigations concerned with onion internal responses to low soil moisture content resulted in similar conclusions (3,28).

Other agronomic and horticultural crops have exhibited an increase in root growth in response to mild drought stress (35,37). However, results with onions indicated that the greatest root extension occurred in the treatment in which heaviest and most frequent irrigation was applied (2). These studies indicate that onions do not respond to drought stress by increasing root growth.

Research has also demonstrated that, for most agronomic and horticultural crops studied, plant water deficits at certain growth stages may cause more plant injury or yield reduction than at other stages (8,23,33,35,37,38, 43). Some crops even benefit by a minor degree of drought stress when properly timed to plant development (23,43). Investigations concerning crops which are grown primarily for non-vegetative yield components (storage roots or reproductive structures) generally have shown that the growth stages most susceptible to stress are during the initiation and development of those structures (35,38,43). Studies with onions have demonstrated that high to moderate drought stress applied during any stage of growth reduces final yield (1,18,24,38,42,46). However, in all of these investigations, growth stages which are more sensitive to water deficit than others have been identified. Unfortunately many of these studies have produced contradictory results by identifying different critical periods. Some of the studies indicate that imposed drought stress has the greatest influence on yield during bulb initiation and during bulb sizing. This is consistent with the aforementioned structure initiation and development hypothesis (1,18,38). Other studies indicated the lowest yield was obtained when stress was applied at the earlier growth stages (24,42).

The purpose of this research was: 1) to develop a relationship between evaporative demand, soil moisture depletion, and stage of growth for a commercially grown onion cultivar; and 2) to determine the relative responses to drought stress at different stages of growth for that cultivar. This research was conducted to provide the necessary information for the development of an irrigation scheduling model for onions which would be user-attractive and result in increased irrigation efficiency.

MATERIALS AND METHODS

Allium cepa L., cv Brown Beauty was used throughout this research. Field plantings were established and maintained using current commercial practices of the Northern Colorado production area. Double row beds 102 cm wide were direct seeded in 41 cm apart. Furrow irrigation was used and water was supplied by either pumped well water or a combination of ditch and well water. Weed control was accomplished by a combination of pre-emergence (Dacthal)^R, and post-emergence herbicide (Brominal)^R applications, and cultivation. Insect pest control was accomplished using applications of Diazinon (primarily for onion thrips).

Onion growth measurements were made on samples taken from field and greenhouse experiments using the following procedures. Leaf area was determined by passing excised leaves through a LI 3100 leaf area meter. The resulting value (cm^2) was multiplied by 2 due to the tubular structure of the leaves. This method of evaluating leaf area was chosen over others on the basis of consistency and time saving. Plant components were oven dried by forced air drying at 70° C until the sample weights became stable over a 24 hour period.

Since the rate of evaporation is controlled by the incident radiant energy and the temperature, humidity and movement of the air immediately above the evaporating surface, Bellani plate atmometers were used to evaluate the evaporative demand (ED) or evaporative power of the air (EPA) (26). These instruments were chosen because of their applicability to the farm management level on the basis of convenience and reliability (22). Tensiometers and resistance blocks were used to monitor soil matric potential (SMP). Germane to this study are the relationships among ED, SMP, and growth stage. Since SMP was measured as a cumulative parameter to correspond with days from last recharge, atmometer water loss (ED) was also expressed as a cumulative parameter. The unit for SMP is negative kilopascals while the unit for atmometer water loss and therefore ED is milliliters. Each Bellani plate has a designated coefficient which was used to standardize al ED readings. All tensiometers were calibrated to a standard instrument prior to installation in the field. The resistance blocks were not calibrated prior to use.

Environmental measurements for all of the field experiments followed the same general procedure. A pair of Bellani plate atmometers with black surfaces were used to monitor evaporative demand (ED). These were placed within an irrigated field crop area no more than 1 km from the research plots. The two plate surfaces were positioned parallel to and 1 meter above the soil surface. Distilled water was used to replenish the 250 ml reservoir when necessary. Precipitation was measured using a standard USDA 8 inch (20.3 cm) diameter rain gauge placed near the Bellani plate atmometer assembly. Maximum and minimum temperature thermometers were located with the atmometers and rain gauge in a standard weather shelter. Temperatures were measured in order to determine heat units for future use. Tensiometers and resistance blocks to monitor SMP were placed at 10 and 20 cm depths in two areas of the plots. These instruments were placed within one of the two rows of onions on a bed. The type of tensiometers used were Irrometer^R Soil Moisture indicators, model 'R', 15 and 30 cm lengths. Gypsum Bouyoucous resistance blocks were used. The field plots, within which the instruments for monitoring SMP were located, were situated sufficiently far from the head and tail ditches to avoid wet or dry extremes. Daily readings of all instruments were made between 7 and 9 A.M., M.D.T.

Onion Growth, SMP, and EPA Investigations - Greeley

It was assumed in the studies presented here that the effective onion root zone (0 - 30 cm) would be filled at each irrigation. In making this assumption, the experiments could be devoted to the timing aspect of irrigation scheduling, rather than the amount of water applied.

The first experiment was initiated to determine the relationship between onion ontogeny, atmometer water loss and root zone moisture depletion as indicated by SMP for a sandy clay loam soil. The research plot was located within a commercial onion field near Greeley in Weld County, Colorado. There are 3885 hectares (9600 acres) of commercially grown onions in this and nearby counties each year. The elevation is 1417 m and sporadic rainfall occurs at a rate of 0.8 to 5.8 cm per month during the growing season, from early March to mid September.

The 1980 research was conducted within a 1.2 hectare (3 acre) plot of a 16 hectare (40 acre) onion field, having a sandy clay loam soil classification. The two row beds were planted on 15 April in an east-west orientation. Population density was 20.6 plants per square meter. The field was irrigated 13 times during the season. All decisions concerning planting, irrigation, and weed, insect, or disease control were made and implemented by the cooperating growers.

Two locations for measuring SMP were established in the field plot area. The first monitoring area was located about one-eighth of the distance (46 m) down the field from the head ditch. The second area was about one-eighth of the distance of the field up from the tail ditch. Each area had 5 tensiometers and 2 resistance blocks at each of the two depths for a total of 20 tensiometers and 8 resistance blocks. Tensiometers and resistance block readings were not taken for 1 or 2 days following a significant rainfall or irrigation.

Weekly whole plant samples were taken from pre-determined 30 cm transects alternating between north or south rows of the two-row beds within the research plot. Numbers of plants per sample were recorded in the field. All plant samples were analyzed in the lab for the following attributes: leaf area, leaf length, sheath length, bulb length, bulb diameter, and number of leaves per plant. The values of each plant attribute were plotted as a function of days from planting.

This study was repeated during the 1981 growing season. Planting was on 10 March, five weeks earlier than the previous season. Population density was 31.8 plants per square meter. The field was located adjacent to the Bellani plate atmometer and rain gauge station with the beds oriented in a north-south direction. Tensiometers were placed in the field, in the manner previously described. Six instruments were set at each depth at the two locations for a total of 24. Resistance blocks were not used. The field was irrigated 10 times during the 1981 season.

Plant samples were collected as described in the 1980 study. Individual samples (plants) were kept separate, however, for statistical analyses. Measurements of leaf area, leaf dry weight, bulb and sheath dry weight, number of bulbs, and number of leaves per plant were conducted in the lab. The resulting values were expressed on a per plant basis.

Growth curves based on dry weights, leaf area, and leaves per plant were established for each of the two seasons and for the two combined. The Richards function (15) as well as a third degree polynomial were fitted to the onion growth data, normalized by time between the two years on the basis of leaf number. Fitting the functions based on the combined data from the two growing seasons (1980 and 1981) was done so the relationships developed would be more applicable to all growing seasons with variable climatic conditions or planting dates. The final fitted curve for leaf area was chosen from a combination of the Richards function and the third degree polynomial functions; growth stage I and II were fitted to the former, while stage III and IV were fitted to the latter in a continuous fashion. The mathematically derived inflection point was used to separate stage II from stage III. This method was chosen because neither functional type adequately described the leaf area data. Onion bulb dry weight data were fitted to the Richards function.

Drought Response at Different Growth Stages - Fort Collins

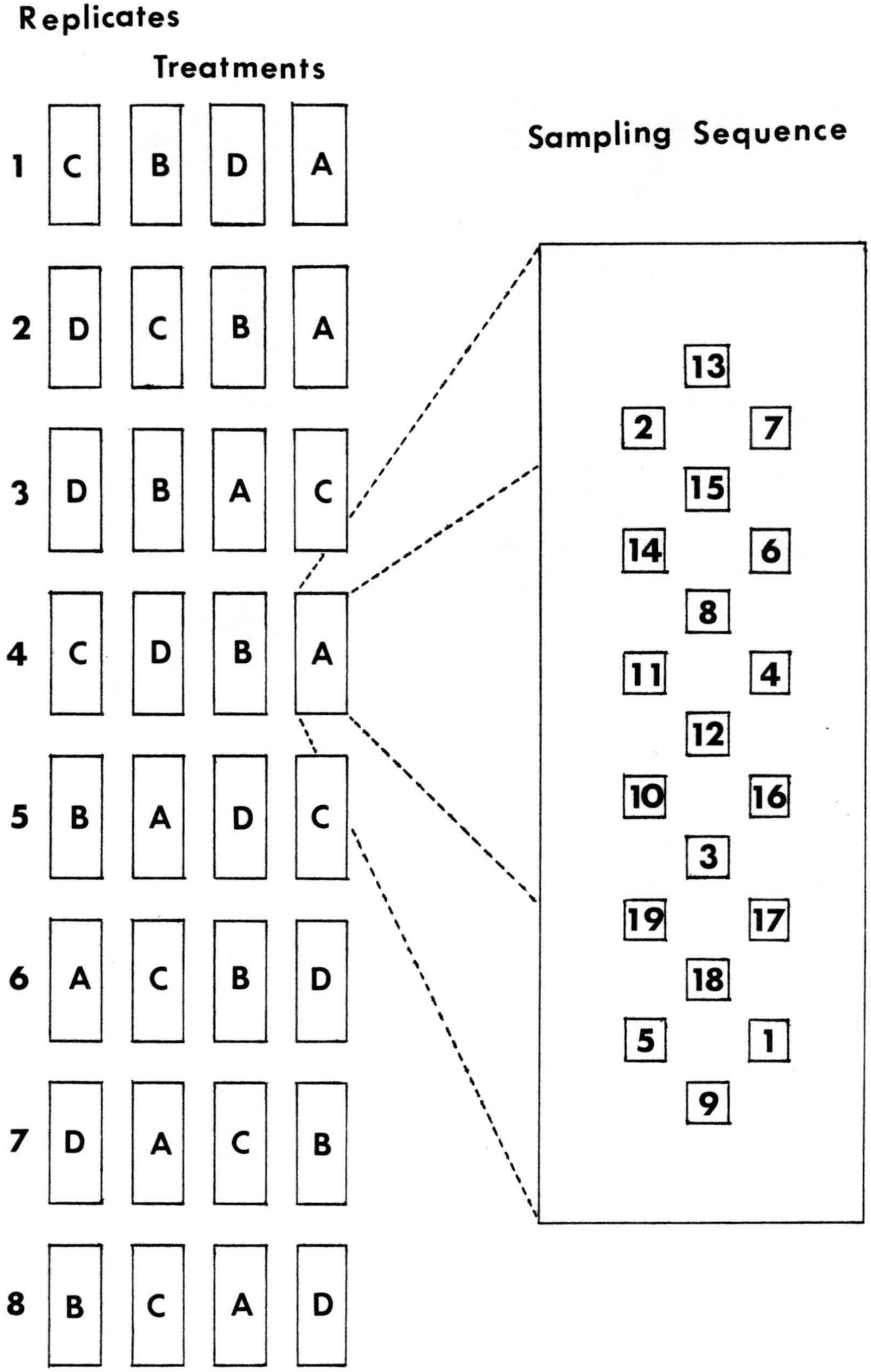
The objective of this investigation was to determine the influence of a moderate drought stress on onion growth and yield when imposed at different growth stages. The research plot was located at the Colorado State University

Horticulture research farm located 13 km northeast of the CSU campus. The plots were adjacent to other surface irrigated vegetable research plots, sugarbeets, field corn, and alfalfa. The elevation is 1524 m and sporadic rainfall occurs on the order of 2.8 to 5.8 cm per month during the growing season.

The stress research was conducted within a 0.4 hectare (1 acre) field plot of a clay soil classification. The field was seeded on 16 April 1981 using uncoated seed (Allium cepa L., cv Brown Beauty) and planted to commercial specifications (previously described). The beds were oriented in an east - west direction. Furrow irrigation supplied by pumped well water was used throughout the season.

Two factors were investigated, using a split plot, randomized, complete block design (Figure 1). Water was applied to the control treatment when a threshold value of 40 kPa (27) soil matric potential was attained. SMP was estimated by an average of the tensiometers placed at 15 cm depth from all of the non-stressed plots. Stress treatments consisted of permitting SMP to decrease to -70 kilopascals prior to irrigation for one cycle only during the leafing, bulbing, and sizing growth stages. Only one stage was stressed during the season in any one of the stress treatments. The -70 kPa level was chosen in part because this is approximately the upper limit to tensiometer function at this elevation. Secondly, this level

Figure 1. Schematic representation of the drought response at different growth stages experiment. Drought stress was applied during the leafing (A), bulbing (B), and sizing (C), stages of growth. No stress was applied to the control (D). These three stress treatments and the control were randomly assigned within each of the eight replicates and constituted the main effect of the split plot design. Weekly whole plant samples were taken from randomly assigned positions within each of the treatment plots. One treatment plot is expanded to illustrate this. Sampling date was the secondary effect of the split plot design.


Replicates
Treatments
Sampling Sequence
1 C B D A
2 D C B A
3 D B A C
4 C D B A
5 B A D C
6 A C B D
7 D A C B
8 B C A D
13
2 7
15
14 6
8
11 4
12
10 16
3
19 17
18
5 1
9

of soil matric potential is significantly lower than the normal commercial threshold matric potential (-40 kPa). The same threshold level of soil matric potential (-40 kPa) was used for these three treatments as for the control during the time when they were not subjected to the imposed drought stress. The four treatments were randomized within each of eight replicated blocks in a field. Each individual treatment main plot consisted of three beds 15.24 m long. Adjacent treatments were separated by one bed in order to limit the influence of lateral water movement. The replication blocks were laid out to minimize bias due to differential wetting which occurs between the head and tail ends of the irrigation set. The timing of the stress treatments was chosen on the basis of the observable developmental plant characteristic which correspond to the growth stages identified in the first study.

Weekly whole plant sampling constituted the sub plot of the split plot design, time being the second of the two independent variables. The samples were taken from randomized 61 cm long sections of an onion row within each replicated treatment plot.

Effect of Imposed Osmotic Stress in the Root Medium on Growth - Greenhouse

This experiment was conducted to evaluate the effect that an imposed plant water stress has on the relative growth of onion leaves and roots. The hypothesis to be tested was that there is a level of drought stress which favors root development over leaf development in onions. The experiment was conducted in a research greenhouse on the CSU campus.

Onions were planted 28 December 1980 and germinated under mist in a flat containing vermiculite and were grown to the two leaf stage (82 days). Onion seedlings were then transferred to aerated containers supplied with half-strength Hoagland's nutrient solution (10). The 7 seedlings transferred to each container were selected for uniformity. The osmotic stress treatments were initiated 14 days after transplanting.

The imposed treatments consisted of 6 levels of osmotic stress in the hydroponic medium: -40, -61, -101, -147, -274, and -622 kilopascals osmotic potential (40). Polyethylene glycol 3500 (PEG 3500) was mixed with Hoagland's solution number 2 (10) and distilled water to achieve these osmotic levels including the contribution of the half-strength Hoagland solution. Plants were transferred directly from the nutrient solution to the respective stress treatment. Eight replications were used in a completely random design.

One plant from each container was sampled just prior to transfer. Root, bulb, and leaf oven dry weights were obtained as a baseline for the experimental treatments. Three of the 6 remaining seedlings were sampled after 2 weeks of treatment and the same parameters measured. After 5 weeks of treatment the remaining 3 plants were removed and dry weights were obtained for statistical analysis.

RESULTS

Onion Growth, SMP, and EPA Investigations - Greeley

The growth curves for onions grown in the furrow irrigated sandy clay loam soil of the Northern Colorado production area are illustrated in Figures 2 and 3. Four distinct growth stages, identified by Roman numerals, are termed stand establishment, leafing, bulbing, and sizing. The four stages of growth were determined by a combination of functional growth analysis (inflection point mathematically determined) and visual approximation of two more critical points in the fitted growth curves.

Three equations were developed using the least squares regression method for SMP as a function of ED as indicated by atmometer water depletion. The data used to develop these equations were chosen from the SMP and ED measurements taken during the latter 3 stages of growth, identified in the onion growth investigations. Figure 4 shows 2 scatter plots, regression curves, and confidence bands representing a 5% probability of error. Confidence bands at this level indicate that 95 times out of 100, the regression line will fall within the area bounded by the bands. Data from the sizing growth stage (IV) are not shown since it was not statisically different from the

Figure 2. Leaf area growth curve. The curve is developed from data pooled over 1980 and 1981. Four growth stages are identified with approximate dates and leaf numbers given to demark them.

ESTABLISHING GROWTH STAGES

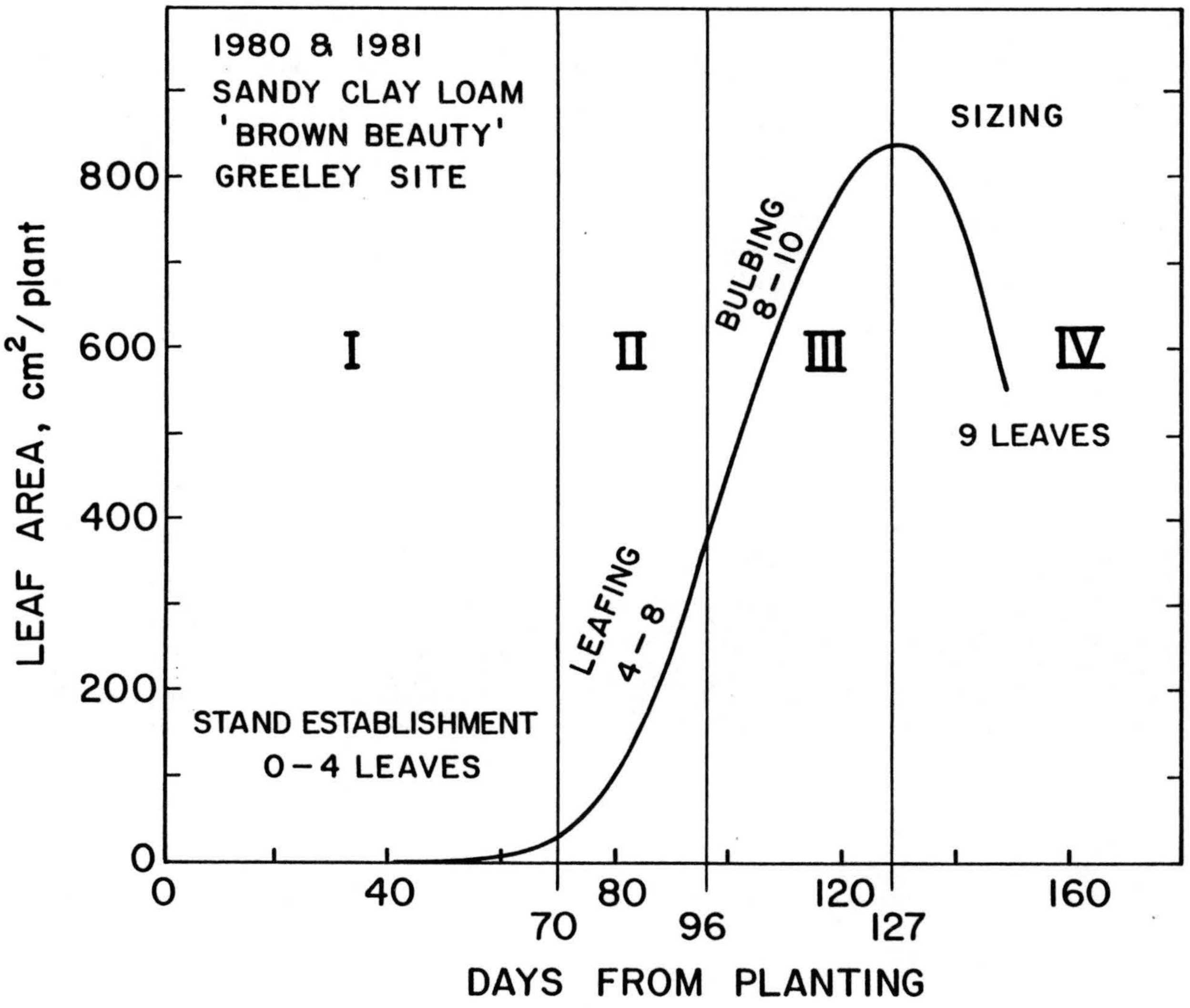


Figure 3. Bulb dry weight growth curve.

ESTABLISHING GROWTH STAGES

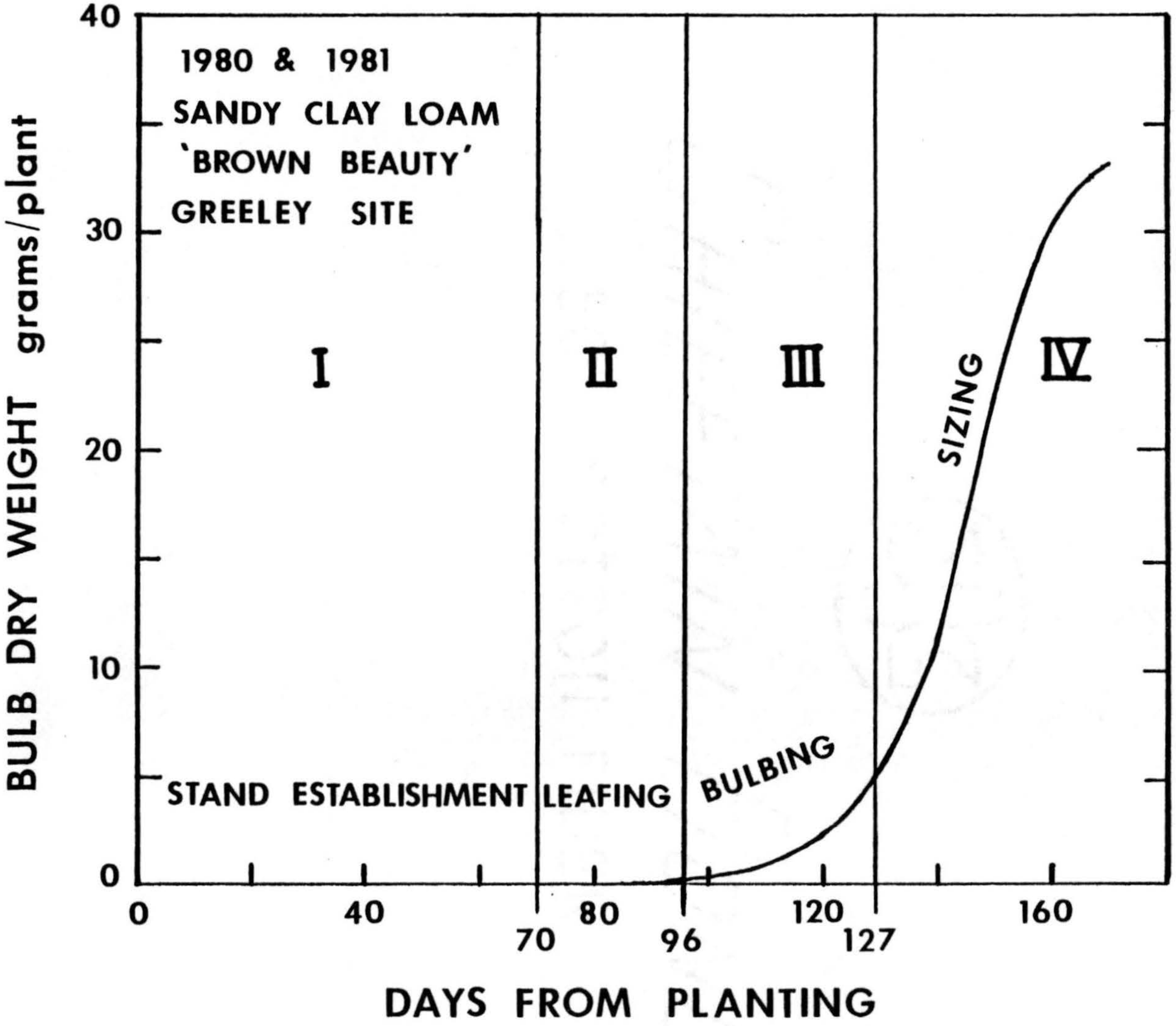
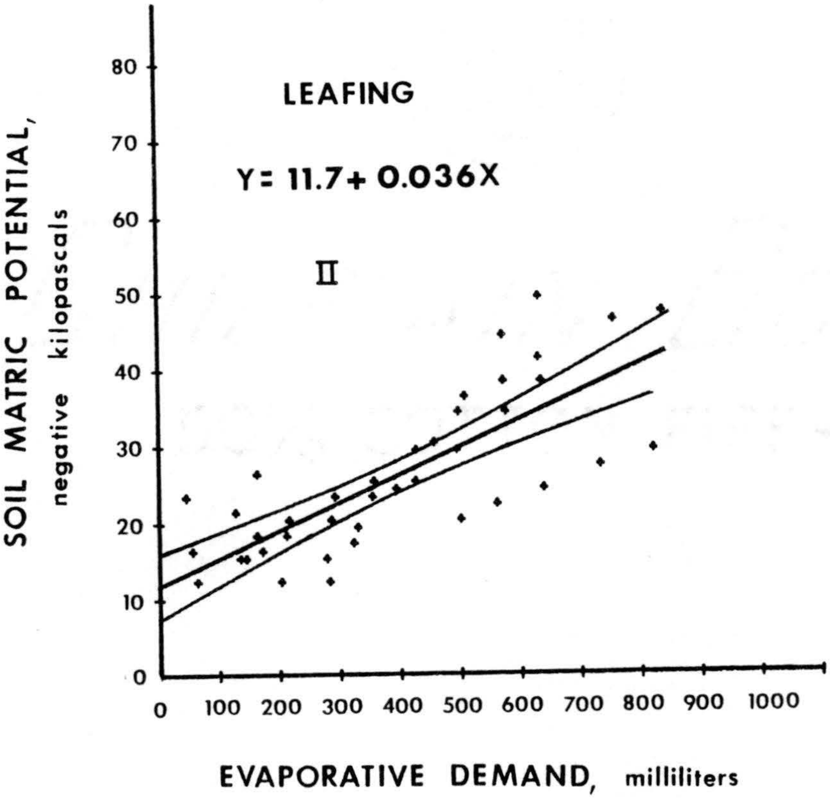
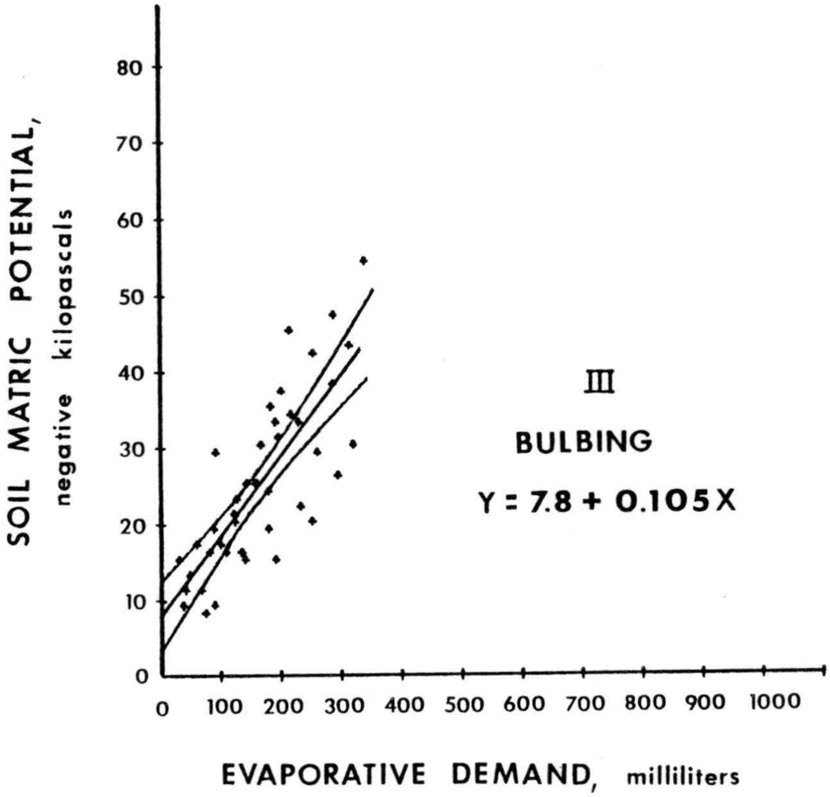


Figure 4. Linear regression of soil matric potential on evaporative power of the air for two of the four onion growth stages. Data were pooled from the two growing seasons and are plotted along with the regression lines and 95% confidence bands. The data points represent daily values of SMP and Cumulative Bellani Plate evaporation from the last irrigation.


LEAFING
Y= 11.7+ 0.036X
II
SOIL MATRIC POTENTIAL, negative kilopascals
0
10
20
30
40
50
60
70
80
0
100
200
300
400
500
600
700
800
900
1000
EVAPORATIVE DEMAND, milliliters


III
BULBING
Y = 7.8 + 0.105X
SOIL MATRIC POTENTIAL, negative kilopascals
0
10
20
30
40
50
60
70
80
0
100
200
300
400
500
600
700
800
900
1000
EVAPORATIVE DEMAND, milliliters

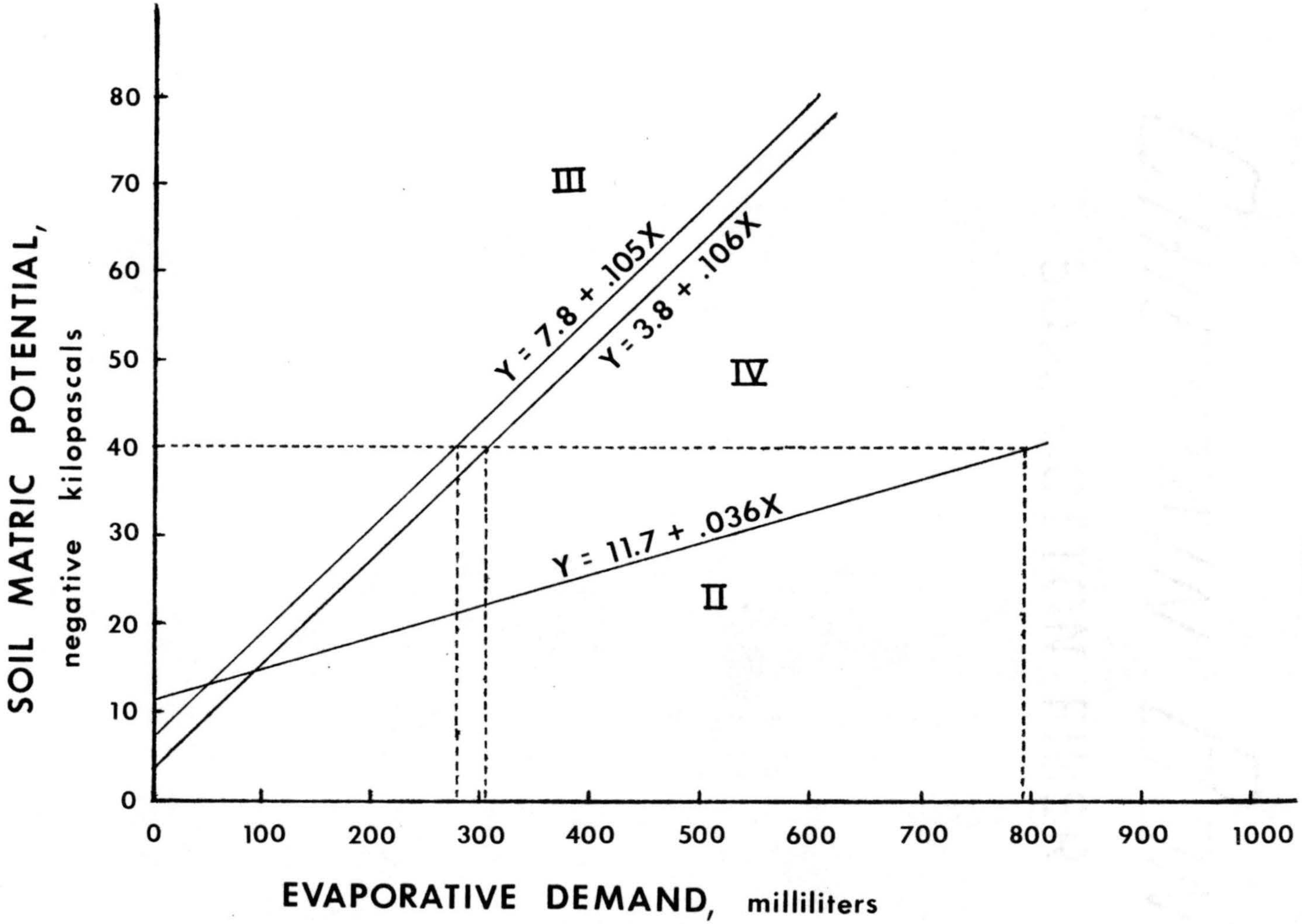
bulbing growth stage (III). Forcing the intercept through the origin was not deemed appropriate considering the property of soils to drain to an equilibrium state (field capacity) which has a lower matric potential than when fully saturated under conditions where no evaporation can occur.

Insufficient data was gathered to make reliable conclusions regarding the relationship between ED and SMP during the stand establishment stage (in this case 0 - 69 days) of onion growth. The data from both years consisted of only five data cases (observations). Regression analysis of this data produced a linear curve with practically zero slope and an intercept of over 12 kPa for SMP as a function of ED (data not shown).

The atmometer cumulative loss values, which would be used for scheduling irrigation, can be calculated with the appropriate growth stage equations which convert ml to kPa. Therefore, it was found that irrigation should occur after 789 ml of water had been lost from the atmometers during the second growth phase if a soil matric tension of less than or approximately equal to 40 centibars is to be maintained. Water loss of 336 ml and 342 ml of water should occur before irrigation takes place during growth stages III and IV respectively for the -40 kPa level of SMP in a sandy clay loam (Figure 5).

Figure 5 illustrates the three regression lines for phases II, III, and IV and corresponding equations used

Figure 5. Linear regression of soil matric potential as a function of evaporative demand for the latter three growth stages. The horizontal dashed line represents a chosen upper limit of matric tension. Bellani plate atmometer depletion levels to be indices for irrigation for each of the three latter growth stages are indicated by vertical dashed lines.


SOIL MATRIC POTENTIAL, negative kilopascals
EVAPORATIVE DEMAND, milliliters
0
10
20
30
40
50
60
70
80
0
100
200
300
400
500
600
700
800
900
1000
III
IV
II
Y = 7.8 + .105X
Y = 3.8 + .106X
Y = 11.7 + .036X

for the sandy clay loam soil. Also indicated on the X axis, are the atmometer cumulative water loss levels (ED constants at which irrigation should take place for each of the three growth periods). It is readily apparent that the regression equations and ED constants for growth stages III and IV are not significantly different. Therefore one regression equation can be used to describe the relationship for SMP as a function of ED for both phase III and IV (figure 6).

Table 1. Intercept, slope, R^2, and F values for the regression equations of SMP as a function of EPA for growth stages II, leafing; III, bulbing; and IV, sizing.

Growth stage	A	B	R^2	F
II	11.7	.036	.5007	56.77
III	7.8	.105	.6277	69.13
IV	3.8	.106	.8103	106.81

The advantage of the Bellani plate atmometers in determining crop water use when compared to instruments which measure soil matric potential (SMP) is due in large part to the consistency of readings between separate instruments. Figure 7 illustrates this point by relating the daily coefficients of variability between each set of

Figure 6. Growth stages III and IV have been combined for purposes of determining timing of irrigation based on Bellani plate depletion.

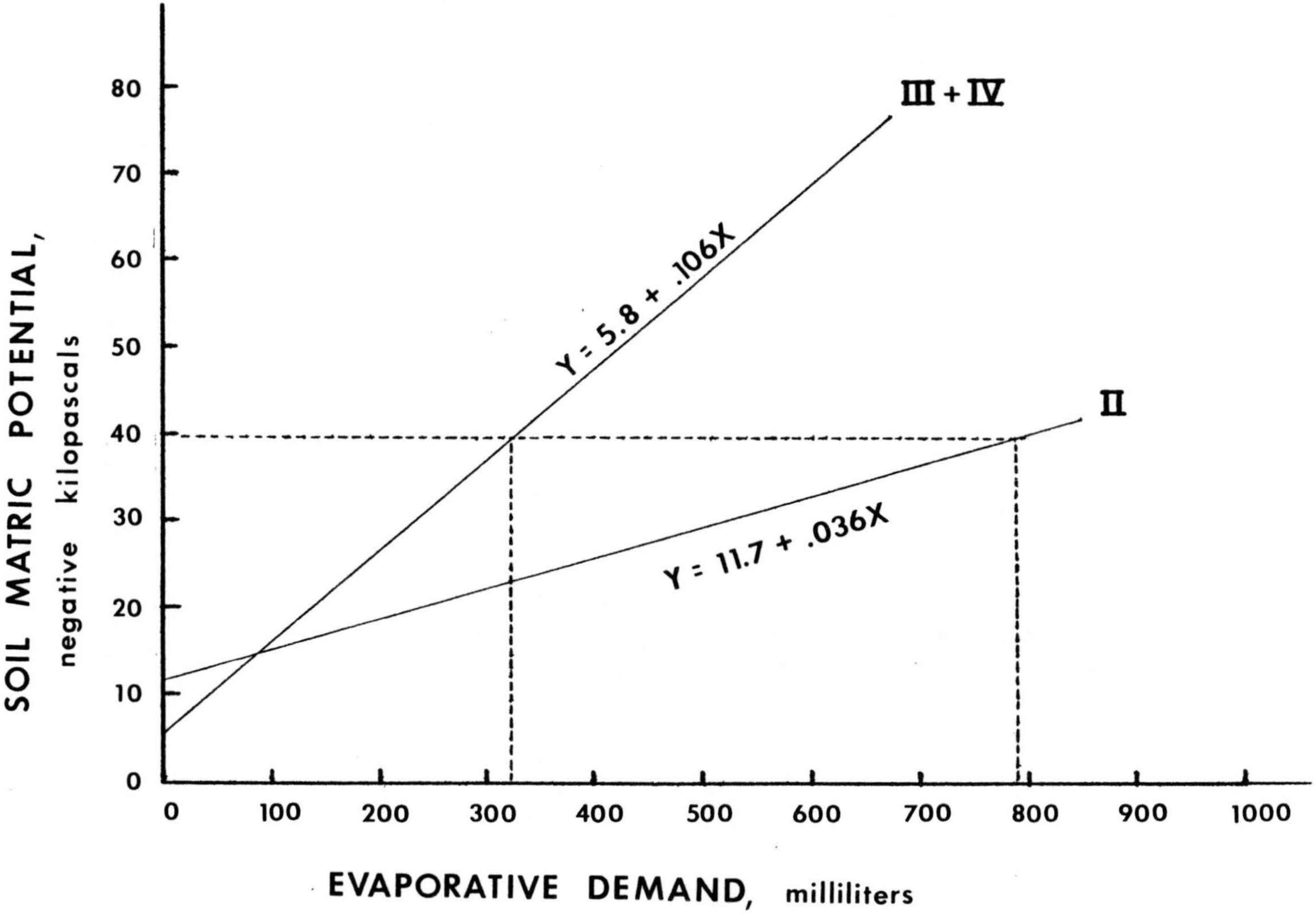
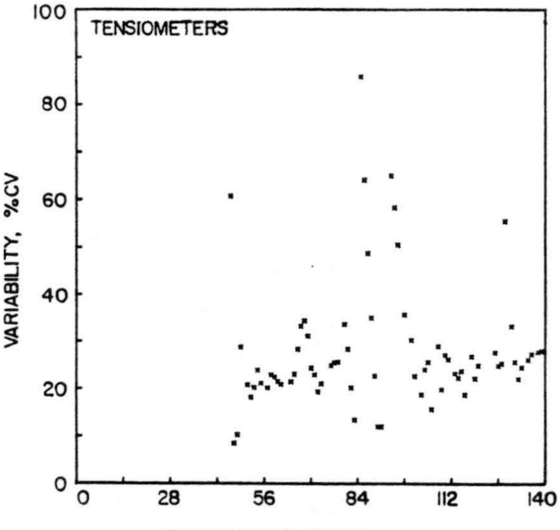
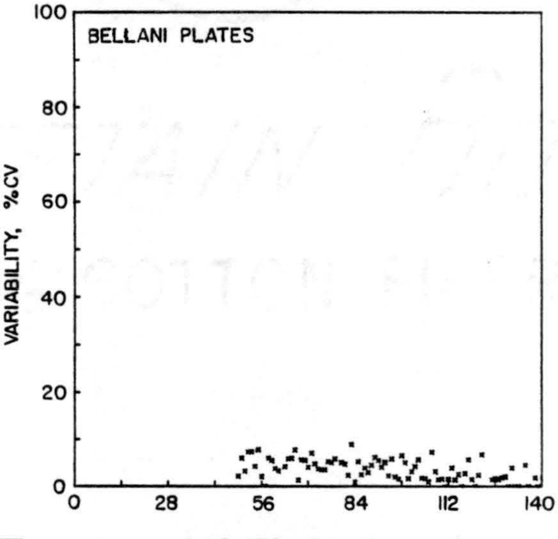
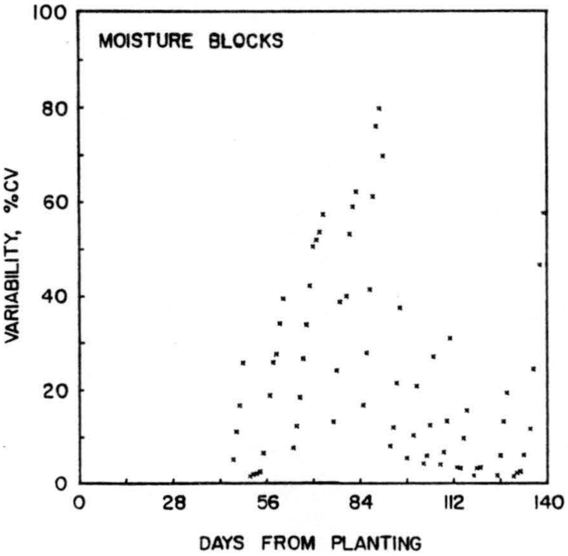

SOIL MATRIC POTENTIAL, negative kilopascals
80
70
60
50
40
30
20
10
0
III + IV
Y = 5.8 + .106X
II
Y = 11.7 + .036X
0
100
200
300
400
500
600
700
800
900
1000
EVAPORATIVE DEMAND, milliliters

Figure 7. Coefficients of variability for three instruments from the 1980 season. High variability is seen between the ten pairs of tensiometers and four pairs of resistance blocks. Low variability is evident between the two Bellani plates.


TENSIOMETERS
VARIABILITY, %CV
0
20
40
60
80
100
0
28
56
84
112
140
DAYS FROM PLANTING


BELLANI PLATES
VARIABILITY, %CV
0
20
40
60
80
100
0
28
56
84
112
140
DAYS FROM PLANTING


MOISTURE BLOCKS
VARIABILITY, %CV
0
20
40
60
80
100
0
28
56
84
112
140
DAYS FROM PLANTING

instruments from the 1980 study; 10 tensiometers, 4 resistance blocks and 2 Bellani plate atmometers. The coefficient of variability is defined as the sample standard deviation expressed as a percentage of the sample mean; the lower the value the less variable the mean. The 2 Bellani plates provided daily readings which resulted in a much lower mean coefficient of variability.

Drought Response at Different Growth Stages - Fort Collins

Table 2 compares the actual timing of the imposed drought stress and the maximum tension attained in that period between the treatments. The three stress treatments fall within the leafing, bulbing, and sizing growth stages identified in the Greeley growth study.

Table 2. Drought response at different growth stages. Stress treatments achieved. Treatment A: stress applied during leafing, B: stress applied during bulbing, C: stress applied during sizing, D: non-stressed control.

Treatment	Growth stage		Duration	Maximum tension achieved (cb)
A	II	leafing	17 June - 1 July	71
B	III	bulbing	18 July - 23 July	73
C	IV	sizing	5 Aug - 14 Aug	73
D	1	control 1	16 April - 11 Sept 1	56

The results of this investigation are summarized in Table 3. No significant differences were observed between the treatment effects (irrigation at -70 kPa instead of -40 kPa) combined by sampling dates on onion growth. There were large differences for all growth parameters between sampling dates. This expected outcome simply illustrates onion growth with time. Most important to this investigation was that there were no significant differences between the interaction of treatments by dates for any of the measured growth parameters. This result indicates that no significant differences were observed in the patterns of growth as a result of the three stress treatments. These results were obtained in spite of the observation that during at least one of the stress treatments (A or Leafing) there was a marked darkening of the leaves, often an early indication of water deficit.

Table 3. Drought response at different growth stages expressed as mean squares. Only mean square values significant at the 5% level are shown.

Source	Leaf area cm^2	Dry matter (g)		
		Total	Leaves	Bulbs
Stress dates	N.S.	N.S.	N.S.	N.S.
Replicates	N.S.	3.24	N.S.	N.S.
Sampling dates	159	114	312	293
Interaction	N.S.	N.S.	N.S.	N.S.

Effect of Imposed Osmotic Stress in the Root Medium on Growth - Greenhouse

Analysis of variance (ADV) tests indicated that there were significant differences among the treatment means for each of the measured plant parameters for both the three week sample and the final sample except for the root:shoot ratio in the final sample. Tukey's "honest significant difference" (HSD) and cluster analysis (6) tests for mean separation were applied for each of the significant ADV tests (Tables 4 and 5).

Table 4. Effect of Imposed Osmotic Stress in the Root Medium on Growth. Results expressed as means; significant separation at the 5% level are indicated.

Three week sample results

	Osmotic	Treatment means (g)														
Treat Number	stress (Bars)	Leaf	z	y	Bulb	z	y	Root	z	y	Total Plant	z	y	Root:Shoot Ratio	z	y
1	-.40	.299	a	a	.098	a	a	.101	a	a	.497	a	a	.250	b	a
2	-.61	.250	a	a	.079	a	a	.090	ab	a	.418	a	a	.276	b	a
3	-1.01	.282	a	a	.100	a	a	.095	a	a	.478	a	a	.245	b	a
4	-1.47	.254	a	a	.089	a	a	.088	ab	a	.429	a	a	.259	b	a
5	-2.74	.114	b	a	.064	ab	a	.051	bc	a	.229	b	a	.295	b	a
6	-6.22	.028	b	a	.036	b	a	.028	c	a	.092	b	a	.437	a	a
EMS		.018			.024			.007			.112			.010		

z Mean separation by Tukey's (hsd) test, 5% level

y Mean separation by Cluster analysis, 5% level

Table 5. Effect of Imposed Osmotic Stress in the Root Medium on Growth. Results expressed as means; significant separation at the 5% level are indicated.

Final (five week) week sample results

	Osmotic	Treatment means (g)														
Treat Number	stress (Bars)	Leaf	z	y	Bulb	z	y	Root	z	y	Total Plant	z	y	Root:Shoot Ratio	z	y
1	-.40	.610	a	a	.908	a	a	.526	a	a	2.05	a	a	.346	a	a
2	-.61	.536	ab	a	.775	ab	a	.399	b	a	1.71	ab	a	.312	a	a
3	-1.01	.553	ab	a	.730	ab	a	.319	b	a	1.60	ab	a	.258	a	a
4	-1.47	.410	b	a	.561	b	a	.279	b	a	1.25	b	a	.283	a	a
5	-2.74	.148	c	b	.212	c	b	.122	c	b	.482	c	b	.351	a	a
6	-6.22	.012	c	b	.077	c	b	.030	c	b	.115	c	b	.396	a	a

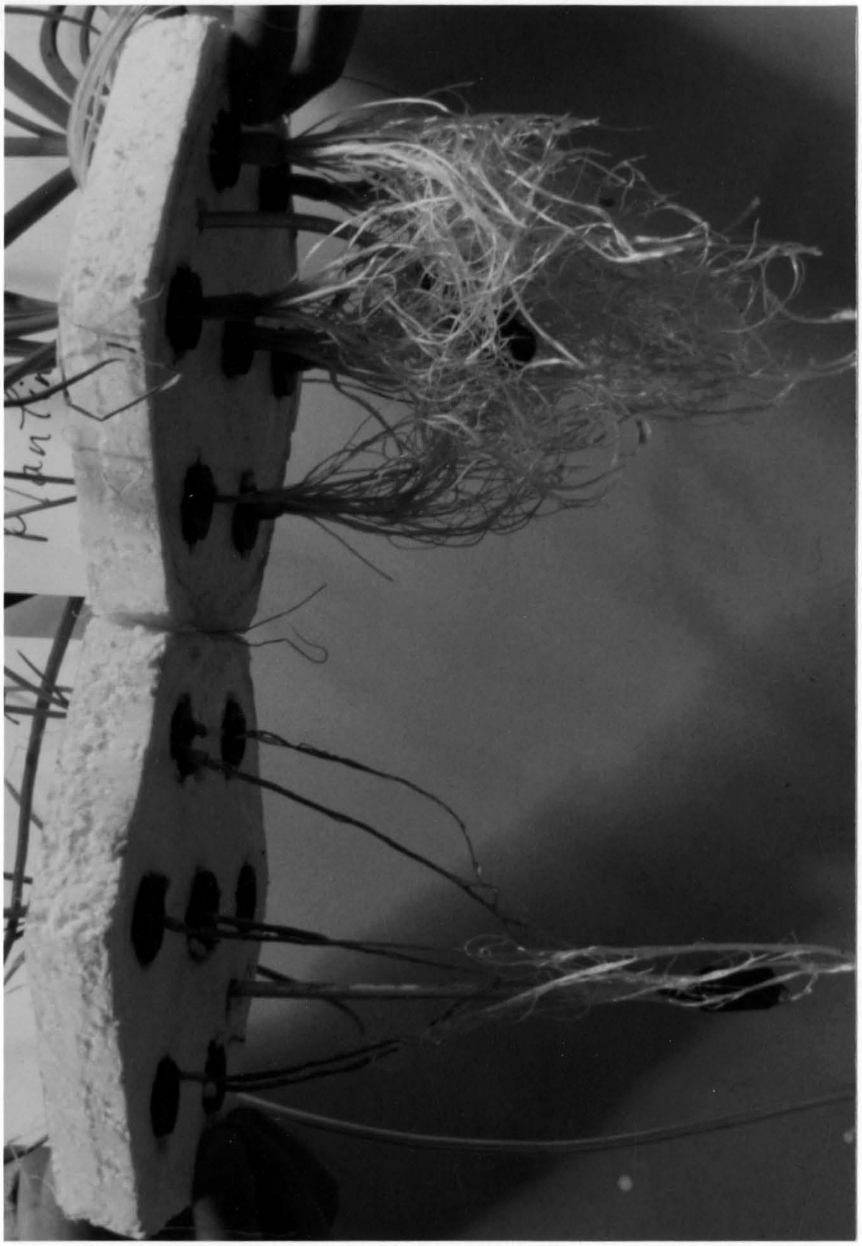
z Mean separation by Tukey's (hsd) test, 5% level

y Mean separation by Cluster analysis, 5% level

The data from this experiment demonstrate that osmotic potentials of -275 kilopascals and lower inhibit onion leaf, bulb, and root growth. Furthermore, the -101 kPa treatment resulted in lower leaf, bulb and total plant dry weights than the control treatment (-40 kPa). The data provide evidence that there is a general trend of growth suppression as osmotic stress increases from -0.4 to -1.5 bars. Figure 8 presents root growth differences between -0.4 and -2.47 bars after two weeks of treatment.

Especially important to this investigation, is evidence that the root:shoot ratio increases at very low osmotic potential. This is evident in the data for the 3 week sample for the -622 treatment (not shown). The ratio for this treatment mean is significantly larger than for any of the other treatment mean root:shoot ratios. It should be noted, however, that the 5 week sampling data is not consistent with this.

Figure 8. A comparison of root growth between two levels of osmotic stress in the root medium; left: following 3 weeks of high stress, right: following 3 weeks of low stress.


Plantin

DISCUSSION

The growth stages in this discussion will be referred to as: stand establishment (0 - 69 days); leafing (70 - 96 days); bulbing (97 - 127 days); and sizing (128 days to undercutting).

Onion Growth, SMP, and EPA Investigations - Greeley

Stage one, or stand establishment, was chosen from the functional growth analysis "lag" period of the leaf area curve. This stage can be observed in the field as the period of relatively slow growth and the period during which the majority of the onion plants have fewer than four green, functional leaves. This growth stage could be further partitioned into a "seedling establishment" portion and a "root establishment" portion. Seedling establishment is the period when there is essentially a bare soil surface and seedlings are emerging. This period may last up to 21 days from planting depending primarily upon temperature. Frequently, late winter and early spring precipitation provides the only water for this stage. The root establishment portion follows emergence and lasts up to the 4 leaf stage, the end of the stand establishment stage. During this period commercial growers often tend to allow initial drought symptons to occur in the onion population prior to irrigating, with the idea that this encourages root growth. The plants are small, thus transpiration is trivial compared to evaporation from the soil surface during the entire first 69 days of the growing season.

Insufficient data was collected from the stand establishment growth stage to adequately determine the relationship between soil matric potential and atmometer water loss for a variety of reasons. The primary difficulty is the adverse effects that freezing temperatures have on the atmometers and tensiometers. Sub-freezing temperatures are likely throughout most of this time in northern Colorado. Fortunately, irrigation scheduling is less critical during this growth stage due to fewer water competitive crops and usually abundant precipitation. Also, onion seed may be protected against desiccation by fairly deep planting.

Stage two, or leafing, begins with the initiation of rapid leaf growth in the "log" stage of growth. Leaf number during stage two progressed rapidly from 4 to 8 leaves on most of the onions. Equation II from Figure 5 represents SMP as a function of ED during this growth stage. Leaf area during this stage expands rapidly and surpasses soil surface area late in the stage. Thus, transpiration becomes a significant factor in soil water depletion. The mathematically determined "inflection" point of the leaf area curve was used to separate stage two from the third growth stage. The rate of increase of leaf area is zero at this point.

The inflection point on the leaf area curve was also found to be at or near the initiation of rapid bulb growth. In other words, this point of onion development signals the beginning of the log stage of bulb growth. The end of the third growth stage, bulbing, and beginning of the fourth stage, sizing, occurs when the leaf area becomes maximum. This point in onion development occurred about 127 days from planting. Preceding this event, the number of readily visible and viable green leaves reached, a maximum of about 10. By the time maximum leaf area is reached, net decline in leaf number is well under way due to senescence and the cessation of new leaf formation. Bulb growth at this time is rapid and approximately 50% of the final bulb diameter has been reached. Equation III from Figure 5 applies to the bulbing stage of growth. During this stage, leaf area reaches its maximum and crop transpiration is subsequently at its maximum as well. Although leaf area may exceed ground area by as much as a factor of 3, direct sunlight still reaches the soil surface. Transpiration is probably the major factor in soil moisture depletion.

The final stage of onion development is characterized by bulb sizing and collapse of the onion leaf bundle. Harvest is usually initiated sometime after 75% of the leaf bundles are no longer erect, up to 160 days from planting. Soil matric tension is related to cumulative atmometer water loss by Equation IV from Figure 5 for this final growth stage. Although leaf area is declining due to senescence of old leaves, transpiration rate is still high. Photosynthates are rapidly transported from the leaves to the expanding bulb. The maturing onion crop has a gradually declining rate of water consumption following the active bulbing phase.

The two equations shown in Figure 6 are for the sandy loam soil. The right angle lines indicate the chosen soil matric tension and the corresponding atmometer water depletion when irrigation should occur for each of the three last growth stages. It is important to note that crop water demand during the bulbing and sizing growth stages are statistically indistinguishable, based upon the evaporative power of the air. The grower should treat both stages identically for irrigation purposes, until harvest is approached.

Crop coefficients used in agronomic irrigation scheduling models account for various stages of growth as well as for adapting the model to other species. The linear equations used for the different growth stages take the place of the crop coefficients used in other models. Adaptation of these equations to other soil types can be approximated by comparing their respective desorption properties and moisture holding capacities as performed by McSay and Moore (26).

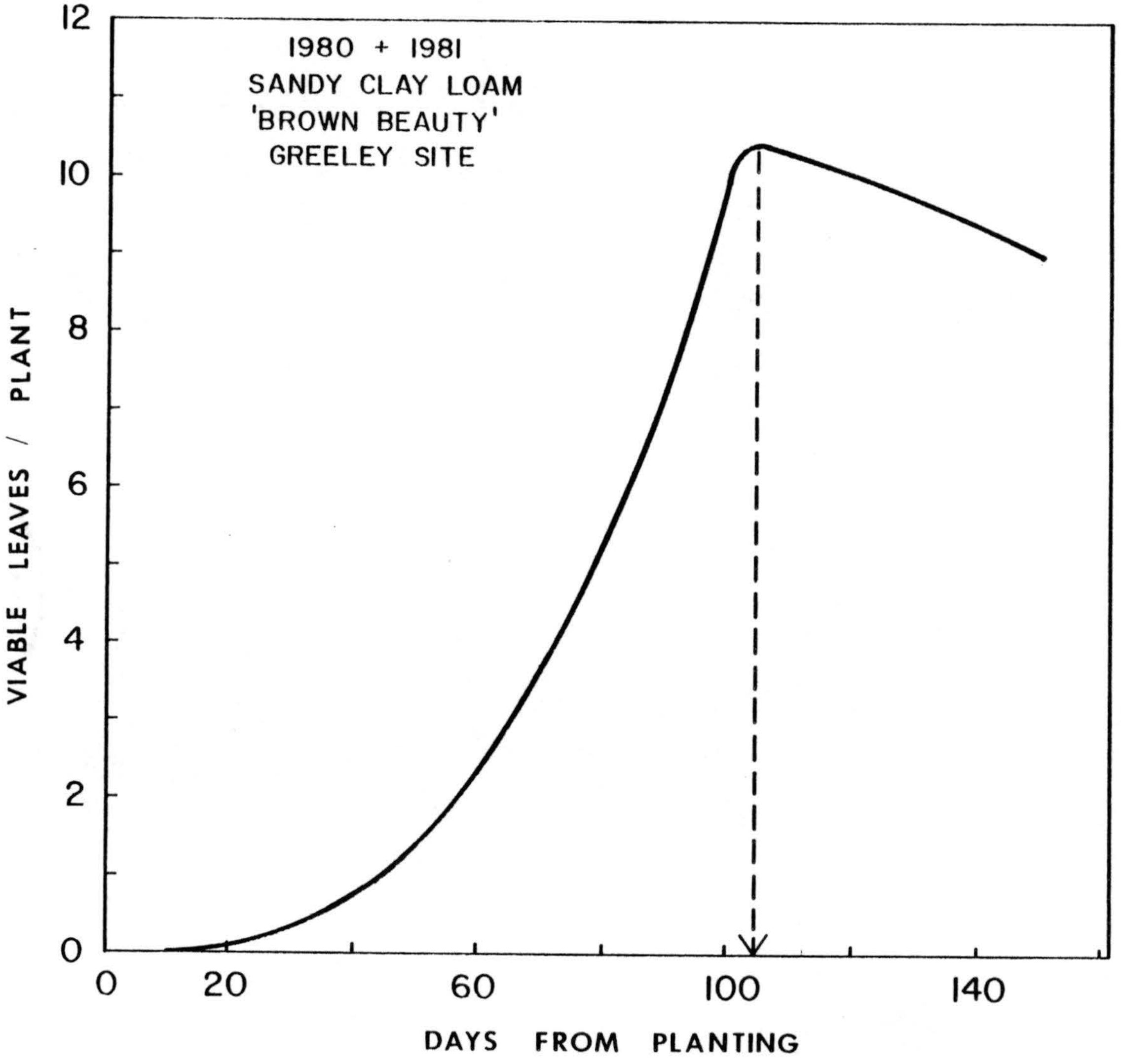
The use of the Bellani plate atmometers in this study to develop the relationship between EPA and SMP for onions provides a basis for using any instrument which measures evaporative demand (EPA) to predict soil moisture depletion by an onion crop. This study (Figure 7) and others (13,16,19,22,25,34) have demonstrated that the Bellani plate is more reliable and can be placed to be much more accessible than instruments which measure soil water content or soil matric potential.

The onion growth patterns for the two consecutive years were related on the basis of leaf number (Figure 9). Different planting dates, spring climatic conditions, and planting densities prevented the use of days from planting to make direct comparisons between the two years. Comparing the actual timing of growth events between the two years by using leaf number as a relative basis gave the best results. This method should be adopted in onion irrigation scheduling for the purpose of determining stage of growth in place of heat unit or chronological time keeping.

Drought Response at Different Growth Stages - Fort Collins

This experiment failed to demonstrate statistically significant differences between any of the stress treatments and the non-stressed control in either final yield of onion bulbs or in the growth patterns of the bulbs and

Figure 9. Mean leaf number per plant as a function of days from planting. Data from the 1980 and 1981 seasons were combined by the averaging of the two dates where the maximum leaf number occurred for both years. Days from planting was adjusted accordingly and should not be relied upon to predict when the maximum leaf number should occur.


1980 + 1981
SANDY CLAY LOAM
'BROWN BEAUTY'
GREELEY SITE
VIABLE LEAVES / PLANT
0
2
4
6
8
10
12
0
20
60
100
140
DAYS FROM PLANTING

leaves. No change in onion growth could be demonstrated as a result of drought stress as imposed in this experiment during any of the three latter growth stages.

I feel that these results were largely the result of inadequate control of the experimental variables. Primarily, plant density within the sample plots was too variable as a result of imprecise planting equipment and uneven germination. Secondly, inexperience with weed control measures on my part resulted in a moderate amount of competitive pressure on all treatments. Although both of these complications were distributed randomly within each replicated block, the net effect is to increase overall variability in the stand. This increased variability effectively masks any real treatment effects on onion plant growth. The weather in 1981 also played an important part in limiting the manipulation of irrigation to impose stress treatments. Both the timing and duration of the latter two stress applications were influenced by rainfall. Neither treatment received as severe a stress as did the stress treatment which was applied during the second or leafing growth stage.

On the basis of other research (2,3,5,11,18,20,21, 32,33) I believe that there would normally be some significant differences between onions stressed by withholding water to the -70 kPa level during one or more of the three latter stages of onion growth and a non-stressed control. However, the results of this experiment indicate a possibility of a stress level (-70 kPa) where the effects on plant growth are modest. This study did not identify a particularly critical period where final bulb yield was most affected by drought stress. I feel that future research should address this issue.

Effect of Imposed Osmotic stress in the Root medium on Growth - Greenhouse

This experiment demonstrated that during the seedling and early leafing growth stage any level of water deprivation inhibits onion growth. Although only the most severe stress levels could be statistically shown to result in reduced plant growth, mean weights of all plant tissues were progressively lower for the more stressed treatments. These results compare favorably with previous research on onion response to osmotic stress and field drought stress experiments (2,3,4,8,15,16,19,21,26). Onions appear to adapt poorly to moderate to high levels of internal water deficits.

The only instance where the root:shoot ratio of a treatment was shown to be significantly different than the control was in the three week sampling of the most severely stressed treatment. This sample's ratio was shown to be higher than all other treatments and the control, indicating that root dry weight relative to shoot dry weight was significantly higher than normally expected. It should be noted, however, that during this period all plant parts showed weight reduction in this treatment. In my estimation the most that one can conclude concerning this phenomenon is that roots may be less susceptible to severe drought stress than are bulbs and leaves. There was no trend evident in the other treatments to suggest that stress can be used to increase the root to shoot ratio. However, observations were not made on onion growth following the imposed osmotic stress in a half-strength Hoagland solution.

This research does not fully rule out the hypothesis that some level of osmotic stress may stimulate onion root growth. It is also possible that onion roots respond differently in soil than in PEG under a moderate drought stress because of the differences in water conductivity properties of the two media. Until these two questions are satisfactorily answered, recommendations to the onion grower should not include stressing onions at the stand establishment or leafing growth stages.

SUMMARY

It was shown that four distinct stages of onion growth can be determined using growth analysis techniques: I, 0 - 4 leaves, 0 - 69 days, stand establishment; II, 4 - 8 leaves, 70 - 96 days, leafing; III, 8 - 11 leaves, 97 - 127 days, bulbing; IV, 9 leaves or less, 128 days to harvest, sizing. The effect of different planting dates on crop development timing is significant enough to preclude using days from planting as an indicator for the onion growth stages. Counting leaves per plant is a fairly accurate and simple method of identifying onion growth stages and is preferable to using planting date.

Close linear relationships were shown to exist between soil matric potential (SMP) and evaporative demand (ED) for the last three onion growth stages; leafing, bulbing, and sizing. Bellani plate atmometers were used to measure ED and tensiometers were used to monitor SMP. From the linear relationships developed one can derive crop coefficients for these three growth stages to use in an irrigation scheduling model based on Bellani plate ED as a predictor of soil water depletion.

The investigations I made involving onion response to drought stress during different growth stages failed to provide significant growth or yield differences.

Further research regarding quantitative crop response to drought stress of differing intensities and during different stages of growth should be continued in order that an economic approach to water application can be implemented.

The greenhouse osmotic stress experiment demonstrated that any level of water deprivation reduces plant growth to some degree but the effect becomes most significant at higher levels of stress, the threshold being somewhere between -1.5 bars and -2.75 bars osmotic potential of the root medium. These tensions can occur in the soil immediately surrounding the individual roots when the rate of transpiration exceeds soil water flow rates even when overall soil moisture levels are moderate to high. The results of this experiment also fail to provide conclusive evidence that forcing plants to undergo moderate drought stress will cause an increase in root expansion relative to leaf and stem growth. Based on these results, maximum yield and economic yield strategies for storage onions should not include this procedure.

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APPENDICES

APPENDIX A

Onion Growth, SMP, and EPA Investigations - Greeley

Julian date	Days from planting	Number of samples (610 cm^2)	Total plants sampled	Leaves/ plant	std dev	L.A./ plant cm^2	std dev	Leaf weight/ plant gm	std dev	Bulb weight/ plant gm	std dev
148-80	42	17	61	-	-	2.6	-	0.01	-	0.01	-
154-80	48	16	53	-	-	5.6	-	0.03	-	0.01	-
161-80	55	12	38	-	-	18.6	-	0.09	-	0.04	-
168-80	62	12	37	4.6	0.72	58.0	-	0.32	-	0.11	-
175-80	69	12	36	5.0	1.06	112.6	-	0.67	-	0.23	-
182-80	76	12	36	6.9	1.30	266.6	-	1.70	-	0.50	-
189-80	83	10	35	7.7	2.39	383.0	-	2.78	-	0.72	-
196-80	90	10	31	9.8	1.78	453.0	-	3.65	-	3.13	-
203-80	97	10	28	9.6	2.25	557.0	-	3.78	-	4.28	-
210-80	104	10	35	10.8	1.97	684.0	-	4.88	-	11.10	-
217-80	111	10	30	10.3	2.56	843.6	-	5.18	-	13.88	-
224-80	118	7.14	25	10.7	3.11	551.6	-	4.63	-	21.25	-
231-80	125	6.90	20	10.5	2.19	619.8	-	4.40	-	24.77	-
238-80	132	6.67	20	10.3	3.49	626.6	-	3.88	-	34.15	-
245-80	139	6.06	20	8.9	2.82	483.2	-	4.32	-	41.15	-
142-81	73	16	80	2.4	0.28	8.0	2.2	0.04	0.01	0.03	0.01
152-81	83	16	75	3.4	0.35	26.8	8.6	0.11	0.04	0.05	0.01
159-81	90	16	96	4.6	0.27	83.4	20.8	0.44	0.12	0.14	0.03
166-81	97	18	99	5.0	0.47	119.4	40.6	0.68	0.24	0.34	0.11
173-81	104	16	76	5.7	1.20	224.8	51.0	1.22	0.31	0.71	0.22
180-81	111	16	69	7.3	0.52	421.0	83.6	2.16	0.46	1.14	0.27
187-81	118	16	73	8.1	0.64	639.4	109.4	3.32	0.63	3.39	0.80
194-81	125	12	60	9.1	0.58	799.8	108.0	4.31	1.35	5.18	0.77
201-81	132	12	56	10.0	1.04	1120.6	149.6	5.48	1.31	8.91	2.29
210-81	141	12	58	9.2	1.17	841.2	152.8	4.30	0.81	13.16	1.91
215-81	146	12	58	8.7	0.83	842.4	143.4	3.70	0.74	17.85	3.63
224-81	155	12	59	8.4	1.10	765.8	202.8	4.10	1.32	19.80	4.63

Onion Growth, SMP, and EPA Investigations - Greeley

Julian date	Days from planting	Total plants sampled	Bulb diam cm	std dev	Bulb length cm	std dev	Leaf length cm	std dev	Sheath length cm	std dev	leaves/ plant	std dev
148-80	42	61	0.2348	0.261	2.1443	0.548	-	-	-	-	-	-
154-80	48	53	0.2540	0.089	2.4906	0.544	-	-	-	-	-	-
161-80	55	38	0.4694	0.132	2.6158	0.425	-	-	-	-	-	-
168-80	62	37	0.6969	0.176	2.9108	0.624	15.573	3.49	4.2324	1.67	4.6486	0.716
175-80	69	36	0.9364	0.485	2.8750	0.552	17.614	6.43	4.2952	0.873	5.0000	1.06
182-80	76	36	1.5724	0.532	3.0278	0.652	23.652	5.37	5.5272	0.900	6.9167	1.30
189-80	83	35	1.8459	0.903	3.3857	0.555	27.139	8.76	6.5829	1.56	7.7429	2.39
196-80	90	31	2.9015	0.967	4.0394	0.554	35.416	6.77	9.8194	1.57	9.8065	1.78
203-80	97	28	3.3748	1.42	4.3607	0.433	37.596	7.36	11.073	1.83	9.6429	2.25
210-80	104	35	5.2432	1.60	4.4171	1.04	42.034	6.56	13.136	1.82	10.839	1.97
217-80	111	30	5.5754	1.80	4.7533	0.638	41.117	5.78	12.835	2.15	10.267	2.56
224-80	118	25	7.0991	1.19	5.7000	0.857	42.496	4.38	14.634	1.58	10.680	3.11
231-80	125	20	7.6131	0.903	6.3500	1.12	40.044	5.94	15.118	2.05	10.450	2.19
238-80	132	20	7.9202	1.32	7.0350	1.09	39.578	5.51	15.382	1.96	10.250	3.49
245-80	139	20	8.0617	1.22	6.9950	0.834	36.704	4.00	15.450	1.91	8.9474	2.82
259-80	153	36	6.7722	1.68								

APPENDIX B

Onion Growth, SMP, and EPA Investigations - Greeley

				Tensiometers				Resistance blocks			
Julian date	Days from planting	Plate EPA ml	Rain cm	10 cm Tension kPa	std dev	20 cm Tension kPa	std dev	10 cm Resistance mhos	std dev	20 cm Resistance mhos	std dev
157-80	51	88	0.00	13	3.75	11	2.46	75	1.54	78	2.83
158-80	52	156	0.00	15	4.38	12	2.05	74	1.00	78	2.38
159-80	53	223	0.00	16	5.43	13	1.99	70	1.26	77	3.00
160-80	54	274	0.00	17	6.28	13	2.00	66	2.22	76	2.99
161-80	55	319	0.00	19	6.36	14	2.35	61	5.00	74	4.51
163-80	57	497	0.36	23	8.12	17	1.51	54	16.7	72	7.27
164-80	58	557	0.00	24	9.30	18	1.69	46	19.9	65	11.4
165-80	59	635	0.00	28	9.97	19	1.35	39	18.1	69	10.4
166-80	60	729	0.00	32	10.6	20	1.18	29	21.1	66	14.4
167-80	61	817	0.00	35	10.5	21	1.62	24	21.4	62	17.4
169-80	63	101	0.00	irrigate							
170-80	64	60	0.00	13	4.88	9	3.32	74	2.58	77	10.5
171-80	65	131	0.00	18	7.74	11	3.35	68	6.70	74	11.2
172-80	66	159	0.00	21	9.80	13	2.20	59	11.3	70	12.9
173-80	67	212	0.28	25	13.8	15	1.80	54	18.1	69	14.8
174-80	68	288	0.00	28	14.8	16	1.73	46	22.4	67	16.1
175-80	69	353	0.00	31	15.3	18	2.13	38	22.9	64	21.1
176-80	70	423	0.00	37	13.2	19	3.80	27	21.9	60	25.8
177-80	71	493	0.00	46	15.0	22	4.90	17	15.0	56	26.0
178-80	72	568	0.00	52	14.8	24	5.45	10	9.42	51	27.2
179-80	73	627	0.00	56	15.6	26	5.00	7	6.00	45	26.7
180-80	74	103	0.00	irrigate							
181-80	75	61	0.00								
182-80	76	52	0.00	19	8.25	12	2.29	66	5.50	73	13.2
183-80	77	124	0.00	26	10.4	15	1.97	52	12.6	67	21.4
184-80	78	160	0.00	32	12.7	18	2.59	40	20.1	64	20.6
185-80	79	28	1.78								
186-80	80	42	0.00	25	11.3	20	6.11	53	24.4	61	20.8
187-80	81	88	0.00	35	12.3	24	8.85	46	30.2	57	25.3
188-80	82	170	0.00	43	9.07	29	10.4	34	23.4	45	26.9
189-80	83	211	0.00	57	9.34	34	11.9	9	3.37	35	27.1
190-80	84	79	0.00	irrigate							

				Tensiometers				Resistance blocks			
Julian date	Days from planting	Plate EPA ml	Rain cm	10 cm Tension kPa	std dev	20 cm Tension kPa	std dev	10 cm Resistance mhos	std dev	20 cm Resistanc mhos	std dev
191-80	85	27	0.00	15	10.7	15	13.9	71	14.2	71	14.2
192-80	86	84	0.00	19	10.0	17	13.4	57	21.9	67	15.0
193-80	87	139	0.00	28	12.0	20	12.4	42	19.4	57	21.4
194-80	88	187	0.00	40	10.7	24	13.0	19	15.2	48	27.3
195-80	89	250	0.00	53	8.33	29	14.2	9	4.40	33	30.5
196-80	90	384	0.00	60	4.68	34	12.1	4	1.50	23	20.6
197-80	91	336	0.00	65	4.66	44	10.7	3	0.96	12	9.29
198-80	92	53	0.00	irrigate							
199-80	93	56	0.00	18	13.9	16	15.7	76	4.32	59	33.7
200-80	94	119	0.00	23	12.3	17	11.5	59	11.3	70	12.9
201-80	95	156	0.00	20	12.5	20	7.96	54	14.7	53	26.4
202-80	96	192	0.36	37	11.0	24	7.56	39	22.8	47	22.9
203-80	97	49	0.00	irrigate							
204-80	98	33	0.00	10	2.79	6	4.14	80	1.26	79	8.77
205-80	99	76	0.00								
206-80	100	118	0.00	26	9.58	16	4.01	62	7.55	69	4.90
207-80	101	163	0.00	38	8.81	23	6.07	42	13.0	61	8.46
208-80	102	51	0.00	irrigate							
209-80	103	38	0.00	12	2.26	9	3.92	79	1.29	79	6.76
210-80	104	78	0.00	19	5.72	13	3.48	71	2.83	76	7.14
211-80	105	123	0.00	28	8.46	19	8.66	55	8.29	70	8.66
212-80	106	197	0.00	47	4.81	31	8.96	31	14.3	57	13.9
213-80	107	30	0.00	irrigate							
214-80	108	45	0.00	15	6.13	11	2.80	77	2.31	79	4.35
215-80	109	95	0.00	20	5.26	15	3.62	70	2.99	74	7.27
216-80	110	140	0.00	30	8.49	22	7.38	54	8.49	69	8.91
217-80	111	203	0.00	41	13.0	34	10.4	27	14.7	52	14.0
218-80	112	46	0.00	irrigate							
219-80	113	36	0.00	11	2.56	9	4.90	78	0.82	80	4.92
220-80	114	87	0.00	17	4.32	14	4.20	74	1.63	79	4.51
221-80	115	143	0.00	28	6.90	19	5.90	63	7.44	73	7.50
222-80	116	173	0.00	34	6.85	25	6.09	46	12.1	68	8.54
223-80	117	51	0.00	irrigate							
224-80	118	38	0.00	11	3.05	9	4.13	80	0.58	81	2.36
225-80	119	86	0.00	18	4.58	13	4.18	73	2.89	80	2.36

				Tensiometers				Resistance blocks			
	Days	Plate		10 cm		20 cm		10 cm		20 cm	
Julian date	from planting	EPA ml	Rain cm	Tension kPa	std dev	Tension kPa	std dev	Resistance mhos	std dev	Resistance mhos	std dev
226-80	120	138	0.00	24	6.95	18	4.60	67	4.11	76	1.73
227-80	121	30	0.00	irrigate							
228-80	122	10	0.51								
231-80	125	100	0.00	17	4.86	11	4.32	73	2.50	80	1.50
232-80	126	142	0.00	23	6.25	15	4.53	65	7.23	78	1.73
233-80	127	189	0.00	31	8.82	20	5.03	52	14.4	74	2.58
234-80	128	227	0.00	37	11.4	25	8.81	43	10.6	67	9.87
235-80	129	35	0.00	irrigate							
236-80	130	45	0.00	10	3.58	8	3.55	78	1.50	83	2.08
237-80	131	91	0.00	13	4.57	10	3.74	76	2.50	81	1.50
238-80	132	124	0.00	17	3.65	12	3.69	73	4.19	81	1.29
239-80	133	158	0.00	21	5.22	15	4.41	66	6.95	76	4.69
241-80	135	221	0.00	28	8.72	22	5.25	50	10.1	70	4.83
242-80	136	262	0.00	35	10.0	27	8.97	35	14.9	65	9.88
244-80	138	301	0.00	42	12.1	35	12.6	20	14.1	48	17.9
245-80	139	345	0.00	45	12.8	41	14.7	15	12.2	40	19.4

APPENDIX C

Onion Growth, SMP, and EPA Investigations - Greeley

Julian date	Days from planting	Plate EPA ml	Rain cm	Max Temp deg C		Min Temp deg C		10 cm Tension kPa	std dev	20 cm Tension kPa	std dev	Profile Tension kPa	std dev
				z	y	x	w						
152-81	83	29.5	0.00	27	26	7	9	13	2.02	13	2.58	13	2.27
153-81	84	89.5	0.00	26	23	7	10	14	2.23	14	2.98	14	2.58
154-81	85	141.0	0.00	25	24	9	15	15	2.43	15	2.66	15	2.50
155-81	86	168.0	0.13	26	24	9	12	17	2.49	16	2.62	16	2.54
156-81	87	208.0	0.00	28	26	9	12	18	2.99	17	3.39	18	3.23
157-81	88	282.0	0.00	31	30	9	13	22	3.63	19	2.90	20	3.56
158-81	89	350.4	9.99	32	32	10	17	26	5.52	20	2.94	23	5.25
159-81	90	422.0	0.00	35	34	12	14	29	8.58	21	3.30	25	7.63
160-81	91	491.0	0.00	32	31	13	14	36	10.42	23	3.92	29	9.89
161-81	92	572.0	0.00	28	29	12	15	44	11.88	25	4.91	34	13.07
162-81	93	631.5	0.00	29	28	11	14	48	11.50	27	6.06	38	13.96
163-81	94	690.0	0.00	36	33	14	17						
164-81	95	752.0	0.00	28	27	13	11	57	12.15	35	9.30	46	15.63
165-81	96	833.0	0.00	19	17	7	8	57	10.78	37	9.13	47	14.43
166-81	97	?	0.00	23	22	6	7	irrigate					
167-81	98	137.0	0.00	28	28	4	5						
168-81	99	199.0	0.00	31	30	11	12	12	2.71	12	2.50	12	2.65
169-81	100	279.5	0.00	23	24	7	8	16	2.79	14	2.80	15	3.02
170-81	101	326.5	0.00	32	32	8	8	20	2.95	17	3.95	19	3.77
171-81	102	390.5	0.00	34	34	11	13	29	6.99	19	2.71	24	7.50
172-81	103	453.5	0.00	28	28	13	13	39	10.81	23	3.98	30	11.49
173-81	104	504.5	0.00	33	33	11	13	46	13.56	27	6.76	36	14.47
174-81	105	566.5	0.00	34	34	13	13	52	12.66	35	10.09	44	14.04
175-81	106	627.5	0.00	31	29	15	17	55	13.95	41	12.06	49	14.09
176-81	107	61.5	0.00	32	32	13	14	irrigate					
177-81	108	129.5	0.00	33	32	13	15						
178-81	109	?	0.00	36	33	14	16						
179-81	110	247.5	0.00	33	31	16	17	23	11.44	17	2.90	20	8.70
180-81	111	290.0	0.00	26	24	13	14	31	13.67	21	3.53	26	10.94
181-81	112	316.5	0.00	32	31	11	12	36	15.26	24	3.61	30	12.37
182-81	113	?	0.00	33	32	14	16	irrigate					
183-81	114	?	1.22	25	23	16	17						
184-81	115	?	0.13	28	26	14	16						

Julian date	Days from planting	Plate EPA ml	Rain cm	Max Temp deg C		Min Temp deg C		10 cm Tension kPa	std dev	20 cm Tension kPa	std dev	Profile Tension kPa	std dev
				z	y	x	w						
185-81	116	64.0	0.00	31	29	12	13	11	3.70	12	2.64	11	3.17
186-81	117	105.0	0.00	33	31	12	13	18	6.87	15	2.57	16	5.39
187-81	118	153.5	0.00	36	34	12	13	30	12.41	20	2.97	25	10.54
188-81	119	212.5	0.00	36	35	14	15	38	17.36	30	5.31	34	13.62
189-81	120	282.5	0.00	27	24	14	16	42	17.95	34	4.57	38	13.37
190-81	121	41.0	0.00	33	32	9	10	irrigate					
191-81	122	86.0	0.00	35	33	14	15						
192-81	123	?	0.00	38	36	14	15						
193-81	124	187.0	0.00	35	32	16	17	15	7.65	15	3.46	15	5.93
194-81	125	228.5	0.61	31	29	14	17	24	12.38	21	4.64	22	9.68
195-81	126	256.5	0.00	33	30	16	15	32	13.10	27	3.85	29	9.73
196-81	127	310.0	0.00	33	31	14	13	46	15.04	40	5.96	43	11.68
197-81	128	41.0	0.00	31	29	17	18	irrigate					
198-81	129	70.5	0.00	30	28	15	17	8	2.72	9	2.69	8	2.78
199-81	130	100.0	0.00	28	26	14	16						
200-81	131	130.0	0.00	35	33	13	13	17	6.41	16	2.99	16	5.10
201-81	132	175.0	0.00	34	31	12	12	27	13.07	21	5.03	24	10.53
202-81	133	225.5	0.00	38	34	13	12	32	18.28	34	5.39	33	13.86
203-81	134	51.0	0.00	28	28	16	15	irrigate					
204-81	135	85.5	0.00	33	33	13	14	9	2.57	9	3.01	9	2.64
205-81	136	136.5	0.00	32	32	17	17	15	4.89	15	3.37	15	4.33
206-81	137	175.0	0.33	27	26	12	14	21	7.95	19	3.53	19	6.34
207-81	138	?	1.45	19	24	10	12	rain					
208-81	139	?	1.78	25	25	9	11						
209-81	140	28.5	0.00	31	29	11	12						
210-81	141	65.0	0.00	34	33	12	12	14	3.83	13	3.37	13	3.69
211-81	142	111.0	0.00	35	33	12	12	21	6.10	18	3.93	19	5.34
212-81	143	43.5	0.00	35	34	14	13	irrigate					
213-81	144	90.5	0.00	31	28	17	14	6	2.10	88	2.06	7	2.26
214-81	145	116.0	0.00	34	32	11	11	9	3.41	10	2.42	10	3.12
215-81	146	169.5	0.00	34	32	13	13	15	3.17	13	2.77	14	3.15
216-81	147	?	0.00	34	34	15	18						
217-81	148	263.5	0.00	31	29	13	12	33	12.02	24	5.75	28	10.24
218-81	149	48.5	0.00	26	26	14	16	irrigate					
219-81	150	86.0	0.00	27	25	13	13						
220-81	151	123.0	0.00	27	28	8	8	9	2.94	11	2.55	10	2.85

z Daily maximum temperatures measured adjacent to field plots.

y Daily maximum temperatures measured at the Weld County research station, approximately 5 km south east of the onion plots.

x Daily minimum temperatures measured adjacent to field plots.

w Daily minimum temperatures measured at the Weld County research station.

APPENDIX D

Drought Response at Different Growth Stages - Fort Collins

Leaves per Plant

Julian date	Days from planting	Early stress mean #	std dev	Middle stress mean #	std dev	Late stress mean #	std dev	Control no str mean #	std dev
163-81	59	2.63	.28	2.65	.44	2.36	.37	2.55	.35
170-81	66	2.68	.30	2.79	.36	2.80	.47	2.71	.36
176-81	72	3.38	.26	3.20	.51	3.31	.57	3.50	.33
183-81	79	3.94	.47	4.19	.41	3.91	.46	4.19	.37
190-81	86	4.28	.34	4.16	.62	4.63	.92	5.16	.72
197-81	93	5.60	.70	6.03	.79	5.76	1.01	5.66	1.26
204-81	100	6.80	.86	6.94	1.04	7.09	1.32	7.20	1.14
211-81	107	7.40	1.22	7.38	.96	7.56	1.33	7.13	.92
219-81	115	8.18	.81	8.48	.49	8.48	1.19	8.23	1.10
226-81	122	8.28	.93	7.81	1.14	8.40	.46	8.58	2.03
232-81	128	9.43	.77	9.24	1.06	8.44	2.11	8.50	1.35

Plants per Sample

Julian date	Days from planting	Early stress mean #	std dev	Middle stress mean #	std dev	Late stress mean #	std dev	Control no str mean #	std dev
163-81	59	10.44	2.29	10.19	3.02	11.00	2.14	7.75	2.49
170-81	66	11.06	2.18	8.81	3.00	9.38	3.25	9.63	2.30
176-81	72	12.88	4.19	11.50	4.31	8.88	3.48	12.00	5.26
183-81	79	10.50	3.42	9.88	4.39	8.38	2.00	7.63	3.42
190-81	86	10.13	2.70	7.25	2.71	8.25	4.37	8.00	3.07
197-81	93	10.25	4.56	8.00	2.20	9.38	2.97	7.75	1.04
204-81	100	11.00	4.75	10.00	2.93	9.25	3.20	8.63	2.39
211-81	107	8.63	3.85	9.38	2.33	8.00	3.51	8.88	2.30
219-81	115	8.00	2.45	9.63	3.20	7.50	3.25	7.25	1.91
226-81	122	9.63	3.66	11.75	4.06	3.00	2.30	10.38	3.81
232-81	128	7.75	2.31	7.88	2.28	9.00	3.21	7.13	2.36
250-81	147	8.25	2.31	11.13	1.73	7.75	2.05	7.75	2.12

Leaf Area per Plant (mean)

Julian date	Days from planting	Early stress cm^2	std dev	Middle stress cm^2	std dev	Late stress cm^2	std dev	Control no str cm^2	std dev
163-81	59	11.54	4.95	11.45	3.84	10.83	6.04	10.02	3.53
170-81	66	11.41	4.34	10.84	3.77	12.93	5.22	11.86	3.95
176-81	72	22.31	5.63	24.49	11.2	27.06	16.3	26.66	5.96
183-81	79	40.45	20.1	39.60	17.2	42.78	24.9	43.02	13.8
190-81	86	51.56	11.4	105.1	43.7	74.65	42.8	98.44	44.1
197-81	93	110.7	51.4	149.6	59.3	169.7	77.0	150.0	78.0
204-81	100	229.4	118.	256.1	77.0	255.4	140.	302.0	101.
211-81	107	302.7	130.	442.4	147.	408.9	152.	368.9	133.
219-81	115	396.3	77.7	514.1	135.	542.5	204.	524.5	226.
226-81	122	482.0	74.8	469.8	119.	572.5	115.	607.5	279.
232-81	128	551.2	144.	615.7	102.	488.6	120.	539.8	185.

Leaf Dry Weight per Plant

Julian date	Days from planting	Early stress gms	std dev	Middle stress gms	std dev	Late stress gms	std dev	Control no str gms	std dev
163-81	59	.0518	.024	.0522	.022	.0384	.010	.0468	.017
170-81	66	.0671	.026	.0639	.020	.0766	.034	.0715	.024
176-81	72	.1176	.032	.1241	.060	.1334	.082	.1316	.036
183-81	79	.2392	.113	.1872	.081	.2305	.160	.2226	.076
190-81	86	.2821	.069	.6207	.282	.4414	.276	.5704	.279
197-81	93	.6020	.344	.8310	.361	.9379	.469	.7971	.442
204-81	100	1.312	.823	1.473	.445	1.525	.876	1.767	.710
211-81	107	1.641	.838	2.400	.861	2.267	.894	2.076	.817
219-81	115	2.308	.579	2.931	.832	3.079	1.11	2.979	1.24
226-81	122	2.720	.673	2.523	.787	3.252	.605	2.995	1.35
232-81	128	3.652	.934	3.568	.636	2.872	.828	3.993	1.94
250-81	147	3.539	1.29	2.698	.572	3.712	1.95	3.707	1.76

Bulb Dry Weight per Plant

Julian date	Days from planting	Early stress gms	std dev	Middle stress gms	std dev	Late stress gms	std dev	Control no str gms	std dev
163-81	59	.0299	.011	.0298	.007	.0256	.005	.0300	.009
170-81	66	.0486	.020	.0437	.010	.0480	.014	.0484	.014
176-81	72	.0826	.018	.0767	.038	.0782	.036	.0818	.020
183-81	79	.1797	.047	.1348	.042	.1773	.124	.1578	.046
190-81	86	.2434	.049	.3978	.208	.3064	.152	.3724	.173
197-81	93	.5285	.284	.6643	.304	.7136	.348	.6389	.373
204-81	100	1.515	1.38	1.641	.466	1.475	.875	1.743	.652
211-81	107	1.971	1.21	3.019	1.42	2.577	1.21	2.530	.752
219-81	115	3.675	1.59	4.604	1.65	5.060	1.84	4.714	1.52
226-81	122	4.992	1.16	5.476	1.10	6.718	2.06	7.315	3.02
232-81	138	9.458	2.79	9.202	1.80	8.951	3.37	10.89	2.28
250-81	147	13.81	2.57	15.13	4.14	15.02	3.33	15.51	5.01

APPENDIX E

Drought Response at different Growth Stages - Fort Collins

Daily Environmental Parameters

Julian date	Days from planting	No Stress plate EPA ml	Stress plate EPA ml	Rain cm	Max temp deg C	Min temp deg C	Treatment mean				Pooled std dev
							A Tension kPa	B Tension kPa	C Tension kPa	D Tension kPa	
150-81	46	-	-	0.00	23	6	8	8	8	7	2.42
151-81	47	-	-	0.00	25	8	10	8	8	8	2.60
152-81	48	-	-	0.00	26	6	11	9	9	9	2.88
153-81	49	-	-	0.00	24	7	11	10	10	10	3.10
154-81	50	-	-	0.00	24	11	12	11	13	11	4.29
155-81	51	-	-	0.91	24	11	11	11	12	11	3.91
156-81	52	41	-	0.00	27	10	12	11	12	12	3.53
157-81	53	97	-	0.00	30	11	13	12	13	13	3.56
158-81	54	177	-	0.00	32	17	14	13	15	14	4.30
159-81	55	241	-	0.00	34	12	16	16	18	16	5.01
160-81	56	313	-	0.00	29	13	19	19	21	19	5.73
161-81	57	365	-	0.00	25	12	22	22	24	21	6.17
162-81	58	390	-	0.20	28	11	25	23	26	23	6.47
163-81	59	419	-	0.00	33	15	25	23	25	23	6.92
164-81	60	486	-	0.00	28	13	27	27	30	25	7.80
165-81	61	563	-	0.00	21	6	31	31	35	28	9.87
166-81	62	618	-	0.00	22	4	36	36	39	31	10.8
167-81	63	689	-	0.00	31	3	40	40	42	34	11.5
168-81	64	768	-	0.00	31	6	42	43	43	36	11.4
169-81	65	72	840	0.00	24	6	47	4	5	7	18.6
170-81	66	125	893	0.00	32	8	49	7	8	8	18.7
171-81	67	214	982	0.00	32	12	54	9	11	10	20.1
172-81	68	306	1074	0.00	32	13	56	14	16	14	19.9
173-81	69	366	1134	0.00	32	11	58	22	22	16	20.6
174-81	70	440	1208	0.00	32	11	61	32	28	20	21.8
175-81	71	512	1280	0.00	28	16	65	39	35	27	21.8
176-81	72	576	1844	0.00	31	13	67	46	41	32	21.0

							Treatment mean				
Julian date	Days from planting	No Stress plate EPA ml	Stress plate EPA ml	Rain cm	Max temp deg C	Min temp deg C	A Tension kPa	B Tension kPa	C Tension kPa	D Tension kPa	Pooled std dev
177-81	73	68	1412	0.00	33	13	67	5	5	6	27.4
178-81	74	36	1448	0.58	34	13	62	4	4	7	25.4
179-81	75	96	1508	0.00	33	16	68	7	7	9	26.9
180-81	76	143	1555	0.00	24	14	70	9	9	10	26.7
181-81	77	168	1580	0.00	30	13	72	11	11	12	26.8
182-81	78	232	1644	0.00	32	13	61	16	15	16	24.9
183-81	79	285	53	0.08	24	12	15	24	22	21	11.2
184-81	80	317	85	0.25	28	14	7	31	28	25	14.7
185-81	81	25	-	2.08	31	12	6	5	9	12	6.92
186-81	82	63	-	0.20	30	12	9	10	10	15	7.69
187-81	83	114	-	0.00	33	11	10	16	15	21	12.0
188-81	84	168	-	0.00	33	14	14	26	25	29	15.9
189-81	85	240	-	0.05	24	15	20	36	38	37	17.5
190-81	86	304	-	0.00	29	9	26	47	48	44	18.5
191-81	87	29	-	0.00	33	15	7	5	5	7	2.50
192-81	88	80	-	0.00	34	16	10	7	7	11	4.46
193-81	89	142	-	0.00	32	15	12	10	12	15	6.41
194-81	90	25	-	1.65	27	14	6	4	5	5	2.73
195-81	91	75	-	0.03	32	15	10	8	9	13	5.76
196-81	92	129	-	0.00	32	13	13	13	17	18	9.14
197-81	93	175	-	0.00	31	16	19	24	32	29	14.6
198-81	94	211	-	0.00	28	16	29	35	45	41	16.5
199-81	95	254	-	0.00	26	14	38	44	56	50	16.9
200-81	96	20	274	0.00	33	12	6	53	4	8	23.1
201-81	97	77	331	0.15	31	10	9	61	8	12	23.6
202-81	98	122	376	0.00	36	12	16	66	19	21	22.5
203-81	99	189	443	0.00	29	14	31	71	42	39	19.2
204-81	100	225	479	0.00	31	13	49	73	62	53	15.0
205-81	101	48	-	0.00	31	14					
206-81	102	99	-	0.45	27	12	6	5	6	5	2.86
207-81	103	18	-	0.25	18	11	6	4	5	6	2.75

							Treatment mean				
Julian date	Days from planting	No Stress plate EPA ml	Stress plate EPA ml	Rain cm	Max temp deg C	Min temp deg C	A Tension kPa	B Tension kPa	C Tension kPa	D Tension kPa	Pooled std dev
208-81	104	-	-	0.64	25	9					
209-81	105	28	-	0.05	29	11	8	6	6	8	2.89
210-81	106	67	-	0.00	33	11	13	10	13	14	5.22
211-81	107	125	-	0.00	31	11	31	20	30	29	10.0
212-81	108	182	-	0.00	33	13	51	31	51	48	13.1
213-81	109	53	-	0.00	31	16	6	4	5	5	2.31
214-81	110	85	-	0.00	32	11	8	6	7	7	3.38
215-81	111	156	-	0.00	34	11	19	11	16	18	6.75
216-81	112	225	-	0.00	34	17	43	24	40	38	12.2
217-81	113	295	-	0.00	32	12	57	41	60	56	12.9
218-81	114	54	349	0.00	32	12	5	3	69	4	28.6
219-81	115	88	383	0.00	27	12	7	5	71	6	28.9
220-81	116	136	431	0.00	28	10	12	8	73	12	28.1
221-81	117	36	-	1.35	30	11	11	5	69	9	27.6
222-81	118	-	-	1.02	21	14	6	4	26	5	14.5
223-81	119	21	-	0.00	25	9	7	5	22	6	11.0
224-81	120	48	-	0.00	24	9	11	7	35	10	12.9
225-81	121	66	-	0.10	29	13	16	11	46	14	16.0
226-81	122	109	-	0.03	28	14	27	18	54	24	15.7
227-81	123	-	-	0.00	26	12					
228-81	124	46	-	0.00	28	10	7	4	6	6	2.64
229-81	125	-	-	1.55	26	9					
230-81	126	44	-	0.00	29	11	8	6	7	8	2.57
231-81	127	87	-	0.00	29	11	12	8	10	11	3.13
232-81	128	119	-	0.00	29	11	24	17	19	23	5.76
233-81	129	150	-	0.00	32	9	37	28	28	37	8.65
234-81	130	190	-	0.00	27	14	49	41	31	50	9.96
235-81	131	20	-	0.00	32	10					
236-81	132	55	-	0.36	28	9	8	5	6	7	2.62
237-81	133	78	-	0.10	31	10	11	7	9	10	2.82
238-81	134	113	-	0.00	27	11	17	13	14	16	4.05
239-81	135	147	-	0.00	24	14	28	22	22	26	7.01
240-81	136	173	-	0.00	27	10	40	34	31	39	9.51

							Treatment mean				
Julian date	Days from planting	No Stress plate EPA ml	Stress plate EPA ml	Rain cm	Max temp deg C	Min temp deg C	A Tension kPa	B Tension kPa	C Tension kPa	D Tension kPa	Pooled std dev
241-81	137	-	-	0.00	30	10					
242-81	138	78	-	0.00	32	9	7	4	6	6	2.67
243-81	139	122	-	0.13	24	8	11	8	9	10	3.07
244-81	140	136	-	0.33	27	6	12	9	11	12	3.64
245-81	141	167	-	0.00	31	8	20	15	15	19	5.75
246-81	142	-	-	0.76	24	12					
247-81	143	203	-	0.00	28	11	16	15	12	20	9.50
248-81	144	227	-	0.00	29	9	22	20	16	25	10.4
249-81	145	-	-	0.18	29	10					
250-81	146	291	-	0.00	24	9	38	36	29	42	12.6
251-81	147	-	-	0.00	27	7					
252-81	148	350	-	0.00	31	7	51	50	42	56	12.2
253-81	149	-	-	0.00	28	12					
254-81	150	448	-	0.00	27	10	56	56	49	61	13.2

APPENDIX F

Effect of Imposed Osmotic Stress in the Root Medium on Growth - Greenhouse

Three week sample

Stress level bars	Leaf dry wt gm	std dev	Bulb dry wt gm	std dev	Root dry wt gm	std dev	Plant dry wt gm	std dev	Root: Shoot ratio	std dev
-0.40	.2989	.0705	.0977	.0408	.1010	.0416	.498	.151	.2502	.0305
-0.61	.2500	.0676	.0786	.0205	.0896	.0218	.419	.108	.2760	.0319
-1.01	.2821	.1062	.1004	.0292	.0951	.0372	.478	.168	.2448	.0229
-1.47	.2544	.0883	.0879	.0316	.0867	.0248	.429	.123	.2542	.0269
-2.74	.1138	.0304	.0640	.0251	.0509	.0107	.229	.062	.2948	.0503
-6.22	.0279	.0196	.0359	.0146	.0282	.0121	.092	.045	.4695	.1322

Five week sample

Stress level bars	Leaf dry wt gm	std dev	Bulb dry wt gm	std dev	Root dry wt gm	std dev	Plant dry wt gm	std dev	Root: Shoot ratio	std dev
-0.40	.610	.128	.908	.217	.5261	.1374	2.045	.467	.3464	.0475
-0.61	.536	.183	.775	.151	.3985	.0802	1.709	.352	.3117	.0730
-1.01	.553	.165	.730	.188	.3186	.0479	1.602	.374	.2575	.0505
-1.47	.410	.140	.561	.108	.2791	.0796	1.249	.293	.2834	.0476
-2.74	.148	.100	.212	.144	.1221	.0714	.482	.309	.3507	.0896
-6.22	.012	.008	.077	.088	.0259	.0173	.115	.083	.3962	.1976

Figure 10. Desorption curves for the sandy clay loam and clay soils used in the field investigations. Samples represent an effective root zone of 0-25 cm (0-10 inches). Soil moisture content at saturation (percent pore space at 0 matric potential was calculated using the respective bulk densities and a real specific gravity of 2.65).

PARTICLE SIZE ANALYSIS

TEXTURE	C	SCL
% SAND	26	50
% SILT	31	23
% CLAY	43	27
BULK DENSITY	1.25	1.42