



This is to certify that the

thesis entitled

A Computer Simulation Model of the Effects of Soil
Structure and Drought Stress on Navy Bean
(Phaseolus vulgaris) Growth and Yield

presented by

Robert Kingsley Hubbard

has been accepted towards fulfillment
of the requirements for

Ph.D. degree in Crop and Soil Sciences

Major professor

Date Sept. 28, 1979

DEC 0 2 1996

APR 0 6 1999

3

A COMPUTER SIMULATION MODEL OF THE EFFECTS OF
SOIL STRUCTURE AND DROUGHT STRESS ON NAVY
BEAN (PHASEOLUS VULGARIS)
GROWTH AND YIELD

By

Robert Kingsley Hubbard

A DISSERTATION

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

Department of Crop and Soil Science

1979

A COMPUTER SIMULATION MODEL OF THE
EFFECTS OF SOIL STRUCTURE AND
DROUGHT STRESS ON NAVY BEAN
(PHASEOLUS VULGARIS)
GROWTH AND YIELD

By

Robert Kingsley Hubbard

Field studies on a Charity clay were conducted in 1977 and 1978 at the Saginaw Valley Bean and Beet Research Farm to determine the effects of soil structure and drought stress on navy bean growth and yield. Studies of drought stress were also conducted both years on a Hillsdale sandy loam at the Soils Research Farm in East Lansing. Soil structure treatments on the Charity clay were defined as excellent, good, or poor. To obtain excellent soil structure an alfalfa timothy mixture was grown for two years and the soil was both deep chiseled and moldboard plowed in the fall prior to spring planting of beans. Soils where the crop rotation did not include two years of alfalfa-timothy and fall chisel and moldboard plowing were defined as having good structure. Poor soil structure was formed by compacting the soil with a tractor prior to planting. Drought was studied on the Charity clay using heavy irrigations at second seedling, flowering, or pod filling. Drought studies

on Hillsdale sandy loam compared no supplemental irrigation with irrigation at specific plant growth stages or all growth stages.

From the 1977 field data, a computer simulation model of navy bean growth and yield as affected by physical stresses was constructed. The model was constructed to study the extent to which physical stresses limit bean production in Michigan. Using climatic and soil information, the model predicts when irrigation should be applied as well as final yield. The model uses equations for percent of total emergence as a function of emergence day and percent of the soil surface not crusted, leaf area as a function of accumulated degree days and soil structure, percent of flowers that set pods as a function of maximum air temperature, and pod weight as a function of pod filling day and soil structure. These equations were statistically derived from field data. The model uses conceptual equations to determine the effects of drought stress on vegetative growth, the number of days the plants will flower, and the rate of increase in pod weights during pod filling. The potential number of flowers that will bloom during flowering is a function of leaf areas on the day prior to the start of flowering. The model divides the total population into three subpopulations (large, medium, and small) based on time of emergence.

The field research showed that water is critical at all growth stages but particularly so during flowering and pod filling. Soil structure is important so that plants will be rooted deeply enough to reach water during drought. Soil crusting during emergence can have serious influence on final yield by reducing the total plant population, or by delaying emergence such that plants emerging late cannot successfully compete for space with other plants. Field verification of the model with 44 sets of data yielded a correlation coefficient R^2 of 0.7 for the equation $Y = A + BX$ ($A = -211.81$, $B = 1.05$) where X is actual yield and Y is predicted yield. The model discriminated well for different soil moisture or soil structure regimes, and accurately predicted yield for a variety of weather conditions. The importance of physical stresses to navy bean growth and yield was successfully demonstrated. The model has good potential for use in predicting when to irrigate and final yield based on weather information. The system science approach to the navy bean yield problem shows the need for homogeneously sized plant populations in the field.

ACKNOWLEDGMENTS

I would first like to thank the Michigan Dry Edible Bean Commission for the support given enabling me to do my doctoral research. I also appreciate the time and efforts contributed by the members of my guidance committee, Professors B. G. Ellis, B. D. Knezek, R. O. Barr, R. J. Kunze, E. H. Kidder, and A. E. Erickson. Statistical advice given by Mr. A. M. Petrovic was quite helpful. Irrigation equipment loaned by Professors E. H. Kidder, A. J. M. Smucker and R. J. Kunze, greatly enhanced the field research.

I would particularly like to thank my major advisor, Professor A. E. Erickson, for all of his help and guidance during my seven years as his technician and graduate student. He has provided both friendship and encouragement for which I feel quite blessed.

Finally, I would like to thank my wife Rae for the encouragement and endurance which has enabled me to complete all my graduate studies at Michigan State University.

TABLE OF CONTENTS

	Page
LIST OF TABLES	v
LIST OF FIGURES.	vi
INTRODUCTION.	1
 Chapter	
I. LITERATURE REVIEW.	4
Seed Germination and Emergence.	4
Root Development in Relation to Compaction and Soil Moisture	10
Effect of Population Density on Yield	15
Effects of Moisture Stress on Plants.	18
Evapotranspiration.	34
Stresses Affecting Plants During Flowering and Pod Filling	37
Plant Water Stress and Irrigation Scheduling.	38
Models.	41
References	68
II. NAVY BEAN (PHASEOLUS VULGARIS) GROWTH AND YIELD AS AFFECTED BY SOIL STRUCTURE AND WATER STRESS.	80
Abstract	80
Introduction.	81
Materials and Methods.	84
Results	90
Conclusions	107
References	109
III. A LIMITED INFORMATION MODEL OF NAVY BEAN (PHASEOLUS VULGARIS) GROWTH AND YIELD AS A FUNCTION OF SOIL STRUCTURE AND WEATHER. PART I: THE MODEL.	110
Abstract	110
Introduction.	112

Chapter	Page
The Model.	118
Germination and Emergence	119
Plant Growth Prior to Flowering	121
Flowering.	126
Pod Filling	131
Yield	134
Soil Moisture and Evapotranspiration.	136
Daily Index of Available Soil Moisture	144
Model Program	145
Model Use for Management Decisions	145
Summary	151
References	155
IV. A LIMITED INFORMATION MODEL OF NAVY BEAN (PHASEOLUS VULGARIS) GROWTH AND YIELD AS A FUNCTION OF SOIL STRUCTURE AND WEATHER. PART II: COMPARISON OF ACTUAL AND PREDICTED GROWTH AND YIELD	159
Abstract	159
Introduction.	160
Procedure.	161
Results	170
Emergence	170
Vegetative Growth	175
Pod Filling	180
Yield	182
Conclusions	186
Reference.	187
V. SUMMARY AND CONCLUSIONS.	188
APPENDIX	192

LIST OF TABLES

Table		Page
 Chapter II		
1.	Dates, Amounts, and Plant Growth Stages for Irrigations on Hillsdale Sandy Loam in 1978 .	88
2.	Percent Final Bean Emergence versus Days from the Start of Emergence for Hillsdale Sandy Loam and for Noncompacted and Compacted Charity Clay in 1977 and 1978.	91
3.	Bean Plant and Pod Tissue Weights (grams/plant) of Samples Collected August 24, 1978 from Charity Clay and Hillsdale Sandy Loam	101
4.	Total Air Dry Bean Root Weights (grams) and Root Sample Volumes (cm ³) from Selected Soil Structure or Irrigation Treatments on Charity Clay in 1977 and 1978 and Hillsdale Sandy Loam in 1977	103
5.	Final Yields (kg/ha) of Beans Grown with Different Soil Structure and Water Regimes on Charity Clay and Hillsdale Sandy Loam in 1977 and 1978	105
 Chapter IV		
1.	Input, Predicted Yield, and Actual Yield from 44 Tests of the Model of Navy Bean Growth and Yield	162

LIST OF FIGURES

Figure		Page
 Chapter II		
1.	Plant Growth Curves of Beans Grown on Excellent, Good or Poor Soil Structure on Charity Clay in 1977	92
2.	Plant Growth Curves of Beans Grown on Charity Clay With Good Soil Structure With and Without Heavy Irrigation at Flowering in 1978	94
3.	Plant Growth Curves of Beans With Supplementary Irrigation as Needed, No Supplementary Irrigation, or Water Stress Only at Second Seedling on Hillsdale Sandy Loam in 1977 . . .	97
4.	Plant Growth Curves of Beans With Supplementary Irrigation as Needed, No Supplementary Irrigation, Supplementary Irrigation Only on July 7, or No Supplementary Irrigation After July 28 on Hillsdale Sandy Loam in 1978 . . .	98
5.	Plant Growth Curves on Beans Not Receiving Supplementary Irrigation on July 7, 14, 21, or 28 on Hillsdale Sandy Loam in 1978	99
 Chapter III		
1.	Flow Chart of Navy Bean Computer Simulation Model.	146
 Chapter IV		
1.	Actual and Predicted Emergence of Beans Grown on Hillsdale Sandy Loam in 1977 and 1978 . . .	171
2.	Actual and Predicted Emergence of Beans Grown on Uncompacted and Compacted Charity Clay in 1977	172

Figure	Page
3. Actual and Predicted Emergence of Beans Grown on Uncompacted and Compacted Charity Clay in 1978	173
4. Actual and Predicted Leaf Areas of Irrigated and Unirrigated Beans Grown on Hillsdale Sandy Loam in 1977	176
5. Actual and Predicted Leaf Areas of Irrigated and Unirrigated Beans Grown on Hillsdale Sandy Loam in 1978	177
6. Actual and Predicted Leaf Areas of Beans Grown on Charity Clay With and Without 8.9 cm of Supplementary Irrigation on 6-29-78.	178
7. Actual and Predicted Pod Weights of Irrigated and Unirrigated Beans Grown on Hillsdale Sandy Loam in 1977	181
8. Predicted Yields Versus Actual Yields by Replication of Bean Grown on Hillsdale Sandy Loam in 1977 and 1978, and Charity Clay in 1978	183
9. Predicted Versus Actual Yields of the 44 Model Verification Runs From Table 1	184

INTRODUCTION

Navy bean (*Phaseolus vulgaris*) yields in Michigan have shown a steady decline over the past ten years. Concern about this problem has led to increased research in all aspects of bean production including seed quality, plant breeding, soil fertility, weed and nematode control, and proper soil management relating to soil physical properties. The fine textured soils, characteristic of much of the Thumb region of Michigan, are quite susceptible to compaction. From the simplest perspective it would appear that increasing use of larger and heavier machinery on these soils may account for the decline in navy bean yields.

To produce maximum quantity and quality yields navy beans must have readily available water from germination through pod filling. Without supplementary irrigation, plants must develop extensive, deep rooting systems to reach water in the subsoil. Although part of the solution to getting deep rooting lies in superior plants with strong potential for rooting, the key to good rooting is soil structure. Without good soil structure, plants cannot be deep rooted and are thus more susceptible to drought stress.

In addition, poorly structured fine textured soils drain slowly and are vulnerable to flooding which causes oxygen stress.

Prior to the use of chemical fertilizers, crop rotation schemes included a legume. In addition to adding nitrogen to the soil through nitrogen fixation by symbiotic bacteria, legumes such as alfalfa are beneficial to the soil by improving soil structure through strong, deep rooting systems and addition of organic matter. Another change in agriculture has been the use of progressively heavier tractors and equipment. When such equipment is used on soils which are too wet, significant soil compaction occurs. Improved traction with flotation tires has encouraged some farmers to enter wet fields too early, defeating any advantages of these tires in reducing soil compaction. Since structure building crops no longer are included in rotation with cash crops, soil structure is not being maintained or restored.

Physical stresses which affect navy bean growth and yield are soil crusting at emergence, mechanical impedance, drought stress, and oxygen stress. Crusting, drought, and oxygen stress are intensified by poor soil structure. Although drought stresses can be eliminated by supplementary irrigation, maintenance of good soil structure will significantly help the problem.

The System Science approach is an organized method of problem solving which generally includes construction

of a computer simulation model. The problem addressed in this research is how to increase navy bean yields in Michigan. The objective of the research were (1) to find if physical stresses are the major yield limiting factors to Michigan Navy Bean growth and yield, and (2) to develop a yield predictive model based on climatic data showing the effects of stresses at different growth stages. The model is to be used as an aid in scheduling irrigation and evaluating the importance of various soil management practices.

CHAPTER I

LITERATURE REVIEW

Seed Germination and Emergence

Percentage and speed of germination and emergence are extremely important with agronomic crops. Poor stands and stands with widely differing plant sizes, due to emergence at different times and competition, result in reduced yields. Assuming quality seed and good seed-soil contact, the critical factors for emergence are temperature, adequate soil moisture for seed imbibition and germination, and low soil impedance to promote emergence of the plant.

A study of the necessary soil moisture for seed imbibition and germination conducted by Hunter and Erickson (1952) concluded that each seed species must attain a specific moisture content for germination. This minimum moisture content is approximately 30.5% for corn, 26.5% for rice, 50% for soybeans, and 31% for sugar beets. At 25°C, a soil should have a moisture tension of not more than 12.5 atmospheres for corn kernels to germinate; 7.9 atmospheres for rice kernels to germinate; 6.6 atmospheres for soybeans to germinate; and 3.5 atmospheres for segmented sugar beet seeds to germinate. Seeds which lie in soil

environments not sufficiently moist for their germination are subject to damage or destruction by fungi in the soil.

Water uptake by seeds as affected by water stress, capillary conductivity, and seed soil water contact was studied by Hadas and Russo (1974). Water uptake rates, seed diameter, and time of germination were determined, and seed-soil water contact was calculated to yield an approximation of the seed-soil water contact impedance. Results showed that the seed-soil water contact impedance increased as the wetted seed area and/or soil hydraulic conductivity decreased. For optimal seed-soil contact in aggregated soils it was concluded that the mean aggregate size should be one-fifth to one-tenth of the seed's diameter. Seed-soil water contact impedance should be minimized by pulverizing the aggregates around the seed, or by compacting the soil area around the seed. Because of hazards involved in excessive compaction for improved seed-soil contact, tilling the sowing row differently from the inter row area should be considered.

Once seeds have imbibed and germinated the next physical stress which may affect the life of the plant and ultimate yield is the impedance of the soil above the seed to the emerging plant. The soil may be compacted over the seed due to poor soil structure from tillage practices or rainfall induced crusts can be formed. Holder and Brown (1974) state that extensive areas of cultivated soil throughout the world develop rainfall-induced crusts which impede seedling emergence. They conducted studies of simulated

seed emergence using guided tubes to allow a probe (simulated seedling) to penetrate the soil crust from below. Simulated rainfall of intensities from 1.3 to 5.1 cm/hour and durations of 19 to 60 minutes were used to form the crusts. Their determinations of crust impedance were made daily for 7 days with a 12-hour drying cycle. Results of their studies show an inverse relation between mechanical impedance and the crust moisture between 20.0 and 2.8% with the maximum impedance occurring between 2.2 and 2.8% moisture for the loam soil tested. Also different durations of rainfall at similar intensities result in larger differences in impedance than do different intensities for the same duration.

Orphanos (1977) found that the failure of *Phaseolus vulgaris* seedlings to emerge when irrigated after seeding was caused mainly by mechanical impedance of the wet soil and not by soaking injury. Seeds sown deeper than 2.5 cm and then irrigated produce abnormal and hollow hypocotyls. Such seedlings often sustain damage such as the loss of a cotyledon or the breaking of the hypocotyl.

McIntyre (1958) describes the sequence of processes leading to crust formation as follows:

- (a) Breakdown and slaking and/or dispersion of the soil particles at the surface due to wetting and rain-drop impact.

- (b) Fine particle movement within the top layer (1 to 2 mm) into the adjacent voids and cracks.
- (c) Cementation of the slaked soil at the soil surface due to reorientation and drying; particle cementation is also due to CaCO_3 precipitation during the drying process.

Hillel (1960) summarizes his results and those of other workers and points out that the soil crust is less penetrable and harder (higher modulus of rupture) if (1) the initial bulk density of the top soil is higher, (2) the initial water content is higher and maintained for a longer time (slower drying) and (3) there are smaller soil aggregates at the surface prior to wetting. Pulverization of the top soil by tillage operations or due to grazing leads to disrupted structure and increased bulk density at the top, thus subjecting the soil to the hazard of severe soil crusting. The hardness of this crust and its impenetrability are affected also by the rainfall amount and the raindrop impact of the first storm.

Hadas and Stibbe (1977) studied soil crusting and emergence of wheat seedlings both in the laboratory and in the field. They found that crusts formed on disked fields are nearly twice as resistant to penetration as those formed on plowed fields. Their paper gives two equations for expressing crust strength

$$(1) S = B \exp (-aP_w), \text{ and}$$

$$(2) S = B \exp (-a(P_{wa} + P_{wi}(R)T^{-b})).$$

In the first equation S is the crust resistance to penetration in bars. Soil constants are a , a constant number, and B , a value expressed in bars which has been assigned to characterize the soil. Both a and B depend on rainfall intensity and total amount. In addition, B depends on soil constituents and the rate of drying, and a depends on the atmospheric drying conditions. Using the concepts of Richards et al. (1956) that the water content change of a soil layer with time is $W = AT^{-b}$, where A , W are water amounts in the soil layer at $T = 1$ and time T , and b is a constant, the second equation was derived. Substituting $P_w = P_{wa} + P_{wi}(R)T^{-b}$ (a form similar to Richards et al. (1950)) for P_w in equation (1) gives $S = B \exp (-a(P_{wa} + P_{wi}(R)T^{-b}))$ where P_{wa} and P_{wi} are water contents at air dryness and added water content above P_{wa} after rainfall R , respectively. A different equation for soil crust strength was derived by Hegarty and Royle (1978)

$$S = 0.30 + 0.3589R + C (0.07343R - 0.03821M + 0.003549M^2)$$

where S is the force of penetration of the crust in Newtons, C is compaction in Newtons/cm², R is rainfall in mm, and M is initial moisture content. Almost 90% of the variation in peak penetration force of a penetrometer is accounted for by their equation.

A thorough review of papers discussing the effects of soil crusts on seedling emergence is found in the text Compaction of Agricultural Soils from the American Society of Agricultural Engineers. When crusting problems occur the elongating shoot may (1) strike a high strength crust portion and be diverted horizontally until reaching a crack, (2) happen to grow upward into a surface crack large enough to accommodate the emerging plant parts, (3) strike a crust of high enough strength to slow emergence rate but allow most seedlings to emerge, or (4) strike a crust of sufficient strength or horizontal extent to stop emergence. With the third and fourth reactions, strength of the crusted soil controls rate of emergence and the proportion of seedlings that ultimately emerge. If seedlings are planted closely the combined thrust of more than one seedling may be sufficient to crack a high strength crust.

The area of crust that dicotyledonous plants such as beans must displace is much larger than the diameter of the stem exerting the plant force. These seedlings emerge by rupturing out the soil crust in a dome or cone large enough to accommodate the cotyledons (Arndt, 1965a, 1965b; Bowen, 1966). Richards (1953) found that emergence of bean seedlings decreased from 100 to 0 percent as dry strengths of Pachappa fine sandy loam crusts increased. Hanks and Thrope (1957) showed that, with crust strength constant, decreasing the soil water content from field capacity to one-fourth available water reduced soybean emergence at a

specific crust strength, and that soybean emergence is reduced as crust strength increases. Sixty percent emergence of soybeans occurred through 0.8 bar strength crusts at field capacity. Hanks and Thorpe (1957) showed that some wheat seedlings can emerge through crusts of 0.8 bar strength, and that about 20% of grain sorghum seedlings can emerge through crusts of 1.4 bars strength.

In addition to soil crusts causing mechanical impedance to an emerging seedling, small seedlings developing within a thick crust may encounter inadequate oxygen for rapid cell enlargement or efficient conversion of reserve foods to energy. Since oxygen is required for the rapid growth and cell enlargement which give the hypocotyl its forward thrust, it is doubtful that a plant can develop its maximum thrust capability under a reduced oxygen supply. It is also possible that the failure of some seedlings to emerge may result from an undesirable associated carbon dioxide increase. It is extremely difficult to conclusively separate high soil strength, oxygen deficiency, and carbon dioxide excess in any study using soil as a test media, since all three occur simultaneously in natural situations.

Root Development in Relation to Compaction and Soil Moisture

Once a seedling has emerged, plant development continues both above the soil surface and below the soil surface. Growth of the plant in each location is dependent on what is happening at the other location. Photosynthesis

provides the energy for plant and root tissue growth.

Roots carry water, nutrients, and oxygen, for photosynthesis and respiration. The ultimate size and seed set of a plant can only be optimized with desirable growing conditions both above and below ground. Soil structure must be desirable so a plant can develop a large deep rooting system to obtain maximum available water and nutrients.

Robertson and Erickson (1978a) summarize the effects of soil compaction on field crops as (1) slow plant emergence, (2) variable sized plants--many shorter than normal, (3) off-colored leaves, (4) shallow root systems, and (5) malformed roots. Slow plant emergence may reflect low soil temperature, wet soil, soil crust, or a cloddy soil condition which can all be related to compact soil. Under wet soil conditions that can be caused by compact soil, both seedlings and more mature plants are susceptible to damage by disease organisms. An example is root rot in beans. The most frequent symptom is shallow rooting systems which have reduced capacity for water and nutrient absorption. The major causes of soil compaction are inadequate drainage, excessive tillage, cropping systems, and untimely field operations (Robertson and Erickson, 1978b). Inadequate drainage, both surface and subsurface, is perhaps the major cause of compact soil conditions in soils that are wet during field operations. Excessive tillage produces a large number of relatively small aggregates which are less stable than larger ones. Opportunities for aggregate decomposition,

crust formation, and accelerated erosion by both wind and water are increased. Cropping systems that do not produce relatively large amounts of crop residues are a major factor in soil structure problems. Soil structure problems are becoming more apparent on farms that produce only sugar beets and beans because these crops produce smaller amounts of residues. Tillage operations when soil is wet result in a deterioration of the soil physical condition. Solutions to compaction problems include providing adequate drainage, operating only on relatively dry soil, using minimum tillage, and maintaining or improving soil organic matter levels (Robertson and Erickson, 1978c).

Voorhees (1977a, 1977b) has written two articles describing the "positive" benefits of soil compaction. His position is that soil compaction is "our newest natural resource" and "its universal presence in modern U.S. agriculture almost makes it a part of our environment." Although it is questionable that the production of heavier machinery justifies the use of such machinery in relation to soil structure problems, and in particular the attitude that because everyone compacts their soil therefore it is now part of the "environment," Voorhees does cite that under certain conditions compaction does reduce wind and water erosion. Compaction of a relatively dry soil will result in a warmer soil temperature in the seed bed and with the smaller capillary pores in a compact soil, more water is provided early in the season. Compaction encourages

greater root branching which in some cases results in better soil exploration for nutrients. It is the opinion of the author that the disadvantages of soil compaction far outweigh advantages.

Voorhees, Senst, and Nelson (1978) found that wheel traffic of normal farming operations on a silty clay loam can compact the soil to a 45 cm depth. Wheel traffic increased soil bulk density by 20% or less, whereas penetrometer resistance was increased by as much as 400%. Averaged over 5 years, wheel traffic associated with spring field operations increased the bulk density of the 0 to 15 cm soil layer by 20%, and the 15 to 30 cm layers of soil by 10% over that of nontracked soil. Strength and density of wheel tracked clods were greater and average aggregate diameter was larger than that of nontracked clods, a difference which persisted over winter. Regardless of overwinter persistence of wheel-induced soil compaction, definite soil structural changes are caused by spring wheel traffic. These changes last throughout the growing season and may be more important agronomically than overwinter persistence of the previous years compaction.

The effect of soil compaction on root anatomy was studied on soybeans by Baligar, Nash, Hare, and Price (1975). They found that increasing bulk density from 1.65 to 1.95 g/cm³ altered the root anatomy. In the high density soil layers a larger percentage of root volume was occupied by cell wall material, and the transverse sections of the roots

had a wavy outline with ruptured epidermal cells. In contrast, roots grown in low density soil had a smooth surface of small, regular, unruptured epidermal cells. Under this layer was a wide cortex of several layers of regularly arranged parenchyma cells which were angular in shape and compactly arranged with few intercellular spaces. The vascular cylinder of low density roots was circular whereas high density roots are oval in outline. With increasing soil density a larger percentage of root volume is occupied by cell wall material. The anatomical changes in soil roots with soil compaction reduce root efficiency in moving air, water, and nutrients into the plant.

Water uptake by roots is affected both by depth and soil water content (Willatt and Taylor, 1978). With soybeans it was found that water uptake rates decreased with soil water content at all soil depths and the soil water content at which roots extracted almost no water increased with depth. The maximum rate of uptake of the deep roots was greater, per unit of length, than shallow roots. In terms of increasing plant water supply through a deepened root system one must consider that the water must be lifted a greater distance and thus the quantity of water added to the plant water supply will be lower than if the water came from closer to the soil surface.

A study of soybean root development and soil water depletion was made by Stone, Teare, Nickell, and Mayaki (1976) to provide data for developing and refining models

that consider root-soil-water interactions. They found that maximum root and water depletion depths are nearly equal during the first half of the season but later water depletion tends to be about 15 cm deeper than root growth (possibly as a result of upward water movement into the water-depleted root zone). As soybean root weight increases, there is a drying effect, so available soil water and soil water potential decrease. Depletion effectiveness (defined as cm^3 of water/g of root/day)) is greatest with lower root weights, higher soil water potentials and greater available soil water. Depletion effectiveness increases with depth in the soil profile; probably as a result of the roots being younger, in wetter soil, and less crowded. The data indicate that a small portion of the root system can be responsible for much water uptake and that water uptake occurs through old root material but possibly more slowly than through new roots.

Effect of Population Density on Yield

Just as rooting conditions affect plant yield through the relation between root distribution and amount of available water and nutrients, population density affects yield through competition for sunlight, water, and nutrients. As population density increases there is more shading of plants and less available water per plant. Individual plants are smaller with lower yield per plant. Scarisbrick, Wilkes, and Kempson (1977) found with navy beans in England

that there was no significant effect of population density on seed yield per m². The advantages of increased plant stand are offset by lower pod retention. The main effect of population density on bean yield is that rate of drying after pod filling significantly increases with increasing plant population density.

Doss and Thurlow (1974) in studying soybeans also showed row width and plant population to have little influence on average bean yields. Working with snap beans, Crothers and Westermann (1976) found that optimum plant population for bush cultivars was approximately 400,000 plants/ha and for semivining cultivars was less than 300,000 plants/ha. At smaller populations, seed yields decrease for bush cultivars and remain constant for semivining cultivars. Harvest index (seed weight/total plant weight) increases slightly for bush cultivars as their plant population decreases but remains constant for semivining cultivars down to 300,000 plants/ha, and then increases rapidly. The production index (seed yield/amount seeded) increases curvilinearly as plant population decreases for all cultivars. An advancement of 7 to 10 days in plant maturity at the highest plant populations agrees with the increased rate of drying with increasing population density noted by Scarisbrick, Wilkes, and Kempson (1977). Pods are located at upper nodes on the plants as the populations increase, suggesting that greater seed yields can be expected with

equidistant plant arrangements as compared with conventional row plantings for bush cultivars.

Dry bean genotypes of different growth habits were studied in the tropics by Kueneman, Hernandez-Bravo, and Wallace (1978). They found that indeterminate large vine and indeterminate small vine genotypes gave higher yields than the determinate genotype. Narrow between-row spacings (50 cm) tended to give higher yields than 75 cm spacings for all habits although the determinate genotype was less responsive. Close within-row spacing (5 versus 10 cm) was not beneficial for beans of any growth habit.

Bennett, Adams, and Burga (1977) examined the components of pod formation that are most sensitive to plant density. Their study showed significant reduction in racemes per node and branches per plant with higher planting density. Both of these components are positively correlated with pods per plant but negatively correlated with each other. They recommend that a bean ideotype for temperate zone monoculture have a high number of nodes per branch and three to five branches per plant.

It was concluded by Sprent, Bradford, and Norton (1977) that water supply may be a more important factor controlling yield of field beans (*Vicia faba*) than either solar radiation or plant competition, with the period following pod setting being especially vital. In their study of the effects of population density and shading of seasonal growth patterns of field beans, they found that at

dense populations the ratio of leaf to stem weights was below that at wider spacings and that leaf senescence was advanced. Root growth stopped at the time when pods began to swell. The pod filling time is believed by the authors to be the most critical in relation to soil water because the plants are particularly susceptible to water stress with root growth stopping. At this time plant water requirement may often be in excess of supply.

Effects of Moisture Stress on Plants

Water moves from regions of higher to lower potential energy as it moves through the soil, into the plant root, and through the plant to the leaves. The potential energy continuously decreases to the point in the leaves at which evaporation is occurring. At the point where evaporation is taking place, an amount of energy must be supplied equal to the heat of vaporization, the necessary energy being supplied through solar radiation, and convection and conduction of heat through the atmosphere and the plant (Gardner, 1960).

Water moves in the soil and plant because of potential difference. In the plant this potential is called the diffusion pressure deficit (DPD), suction or tension. Since the absolute value of the suction of the DPD increases with decreasing potential energy, water moves from lower to higher suction. The suction of soil water increases as water content decreases, so suction in plants must increase

to remove water from the soil as soil water content decreases (Gardner, 1960).

The rate of uptake of water per unit length of root is proportional to the total transpiration rate, and inversely proportional to the effective length of the root system. Assuming a given rate of transpiration, the more extensive the root system the lower the rate of uptake per unit length of root. The water content gradient and the suction gradient in the vicinity of a plant root remain small until the water content approaches the wilting range (Gardner, 1960).

During transpiration, the vapor pressure of the water in the leaves decreases very slowly as the DPD increases. The permeability of the plant decreases as the DPD in the leaves increases. With increasing DPD in the leaves turgor pressure decreases, stomata close, and the leaves dehydrate. The decreasing permeability of the plant with increasing DPD tends to set an upper limit upon the DPD of the leaves, this limit being of the order of the osmotic pressure in the leaves. As soil suction increases, the transpiration rate must decrease. This decrease is small when soil suction is low, but becomes large as soil suction approaches the maximum DPD in the leaves (Gardner, 1960).

It now is generally agreed that water becomes progressively less available as the water content of the soil decreases rather than remaining available until the water content falls almost to permanent wilting, then suddenly becoming unavailable (Kramer, 1963). According to Kramer

(1963), much of the difference of opinion concerning the effects of moderate soil water stress on plant growth comes from a mistaken belief that plant growth should be consistently reduced by some predictable level of soil water stress. Kramer devotes his paper to a discussion of plant water stress, how it effects growth, and how it can be measured.

The essential feature in plant water relations is the internal water balance, water stress, or degree of turgidity which exists in plants, because this is what controls those physiological processes and conditions which in turn determine the quantity and quality of growth (Kramer, 1963). The four general functions of water in plants are:

1. It is the major constituent of physiologically active tissue.
2. It is a reagent in photosynthesis and in hydrolytic processes such as starch digestion.
3. It is the solvent in which salts, sugars, and other solutes move from cell to cell and organ to organ.
4. It is essential for the maintenance of the turgidity necessary for cell enlargement and growth.

Vegetative growth is particularly sensitive to water deficits because growth is closely related to turgor and loss of turgidity stops cell enlargement and results in smaller plants. The root-shoot ratio, thickness of cell walls and amount of cutinization lignification are often increased by water stress. Water stress in plants causes

premature closure of stomata which reduces water loss, but stomatal closure also interferes with the entrance of carbon dioxide which is necessary for photosynthesis. Plant water stress reduces photosynthesis directly because dehydrated protoplasm has a lowered capacity for photosynthesis. Various biochemical reactions are often changed by water deficits (Kramer, 1963).

The rate of water absorption into plants is controlled by rate of water loss, the extent and efficiency of root systems, and by environmental factors such as soil aeration, soil temperature, concentration of soil solution, and the free energy status of the soil moisture. The transpiration rate is determined by leaf area and leaf structure, extent of stomatal opening, and by those environmental factors which affect the steepness of the vapor pressure gradient from leaf to air, such as temperature and vapor pressure of the atmosphere. There is always a tendency for water absorption to lag behind water loss because of resistance to water movement in the plant, primarily in the roots where water must cross the relatively compact layers of cells found in the epidermis, cortex, and endodermis. On sunny days the absorption lag results in development of temporary water deficits and measurable water stress, even in plants growing in well watered soil. These temporary water deficits are caused by removal of water from the plant tissue to make up the difference between water loss and water absorption, and are usually eliminated overnight when

water absorption exceeds water loss. As soil moisture is depleted water absorption becomes slower and slower and midday water deficits last longer and longer until permanent wilting occurs (Kramer, 1963).

Kramer (1963) recommends that plant water stress be measured rather than soil moisture because it probably occurs much more frequently than soil water stress. The methods of measuring plant water deficits listed by Kramer are water content, water deficit, relative turgidity, osmotic pressure, or diffusion pressure deficit.

The available literature concerning the effects of moisture stress on plants is tremendous. Research has been done in areas ranging from very specific study of the effects of stress on anatomy, to studies on the effects of stress on yield. Regarding the internal water balance of plants under stress Millar, Duysen, and Wilkinson (1968) found with barley that the leaf moisture characteristic curve (relative water content versus leaf water potential) remains the same for leaves of the same age growing in the same environment until the heading to maturity stage when it shifts to a higher leaf relative water content for a given leaf water potential. They found that barley stomates close at a water potential of about -22 bars and that leaf water potential increases basipetally with plant leaf position. In a soil with a moisture content near field capacity a difference of about 16.5 bars was observed between the top and bottom leaves on the same plant, while in soil

with a moisture content near the permanent wilting point the difference was only 5.6 bars between the same leaf positions.

Namken and Lemon (1960) studied the internal moisture relations of stressed corn using an electrical resistance method. They show that plant stem resistance measurements taken before 8:00 a.m. show a carry-over effect of moisture stress experienced by the plant during the preceding 24 hour period or longer. In contrast relative turgidity measurements of corn leaves taken at the same time do not show a marked carry-over effect of internal moisture stress. Turgor pressure decreases during the day and recovers at night but plants are often unable to recover full turgor pressure overnight after experiencing moisture stress during the day. The turgor status of plants at dawn reflects the atmospheric and soil moisture conditions affecting the plant during the preceding 24 hour period or longer.

Slatyer (1957) found that permanent wilting of leaves is associated with the point of zero turgor pressure. Also, his results indicate that the permanent wilting percentage of any one soil is determined by the osmotic characteristics of the plant under study rather than by any soil characteristic. He found permanent wilting with tomato, privet, and cotton respectively to be at 20, 38, 48 atm. In a different study Slatyer (1955) found that when comparing cotton, peanuts, and grain sorghum, grain

sorghum had the best developed root system and most effective internal control over transpiration, whereas cotton was least well equipped.

Gardner and Nieman (1964) investigated the lower limit of water availability to plants. They found that leaf suction is not affected until soil suction exceeds 2.5 bars, which is approximately the suction at which the unsaturated conductivity of the soil has become low enough to restrict water movement significantly. Leaf suction reaches progressively higher peaks during the light period as the soil suction increases and then drops back to a value approximately equal to the soil suction at night. A leaf suction value of about 11 bars causes marked wilting in many plants. Closing of stomata and reduction in transpiration rate occur at approximately the same value of leaf suction at which very definite wilt symptoms appear. Actual transpiration rate is reduced below the potential rate at soil suctions much less than 15 bars. When leaf suction is less than the critical value at which the stomata close, soil suction has little effect upon transpiration. Above this critical leaf suction, increasing soil suction reduces the transpiration rate but does not eliminate transpiration completely. The critical leaf suction cannot be universally related to any particular soil suction since it is a function of both plant and soil properties.

Gardner and Ehlig (1965) define the state of water in plant leaf cells under equilibrium conditions as

$$\psi = \psi_{\pi} + \psi_p + \psi_m$$

where ψ is the total potential, ψ_{π} is the osmotic potential component, ψ_p the pressure potential component (turgor pressure) and ψ_m is the component due to adsorption forces such as those in the cell wall. Adsorption potential is usually neglected and the equation is reduced to $DPD = OP - TP$ where DPD is diffusion pressure deficit, OP is osmotic pressure, and TP the turgor pressure. The authors develop further equations relating water potential, osmotic potential, pressure potential, and relative water content based on two simple assumptions and go on to measure these quantities in cotton, sunflower, pepper, and birdsfoot trefoil. They found marked change in the modulus of elasticity of the leaves at a turgor pressure of about 2 bars, corresponding to a water potential of about -12 bars, and explained permanent wilting in terms of variation in elastic modulus.

Soybean leaf water potentials were found to decrease an average of 9 to 10 bars as a result of daily atmospheric demand during the vegetative stage by Brady, Powers, Stone, and Goltz (1974). Also, soybean leaf water potential was as responsive to changes in soil water during the podding stage as during the vegetative stage. Millar, Duyssen, and Norum (1970) found a change in the elasticity of barley leaves at about 2 bars pressure potential and -12 bars

water potential. First visible wilting of leaves was observed between 75 and 80% relative water content. Also, there was a shift to lower relative water content and water potential values as plants became older when the soil matric potential decreased. This is explained by increased root density and higher evaporative demands on older plants. Increased soil density due to compaction causes leaf water potential to decline more rapidly during light and increase more slowly during dark intervals because of restricted root growth (Morris and Daynard, 1978). Leaf area index of corn is also reduced by compaction.

Photosynthesis rates are very much affected by low leaf water potentials due to water stress. Boyer (1970) found that soybeans are unaffected by dessication until leaf water potentials are below -11 bars, whereas rates of photosynthesis in corn are inhibited whenever leaf water potentials drop below -3.5 bars. Differences in photosynthetic behavior can be attributed solely to differences in stomatal closure down to leaf water potentials of -16 bars in soybeans and -10 bars in corn. Corn generally has a higher rate of photosynthesis than soybeans during dessication, but inhibition of photosynthesis begins at higher levels with corn. Inhibition of photosynthesis in both species does not occur unless stomatal closure and reduction in transpiration occur. Initial inhibition of photosynthesis can be well correlated with stomatal behavior. Estimates of stomatal diffusive resistance indicate that

resistance increases whenever rates of photosynthesis decrease for both corn and soybeans.

Brix (1962) found with loblolly pine that leaf DPDs up to 4 atmospheres do not affect the rate of photosynthesis, but higher DPDs result in a large reduction. At a leaf DPD of 11 atmospheres net photosynthesis ceases and higher DPDs have no further effect. Reduction in photosynthesis of tomato with increasing water stress is similar to that of loblolly pine seedlings, except that a leaf DPD greater than 7 atmospheres is required before photosynthesis is reduced and a DPD of at least 14 atmospheres is necessary to reduce the rate to zero. Close relationships between decreases in rates of transpiration and photosynthesis with increasing water stress are shown. Water stress affects photosynthesis chiefly by increasing the diffusion resistance to CO_2 , and by affecting the stomatal openings and the resistance of the mesophyll cells to CO_2 diffusion. Regarding recovery of growth and photosynthesis from water stress, loblolly pine seedlings with a leaf DPD of 27 atmospheres or below will recover, whereas plants with a higher leaf DPD will die. Lower leaves of tomato plants subjected to a leaf DPD of 18 atmospheres do not recover following rewatering, but younger leaves recover readily. In general, the first increase in photosynthesis after rewatering is rapid, but the subsequent recovery is slow and some irreversible damage, especially of the lower leaves, may prevent complete recovery. A decrease in the water absorbing or water

conducting capacity of the root system during wilting results in a slow rate of decrease of the water stress in the leaves following rewatering of the soil.

The rate of photosynthesis and translocation of labelled assimilates in wheat plants placed under water stress 15-20 days after anthesis was followed by Wardlaw (1967). Progressive reduction in the rate of photosynthesis occurs once wilting begins. The rate of photosynthesis of wilted leaves is lower than that of turgid leaves even when light is limiting. The difference in rate of photosynthesis between fully turgid and wilted leaves is not reduced by increasing CO₂ concentration. The authors were unable to find a decrease in the velocity of assimilate movement with the wilting of leaves under water stress. In studying the effects of both temperature and plant water stress on photosynthesis, diffusion resistance, and leaf water potential in wheat, Frank, Power, and Willis (1973) showed that stomatal closure of stressed plants is affected by both leaf position and age. Closure occurred at -13, -13, and -15 bars leaf water potential at tillering and at -18, -17, and -26 bars at heading for temperatures of 10, 18, and 27°C, respectively. Stomatal diffusion resistance recovered to prestress levels within 2 hours, except at grain-filling, when recovery was incomplete after 48 hours. Recovery of photosynthesis is related to recovery of stomatal diffusion resistance at tillering and heading, except that photosynthesis never fully recovers to prestress levels.

Photosynthesis of plants stressed at grain-filling does not recover due to stress-induced senescence.

Using tobacco Redshaw and Meidner (1972) studied the relative importance of the stomata in restricting CO_2 uptake under conditions of water stress. They found that air-phase resistances (stomata) can account for only half the reduction in the rate of photosynthesis. Experiments in which air was passed through the leaf showed that water stress also restricts CO_2 fixation within the leaf itself. Fischer, Hsaio, and Hagan (1970) showed a marked after effect of water stress on the light opening ability of stomata of tobacco wilted 2 to 4 days. The ability of the stomata to open in light is depressed and complete recovery from this depression requires two to five days after rewatering. In some cases over-recovery was observed; this was probably related to a physiologically younger condition of leaves of stressed plants following turgor recovery. In beans similar stresses cause after-effects smaller in magnitude but qualitatively similar to those in tobacco. In both tobacco and beans the magnitude of the after-effect is approximately proportional to the leaf-water deficit attained immediately prior to rewatering.

Carbon dioxide exchange in water-stressed sorghum was studied by Shearman, Eastin, Sullivan, and Kinbacher (1972). Carbon dioxide uptake in light decreases to near the compensation point at water potentials near -25 atmospheres. Leaf resistance to gaseous exchange is high at this point. Evolution of CO_2 in light occurs as stress

becomes greater, and dark evolution of CO_2 is higher at water potentials near -20 atmospheres than in either the more severely stressed or nonstressed condition.

Plaut and Reinhold (1965) followed the passage of ^{14}C through stressed and control bean seedlings after supply of (^{14}C) sucrose to a primary leaf. When the interval between ^{14}C application and assessment of transport exceeded 45 min, the amount of ^{14}C which moved out of the leaf was found to be much reduced by water stress. With increasing length of translocation interval the disparity in upwards transport between stressed and control plants increased. Within an hour of irrigation of wilting plants, a sharp acceleration in downwards transport was observed as compared with both fully irrigated and nonirrigated controls. With Ponderosa Pine seedlings, assimilation, distribution, and root exudation of ^{14}C is inhibited during water stress (Reid, 1974). Six days after $^{14}\text{CO}_2$ introduction into the pine seedlings essentially no ^{14}C was detected in the roots of plants maintained at solution potentials of -5.5 bars or below.

The effect of moisture stress on leaf anatomy and water-use efficiency on peas was determined by Manning, Miller, and Teare (1977). They found water-use efficiency to be positively correlated with moisture regime, plant height, leaf area, and seed yield. They defined water use efficiency as:

$$\text{WUE} = \frac{\text{grain yield or total dry matter yield (g)}}{\text{water used (kg)}}$$

Declines in water use efficiency are accounted for by reduction in total plant growth (plant height, leaf area, and seed yield) during moisture stress. Thickness of leaf blades is significantly less in plants grown at 100 to 80% and 40 to 20% field capacity than in those grown at 80 to 40% field capacity. This appears to be regulated by the size of the palisade and spongy mesophyll cells of peas. Intercellular air spaces and substomatal cavities of plants grown at 40 to 20% of field capacity are much reduced and had less xylem area and fewer xylem elements in the primary vascular bundle than plants grown with higher soil moisture levels. Stomatal density was found to increase with increasing soil moisture stress. With corn, ultrastructural changes are correlated with leaf water potential, relative water content, and abscisic acid levels in the leaf (Giles et al., 1974). Mesophyll cells are more prone to damage than bundle sheath cells at a leaf water potential of -18.5 bars. Tonoplast breakdown and cell disruption occurs in 25% of the mesophyll cells and on rewatering, these disrupted cells do not recover.

The effects of soil moisture stress on plant growth and yield have been examined by numerous researchers. Bole and Dubetz (1978) in studying wheat found that soil water stress reduces yields by reducing the number of spikes per

plant and, to a lesser but significant degree, the number of kernels per spike and the average kernel weight. Musick, New, and Dusek (1976) showed that depletion of soil water in the 0 to 120 cm depth to -15 bars potential results in relative yields of 73% for grain sorghum, 80% for winter wheat, and 47% for soybeans as compared to adequately irrigated treatments.

In studying the effects of soil water levels at various growth stages on growth and yield in peas, Miller, Manning, and Teare (1977) showed that maintaining a high watering level during pod filling or flowering results in highest seed yield. At constant water levels total dry matter, seed yield, seed size, number of seeds per plant, watering level, and water used are positively related. Plant height is significantly reduced with decreasing water levels for constant water regimes. At variable water regimes taller plants are evident when water is high during flowering to early pod filling. Hoffman, Jobes, Hanscom, and Maas (1978) found with pinto beans that growth and pod yield of bean plants exposed to a hot, dry environment during the vegetative stage are comparable with those plants continuously exposed to a cool, humid environment. Exposure to a hot dry environment during flowering, however, reduces yields significantly, but not to levels for plants exposed continuously to a hot, dry environment. Sionit and Kramer (1977) in studying the soybean show that plants stressed during flower induction and flowering produce fewer flowers,

pods, and seeds than controls because of a shortened flowering period and abortion of some flowers. In their study stress during early pod formation caused the greatest reduction in number of pods and seeds at harvest. Yield as measured by weight of seeds was reduced most by stress during early formation and pod filling. Doss, Pearson, and Rogers (1974) in Alabama found the same results. They found more bean production is obtained from water applied after full bloom than earlier, and conclude that the pod-fill stage is the critical time for adequate water for maximum yields.

In summary, water is the most critical factor affecting plant growth. Less than optimum amounts result in reduced growth and yield or in plant death. Excessive amounts cause oxygen stress which also reduce growth and yield or if severe kill the plant. Water moves through the soil and the plant due to potential differences. In the plant this is called diffusion pressure deficit. During transpiration, the vapor pressure of water in leaves decreases very slowly as DPD increases. During plant water stress turgor pressure decreases, stoma close, and leaves dehydrate. Numerous studies have defined the leaf water potentials at which stomates close for a variety of plant species. Leaf water contents have been shown to be greater on leaves near the soil surface than those higher on the plant. Permanent wilting points for plant species have been determined both in terms of soil and plant water

potentials. Negative effects of water stress on rate of photosynthesis, translocation of assimilates, and CO_2 uptake (due to closing of stomata) have been shown. Both detailed studies of the effects of water stress on plant anatomy, and macroscopic studies of the effects of water stress at plant growth stages on yield have been done. Anatomical studies show increasing stomatal density with increasing moisture stress and general disruption or breakdown of cells. Yield related studies show yield reduction with less than optimum water. Studies with peas, pinto beans, and soybeans show that water is very critical in relation to final yield at the flowering and pod filling growth stages.

Evapotranspiration

Evaporation is the conversion of water into vapor and its subsequent transfer from a soil or water surface to the atmosphere; transpiration is evaporation from a plant surface. It is extremely difficult to measure evaporation separately from transpiration in a soil in which plants are growing; also, evaporation probably cannot be influenced independently of transpiration within a plant community. The two processes are therefore considered together and combined under the name evapotranspiration (Taylor and Ashcroft, 1972).

An excellent discussion on methods of estimating evapotranspiration is contained in the text Physical

Edaphology by Taylor and Ashcroft (1972). Their discussion includes both theoretical methods, such as aerodynamic or mass transfer methods and energy balance methods, combination methods including both aerodynamics and energy balance, and empirical methods of estimating evapotranspiration. Among the empirical methods discussed are included the Dalton formula, Penman formula, Thornthwaite formula, Lowrey-Johnson method, and methods using open pan evaporation data.

An extensive review of using pan evaporation as a method of estimating evapotranspiration is given by Pruitt (1966). Evaporative coefficients for using pan evaporation have been worked out by Ashcroft and Taylor (1953) for several crops. These coefficients vary with the crop variety, the crop's stage of maturity, and the fraction of soil surface covered by the crop. Coefficient tables for beans near maturity vary from .6 to 1.25 depending on the author.

The fraction of soil surface covered by the crop can be expressed as leaf area index which is leaf area divided by land surface area. The correction coefficients are usually determined by a controlled experiment in a locality where evapotranspiration from field plots and evaporation from a pan are simultaneously measured. The correction coefficient is the slope of the line found by plotting actual evapotranspiration versus pan evaporation (Taylor and Ashcroft, 1972).

The relationship between transpiration, the internal water relations of plants, growth rate, and yield of plants has been studied by numerous authors. Ehlig and Gardner (1964) report that below a characteristic diffusion pressure deficit for each plant, transpiration rate is proportional to potential transpiration. Above the value, the transpiration rate decreases rapidly at first and then more slowly with increasing DPD. Using lysimeters, Hanks, Gardner, and Florian (1969) showed a strong linear relationship between evapotranspiration and yield. With 10 cm of additional water available for growth in the lysimeter as compared to soil in the field, evapotranspiration from grain sorghum increased 50% and yields were doubled. Rawitz (1969) found a linear relationship between the specific transpiration rate and growth rate. Using snap beans (*Phaseolus vulgaris* L., var. Brittle Wax) he determined that growth rate fell somewhat more rapidly than transpiration in the high-potential range and then reversed itself in the low potential range. Using maize Hillel and Guron (1973) found a threshold evapotranspiration of 250-300 mm/growing season below which production is negligible and above which production rises linearly with the amount of water applied. They conclude that a 'wet' irrigation regime, permitting a crop to transpire at a rate approaching the climatically induced potential, and simultaneously preventing the occurrence of moisture deficits can help realize the full productivity of a crop.

Stresses Affecting Plants During Flowering
and Pod Filling

Flowering and pod filling are the most critical growth stages relating to bean yields. Hoffman, Jobes, Hanscom, and Maas (1978) found that yields of pinto beans are significantly reduced by exposure of the plants to a hot dry environment during flowering and early pod filling. Their results show that cool humid conditions promote pod production whereas a hot dry environment stimulates vegetative growth. They conclude that a hot dry environment during flowering and early pod filling forces the metabolic processes of the plant into shoot growth rather than pod production. Sionit and Kramer (1977) and Doss, Pearson, and Rogers (1974) found yield to be critically affected by drought stress at flowering and pod filling.

Davis, in his thesis, "The Effect of Temperature, Humidity, Fertilizer, Soil Moisture, and Leaf Area on the Set of Pods and Yield of White Pea Beans," 1943, found significant relationships between percent set of pods and minimum relative humidity and maximum temperature. He concludes that maximum air temperature is the most important climatic factor affecting blossom development of the field bean. He found a two percent reduction in the percent of pods that set for each degree of temperature above 75°F. Approximately 57% of the blossoms should set pods if the average maximum temperature for two successive days during the blooming period did not exceed 75°F. He developed an

equation to predict percent pod set as a function of average maximum temperature for two successive days.

$$y = -1.8X + 192$$

where X is the average maximum temperature for two successive days and y the percent set of pods. The standard error of prediction was 3.82, the percent error of the mean 7.62, and the correlation coefficient $-.3078$.

Plant Water Stress and Irrigation Scheduling

Because of the severe effects water stress has on plant growth and yield, irrigation timing and amount of water applied are critical. For ideal irrigation management, water should be applied before stress begins and amount of water applied should be minimized to conserve water. In order to schedule irrigation and decide how much to apply, concepts of soil moisture and plant stress must be used.

Franzmeier, Whiteside, and Erickson (1960) use the concept of readily available water capacity (RAWC) to characterize water in the soil available for plant growth. They define RAWC as the difference between the water content of the soil at field capacity and the lower turgor pressure percentage, or the difference in weight percentage between the water content of an undisturbed soil sample at 0.06 atmospheres tension and that of a disturbed sample at 6 atmospheres tension. Lower turgor pressure percentage is defined by Stolzy and Erickson (1959) as the water content

of the soil when the water is held at the highest tension that will still allow a plant to maintain full turgidity. They found that the water content of air-dried and sieved soil samples at 6 atmospheres tension was a reliable estimate of this condition. The concept of using 60% of the total water held between .06 atmospheres and 15 atmospheres tension as the point below which plant stress begins was discussed in personal communication with Dr. A. E. Erickson of Michigan State University. With this concept, plant stress increases exponentially as percent of total water held between .06 atmospheres and 15 atmospheres drops linearly below 60%.

A stress day index concept of plant stress for use in irrigation scheduling was developed by Hiler, Howell, Lewis, and Boos (1974). Stress day index (SDI) is defined as the product of a crop susceptibility factor (CS) and a stress day factor (SD). Values of (CS) depend on species and stage of development and indicate the plant's susceptibility to a given water deficit at different growth stages. The (SD) factor indicates plant water deficit. They accomplish irrigation timing by irrigating when the daily SDI reaches a predetermined critical value. Their concepts were tried with three different characterizations of stress deficit: soil water potential, leaf water potential, and percentage available soil moisture depleted.

Slightly different water concepts for planning irrigation and drainage systems are advanced by Campbell

and Lembke (1975). They replace the field capacity concept with "retention limit," which they define as the desorption soil water potential at which the leaching rate line intersects the soil drainage rate curve. Wilting percentage is replaced with the "extraction limit" which is defined as the desorption soil water potential at which plant growth is first restricted by water stress. Soil water outside these limits is either lost through drainage or results in retarded plant growth. Water held between the two limits is not considered uniformly available for plant growth.

Irrigation schedules based on pan evaporation and growth stages in winter wheat are discussed by Prihar, Khera, Sandhu, and Sandhu (1976). They compare different ratios of a fixed amount of irrigation water (IW) to pan evaporation, PAN-E (cumulative evaporation from U.S. Weather Bureau Class A pan less rain since previous irrigation). Their results indicate that irrigating wheat, sown after a presowing irrigation, on the basis of IW/PAN-E of 0.75, irrespective of growth stage, offers a practical means to economize irrigation water without reduction in yield.

In a study of proper irrigation timing to maximize soybean yields, Brady, Stone, Nickell, and Powers (1974) found that one-third to one-half the water necessary for full-season irrigation produced equally good yields if applied during the podding stage of growth. The most efficient use of water occurs when irrigation is initiated

in the podding stage or at the 60 to 65% soil-moisture-depletion level in the vegetative or flowering stages.

Models

Considerable research in Soil Physics for many years has been devoted to development of mathematical equations to describe water movement in soils and plants. In fact instruction in Soil Physics often starts with the equation for isothermal steady state water flow in porous media which is known as Darcy's law. This equation can be written as

$$J_w = K_w \frac{\partial h}{\partial s}$$

where J_w is the water flow density, K_w is the hydraulic conductivity, and $\frac{\partial h}{\partial s}$ is the hydraulic potential gradient. With the advent of the digital computer the mathematics describing soil water movement, water movement in plants and evapotranspiration can be quickly calculated. This has led to the construction of computer simulation models where attempts are made to simulate what actually occurs in nature by making many calculations on a day to day basis. There are currently many articles discussing mathematical or computer simulations of soil water movement, water uptake by roots, water movement in plants, evapotranspiration, soil-water-plant-atmosphere balances, and plant yields as affected by all of the previous. It is anticipated that many more computer simulation models will be made in the next few years.

Examples of numerical solutions to water movement in soils can be found in such works as those of Wang and Lakshminarayana (1968), Zaradny (1978), Rowse and Stone (1978), Rowse, Stone, and Gerwitz (1978), Beese, Van Der Ploeg, and Richter (1977) and James and Larson (1976). Wang and Lakshminarayana (1968) developed a numerical technique to simulate water movement through unsaturated nonhomogeneous soils and programmed it on an IBM 7094. They use the basic equation of Richards (1931) which describes flow of water through an unsaturated porous medium:

$$\frac{\partial \theta}{\partial t} = \nabla \cdot (k \nabla \phi)$$

where θ is soil water content on a volume basis, t is time, K is capillary conductivity, and ϕ is a potential function. Zaradny (1978) modeled the same thing on the Polish computer, Odra 1204, but concluded that the boundary condition of water content being constant at the supply boundary can bring erroneous conclusions. Rowse and Stone (1978) describe a mathematical simulation model which enables the flow of water, water content, and matric potential to be calculated for any depth in an uncropped soil. Their model is based on a numerical solution to the flow equation and requires data describing the weather and soil hydraulic properties. They assume the soil to consist of a stack of horizontal layers, and from hydraulic properties calculate instantaneous

flow rates between adjacent layers. Rate of evaporation from a wet soil surface is estimated from the rate of evaporation from an open water surface, which in the model is assumed to follow a half sine wave during daylight hours.

Rowse, Stone, and Gerwitz (1978) improved the model for a fallow soil of Rowse and Stone (1978) by including water extraction by plant roots. Using the equation

$$S = \Delta z L (h_s - h_p) / (R_s + R_p)$$

for extraction of water by plant roots in

$$\frac{d\theta}{dt} = \frac{d}{dz} \left(D \frac{d\theta}{dz} + K \right) - S(z, t)$$

they were able to get good results between the model and field studies. In the first equation the terms are:

S = extraction of water by plant roots

h_s = bulk soil pressure head

h_p = plant water potential

R_s = soil resistance associated with unit length of root

R_p = plant resistance associated with unit length of root

The terms of the second equation are:

θ = volumetric water content

t = time

D = soil water diffusivity

z = depth

K = hydraulic conductivity

S = extraction of water by plant roots

Beese, Van Der Ploeg, and Richter (1977) carried out a 218 day experiment on fallow loess soil to compare actual moisture contents with numerical solutions to the unsaturated flow equation

$$\frac{\partial \theta}{\partial t} = \partial (K \frac{\partial h}{\partial z}) / \partial z$$

θ is the volumetric moisture content, t the time, K the capillary conductivity, h the hydraulic head, and z the depth. The purpose of their study was to see if the unsaturated soil moisture flow equation does describe observed soil moisture behavior for such a long period. They observed that their calculated soil suction values for all depths deviate less than 15% from measured ones.

James and Larson (1976) modeled infiltration and redistribution of soil water during intermittent application. Their objective was to use physically based equations to develop an overall model for water movement into and within the soil for intermittent water applications. The Green and Ampt infiltration equation as modified by Mein and Larson (1971), the infiltration relationships of Rubin, Steinhardt, and Reiniger (1964) and the redistribution equation of Gardner, Hillel, and Benyamini (1970) are the basic equations for their model. The model neglects evapotranspiration losses. The model is successful in predicting the amount and timing of both surface and subsurface runoff, the volume of water stored in the soil zone, and

soil moisture profiles for intermittent water application with a wide range of application rates. The model consistently overpredicts the infiltration rate when application rate exceeds the infiltration capacity of the soil.

Models of soil water uptake by plant roots include those of Hillel, Van Beek, and Talpaz (1975), Hillel, Talpaz, and Van Keulen (1976), and Slack, Haan, and Wells (1977). The model of Hillel, Van Beek, and Talpaz (1975) is a microscopic-scale model of soil water uptake and salt movement to plant roots. Inputs to the microscopic model are soil suction and conductivity function, the soil solution's content and concentration, root density and permeability, and the required uptake rate (whether constant or diurnally fluctuating). The output gives the time-dependent drawdown of matric and osmotic potentials in the immediate vicinity of the root, the gradients and flow rates of water and solutes in the soil, and the plant water potentials needed to maintain different uptake rates.

The equation used for radial flow to a line sink such as an individual root is

$$\frac{\partial \theta}{\partial t} = \left(\frac{1}{r}\right) \left(\frac{\partial}{\partial r}\right) [rK(\theta) \left(\frac{\partial \phi}{\partial r}\right)]$$

where r is the radial distance from the line sink, θ is volumetric water content (wetness), t time, z depth, $K(\theta)$ hydraulic conductivity (a function of wetness), and ϕ matric potential (pressure) head. The transfer of water

from soil surrounding each root into the root itself, and thence to a point where all roots converge and where the plant emerges from the soil with a single potential is described by an analogy of Ohm's law:

$$q_{\text{ex}} = (\phi_m + \phi_o - \phi_c) / (R_s + R_r)$$

q_{ex} is the volume of water extracted per unit time from a unit volume of soil, ϕ_m is the matric potential of some finite ring of soil immediately surrounding any particular root, ϕ_o is the osmotic potential of the soil solution in the same ring of soil which has a hydraulic resistance R_s ; and R_r is the hydraulic resistance of the root.

The macroscopic model of Hillel, Talpaz, and Van Keulen (1976) uses soil and root system hydraulics, initial water content and solute concentration, density and distribution of active roots in the soil profile, and the climatically imposed evapotranspiration rate with its diurnal fluctuation for inputs. The output provides the pattern of soil moisture depletion and of water potential distribution in the plant as needed to maintain various transpiration rates, as well as the flow of water and salt through the bottom of the root zone. The basic equations for the model are:

1. For transient state flow of water in a stable and uniform zone of the soil:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left[K(\theta) \frac{\partial (\phi_m - z)}{\partial z} \right] - S_w$$

θ = volume wetness

t = time

z = depth

$K(\theta)$ = hydraulic conductivity

ϕ_m = matric potential head

S_w = sink term for roots

2. Rate of extraction of water from a unit volume of soil

$$S_w = \frac{\phi_{\text{soil}} - \phi_{\text{plant}}}{R_{\text{soil}} + R_{\text{roots}}}$$

ϕ_{soil} = total potential of soil water

$\phi_{\text{soil}} = \phi_m + \phi_g + \phi_o$

ϕ_m = matric potential

ϕ_g = gravitational potential

ϕ_o = osmotic potential

$R_{\text{soil}} = 1/BKL$

R_{soil} = hydraulic resistance to flow in soil towards roots

B = constant

K = hydraulic conductivity

L = total length of active roots in the unit volume of soil.

3. Flow rate (q_r); delivered by the roots from any particular layer is in the soil to the crown.

$$(q_r)_i = \frac{(\phi_s)_i - \phi_c}{(R_r)_i + (R_s)_i}$$

$(\phi_s)_i$ = soil moisture potential

$(R_r)_i$ = resistance of the roots

$(R_s)_i$ = hydraulic resistance of the soil

ϕ_c = crown water potential

4. Total extraction rate (Q):

$$Q = \sum_{i=1}^n \frac{(\phi_s)_i - \phi_c}{(R_r)_i + (R_s)_i}$$

Both the microscopic and macroscopic models were written in IBM S/360 CSMP language.

The model of Slack, Haan, and Wells (1977) describes uptake of water by plant roots as a function of leaf and soil water potentials and is used to estimate transpiration from corn grown in a controlled environment under soil drying conditions. The basis of the model is a combination of the solution to the general equation of flow for an unsaturated soil and an equation for flow of water through a plant:

$$F = \frac{\psi_r - \psi_L}{R}$$

where F is the rate of water flow between the root surface and the leaf surface, ψ_r and ψ_L are the water potentials at these surfaces, respectively, and R is resistance to flow within the plant.

A number of authors have modeled soil water movement in the soil-plant-atmosphere system. Cowan (1965), Nimah and Hanks (1973a, 1973b), Hansen (1975), Dutt, Shaffer, and Moore (1972), and Anderson, Johnson, and Powers (1978) modeled these phenomena. The paper of Cowan (1965) reviews mathematical descriptions of water movement, factors involved in transpiration, and the internal impedance of a crop. For steady rate of water transport Cowan uses the equation of van den Honert (1948)

$$\frac{dm}{dt} = \frac{\psi_1 - \psi_2}{z_{12}} = \frac{\psi_2 - \psi_3}{z_{23}} = \text{etc.}$$

where $\psi_1 - \psi_2$, $\psi_2 - \psi_3$ are the potential differences across successive components of the system, and z_{12} , z_{23} are the corresponding impedances to water flow across the components. Rate of transpiration per unit area of crop is expressed as

$$E = \frac{D_v (c_o - c)}{p (L_a + L_s)}$$

when c_o and c are the vapour concentrations at the evaporating surface and at an arbitrary height above the crop respectively, D_v is the coefficient of molecular diffusion of water vapor in air, p is the density of liquid water and L_s and L_a are the effective lengths of the paths of vapour transport through the stomata and away from the crop as defined by Penman and Schofield (1951). Rate of

transpiration per unit area of the crop is related to the flow of liquid water through the plants by writing

$$E = \frac{t_r - \psi}{z}$$

where t_r is the soil water potential at the root surface, ψ is the water potential in the leaves of the crop, and z is the internal impedance of unit area of the crop to the transport of water. Cowan (1965) presents an approximate solution of the differential equation describing soil moisture flow towards a plant root which is absorbing water at a periodically varying rate and combines this with hypothetical plant characteristics to form a model of the hydraulic behavior of a crop. The characteristics specified by the model are the depth of penetration of roots into the soil, the density of rooting (length of root per cm^3 of soil volume), the internal resistance of the crop to the flow of water and the critical value of leaf water potential which is associated with stomatal closure. The level of leaf water potential in relation to environmental conditions, and the rate of transpiration from the crop when leaf water potential falls to the critical value, are determined by the 'supply function' which is a measure of the ability of the soil-crop system to supply water to the evaporating surfaces within the leaves.

Nimah and Hanks (1973a, 1973b) field tested their model of soil, plant, and atmospheric interrelations. The

model and its numerical solution were developed to predict water content profiles, evapotranspiration water flow from or to the water table, root extraction, and root water potential under transient field conditions. Soil properties needed for the model are hydraulic conductivity and soil water potential and functions of water content. Plant properties needed are rooting depth and limiting root water potential. Climatic properties needed are potential evaporation and transpiration. The model is similar to previous models discussed in that the general flow equation for one dimension with modification for plant root extraction is used. The model was field tested in 1970 and 1971 using alfalfa (*Medicago sativa* L.). The results show best agreement between actual and computed water content-depth profiles 48 hours after any water addition, and poorest agreement right after irrigation.

Using DYNAMO II, a continuous simulation language where the basic tool is Euler integration, Hansen (1975) constructed a model of water state and transportation in the soil-plant-atmosphere system. In the model, vertical water flux in the soil is based on Darcy's law for flow in porous media. Water flow is based on Gardner's model (1960) for water flow to single roots, but modified to steady rate. The physiological plant parameters are based on experimentally derived functions from experiments with Italian rye grass (*Lolium multiflorum*) in growth chambers. The atmospheric part of the model is based on a model of

Monteith (1965). Simulation runs were made with a fixed time interval of 0.001 day and behavior of the model was demonstrated by a growth period of 20 days without precipitation.

Technical Bulletin 196, "Computer Simulation Model of Dynamic Bio-Physicochemical Processes in Soils," from the Agricultural Experiment Station of the University of Arizona, by Dutt, Shaffer, and Moore (1972) includes a model of infiltration and redistribution of soil water and evapotranspiration. The model uses the moisture flow equation corrected for water consumption by roots already discussed with several other models, and the Blaney-Criddle formula to estimate the total extraction rate, U , due to crop consumptive use. Boundary conditions are employed at the soil surface to simulate infiltration, evaporation, or zero flux. The model is written in FORTRAN IV and is a subroutine to the overall model presented in the bulletin which also considers (1) nitrogen transformations including hydrolysis of urea-N, immobilization of $\text{NH}_4^+\text{-N}$, mineralization of organic-N, and immobilization of $\text{NO}_3^-\text{-N}$; (2) changes in the solute concentration of soil water due to ion exchange solubility of gypsum and lime (CaCO_3), and dissociation of certain ion pairs; and (3) nitrogen uptake by crops.

The model of Anderson, Johnson, and Powers (1978) was developed to simulate the moisture balance on an agricultural watershed, including interception, infiltration, surface depression storage, surface runoff, soil moisture

redistribution, deep percolation, and evapotranspiration. Rain gauge chart data are used for total rainfall and rainfall intensity, and the Penman equation is used for predicting potential evapotranspiration. Maximum and minimum potential interception of precipitation are determined as linear functions of crop leaf area index. Storage of intercepted precipitation is allowed up to a maximum potential value of crop leaf area index. A subroutine for drainage and soil moisture redistribution is included in the model. The authors were able to get correlations of 0.8 between measured and predicted surface runoff depths for individual events, and 0.91 between predicted soil moisture in the root zone and bi-weekly measurements for a 4 year period.

There are a number of modeling papers in the literature concerned with evaporation, transpiration, or both. Papers by Gardner and Hillel (1962), Staple (1974), Black, Gardner, and Thurtell (1969), and Hillel (1975) discuss equations to predict evaporation from a bare soil. Changes in available water under dry-land wheat are estimated from evaporation and rainfall in papers by Fawcett and Carter (1973) and Fitzpatrick and Nix (1969). In a later paper Fawcett and Carter (1974) use a regression equation to relate the potential transpiration function (T/E_o) with the yield of tops, week of sowing, and available fallow moisture. Saxton, Johnson, and Shaw (1974) constructed a digital model of daily actual evapotranspiration and soil moisture from inputs of daily potential evaporation and crop and soil

moisture characteristics. Molz and Remson (1970) developed a mathematical model describing moisture removal from soil by the roots of transpiring plants. Hanson (1976) modeled evapotranspiration from native rangelands. Ritchie's (1972) model predicted evaporation from a row crop with incomplete cover. An evapotranspiration model of Monteith (1965) was tested with snap beans by Black, Tanner, and Gardner (1970), and with soybeans and sorghum by Brun, Kanemasu, and Powers (1972).

The paper by Gardner and Hillel (1962) discusses a study with laboratory soil columns showing that the length of time a given evaporation rate can be maintained by the soil is in good agreement with an approximate solution of the isothermal equation for unsaturated flow. During the falling-rate period of drying, the evaporation rate was found to approach very nearly a function of the water content of the soil and to be nearly independent of the potential evaporation rate. Staple (1974) modified Penman's equation for potential evaporation by including in it the relative vapor pressure of partially dried surface soil. He used the modified equation to predict evaporative flux from drying soil as a boundary condition in the finite difference solution of the flow equation. His method gave satisfactory agreement in a 20 day test in which evaporation was measured from short columns of soil in a fallowed plot. Black, Gardner, and Thurtell (1969) measured evaporation, drainage, and changes in storage for a bare Plainfield sand in a

lysimeter under natural rainfall conditions. Their results show that cumulative evaporation at any stage is proportional to the square root of time following each heavy rainfall. The drainage rate was found to be an exponential function of water storage. By predicting these two relations from flow theory with knowledge of soil capillary conductivity, diffusivity, moisture retention characteristic, and daily rainfall data, they were able to predict water storage over the season in the top 150 cm to within .3 cm. Hillel (1975) designed a mechanistic numerical model to compare evaporation of soil moisture under steady versus fluctuating evaporativity. The model, written in IBM System/360 CSMP language, requires data on soil hydraulic characteristics and on potential evaporation. It calculates the rate and cumulative quantity of evaporation, as well as the change in profile water content and distribution, as functions of time. The results confirm experimental findings that the diurnal cycle of evaporativity causes nighttime resorption of moisture and hence an appreciable higher average wetness in the soil surface zone.

A regression equation relating the cumulative potential transpiration function (T/E_o) with the yield of tops, week of sowing and available fallow moisture under wheat was developed by Fawcett and Carter (1974). In earlier papers (Fawcett and Carter (1973) and Fitzpatrick and Nix (1969)) changes in available water under dry-land

wheat are estimated from rainfall and evaporation data using a simple budget model.

These papers express changes during the growing season of the potential evapotranspiration (E_t), relative to a measure of the potential evaporation from a free water surface (E_o), by the potential evaporation function (E_t/E_o). In the 1974 paper Fawcett and Carter use field data and multiple regression analysis to obtain a linear function of the form $y = mx + c$ relating the initial E_t/E_o at the week of sowing to the final E_t/E_o value at the week of crop maturity. T/E_o , the transpiration component, is found by subtracting the calculated evaporation component from the E_t/E_o value for a given week.

A digital model to compute daily actual evapotranspiration and soil moisture profiles from inputs of daily potential evaporation and crop and soil moisture characteristics was constructed by Saxton, Johnson, and Shaw (1974). Vertical soil moisture redistribution is computed with the one-dimensional Darcy equation for unsaturated flow utilizing reported moisture-tension and moisture-conductivity relationships (Melvin, 1970). Infiltration is calculated as the difference between observed watershed precipitation and runoff. Three major sequences are involved in the model: (a) calculating actual evapotranspiration and withdrawing it from the soil moisture, (b) adding infiltration to the soil moisture, and (c) redistributing the soil moisture. Interception evaporation, soil evaporation, and plant

transpiration are computed separately by several relationships; then these values are combined to provide daily actual evapotranspiration estimates.

Molz and Remson (1970) developed a mathematical model describing moisture removal from soil by the roots of transpiring plants. Their model uses a macroscopic extraction term in the one dimensional soil moisture flow equation. In a macroscopic approach, the flow to individual roots is ignored and the overall root system is assumed to extract moisture from each differential volume of the root zone at zone rate S . Their model describes both moisture removal by the plant and induced moisture movement through the soil. A numerical procedure based on the Douglas-Jones predictor corrector method is used to solve the model, which successfully compares with experimental data.

Evapotranspiration from native rangelands in the northern great plains is predicted in a model developed by Hanson (1976). The equation used in the model is:

$$ET_q = ET_p (K_p K_{sw}) + EV \dots$$

where

ET_q = daily evapotranspiration

ET_p = potential evapotranspiration per day

K_p = plant coefficient

K_{sw} = coefficient for limiting soil water

EV = evaporation from the soil and plants per day

Potential evapotranspiration is calculated according to an approximate energy balance method (Jensen et al., 1970) and from United States Weather Bureau Class A pan evaporation data. The approximate energy balance method requires daily solar radiation and mean daily air temperature. The model worked better with the approximate energy balance method than the Class A pan method for ET_p . The recommended parameter for computing ET_p by the pan method was 0.8.

A model for predicting evaporation from a row crop with incomplete cover was developed by Ritchie (1972). The model applies to a row crop canopy. Evaporation from the soil surface E_s is calculated in two stages: (1) the constant rate stage in which E_s is limited only by the supply of energy to the surface and (2) the falling rate stage in which water movement to the evaporating sites near the surface is controlled by the hydraulic properties of the soil. Evaporation from the plant surfaces E_p is predicted by using an empirical relation based on local data, which shows how E_p is related to E_o through the leaf area index. The model was used to obtain the total evaporation rate $E = E_s + E_p$ of a developing grain sorghum (*Sorghum bicolor* L.) canopy in Texas. Results agreed well with values for E measured directly with a weighing lysimeter.

Monteith's model (1965) of evapotranspiration was tested by Black, Tanner, and Gardner (1970) using snap beans (*Phaseolus vulgaris* L.). Monteith's model is written as:

$$E = E_p / (1 + (\gamma / (\gamma + s)) (r_c / r_a))$$

where

E = evapotranspiration (mm/day)

E_p = potential evaporation (mm/day)

γ = psychometric constant (mb/k)

S = slope of saturation water vapor curve (mb/k)

r_a = diffusion resistance of air layer from the leaf to Z

r_c = crop resistance (sec/cm)

Black et al. (1970) concluded that realistic models must consider soil evaporation and transpiration separately. They used Monteith's model to calculate transpiration (where the crop resistance was found from the measured stomatal resistance weighted by the leaf area index) once evaporation from the soil was considered to be either limited by the energy supply or capillary flow to the soil surface. The test of the model on snap beans resulted in a 4% overestimation of transpiration which was attributed to the inaccuracy of the estimate of the evaporation from the soil.

Brun, Kanemasu, and Powers (1972) also tested Monteith's model but used soybeans and sorghum. Soil evaporation is estimated as the net radiation below the crop canopy minus the soil heat flux. Stomatal resistance is determined with a diffusion porometer (Kanemasu et al., 1969). Potential evapotranspiration, soil evaporation, and transpiration rates are calculated by the model on an

hourly basis. The model showed that the proportion of water lost as transpiration is closely correlated to leaf area index (LAI) with transpiration being approximately 50% of the total evapotranspiration at a LAI of 2, and as much as 95% at a LAI of 4.

Many researchers have developed methods of predicting crop yield as a function of available water. Reviews of different methods are contained in papers by Lewin and Lomas (1974), and Neghassi, Heerman, and Smika (1975). Crop yield models are presented in papers by Hanks (1974), Rawitz and Hillel (1969), and Heapy, Webster, Love, McBeath, Von Maydell, and Robertson (1976).

Lewin and Lomas (1974) compare statistical methods and models of soil water balance for predicting wheat yield under semi-arid conditions. The statistical methods are those of Fisher (1924), Staple and Lehane (1954), Gangopadhyaya and Sarker (1965), Lomas (1972) and others. The models of soil-water balance referred to are those of Denmead and Shaw (1962), Dale and Shaw (1965), Baier and Robertson (1966) and Fitzpatrick and Nix (1969). The three statistical methods used in analyzing the effect of rainfall on wheat yield are (1) multiple regression; (2) principal components (Kendall, 1957); and (3) Fisher's orthogonal polynomial method (Fisher, 1924). The soil-water balance model used is one explained in detail in previous paper by Lewin (1972) and is summarized by: (1) 90% of the water extraction occurs in the 0-90 cm soil layer; (2) in

this layer daily water loss rate is linearly related to the water content, i.e., $dw/dt = a + bw$ where w = soil water content (percentage of dry weight) and dw/dt = soil water change per unit time (percentage per day); (3) the coefficients of the regression (a , b) are mostly related to the climate, and therefore change during the growing season; (4) the crop yield is inversely and linearly related to the length of time (expressed in days) that the soil-water in the main root zone decreased below a certain critical level. The three statistical methods and the simulation model gave good results in the arid zone, accounting in all cases for more than 70% of the yield variations. In areas of higher rainfall the statistical methods explained about 30% of the variations in yield, as compared to 50% of these variations that were accounted for by the simulation model.

Neghassi, Heermann, and Smika (1975) give a review of a number of different models of grain yield versus soil water and also discuss which equations are most successful with the data they collected. Models they mention or discuss include those of de Wit (1958a), Heady and Dillon (1961), Moore (1961), Flinn and Musgrave (1967), Dudley, Howel, and Musgrave (1971), Jensen (1968), Hall and Butcher (1968) and Anderson and Maas (1971). Their discussion separates models into model types which are asymptotic, additive, or multiplicative. From their own experiments they were able to correlate dry matter yield (DM) of winter wheat with either cumulative evapotranspiration (W_{et}) or

cumulative relative evapotranspiration (W_r) by equations of the form

$$DM = k_o + k_1 W_{et} + k_2 W_{et}^2$$

$$\text{and} \quad DM = r_o + r_1 W_r + r_2 W_r^2$$

Both linear and quadratic forms of the above equations were tested. The linear forms were found to be superior in explaining variation. The linear model which they found to best approximate grain yields (G) is

$$G = 232 + 1.27 DM_p + 0.91 N_t + 0.31 DM_F - 114M.$$

where

DM_p = the dry matter produced during the preceding fall
($kg \ ha^{-1}$)

DM_F = the final dry matter ($kg \ ha^{-1}$)

N_t = tillers per m^2

M denotes the number of days

$T_{max} \geq 27C$, and wind $U_a \geq 10$ Kph.

Hanks (1974) predicts plant yield, both total dry matter and grain, as a function of transpiration. His basic assumption is that the ratio of actual to potential dry matter yield is directly related to the ratio of actual to potential transpiration. The equation used is $Y/Y_p = T/T_p$ where Y_p is potential yield when transpiration is equal to potential transpiration, Y is yield, T_p is transpiration which occurs when soil water does not limit transpiration,

and T is transpiration in cm. This equation is derived from the equation of de Wit (1958b). $Y = mT/E_0$ where E_0 is average free water evaporation rate and m is a crop factor. Several different methods of computing transpiration were tried by Hanks with best results coming from the "on-off" relationship of Veihmeyer and Hendrickson (1955). The equation for this is $T = T_p$ if $SWS/AW > 0$ where SWS is the actual soil water storage in any given time and AW is the so-called amount of available water (the product of the depth of the root zone by the difference in volumetric water content between field capacity and wilting). If SWS equals 0 in the model there is no transpiration.

Computation in the model of Hanks (1974) proceeds on a day-to-day basis by using a simple accounting procedure to keep a running account of SWS , cumulative T_p , T , E , drainage, irrigation, rain, and stage of growth. At the end of each growth stage new values of E_p and T_p are selected according to the input conditions. At the end of the season, print-out contains cumulative T , E , irrigation, rain, drainage, total water use, T/T_p for each growth stage and relative grain and dry matter yields. Hanks found good fit of predicted versus measured dry matter yield on sorghum (*Sorghum vulgare* L.) in Colorado, corn (*Zea mays* L.) dry matter and grain yields in Israel, and corn grain yields in Nebraska.

Rawitz and Hillel (1969) compare four different indexes of soil moisture status to dry matter yield of

container-grown sunflowers and snapdragons. The indexes studied are (1) the minimum moisture content index, (2) the mean integrated moisture content index, (3) the mean integrated capillary suction index, and (4) the mean maximum capillary suction index. The minimum moisture content index is the minimum (i.e., pre-irrigation) soil moisture content, averaged for all irrigation dates and replications. The mean integrated moisture index results in an averaging of conditions throughout the growing period. The mean integrated capillary suction index is analogous to the mean integrated moisture stress used by Wadleigh and Ayers (1945) except that it does not include the osmotic component. Suction values are based on soil moisture content and the desorption curve, and are plotted as a function of time. Integration is carried out over nonuniform time intervals in order to have each time increment include an essentially linear segment of the curve. The mean maximum capillary suction index is analogous to the minimum moisture content index. Its value is obtained by averaging the suction values, taken from the desorption curve, of the minimum moisture content of each irrigation cycle. Among the four indexes examined, the maximum capillary suction index was found to be the most convenient for control of soil moisture regimes. With the maximum capillary suction index, most of the yield depression occurs at suctions lower than two bars after which yield decreases at a much lower and constant rate to that of the 15 bar suction.

Moisture stress is included in a barley yield equation developed by Heapy, et al. (1976). The equation relates barley yield to inputs of fertilizer nitrogen and phosphorus, soil test values for nitrate nitrogen and extractable phosphorus, and moisture stress. Days of moisture stress are identified by calculating a daily soil moisture budget. The daily index of available soil moisture (DMI) is calculated using an equation similar to one used by Baier and Robertson (1966):

$$DMI_i = \sum_{j=1}^4 k_j S_{ij}$$

where DMI_i is the index of available soil moisture on the i th day, k_j is a weighting coefficient for the j th depth, and S_{ij} is the moisture stored within the j th depth on the i th day. Values of k_j change with development of the crop to simulate the effect of root development. A value of DMI less than 1.125 (45% of the maximum value of 2.50) was chosen as the criterion for a moisture stress day. For the calculations of daily soil moisture it was assumed that a capacity of 10 cm of available soil moisture was applicable to the soil used. Observed precipitation is used and daily potential evaporation is estimated by the Penman method (1965). For the purpose of stress analysis, the rooting zone of the crop was divided into four depths, each with a capacity of 2.5 cm of available moisture. Crop

development was divided into seven intervals: planting-emergence, emergence-tillering, tillering-jointing, jointing-heading, heading-milk, milk-soft dough, and soft dough-hard dough. A technique similar to that employed by Parks and Knetsch (1959) is used to estimate the relative effect on barley yield of moisture stress occurring at different stages of crop development. The relationship between yield and moisture stress is described by the equation

$$Y_m = 31.4 - 5.4M_1 - 7.0M_2 - 13.8M_4$$

where Y_m is the mean yield of barley in quintals/hectare of plots adequately supplied with N, P, and K and M_1 , M_2 , and M_4 are stress ratios (stress days/total days) within the first (planting-emergence), second (emergence-tillering) and fourth (jointing-heading) intervals of barley development.

The objective for the model of navy bean growth and yield as affected by crusting at emergence, soil structure, and water stress was to create a simple, limited input model. The model is designed to function for field situations with input data being weather, planting date, and estimates of soil moisture on the planting date, bulk density, soil moisture contents at .06 and 15 bars; crusting problems during emergence, and final plant stand. The model is similar to that of Heapy, et al. (1976) in that water stress is determined from a daily index of available soil moisture. The model differs from many models in that

drainage and unsaturated water movement within the soil profile are not considered. The soil in the model was wetted by rain and irrigation to a maximum moisture content of .06 bars. It was dried according to pan evaporation, as adjusted by conceptual equations, to a minimum moisture content of 15 bars. In contrast to many of the yield-available water or transpiration models in the literature, the model grows plants from germination through emergence, vegetative growth, flowering, and pod filling. The model was formed by generating multiple linear regression equations from field data for emergence, vegetative growth, pod setting during flowering, and pod filling, and then creating conceptual equations to decrease growth and ultimate yield for conditions of crusting during emergence or drought stress. In summary, the model combines statistically derived and conceptual equations, uses an addition-subtraction approach to soil water without providing for redistribution of water in the soil profile, characterizes plant water stress as occurring when soil moisture in the rooting zone is less than 60% of that held between .06 and 15 bars, grows three subpopulations of plants on a daily basis, and limits needed input data to that which can be simply provided.

References

- American Society of Agricultural Engineers. 1971. Compaction of agricultural soils. The American Society of Agricultural Engineers, 2950 Niles Road, St. Joseph, MI 49085. 471 p.
- Anderson, C. E.; H. P. Johnson; and W. L. Powers. 1978. Water balance model for deep loess soils. Am. Soc. Agric. Engin. Trans. 21: 314-320.
- Anderson, R. L., and A. Maas. 1971. A simulation of irrigation systems: the effect of water supply and operating rules on production and income on irrigated farms. Tech. Bul. 1431. USDA-ERS and JFK School of Government.
- Arndt, W. 1965a. The impedance of soil seals and the forces of emerging seedlings. Austral. J. Soil Res. 3: 55-68.
- Arndt, W. 1965b. The nature of the mechanical impedance to seedlings by soil surface seals. Austral. J. Soil Res. 3: 45-54.
- Ashcroft, G. L., and S. A. Taylor. 1953. Soil moisture tension as a measure of water removal rate from soil and its relation to weather factors. Soil Sci. Soc. Amer. Proc. 17: 171-174.
- Baier, W., and G. W. Robertson. 1966. A new versatile soil moisture budget. Can. Jour. Plant Sci. 46: 299-315.
- Baligar, V. C.; V. E. Nash; M. L. Hare; and J. A. Price, Jr. 1975. Soybean root anatomy as influenced by soil bulk density. Agron. J. 67: 842-844.
- Beese, F. R.; R. Van der Ploeg; and W. Richter. 1977. Test of a soil water model under field conditions. Soil Sci. Soc. Am. J. 41: 979-984.
- Bennett, J. P.; M. W. Adams; and C. Burga. 1977. Pod yield component variation and intercorrelation in *Phaseolus vulgaris* L. as affected by planting density. Crop Sci. 17:73-75.

- Black, T. A.; W. R. Gardner; and G. W. Thurtell. 1969. The prediction of evaporation, drainage, and soil water storage for a bare soil. *Soil Sci. Soc. Am. Proc.* 33: 655-660.
- Black, T. A.; C. B. Tanner; and W. R. Gardner. 1970. Evapotranspiration from a snap bean crop. *Agron. J.* 62: 66-69.
- Bole, J. B., and S. Dubets. 1978. Effects of various soil supplements and water stress on the yield and yield components of wheat. *Can. J. Soil Sci.* 58: 321-323.
- Bowen, H. D. 1966. Measurement of edaphic factors for determining planter specifications. *Trans. of Am. Soc. Ag. Eng.* 9: 725-735.
- Boyer, J. S. 1970. Differing sensitivity of photosynthesis to low leaf water potentials in corn and soybeans. *Plant Physiol.* 46: 236-239.
- Brady, R. A.; W. L. Powers; L. R. Stone; and S. M. Goltz. 1974. Relationship of soybean leaf water potential to soil water potential. *Agron. J.* 66: 795-798.
- Brady, R. A.; L. R. Stone; C. D. Nickell; and W. L. Powers. 1974. Water conservation through proper timing of soybean irrigation. *J. Soil and Water Conser.* 29: 266-268.
- Brix, H. 1962. The effects of water stress on rates of photosynthesis and respiration in tomato plants and loblolly pine seedlings. *Physiol. Plant* 15: 10-20.
- Brun, L. J.; E. T. Kanemasu; and W. L. Powers. 1972. Evapotranspiration from soybean and sorghum fields. *Agron. J.* 64: 145-148, 197.
- Campbell, M. D., and W. D. Lembke. 1975. Planning irrigation and drainage systems using retention and extraction limits. *Am. Soc. Ag. Eng. Trans.* 18: 514-517.
- Cowan, I. R. 1965. Transport of water in the soil-plant-atmosphere system. *J. Appl. Ecol.* 2: 221-239.
- Crothers, S. E., and D. T. Westermann. 1976. Plant population effects on the seed yield of *Phaseolus vulgaris* L. *Agron. J.* 68: 958-960.

- Dale, R. F., and R. H. Shaw. 1965. The climatology of soil moisture, atmospheric evaporative demand, and resulting moisture stress days for corn at Ames, Iowa. J. Appl. Met. 4: 661-669.
- Davis, J. F. 1943. The effect of temperature, humidity, fertilizer, soil moisture, and leaf area on the set of pods and yield of white pea beans. Ph.D. Thesis, Michigan State University Library, East Lansing, Michigan.
- Denmead, O. T., and R. H. Shaw. 1962. Availability of soil water to plants as affected by soil moisture content and meteorological conditions. Agron. J. 45: 385-390.
- de Wit, C. T. 1958a. Transpiration and crop yields. Verslag van Landbouwk Onderzoek No. 64.4, 88 p.
- de Wit, C. T. 1958b. Transpiration and crop yields. Institute of Biological and Chemical Research on Field Crops and Herbage. Wageningen, the Netherlands, Verslag Landbouwk, onder Z. No. 64.6-S Gravenhage.
- Doss, B. D.; R. W. Pearson; and H. T. Rogers. 1974. Effect of soil water stress at various growth stages on soybean yield. Agron. J. 66: 297-299.
- Doss, B. D., and D. L. Thurlow. 1974. Irrigation, row width, and plant population in relation to growth characteristics of two soybean varieties. Agron. J. 66: 620-623.
- Dudley, N. J.; D. T. Howell; and W. F. Musgrave. 1971. Optimal intraseasonal irrigation water allocation. Water Resour. Res. 7: 770-788.
- Dutt, G. R.; M. J. Shaffer; and W. J. Moore. 1972. Computer simulation model of dynamic bio-physico-chemical processes in soils. Technical Bulletin 196. Agricultural Experiment Station of the University of Arizona.
- Ehlig, C. F., and W. R. Gardner. 1964. Relationship between transpiration and the internal water relations of plants. Agron. J. 56: 127-130.
- Fawcett, R. G., and O. G. Carter. 1973. Utility of a simple soil water budget in agronomic research; effects of plant density, time of sowing, and fallow water on available soil water under spring wheat. Aust. J. Exper. Agric. 13: 714-717.

- Fawcett, R. G., and O. G. Carter. 1974. Utility of a simple soil water budget model in agronomic research. 3. Estimation of the potential evapotranspiration function. *Aust. J. Exper. Agric.* 14: 684-688.
- Fischer, R. A.; T. C. Hsiao; and R. M. Hagan. 1970. After-effect of water stress on stomatal opening potential. I. Techniques and magnitudes. *J. Exp. Bot.* 21: 371-385.
- Fisher, R. A. 1924. The influence of rainfall distribution on the yield of wheat crop. *Phil. Trans. R. Soc. Ser. B.* 213: 89-412.
- Fitzpatrick, E. A., and H. A. Nix. 1969. A model for simulating soil water regime in alternating fallow-crop systems. *Agric. Meteorol.* 6: 303-319.
- Flinn, J. C., and W. F. Musgrave. 1967. Development and analysis of input-output relation for irrigation water. *Aust. J. Agr. Econ.* 11: 1-19.
- Frank, A. B.; J. F. Power; and W. O. Willis. 1973. Effect of temperature and plant water stress on photosynthesis, diffusion resistance, and soil water potential in spring wheat. *Agron. J.* 65: 777-780.
- Franzmeier, D. P.; E. P. Whiteside; and A. E. Erickson. 1960. Relationship of texture classes of fine earth to readily available water. 7th Intern. Congress of Soil Science, Madison, Wisc. U.S.A. Vol. I: 354-363.
- Gangopadhyaya, M., and R. P. Sarker. 1965. Influence of rainfall distribution on the yield of wheat crop. *Agric. Meteorol.* 2: 331-350.
- Gardner, W. R. 1960. Dynamic aspects of water availability to plants. *Soil Sci.* 89: 63-73.
- Gardner, W. R., and C. F. Ehlig. 1965. Physical aspects of the internal water relations of plant leaves. *Plant Physiol.* 410: 705-710.
- Gardner, W. R., and D. I. Hillel. 1962. The relation of external evaporation conditions to the drying of soils. *J. Geophys. Res.* 67: 4319-4325.
- Gardner, W. R.; D. I. Hillel; and Y. Benyamini. 1970. Post-irrigation movement of soil water. 1. Redistribution. *Water Resour. Res.* 6: 851-861.

- Gardner, W. R., and R. H. Nieman. 1964. Lower limit of water availability to plants. *Science* 143: 1460-1462.
- Giles, K. L.; M. F. Beardsell; and D. Cohen. 1974. Cellular and ultrastructural changes in mesophyll and bundle sheath cells of maize in response to water stress. *Plant Physiol.* 54: 208-212.
- Hadas, A., and D. Russo. 1974. Water uptake by seeds as affected by water stress, capillary conductivity, and seed-soil water contact; II. Analysis of experimental data. *Agron. J.* 66: 647-652.
- Hadas, A., and E. Stibbe. 1977. Soil crusting and emergence of wheat seedlings. *Agron. J.* 69: 547-550.
- Hall, W. A., and W. S. Butcher. 1968. Optimal timing of irrigation. *Journal of the Irrigation and Drainage Division. Proceedings of the American Society of Civil Engineers* 94: 267-275.
- Hanks, R. J. 1974. Model for predicting plant yield as influenced by water use. *Agron. J.* 66: 660-665.
- Hanks, R. J.; H. R. Gardner; and R. L. Florian. 1969. Plant growth-evapotranspiration relation for several crops in the Central Great Plains. *Agron. J.* 61: 30-34.
- Hanks, R. J., and F. C. Thorpe. 1957. Seedling emergence of wheat as related to soil moisture content, bulk density, oxygen diffusion rate and crust strength. *Soil Sci. Soc. Amer. Proc.* 20: 307-310.
- Hansen, G. K. 1975. A dynamic continuous simulation model of water state and transportation in the soil-plant-atmosphere system. 1. The model and its sensitivity. *Acta. Ag. Scand.* 25: 129-149.
- Hanson, C. L. 1976. Model for predicting evapotranspiration from native rangelands in the Northern Great Plains. *Am. Soc. Ag. Engin. Trans.* 19: 471-477.
- Heady, E. O., and J. L. Dillon. 1961. *Agricultural production functions.* Iowa State University Press, Ames, Iowa. 667 p.
- Heapy, L. A.; G. R. Webster; H. C. Love; D. K. McBeath; U. M. von Maydell; and J. A. Robertson. 1976. Development of a barley yield equation for central Alberta. 2. Effects of soil moisture stress. *Can. J. Soil Sci.* 56: 249-256.

- Hegarty, T. W., and S. M. Royle. 1978. Combined effects of moisture content prior to compaction, compactive effort, and rainfall quantity on soil crust strength. *J. Soil Sci.* 29: 167-173.
- Hiler, E. A.; T. A. Howell; R. B. Lewis; and R. P. Boos. 1974. Irrigation timing by the stress day index method. *Am. Soc. Agric. Engin. Trans.* 17: 393-398.
- Hillel, D. I. 1960. Studies on loessial crusts. *Bull. Agric. Res. Stn., Rehovot, Israel.*
- Hillel, D. I. 1975. Simulation of evaporation from bare soil under steady and diurnally fluctuating evapotranspiration. *Soil Sci.* 120: 230-237.
- Hillel, D. I., and Y. Guron. 1973. Relation between evapotranspiration rate and maize yield. *Water Resour. Res.* 9: 743-748.
- Hillel, D. I.; H. Talpaz; and H. van Kuelen. 1976. A microscopic-scale model of water uptake by a non-uniform root system and of water and salt movement in the soil profile. *Soil Sci.* 121: 242-255.
- Hillel, D.; C. G. E. M. van Beek; and H. Talpaz. 1975. A microscopic-scale model of soil water uptake and salt movement to plant roots. *Soil Sci.* 120: 385-399.
- Hoffman, G. J.; J. A. Jobes; Z. Hanscom; and E. V. Maas. 1978. Timing of environmental stress affects growth, water relations, and salt tolerance of pinto bean. *Am. Soc. Agric. Engin. Trans.* 21: 713-718.
- Holder, C. B., and K. W. Brown. 1974. Evaluation of simulated seedling emergence through rainfall induced soil crusts. *Soil Sci. Soc. Am. Proc.* 38: 705-710.
- Hunter, J. R., and A. E. Erickson. 1952. Relation of seed germination to soil moisture tension. *Agron. J.* 44: 107-109.
- James, L. G., and C. L. Larson. 1976. Modeling infiltration and redistribution of soil water during intermittent application. *Am. Soc. Agric. Engin. Trans.* 19: 482-488.
- Jensen, M. E. 1968. Water consumption by agricultural plants. Ch. 1 in T. T. Kozlowski (ed.), *Water deficits and plant growth*. Vol. 2. Academic Press, New York.

- Jensen, M. E.; D. C. N. Robb; and C. E. Franzoy. 1970. Scheduling irrigations using climate-crop-soil data. *Journal of the Irrigation and Drainage Division, ASCE* 96: 25-38.
- Kanemasu, E. T., and C. B. Tanner. 1969. Stomatal diffusion resistance of snap beans. I. Influence of leaf water potential. *Plant Physiol.* 44: 1547-1552.
- Kendall, M. G. 1957. A course in multivariate analysis. Hafner, New York.
- Kramer, D. J. 1963. Water stress and plant growth. *Agron. J.* 55: 31-35.
- Kueneman, E. A.; G. Hernandez-Bravo; and D. H. Wallace. 1978. Effects of growth habits and competition on yields of dry beans (*Phaseolus vulgaris*) in the tropics. *Exper. Agric.* 14: 97-104.
- Lewin, J. 1972. A simple water simulation model for assessing the irrigation requirements of wheat. *Israel J. Agric. Res.* 22: 201-213.
- Lewin, J., and J. Lomas. 1974. A comparison of statistical and soil moisture modeling techniques in a long-term study of wheat yield performance under semi-arid conditions. *J. Appl. Ecol.* 11: 1081-1090.
- Lomas, J. 1972. Economic significance of dry-land farming in the arid northern Negev of Israel. *Agric. Meteorol.* 10: 383-392.
- Manning, C. E.; D. G. Miller; and I. D. Teare. 1977. Effect of moisture stress on leaf anatomy and water-use efficiency of peas. *Am. Soc. Hort. Sci. J.* 102: 756-760.
- McIntyre, D. S. 1958. Permeability measurements of soil crusts formed by raindrop impact. *Soil Sci.* 85: 185-189.
- Mein, R. G., and C. L. Larson. 1971. Modeling the infiltration component of the rainfall-runoff process. University of Minnesota Water Resources Research Center Bulletin 43.
- Melvin, S. W. 1970. Determination of deep percolation losses in loessial soils. Unpublished Ph.D. Thesis, Iowa State University Library, Ames, Iowa (Dissertation Abstracts International 31(4): 1909b, Oct. 1970, Order No. 70-18, 893).

- Millar, A. A.; M. E. Duysen; and E. B. Norum. 1970. Relationship between the leaf water status of barley and soil water. *Can. J. Plant Sci.* 50: 363-370.
- Millar, A. A.; M. E. Duysen; and E. Wilkinson. 1968. Internal water balance of barley under soil moisture stress. *Plant Physiol.* 43: 968-972.
- Miller, D. G.; C. E. Manning; and I. D. Teare. 1977. Effects of soil water levels on components of growth and yield in peas. *Am. Soc. Hort. Sci. J.* 102: 349-351.
- Molz, F. J., and I. Remson. 1970. Extraction term models of soil moisture use by transpiring plants. *Water Resour. Res.* 6: 1346-1356.
- Monteith, J. L. 1965. Evaporation and environment. *Symp. Soc. Exp. Biol.* 29: 205-234.
- Moore, C. W. 1961. A general analytical framework for estimating production functions for crops using irrigation water. *J. Farm Econ.* Vol. XVIII, No. 4, Part I, 876-888.
- Morris, D. T., and T. B. Daynard. 1978. Influence of soil density on leaf water potential of corn. *Can. J. Soil Sci.* 58: 275-278.
- Musick, J. T.; L. L. New; and D. A. Dusek. 1976. Soil water depletion-yield relationships of irrigated sorghum, wheat, and soybeans. *Am. Soc. Ag. Eng. Trans.* 19: 489-493.
- Namken, L. N., and E. R. Lemon. 1960. Field studies of internal moisture relations of the corn plant. *Agron. J.* 52: 643-646.
- Neghassi, H. M.; D. F. Heermann; and D. E. Smika. 1975. Wheat yield models with limited soil water. *Am. Soc. Agric. Engin. Trans.* 18:549-553.
- Nimak, M. N., and R. J. Hanks. 1973a. Model for estimating soil water, plant, and atmospheric inter-relations: I. Description and sensitivity. *Soil Sci. Soc. Am. Proc.* 37: 522-527.
- Nimak, M. N., and R. J. Hanks. 1973b. Model for estimating soil water, plant, and atmospheric inter-relations: II. Field test of model. *Soil Sci. Soc. Am. Proc.* 37: 528-532.

- Orphanos, P. I. 1977. Emergence of *Phaseolus vulgaris* seedlings from wet soil. J. Hort. Sci. 52: 447-455.
- Parks, W. L., and J. L. Knetsch. 1959. Corn yields as influenced by nitrogen level and drought intensity. Agron. J. 51: 363-364.
- Penman, H. L. 1965. Vegetation and hydrology. Comm. Bur. Soils, Tech. Commun. No. 53. Harpenden. 124 p.
- Penman, H. L., and R. K. Schofield. 1951. Some physical aspects of assimilation and transpiration. Symp. Soc. Exp. Biol. 5: 115-129.
- Prihar, S. P.; K. L. Khera; K. S. Sandhu; and B. S. Sandhu. 1976. Comparison of irrigation schedules based on pan evaporation and growth stages in winter wheat. Agron. J. 68: 650-653.
- Plaut, Z., and L. Reinhold. 1965. The effect of water stress on ^{14}C -sucrose transport in bean plants. Aust. J. Biol. Sci. 18: 1143-1155.
- Pruitt, W. O. 1966. Evapotranspiration and its role in water resources management. Conf. Proc. St. Joseph, Michigan. Am. Soc. of Ag. Eng., pp. 57-61.
- Rawitz, E. 1969. The dependence of growth rate and transpiration on plant and soil physical parameters under controlled conditions. Soil Sci. 110: 172-182.
- Rawitz, E., and D. I. Hillel. 1969. Comparison of indexes relating plant response to soil moisture status. Agron. J. 61: 231-235.
- Redshaw, A. J., and H. Meidner. 1972. Effects of water stress on the resistance to intake of carbon dioxide in tobacco. J. Exp. Bot. 23: 229-240.
- Reid, C. P. 1974. Assimilation, distribution, and root exudation of ^{14}C by ponderosa pine seedlings under induced water stress. Plant Physiol. 54: 44-49.
- Richards, L. A. 1931. Capillary conduction of liquids in porous medium. Physics 1: 318-333.
- Richards, L. A. 1953. Modulus of rupture as an index of crusting of soil. Soil Sci. Soc. Am. Proc. 17: 321-323.

- Richards, L. A.; W. R. Gardner; and G. Ogata. 1956. Physical processes determining water loss from soil. *Soil Sci. Soc. Am. Proc.* 20: 310-314.
- Ritchie, J. T. 1972. Model for predicting evaporation from a row crop with incomplete cover. *Water Resour. Res.* 8: 1204-1213.
- Robertson, L. S., and A. E. Erickson. 1978a. Soil compaction, symptoms-causes-remedies. Part I. Symptoms. *Crops and Soils* 30(4): 11-14.
- Robertson, L. S., and A. E. Erickson. 1978b. Soil compaction, symptoms-causes-remedies. Part II: Causes. *Crops and Soils* 30(5): 7-9.
- Robertson, L. S., and A. E. Erickson. 1978c. Soil compaction, symptoms-causes-remedies. Part III. Remedies. *Crops and Soils* 30(6): 8-10.
- Rowse, H. R., and D. A. Stone. 1978. Simulation of the water distribution in soil; measurement of soil hydraulic properties and the model for an uncropped soil. *Plant and Soil* 49: 517-531.
- Rowse, H. R.; D. A. Stone; and A. Gerwitz. 1978. Simulation of the water distribution in soil; the model for cropped soil and its comparison with experiment. *Plant and Soil* 49: 533-550.
- Rubin, J.; R. Steinhardt; and P. Reiniger. 1964. Soil water relations during rain infiltration: II. Moisture content profiles during rain of low intensities. *Soil Sci. Soc. Am. Proc.* 28: 1-5.
- Saxton, K. E.; H. P. Johnson; and R. H. Shaw. 1974. Modeling evapotranspiration and soil moisture. *Am. Soc. Ag. Engin. Trans.* 17: 673-677.
- Scarisbrick, D. H.; J. M. Wilkes; and R. Kempson. 1977. Effect of varying plant population density on the seed yield of navy beans (*Phaseolus vulgaris*) in southeast England. *J. Agric. Sci.* 88: 567-577.
- Shearman, L. L.; J. D. Eastin; C. H. Sullivan; and E. J. Kinbacker. 1972. Carbon dioxide exchange in water stressed sorghum. *Crop Sci.* 12: 406-409.
- Sionit, N., and P. J. Kramer. 1977. Effect of water stress during different stages of growth of soybean. *Agron. J.* 69: 274-278.

- Slack, D. C.; C. T. Haan; and L. G. Wells. 1977. Am. Soc. Agric. Engin. Trans. 20: 919-927.
- Slatyer, R. O. 1955. Studies of the water relations of crop plants grown under natural rainfall in northern Australia. Aust. J. Agr. Res. 6: 365-377.
- Slatyer, R. O. 1957. The influence of progressive increases in total soil moisture stress on transpiration, growth, and internal water relations of plants. Aust. J. Biol. Sci. 10: 320-336.
- Sprent, J. I.; A. M. Bradford; and C. Norton. 1977. Seasonal growth patterns in field beans (*Vicia fabia*) as affected by population density, shading, and its relationship with soil moisture. J. Agric. Sci. 88: 293-301.
- Staple, W. J. 1974. Modified Penman equation to provide the upper boundary condition in computing evaporation from soil. Soil Sci. Soc. Am. Proc. 38: 837-839.
- Staple, W. J., and J. J. Lehane. 1954. Weather conditions influencing wheat yields in tanks and field plots. Can. J. Agric. Sci. 34: 553-564.
- Stolzy, L. H., and A. E. Erickson. 1959. A soil suction value associated with moisture levels adjusted by the adventitious root technic. Soil Sci. 88: 77-79.
- Stone, L. R.; I. D. Teare; C. D. Nickell; and W. C. Mayaki. 1976. Soybean root development and soil water depletion. Agron. J. 68: 677-680.
- Taylor, S. A., and G. L. Ashcroft. 1972. Physical edaphology. W. H. Freeman and Company, San Francisco, 533 p.
- Viehmeyer, F. J., and A. H. Hendrickson. 1955. Does transpiration decrease as the soil moisture decreases? Trans. Am. Geophys. Un. 36: 425-448.
- Voorhees, W. B. 1977a. Soil compaction; how it influences moisture, temperature, yield, root growth. Crops and Soils 29: 7-10.
- Voorhees, W. B. 1977b. Soil compaction; our newest natural resource. Crops and Soils 29: 13-15.
- Voorhees, W. B.; C. G. Senst; and W. W. Nelson. 1978. Compaction and soil structure modification by wheel traffic in the northern corn belt. Soil Sci. Soc. Am. J. 42: 344-349.

- Wadleigh, C. H., and A. D. Ayers. 1945. Growth and biochemical composition of bean plants as conditioned by soil moisture tension and salt concentration. *Plant Physiol.* 20: 106-132.
- Wang, F. C., and V. Lakshminarayana. 1968. Mathematical simulation of water movement through unsaturated nonhomogeneous soils. *Soil Sci. Soc. Am. Proc.* 32: 329-334.
- Wardlaw, I. F. 1967. The effect of water stress in relation to photosynthesis and growth. I. Effect during grain development in wheat. *Aust. J. Biol. Sci.* 20: 25-39.
- Willatt, S. T., and H. M. Taylor. 1978. Water uptake by soya-bean roots as affected by soil water content. *J. Agric. Sci.* 90: 205-213.
- Zaradny, H. 1978. Boundary conditions in modeling water flow in unsaturated soils. *Soil Sci.* 125: 75-82.

CHAPTER II

NAVY BEAN (PHASEOLUS VULGARIS) GROWTH AND YIELD AS AFFECTED BY SOIL STRUCTURE AND WATER STRESS

Abstract

Field studies were conducted on Charity clay (Aericha-plaquept, fine, mixed, mesic) and Hillsdale sandy loam (Typichapludalf, coarse loamy, mixed, mesic) soils in 1977 and 1978 to determine the effects of water stress and soil structure on navy bean growth and yield. The soil structure studies were conducted on the Charity clay with structure treatments defined as excellent, good, or poor. To obtain excellent soil structure an alfalfa timothy mixture was grown for two years and the soil was both deep chiseled and moldboard plowed in the fall prior to spring planting of beans. Soils where the crop rotation did not include two years of alfalfa timothy and fall chisel and moldboard plowing were defined as having good structure. Poor soil structure was created by compacting the soil with a tractor prior to planting. Water stress on Charity clay was examined by studying the benefits of heavy irrigation at second seedling, flowering, or pod filling. Water stress on the Hillsdale sandy loam was studied with application of supplementary irrigation

as needed, no supplementary irrigation during the growing season, or no supplementary irrigation during the vegetative, flowering, or pod filling growth stages.

Results from the studies show that on Charity clay good soil structure is crucial to plant growth and yield. Plants grown on the excellent soil structure treatment were deep rooted and had greater leaf areas and plant weights than those grown on less favorable soil structures. Rainfall induced crusts or crusting from soil compaction delayed plant emergence and resulted in reduced plant stands. Drought stress at any plant growth stage reduced yield. At the flowering and pod filling stages navy beans are particularly sensitive to drought. With a limited irrigation resource the best use would be made by applying irrigation from flowering through early pod filling.

Introduction

Soil compaction affects soil conditions influencing the timeliness with which seedbed preparation, cultural practices, and crop harvests can be performed; the germination of seedlings; and the subsequent growth and development of plants (Compaction of Agricultural Soils, 1971, American Society of Agricultural Engineers). The soil conditions most seriously affected are those that control the content and transmission of water, air, and nutrients, and those that change soil strength. The detrimental effects of soil crusting (compaction) at time of emergence include

slower rate of seedling emergence, damage to seedlings during emergence, and reduced percent final emergence. Mechanical impedance to growing roots reduces the rooting volume from which the plant can obtain water and nutrients. A compressed soil surface reduces the infiltration of rainfall and increases runoff. This can result in reduced moisture storage for a maturing crop. Compaction of soil results in slower air and water movement. Following heavy rains there is increased probability of flooding and oxygen stress, which can damage or kill the plant. In summary, both direct and indirect effects of crusting during emergence and/or compaction of the plant rooting volume can result in reduced plant growth and yield.

Drought affects plant growth and ultimate yield at all plant growth stages. The magnitude of the effects on yield however are related to growth stage. Miller, Manning, and Teare (1977) obtained the highest seed yields of peas by maintaining a high soil moisture content during flowering or pod filling. Their plants also were taller with maintenance of high soil moisture content from flowering to early pod filling. Hoffman, et al. (1978) found with pinto beans that growth and pod yield of bean plants exposed to a hot, dry environment during vegetative stage were comparable with those plants continuously exposed to a cool, humid environment. Exposure to a hot dry environment during flowering, however, reduced yields significantly, but not to levels for plants exposed continuously to a hot, dry

environment. Sionit and Kramer (1977) in studying the soybean showed that plants stressed during flower induction and flowering produce fewer flowers, pods, and seeds than controls because of a shortened flowering period and abortion of some flowers. In their study stress during early pod formation caused the greatest reduction in number of pods and seeds at harvest. Yield as measured by weight of seeds was reduced most by stress during early pod formation and filling. Doss, Pearson, and Rogers (1974) in Alabama had similar results. They found more bean production was obtained from water applied after full bloom than earlier, and concluded that the pod-fill stage is the critical time for adequate water for maximum yields.

The objective of the field research conducted in 1977 and 1978 on Charity clay (Aeric haplaquept, fine, mixed, mesic) and Hillsdale sandy loam (Typic hopludalf, coarse loamy, mixed, mesic) was to study the effects of both soil structure and water stress on growth and yield of navy beans. Soil structure studies were done on the Charity clay with structures ranging from severely compacted to excellent. Water stress was studied on both the Charity clay and Hillsdale sandy loam. The benefits of heavy irrigation at the vegetative, flowering, or pod filling stages were determined on the Charity clay. The Hillsdale sandy loam was used to determine the effect of water stress at either specific or all growth stages. By evaluating the effects of soil structure and water stress on plant growth, the study

determined the navy bean yield limitations imposed by physical stresses.

Materials and Methods

Field research was conducted at two locations in 1977 and 1978. A Charity clay soil (Aeric haplaquept, fine, mixed, mesic) located at the Saginaw Valley Bean and Beet Research Farm near Saginaw, Michigan was used for study of soil compaction and the benefits of heavy irrigation at different plant growth stages. Hillsdale sandy loam (Typic hapludalf, coarse loamy, mixed, mesic) was used on the Soils Research Farm at East Lansing to study water stress. The navy bean (*Phaseolus vulgaris*) variety used for all studies was Sanilac. Row spacings were 71 cm (28 inches) at East Lansing both years, and 71 cm (28 inches) in 1977, and 51 cm (20 inches) in 1978 at Saginaw. Planting was made with a three row planter on the Hillsdale sandy loam and a four row planter on the Charity clay. Four replications per treatment were used at each site. Experimental design was best possible complete randomization under the limitation of available field space. Plot length on the Charity clay was 20 meters (66 feet). Number of rows per plot was 12 in 1977 and 16 in 1978, except for the compacted treatments and the 1978 treatments not receiving heavy irrigation. Compacted treatments were 8 rows in 1977 and 4 rows in 1978. Treatments not receiving heavy irrigation in 1978 were 12 rows. Plot size on the Hillsdale sandy loam each year was 12 rows by 15 meters (50 feet).

Beans were planted on the Charity clay in 1977 on June 15. No secondary spring tillage was made prior to planting. Two hundred forty-six kilograms/hectare of 18-46-0 was banded at planting. Amiben and Dinitrol amine were used as pre-emergence herbicides. Soil structure treatments used were defined as excellent, good, or poor. To obtain excellent soil structure an alfalfa-timothy mixture was grown for two years and the soil was both deep chiseled and moldboard plowed in the fall prior to spring planting of beans. The herbicide Roundup was applied in the fall prior to deep chiseling and again in the spring to insure kill of the alfalfa-timothy mixture. Soils where the crop rotation did not include two years of alfalfa-timothy and fall chisel and moldboard plowing were defined as having good structure. Poor soil structure was created by compacting the soil with a tractor prior to planting. Water stress was studied by examining the benefits of heavy irrigation at the second seedling, flowering, or pod filling growth stages. Large quantities of water were applied by overhead sprinklers on June 28, August 3, and August 23 for the respective irrigation treatments at second seedling, flowering, and pod filling. Applied water for each treatment was 7.6 to 10.2 cm depending on field conditions. Additional irrigations of 1.2 cm were made on all treatments on July 13 and August 1. Benlate was applied as recommended for prevention of white mold during pod filling. Harvest was made on October 6, 1977, by cutting 18 row

meters (60 row feet cut from two different rows in 30 foot sections) per replication. Over 13 cm of rain falling on September 17 and 18 on the Charity clay soil severely damaged the beans during the pod filling stage.

Planting in 1978 on the Charity clay was done on May 25. Fertilizer application was the same as in 1977, and Amiben and Dinitrol amine were used as pre-emergence herbicides. Soil structures were again defined as excellent, good, or poor. Structure of the 1977 excellent structure plots was still better than that of other areas, so these plots served as the 1978 excellent structure plots. The area defined as having good soil structure had three months of alfalfa the previous summer followed by conventional fall plowing and secondary spring tillage to smooth the surface. Poor soil structure was again formed by compacting the soil with a tractor prior to planting. Treatments in 1978 were compacted, irrigated and unirrigated "excellent" soil structure, "good" soil structure, heavy irrigation at second seedling, heavy irrigation at flowering, and heavy irrigation at pod filling. Heavy irrigations were: second seedling, 8.9 cm on June 29, flowering, 8.9 cm on July 19, and pod filling, 10.2 cm on August 2 and 10.2 cm on August 3. Additional supplementary irrigations of 2.3 cm on June 5, 0.7 cm on August 8, and 1.9 cm on August 11 were made on the area with "good" soil structure, and irrigations of 0.7 cm on June 6, 1.9 cm on June 9, and 2 cm on August 8 were made on the area with "excellent" soil structure with the

exception of the unirrigated treatment. Liquid nitrogen at a rate of 34 kg/ha was applied to half the area of the treatment receiving heavy irrigation during pod filling, to study the possible effects of nitrogen loss through leaching. Benlate for prevention of white mold was applied on August 1. Beans were harvested on August 29 and August 31.

Beans were planted in 1977 on the Hillsdale sandy loam on June 17. Fertilizer was applied at rates of 291 kg/ha of 52-0-20 banded, and 112 kg/ha 0-0-60 and 112 kg/ha 0-46-0 broadcast. Pre-emergence herbicides were Amiben and Dinitrol amine. Irrigation treatments with overhead sprinklers in 1977 were no irrigation, irrigation as needed and water stress only at second seedling. Irrigations were made on July 14, 1.1 cm, July 22, 1.1 cm, July 28, 1.0 cm and August 24, 0.8 cm. The treatment stressed at second seedling received no irrigation water on July 14, 1977. Yields were harvested September 28.

Planting on the Hillsdale sandy loam in 1978 was done on June 6. The area had been spring plowed, disked, and sprayed with Eptam and Trifluralin prior to planting, due to quack grass problems. Fertilizer application was 280 kg/ha of 6-24-24 banded at planting. Table 1 summarizes the 1978 water stress treatments on the sandy soil. Dates and amounts of applied irrigation water and plant growth stages are shown. Amounts of applied irrigation for irrigations both years on both soils were measured using

Table 1.--Dates, Amounts, and Plant Growth Stages for Irrigations on Hillsdale Sandy Loam in 1978.

Date	Irrigation Amount cm	Plant Growth Stage	Treatments							
			Irrigation as Needed	No Irr. 7-7-78	No Irr. 7-14-78	No Irr. 7-21-78	No Irr. 7-28-78	Irr. Only 7-7-78	No Irr. After 7-28-78	No Irrigation
7-7-78	2.2	Second Seedling	X*		X	X	X	X	X	
7-14-78	2.5	Vegetative Growth	X	X		X	X		X	
7-21-78	1.6	Early Flowering	X	X	X		X		X	
7-28-78	1.6	Late Flowering	X	X	X	X			X	
8-10-78	1.6	Pod Filling	X	X	X	X	X	X		
8-18-78	1.6	Late Pod Filling	X	X	X	X	X			

*X = irrigation.

containers distributed over the irrigation area. Yields were harvested on September 1, 1978.

Plant growth parameters were measured throughout the growing season each year on both soils. Number of plants emerged was counted on replicated 9 meter row lengths from the start of emergence until a final stand count was made. Weekly leaf area measurements, using ten plants consecutively cut from the selected row of each treatment replicate, were made with a lambda leaf area meter. Combined leaves and stems from the ten plants were dried at 60°C, and weighed as a second method of characterizing plant growth. During pod filling, pods were separated from stems and leaves and both number of filled and unfilled pods and total weight of unshelled beans was recorded. Final yield as cut from 18 meters of row per plot (2 subcuttings of 9 meters of row from different rows) was expressed at 16% moisture.

Root samples were collected twice each summer at each location. Samples were collected in 10 x 10 x 15 cm metal cores which were driven into the ground. A location within the plot was first found such that the stems of three plants could be centered in one core. Additional core samples, depending on growth stage and root distribution, were taken on either side and underneath the central core so as to obtain row cross sectional root distribution. No samples were taken deeper than 45.7 cm. Soil and roots within each core were removed and sectioned into 10 x 10 x

5 cm blocks. Roots were separated from the soil by soaking the cores in Calgon solution and then washing the soil from the roots through screens. Root samples were weighed air dry.

Results

Table 2 shows percent of final stand count emerged versus days since beans first began to emerge on Charity clay and Hillsdale sandy loam in 1977 and 1978. Plots of this data are available in Figure 1 of Chapter 4. Emergence proceeded faster on the Hillsdale sandy loam each year than on the Charity clay. Emergence through the Charity clay was impeded by the fine soil. The emerging plant must exert considerable thrust to push through the clay. Emergence on the compacted treatment shows both the mechanical difficulty of planting on severely compacted soil, and the difficulty that the seedlings have emerging through a crust.

Figure 1 shows plant growth curves for the soil structure treatments on Charity clay in 1977. During pod filling, plant and pod weights of the beans grown on soil with excellent structure were greater than those of other treatments. The curves for good and poor soil structure show that these plants were starting to senesce by August 31. In contrast, beans growing on excellent structure were still growing new leaves and stems in addition to setting and filling pods. Rain and hail storms on September 17 and 18 (13 cm of rain) severely damaged all plots and flooded the area for two days. The dip in the plant weight curves between plant samples collected on September 12 and

Table 2.--Percent Final Bean Emergence versus Days from the Start of Emergence for Hillsdale Sandy Loam and for Noncompacted and Compacted Charity Clay in 1977 and 1978.

	Emergence Day*									
	1	2	3	4	5	6	7	8	9	10
	Percent Emergence**									
<u>1977</u>										
Hillsdale sandy loam	12	35	74	90	98	100				
Uncompacted Charity clay	8	23	46	60	76	92	93	94	96	98
Compacted Charity clay	0	0	1	2	17	56	60	64	79	85
 <u>1978</u>										
Hillsdale sandy loam	55	71	90	99	100					
Uncompacted Charity clay	23	24	25	42	46	50	54	60	74	78
Compacted Charity clay	4	5	6	14	26	27	28	30	75	81

*Emergence day 1 is the first day beans began to emerge on uncompacted treatments.

**Percent emergence of final stand count.

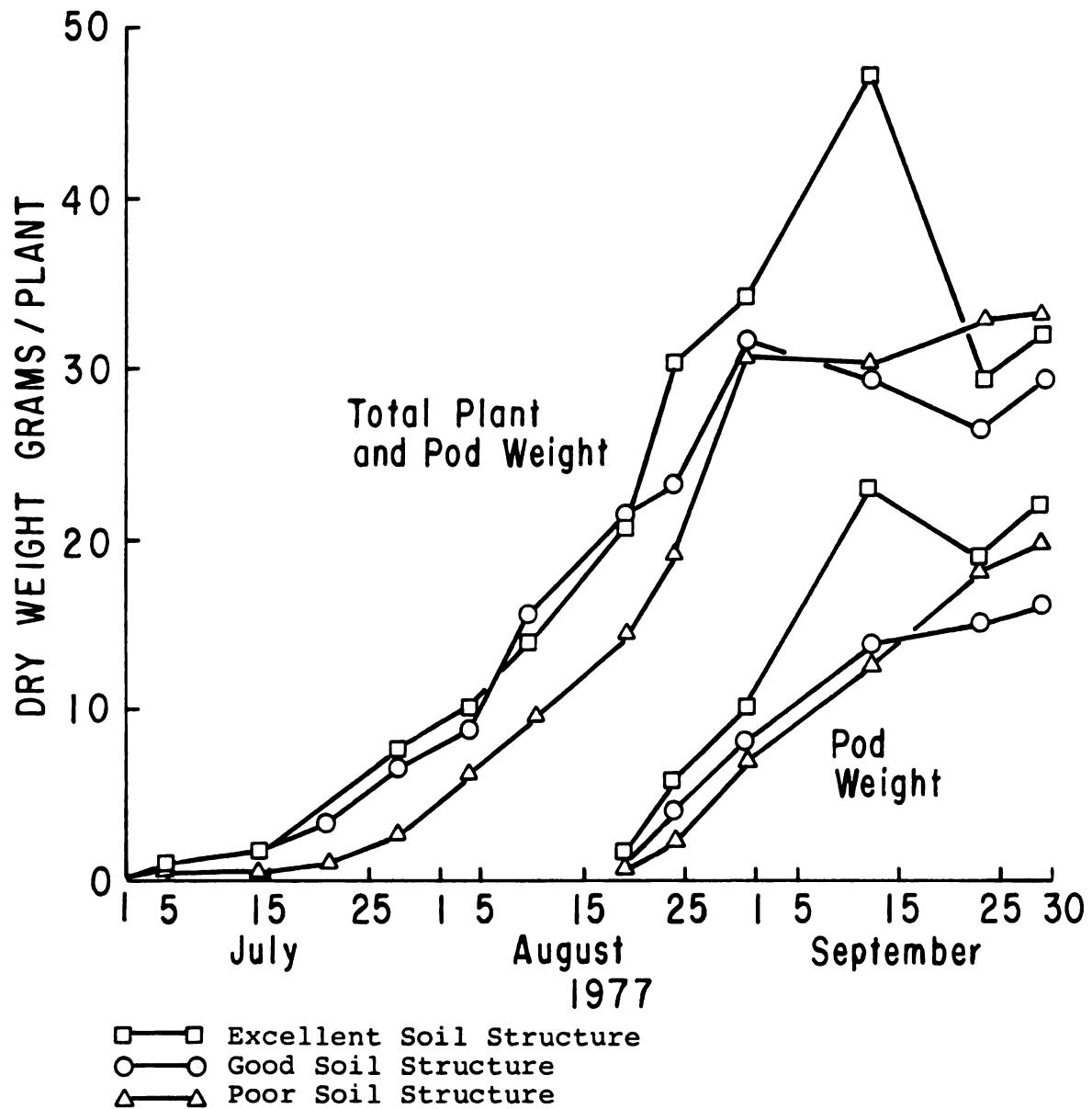


Figure 1. Plant Growth Curves of Beans Grown on Excellent, Good or Poor Soil Structure on Charity Clay in 1977.

September 23 is due to crop damage from these storms. The yield would have been substantially higher with excellent soil structure than with good or poor soil structure had there not been storm damage. The plant growth curves from poor or compacted soil structure are similar to the growth curves from good soil structure. However, plant population on the compacted treatment was much lower than on the other treatments due to emergence problems. Plants were widely spaced and received more sunlight, so that when ten plants were consecutively cut there were more large plants within the ten than on other treatments. Leaf area indexes just prior to flowering for excellent, good, and poor soil structure were 2.3, 2.0, and 0.3 respectively. The leaf area index for compacted soil was substantially lower than on the other treatments because of both fewer and smaller plants. The superior plant growth obtained from excellent soil structure in 1977 was the result of greater rooting volume from which the plants could obtain water and nutrients.

The plant growth difference between excellent and good soil structure found in 1977 did not exist in 1978. The 1978 excellent structure plant growth curve was the same as the curve of good soil structure without heavy irrigation shown in Figure 2. Differences in soil structure between excellent and good may have been less in 1978 than in 1977. The excellent structure in 1978 was in second year beans whereas the good structure did have three months

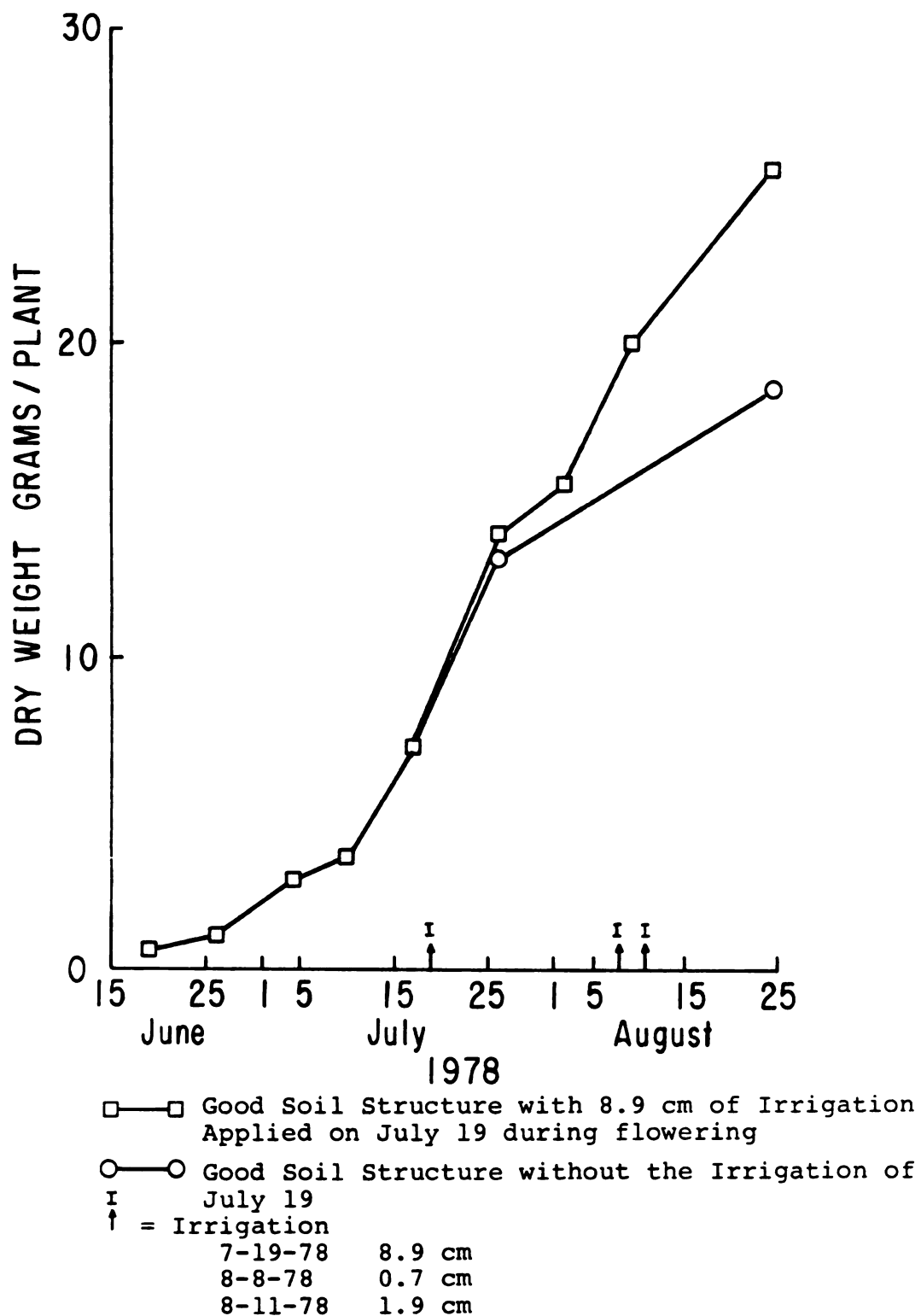


Figure 2. Plant Growth Curves of Beans Grown on Charity Clay With Good Soil Structure With and Without Heavy Irrigation at Flowering in 1978.

growth of alfalfa the previous summer. Although the growth curves were not different, 1978 yield was significantly higher with excellent soil structure.

Application of heavy irrigation during flowering on the Charity clay in 1978 significantly increased plant growth. As shown in Figure 2, the flowering irrigation of July 19 resulted in the plant growth rate remaining linear rather than decreasing, as was the case with the other 1978 Charity clay treatments. Plant water stress was not visible in late July or early August on the treatments not irrigated on July 19. However the plant growth curves clearly show that the water applied on July 19 provided needed moisture through the flowering and pod filling stages. Light irrigations on August 8 and August 11 did not restore growth curves to the level of the plants irrigated on July 19. Heavy irrigations on August 2 and 3 during pod filling increased yields but not to the level of the irrigation of July 19. The growth curve of plants receiving heavy irrigation at second seedling in 1978 was similar to that of plants grown on good soil structure without heavy irrigation. The treatments of heavy irrigation at second seedling, flowering, and pod filling in 1977 increased the plant growth above that of plants grown on good soil structure, but not above that of plants grown on excellent soil structure.

Plant growth curves of beans irrigated as needed, never irrigated, or water stressed only at second seedling

on the Hillsdale sandy loam in 1977 are shown in Figure 3. The positive benefits of supplementary irrigation are reflected in the difference between the irrigated and non-irrigated treatments. Beans not irrigated on July 14 (stress at second seedling) were badly damaged by a severe water stress. These plants were yellow and only half as tall as irrigated plants by July 17. Total plant and pod weights never recovered to the levels of those kept irrigated as needed. The pod filling stage irrigation of August 24 enabled growth curves and yields of these plants to surpass those of the treatment receiving no supplementary irrigation. Decreasing total plant and pod weights in late pod filling for each treatment are due to plant senescence and accompanying leaf drop.

Figures 4 and 5 show the plant growth curves from the drought stress experiments on Hillsdale sandy loam in 1978. Plants that were irrigated when needed were still growing on August 24, whereas the plants on other treatments were already decreasing in weight due to leaf drop and senescence. Plants irrigated only on July 7 grew bigger than those never irrigated. Those irrigated through July 28 had water stress during August and the benefits of extra water through flowering were lost. Figure 5 shows that plant growth on the treatment missing irrigation only on July 7, differed little from that of the treatment of irrigation as needed including July 7. The sharp reductions in growth rates for irrigations missed on July 14 or July 28

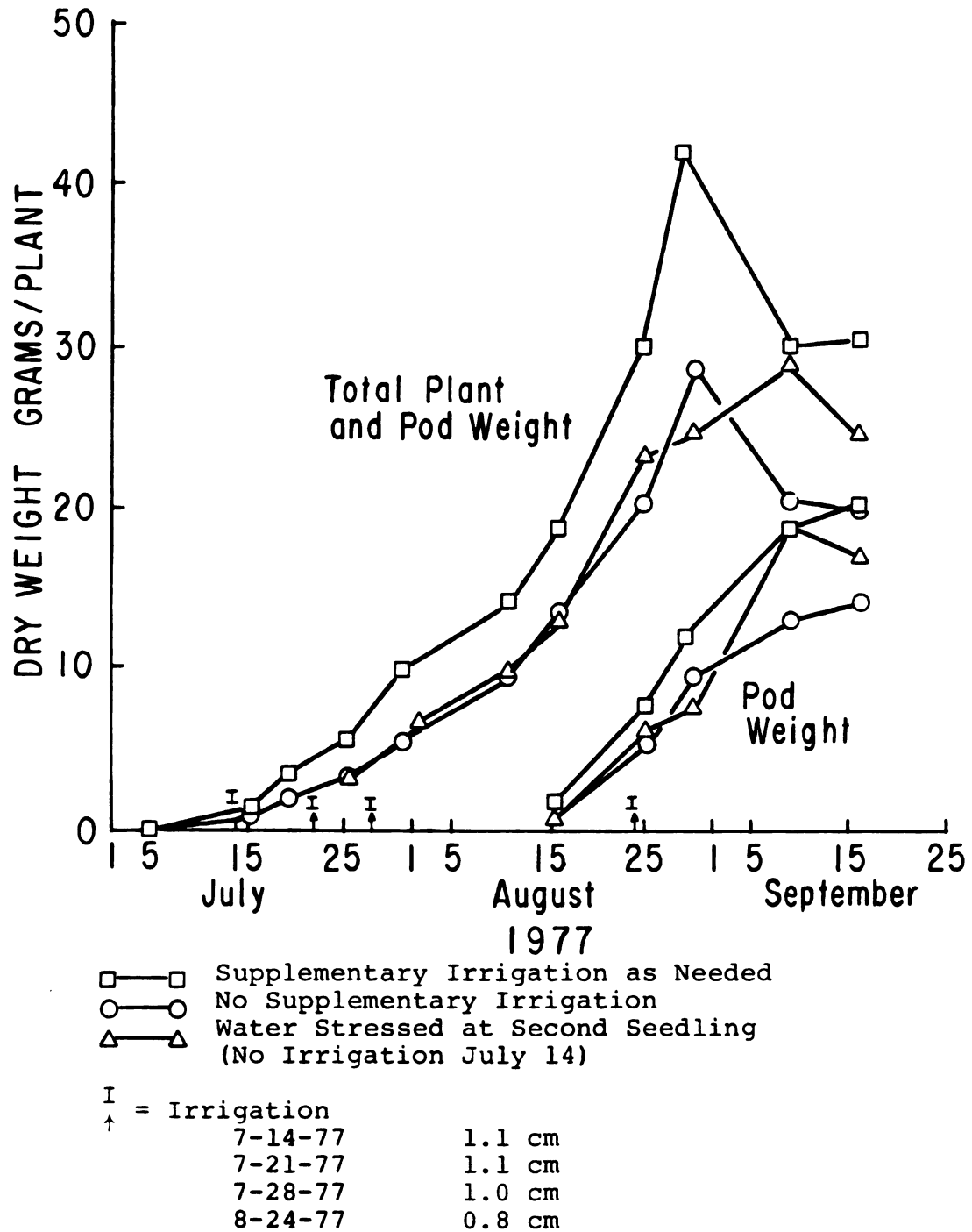


Figure 3. Plant Growth Curves of Beans With Supplementary Irrigation as Needed, No Supplementary Irrigation, or Water Stress Only at Second Seedling on Hillsdale Sandy Loam in 1977.

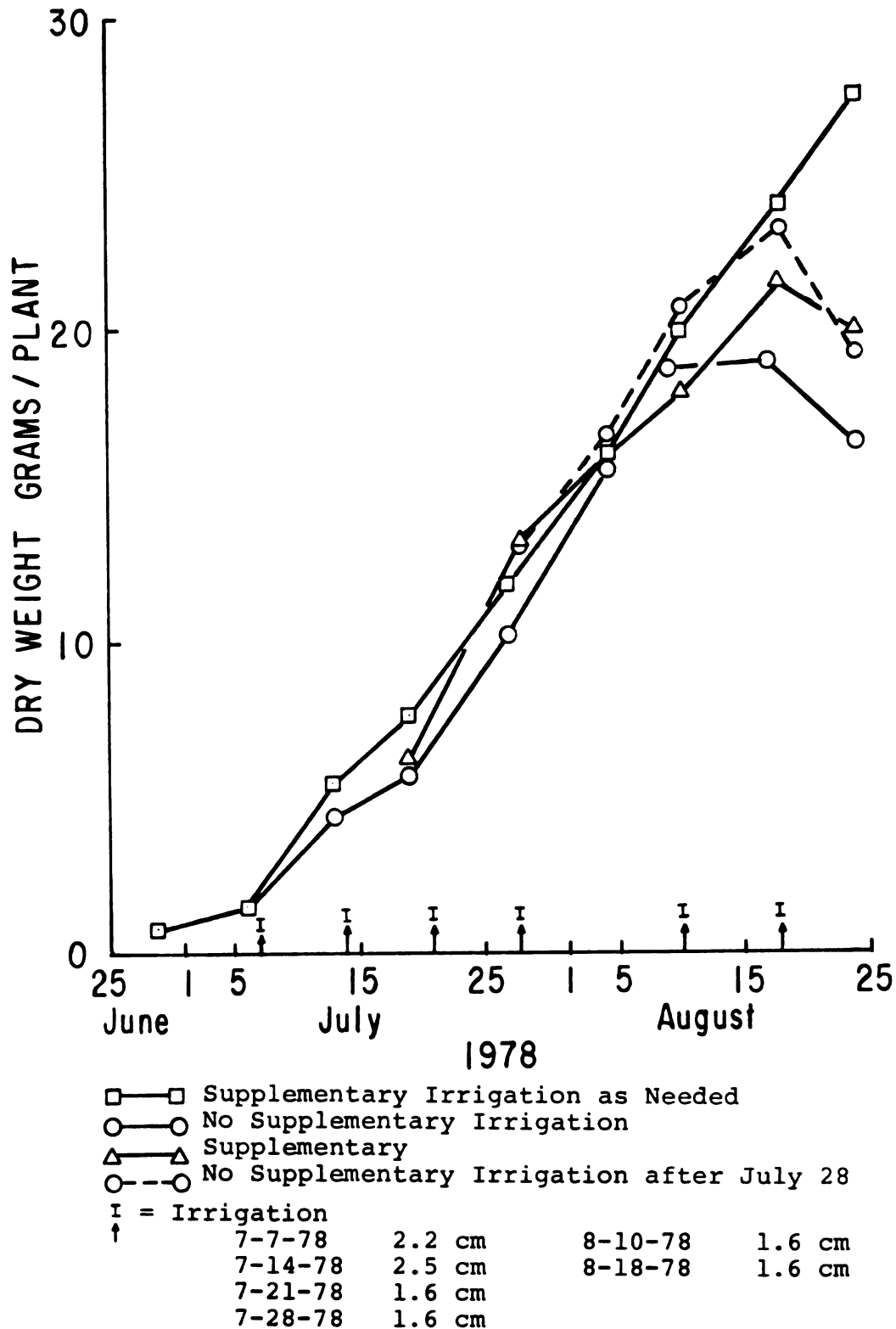


Figure 4. Plant Growth Curves of Beans With Supplementary Irrigation as Needed, No Supplementary Irrigation, Supplementary Irrigation Only on July 7, or No Supplementary Irrigation After July 28 on Hillsdale Sandy Loam in 1978.

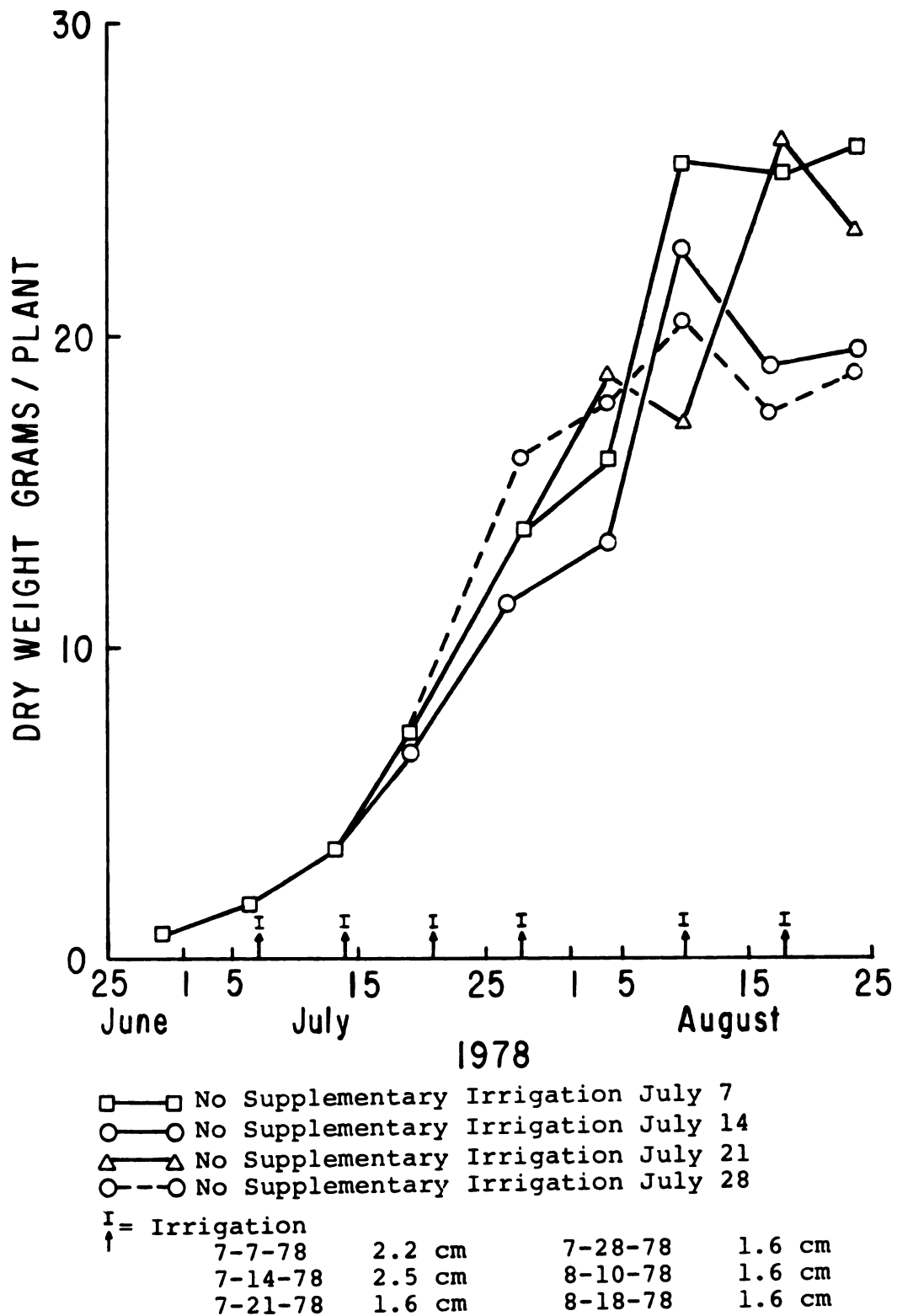


Figure 5. Plant Growth Curves of Beans Not Receiving Supplementary Irrigation on July 7, 14, 21, or 28 on Hillsdale Sandy Loam in 1978.

show that plant water stress occurred at these times. Reduction was slight when irrigation was missed on July 21, so at this time water was less critical. Plant growth was significantly reduced without supplementary irrigation on July 14, July 28, or August 10 and August 18. Water stress during August was sufficient to stop plant growth when irrigation was not applied on August 10 or August 18.

Pod weight curves from 1977 are included in Figures 1 and 3. Figure 1 shows that pod weights from excellent soil structure are greater than those from good or poor soil structure on the Charity clay. Differences are substantial prior to the crop damage occurring on September 17 and 18. Differences in pod weights between plants irrigated as needed and those never irrigated on the Hillsdale sandy loam are seen in Figure 3. The irrigation of August 24, 1977 appears to have greatly benefited pod filling of the plants stressed only at second seedling. Table 3 shows weights of plant and pod tissues collected on August 24, 1978 from both the Charity clay and the Hillsdale sandy loam. August 24 was one week prior to harvest at both locations. On the Charity clay, pod weights of plants receiving heavy irrigation at flowering are significantly higher than those from all other treatments. The plant tissue weights of heavy irrigation at flowering are greater than those from all treatments except heavy irrigation at pod filling, indicating that those plants receiving water at pod filling were undergoing additional vegetative growth.

Table 3.--Bean Plant and Pod Tissue Weights (grams/plant) of Samples Collected August 24, 1978 from Charity Clay and Hillsdale Sandy Loam.

Treatment	Plant Tissue Weight grams/plant	Pod Weight grams/plant
<u>Charity clay</u>		
Good soil structure--irrigated as needed	5.2b	12.1b
Good soil structure--irrigated as needed plus heavy irri- gation at second seedling	4.9b	13.0b
Good soil structure--irrigated as needed plus heavy irri- gation at flowering	7.8a	17.6a
Excellent soil structure-- never irrigated	4.2b	12.5b
Excellent soil structure-- irrigated as needed	5.2b	13.4b
Excellent soil structure-- irrigated as needed plus heavy irrigation at pod filling	6.0ab	10.7b
Poor soil structure	4.3b	11.4b
<u>Hillsdale sandy loam</u>		
Irrigation as needed	9.2a	18.5a
No irrigation 7-7-78	8.6ab	17.3ab
No irrigation 7-14-78	6.3bc	13.3bc
No irrigation 7-21-78	7.5abc	15.8abc
No irrigation 7-28-78	5.4c	13.5bc
Irrigated only 7-7-78	5.1c	15.0abc
No irrigation after 7-28-78	7.0abc	12.4c
Never irrigated	4.9c	11.4c

Letters indicate Duncan's Multiple Range Test at the 5% level.

Pod weights of beans supplied irrigation as needed on the Hillsdale sandy loam are significantly greater than those of beans never irrigated, not irrigated on 7-14-78, not irrigated on 7-28-78, or not irrigated after 7-28-78. Plant tissue weights of beans irrigated as needed on the Hillsdale sandy loam are significantly greater than those of beans never irrigated, not irrigated on 7-14-78, not irrigated on 7-28-78, or irrigated only on 7-7-78. The significant difference between pod weights but not plant tissue weights from beans irrigated as needed and those not irrigated after 7-28-78 indicates the need for water during pod filling.

Table 4 shows bean root sample volumes (cm^3) and root weights (grams/plant) from selected soil structure or irrigation treatments on Charity clay in 1977 and 1978 and Hillsdale sandy loam in 1977. Prior to collecting root weight samples, plant root systems for each treatment were excavated to determine the volume of soil explored.

When roots were sampled on July 6, 1977 on the Hillsdale sandy loam and on July 7, 1977 on the Charity clay, plants were quite small so root samples were collected no deeper than 15 cm. With poor structure on Charity clay in 1977, roots were not penetrating deeper than 30 cm. Roots were penetrating as deep as 46 cm on the excellent soil structure. The difference between root sample volumes of August 4, 1977 and August 9, 1978 on the Charity clay is due to plant growth stage. The August 1978 samples were taken during pod filling whereas the August 1977 samples were at

Table 4.--Total Air Dry Bean Root Weights (grams) and Root Sample Volumes (cm³) from Selected Soil Structure or Irrigation Treatments on Charity Clay in 1977 and 1978 and Hillsdale Sandy Loam in 1977.

Treatment	Sample Collection Dates			
	Root Sample Volume cm ³	Root Weight grams/plant	Root Sample Volume cm ³	Root Weight grams/plant
Excellent soil structure on Charity clay, 1977	4,719	.08	<u>July 7, 1977</u>	
			<u>August 4, 1977</u>	
Poor soil structure on Charity clay, 1977	4,719	.08	14,158	.41
			11,012	.27
Good soil structure without heavy irrigation on Charity clay, 1978	12,585	.51	<u>July 18, 1978</u>	
			<u>August 9, 1978</u>	
Good soil structure on Charity clay with heavy irrigation on June 29, 1978	12,585	.64	15,732	.70
			15,732	.88
Beans irrigated as needed on Hillsdale sandy loam, 1977	4,719	.06	<u>July 6, 1977</u>	
			<u>August 9, 1977</u>	
Beans never irrigated on Hillsdale sandy loam, 1977	4,719	.06	14,158	.75
			14,158	.47

early flowering. The August 9, 1977 sampling on Hillsdale sandy loam also occurred during early flowering. The 1977 Charity clay root sample weights from early flowering show the difference in rooting between excellent soil structure and compacted soil. The 1978 Charity clay root samples show that the heavy irrigation at second seedling increased root growth. This increase lasted for the remainder of the season. On the Hillsdale sandy loam in 1977 the root growth at early flowering was greater than on the Charity clay. The beneficial effects of supplementary irrigation on root growth are also shown on the Hillsdale sandy loam in 1977.

Final bean yields (kg/ha) in 1977 and 1978 from soil structure and irrigation treatments on the Charity clay and Hillsdale sandy loam are shown in Table 5. The 1977 Charity clay yields show significant differences between poor soil structure and all other treatments. Differences among the other treatments are believed to have been eliminated by hail and flooding during pod filling. The 1978 Charity clay data shows highest yield with heavy irrigation at flowering. Heavy irrigation at pod filling also improved yields. Probable loss of nitrogen from leaching is shown when comparing heavy irrigation at pod filling with and without application of supplementary nitrogen (34 kg/ha) several days later. Yield differences were significantly different between excellent and good soil structures receiving light supplementary irrigation during emergence and flowering. Excellent soil structure without supplementary irrigation

Table 5.--Final Yields (kg/ha) of Beans Grown with Different Soil Structure and Water Regimes on Charity Clay and Hillsdale Sandy Loam in 1977 and 1978.

Treatment	Location and Yield	
	1977	1978
	Yield kg/ha	Yield kg/ha
Charity clay		
Excellent soil structure--supplementary irrigation	1813a	2652cd
Excellent soil structure--no supplementary irrigation		2200e
Good soil structure--supplementary irrigation	1942a	2101e
Poor soil structure--supplementary irrigation in 1977	858b	2433de
Heavy irrigation at second seedling	1991a	2380de
Heavy irrigation at flowering	1816a	3687a
Heavy irrigation at pod filling	1842a	2933bc
Heavy irrigation at pod filling with supplementary N		3243b
Hillsdale sandy loam		
Irrigation as needed	2633a	2460a
Never irrigated	2009b	1673b
Water stress at second seedling only (7-14-77, 7-7-78)	2226ab	1900b
Water stress at preflowering (7-14-78)		1888b
Water stress at early flowering (7-21-78)		1924b

Table 5.--Continued.

Treatment	Location and Yield	
	1977	1978
	Yield kg/ha	Yield kg/ha
Hillsdale sandy loam		
Water stress at late flowering (7-28-78)		1971b
Water stress at pod filling (no irrigation after 7-28-78)		1739b
Water stress after second seedling (no irrigation after 7-7-78)		1838b

Letters indicate Duncan's Multiple Range Test at 5% level.

was not significantly different from good soil structure with supplementary irrigation. The high yield on the compacted plot in 1978 demonstrates the importance of soil moisture during tillage. Soil was considerably wetter in 1977 at the time of compaction than in 1978. Damage to the soil structure was thus much greater in 1977. The poor structure in 1977 resulted in poor emergence, low final plant population and significantly reduced yield. In 1978 compaction reduced plant stand some, but yield was not significantly different from that of several other treatments.

The 1977 water stress experiments on Hillsdale sandy loam show significant yield differences between irrigation as needed and no irrigation. Yields from beans stressed only at second seedling are not significantly different from those of the other two treatments. The 1978 Hillsdale sandy loam data show water to be important at all stages of plant growth. However the sharp depression in yield when supplementary irrigation was not applied during pod filling in 1978, coupled with the increase in yield with heavy irrigation during flowering on Charity clay in 1978, demonstrate that flowering and pod filling are the most critical plant growth stages for water needs in relation to navy bean yield.

Conclusions

Water is important for bean growth and yield at all plant growth stages. Particular attention must be paid to

water needs during flowering and pod filling. Soil structure influences the plant through impedance of root growth and the effects of crusting on bean emergence. Poor root distribution with mechanical impedance affects plant growth because the roots do not explore a sufficient soil volume to get optimum water and nutrients. Water is the major limiting factor to navy bean yield in Michigan. Concern for improving and/or maintaining good soil structure to promote maximum root growth, and possible investment in sprinkler irrigation can reverse the trend of declining navy bean yield in Michigan.

References

- American Society of Agricultural Engineers. 1971. Compaction of agricultural soils. The American Society of Agricultural Engineers, 2950 Niles Road, St. Joseph, MI 49085. 471 p.
- Doss, B. D.; R. W. Pearson; and H. T. Rogers. 1974. Effect of soil water stress at various growth stages on soybean yield. Agron. J. 66: 297-299.
- Hoffman, F. J.; J. A. Jobes; Z. Hanscom; and E. V. Maas. 1978. Timing of environmental stress affects growth, water relations, and salt tolerance of pinto bean. Am. Soc. Agric. Engin. Trans. 21: 713-718.
- Miller, D. G.; C. E. Manning; and I. D. Teare. 1977. Effects of soil water levels on components of growth and yield in peas. Am. Soc. Hort. Sci. J. 102: 349-351.
- Sionit, N., and P. J. Kramer. 1977. Effect of water stress during different stages of growth of soybean. Agron. J. 69: 274-278.

CHAPTER III

A LIMITED INFORMATION MODEL OF NAVY BEAN (PHASEOLUS VULGARIS) GROWTH AND YIELD AS A FUNCTION OF SOIL STRUCTURE AND WEATHER. PART I: THE MODEL

Abstract

A model was constructed from field data of navy bean growth and yield on Hillsdale sandy loam and Charity clay soils in 1977. The model predicts navy bean growth and yield based on soil and weather data. Data required for the model are bulk densities of the 0-15 and 15-45 cm soil depths, soil moisture percent by weight at .06 and 15 bars tension, soil moisture content on the planting date, percent of the soil surface which is not crusted during emergence, an evaluation of the soil structure as excellent, good, or poor, the number of seeds planted per hectare, the percent of seeds that will emerge, the planting date, and the daily rainfall, pan evaporation, and maximum and minimum air temperatures. Equations predicting daily percent emergence, vegetative growth prior to flowering, and pod weights during pod filling were derived from the 1977 field data using multiple linear regression. An equation was created

to predict the potential number of flowers per day that bloom during flowering and an equation from Davis (1943) was used to predict the percent of blooming flowers that set pods.

Soil structure factors were included in the multiple linear regression equations to simulate the effects of crusting on seedling emergence, and the effects of soil structures ranging from ideal for root growth (excellent) to severely compacted (poor) on plant growth. Soil water is described linearly in the model with the moisture content of 0.06 bars tension being 100 percent, readily available moisture, and the moisture content of 15 bars tension being 0 percent readily available soil moisture. Seeds are considered to germinate when soil moisture of the seed zone exceeds 30 percent readily available soil moisture, and plants are water stressed when readily available soil moisture in the root zone drops below 60 percent. During plant water stress the model uses conceptual equations to reduce the values of terms in the equations for vegetative growth prior to flowering and pod weights during pod filling. The effect of water stress during flowering in the model is to reduce the number of flowering days. The model uses boundaries to define the number of days for germination, emergence, vegetative growth prior to flowering, flowering, and pod filling.

The model of navy bean growth and yield is programmed in Fortran IV, and has been run on a Control Data Corporation

6500 computer. The model consists of a main program and subroutines for calculating emergence, plant growth until flowering, flowering, pod filling, soil moisture, and weather data. The model can be used to predict yields based on soil conditions and weather, and to make management decisions regarding soil structure and irrigation needs.

Introduction

A number of detailed models for soil moisture, evaporation, transpiration, and crop yield as a function of soil moisture have been constructed in recent years. The majority of these require quite detailed information regarding soil and plant parameters. The approach used in construction of the Navy Bean model was to simplify the system as much as possible so that required environmental inputs are kept to a minimum.

Soil water models both separate from growing plants (Rowse and Stone, 1978; Beese, Van Der Ploeg, and Richter, 1977; James and Larson, 1976), and including plants (Anderson, Johnson, and Powers, 1978; Rowse, Stone, and Gerwitz, 1978) have been developed. Measured soil data required for the model of Rowse and Stone (1978) are initial water distribution, matric suction at 60 cm, hydraulic conductivity-water content relationship, and the diffusivity-water content relationship. The model by Rowse, et al. (1978) including plant parameters calculates the volumetric rate

of water uptake per unit volume of soil from the bulk soil pressure head (sum of potentials due to matric forces and gravity), plant water potential, and soil and plant resistances associated with unit length of root. Transpiration in the model is assumed either to be equal to an energy limited rate given by $f \cdot E$ where E is the Penman potential transpiration and f is the fraction of crop cover, or equal to the rate at which water can be extracted from the soil at a critical plant water potential at which stomatal closure is assumed to occur. Both the model of Rowse and Stone (1978) and the one of Beese, Van Der Ploeg and Richter (1977) use the basic equation for unsaturated soil moisture flow.

James and Larson (1976) chose not to use the basic equation for unsaturated soil moisture flow, because it is difficult to use and requires very detailed input data. They instead used submodels to characterize four different types of infiltration and three different patterns of redistribution under intermittent water application. Anderson, et al. (1978) used the one-dimensional Darcy equation for moisture redistribution after occurrence of infiltration or transpiration, the model used by Saxton (1972) and Campbell (1973) for distribution of infiltrating water, modification by Huggins and Monke (1968) of Holtan's (1961) equation for average infiltration capacity during any period, the method of Jensen, Wright, and Pratt (1971) for using the Penman equation for predicting potential

evapotranspiration, and a conceptual model of water interception by plants based on maximums and minimums as linear functions of crop leaf area index. Their model produced continuous simulation of the moisture balance during the growing season including interception, infiltration, surface depression storage, surface runoff, soil moisture redistribution, deep percolation, and evapotranspiration.

Models including soil water, plant water movement, and evapotranspiration include those of Cowan (1965), Nimah and Hanks (1973a, 1973b), and Hansen (1975). Cowan (1965) mathematically described transpiration as a function of climatic factors at the plant leaf surface, flow of water through the plant based on water potential and crop impedance, and flow of water through the soil and into the roots. The model of Nimah and Hanks (1973a, 1973b) predicts water content profiles, evapotranspiration, water flow from or to the water table, root extraction and root water potential under transient field conditions. Like Rowse, Stone, and Gerwitz (1978), their model includes a root extraction term added to the basic one dimensional flow equation. Hansen's model uses Darcy's law for flow in porous media for vertical water flux, Gardner's model (1960) for water flow to single roots, and Monteith's model (1965) for atmospheric relations.

Models of soil water evaporation include those of Hillel (1975), Black, Gardner, and Thurtell (1969), and Gardner and Hillel (1962). Ritchie (1972) developed a model

for predicting crop evaporation from a row crop with incomplete cover, where crop evaporation rate is a function of soil surface and plant surface components, potential evaporation, rainfall, and net radiation above the canopy. Brun, Kanemasu, and Powers (1972) tested Monteith's (1965) model of evapotranspiration with soybeans and sorghum, whereas Black, Tanner, and Gardner (1970) tested the same model with snap beans (Phaseolus vulgaris). Saxton, Johnson, and Shaw (1974) developed a digital model to compute interception evaporation, soil evaporation, and plant transpiration to provide daily actual evapotranspiration estimates. All of these very detailed models use physical principles, but require detailed input data. A somewhat simpler approach using leaf area index, an approximate energy balance and pan evaporation to estimate potential evapotranspiration, and a coefficient of limiting soil water has been used by Hanson (1976) to predict evapotranspiration from Native Rangelands in the Northern Great Plains.

The logical extension of models of soil moisture, evaporation, and transpiration, is to make a simulation model which predicts plant growth and yield as a function of water use. Models of soil-water balance which successfully predict crop yields of cereals have been made by Denmead and Shaw (1962), Dale and Shaw (1965), Baier and Robertson (1966), and Fitzpatrick and Nix (1969). A paper by Lewin and Lomas (1974) compares crop yield predictions of three statistical methods and four soil water simulation models,

and concludes that in arid climates both statistical and simulation methods work successfully, whereas in areas of higher rainfall simulation models work best. Hanks (1974) modeled plant yield as influenced by water use using the assumption that the only process influencing plant growth directly is transpiration. Using de Wit's (1958) equation relating dry matter yield to transpiration ($Y = mT/E_o$ where Y is yield, T is transpiration in cm, E_o is average free water evaporation rate in cm day^{-1} , and m is a crop factor having dimensions of $\text{kg ha}^{-1} \text{ day}^{-1}$ when yield is in kg ha^{-1}) he predicted yield from $Y/Y_p = T/T_p$ where Y_p is potential yield when transpiration is equal to potential transpiration. His model divides the growing season into five stages, calculates T/T_p for each stage with the model accumulating information in one day increments, and at the end of the season predicts Y/Y_p from a product of the T/T_p 's adjusted by field determined coefficients.

Neghassi, Heermann, and Smika (1975) provide a review of various models of yield versus moisture. In their paper they compare linear and quadratic forms of yield models based on cumulative evapotranspiration or cumulative relative evapotranspiration, and conclude that the linear forms of their models are sufficient for predicting dry matter yield when soil water is limiting. The concept of a daily index of available soil moisture is used in a barley model by Heapy, et al. (1976). Days with moisture stress in the model occur when the available soil moisture

dips below a critical value. Final yield is predicted in a summation equation of coefficients times stress ratios (stress days/total days) during planting-emergence, emergence-tillering, and jointing-heading. Other models of yield as a function of soil water levels during the crop season include asymptotic (Mitscherlich and Spillman; Heady and Dillon, 1961), additive (Moore, 1961; Flinn and Musgrave, 1967; Dudley, Howell, and Musgrave, 1971), and multiplicative (Jensen, 1968; Hall and Butcher, 1968; Anderson and Maas, 1971) models.

The objective in constructing this navy bean model was to predict growth and yield as functions of soil structure and weather using limited input information. Soil information needed by the model is bulk densities of the 0-15 and 15-45 cm soil depths, soil moisture percent by weight at .06 and 15 bars tension, soil moisture percent by weight on the planting date, the percent of the soil surface which is not crusted during emergence, and classification of soil structure as excellent, good, or poor. Final plant stand must be known or estimated, and is entered in the model as number of seeds planted per hectare, and final percent that emerge. Needed weather data is daily rainfall, pan evaporation, and maximum and minimum air temperatures. In contrast to the majority of plant growth models presently available, which require such input data as hydraulic conductivity, diffusivity, or input radiant energy, the data

needed for this model is easily obtained or estimated. Although oversimplification of naturally occurring events can lead to erroneous predictions of soil moisture or plant growth, the practical advantages of a model requiring minimal input data can outweigh the disadvantages, particularly when the model is used to predict field results under a variety of different management regimes. The ultimate goal of the study was to create a model which would discriminate between differing soil structure and moisture regimes so as to assist in making correct decisions regarding crop and soil management.

The Model

The model of navy bean (Phaseolus vulgaris) growth and yield as a function of soil moisture and structure was developed by using multiple linear regression on field data, and by developing conceptual equations. Equations for percent emergence, plant leaf area prior to flowering, and daily pod weight during pod filling were derived from field data of navy bean growth and yield on Hillsdale sandy loam and Charity clay soils in 1977. The data used for equations of plant growth and yield were collected from beans irrigated as needed on the Hillsdale sandy loam, and from beans growing on structures defined as excellent, good, or poor on the Charity clay. Excellent soil structure on the Charity clay was obtained by two years growth of an alfalfa-timothy mixture, followed by deep chiseling and moldboard

plowing in the fall prior to spring bean planting. Good soil structure was that where two years growth of alfalfa-timothy and fall deep chiseling and moldboard plowing were not included in the crop and soil management scheme. Poor soil structure was made by compacting the soil with a tractor prior to planting. The model uses an equation of Davis (1943) to predict the percent of flowers which will successfully set pods. Water stress during vegetative growth or pod filling is simulated by reducing terms in the derived equations. The model reduces the length of flowering when water stress occurs. A soil moisture submodel determines times and amounts of water stress. The model uses a time interval of one day in following plant growth from germination through harvest.

Germination and Emergence

Field and greenhouse observations in 1977 and 1978 showed that navy beans begin emerging on the fifth day following sufficient soil moisture for seed imbibition. Hunter and Erickson (1952) found that a soil moisture content of greater than 6.6 bars tension was necessary for soybeans to germinate. The model starts seed imbibition when soil moisture at 2.5 to 5 centimeters exceeds 30 percent of the total that can be held between 15 and .06 bars tension for the particular soil. The day on which soil moisture is sufficient for imbibition is counted as day one, and emergence begins on day five. The model calculates

cumulative percent emergence for a ten day period from equation (1);

$$(1) \text{EMERGE}_t = (0.7764 + 0.101 \times te_t + 0.5427 \times \text{UNCRUST}_T) - 1$$

EMERGE_t = percent emergence on day t

te_t = emergence day (1 through 10)

UNCRUST_t = percent of the soil surface not crusted
on day te_t

Equation (1) was derived using multiple linear regression on 1041 values of percent emergence versus emergence day and percent of soil surface not crusted. Four values of percent emergence versus emergence day and percent of soil surface with crust strength greater than 15 bars were available from years with severe crusting problems during emergence. The remaining data was assumed to have no crusting during emergence except for 120 cases where the soil had been severely compacted by a tractor prior to planting. For these cases percent of the surface not crusted was assumed to be 5 percent. Boundaries for the percent emergence equation are 0 and 100 percent. The correlation coefficient is $R^2 = 0.74$.

Equation (1) calculates percent emergence of the final plant stand. The model user must supply the percent of planted beans that will emerge by estimation or from final plant stand counts. The user must also provide estimates of the percent of soil surface not crusted during

emergence. This may be supplied either daily or as a single value to represent the entire emergence time.

Plant Growth Prior to Flowering

The purpose of calculating percent of final emergence for each emergence day is to separate the plant population into subpopulations. Leaf area data collected from beans grown on Hillsdale sandy loam or Charity clay in 1977 and 1978 showed that regardless of soil structure, or time and amount of plant water stress, navy bean populations from emergence through harvest consist of plants of strikingly different sizes. When ten navy bean plants were consecutively cut from a row each week, plant size ranged from extremely small to quite large. This is in contrast to corn or soybeans, which have plants of relatively uniform size within the total plant population. The problem of navy bean populations which are not uniform in size may be due to seed quality, plant competition, or both. The model treats the problem as being due to plant competition. It separates the total population into subpopulations of large, medium, and small plants based on time of emergence. Large plants are defined as those emerging on day 1, medium plants as those emerging on days 2 through 5, and small plants as the remaining number of plants that emerge. The effect of crusting during emergence in the model, is to decrease the number of large plants and increase the number of medium and small plants.

The model represents each subpopulation by a single plant and predicts leaf areas as functions of accumulated degree days per subpopulation and soil structure. Daily degree days are first calculated in equation (2) using 55°F as a base.

$$(2) \text{DEGDAY}_t = \frac{\text{MAXT}_t + \text{MINT}_t}{2} - 55$$

DEGDAY_t = degree days on day t

MAXT_t = maximum air temperature (F°) on day t

MINT_t = minimum air temperature (F°) on day t

If water stress occurs prior to flowering the model reduces the daily degree days of equation (2). In determining water stress the model uses a concept of daily index of available soil moisture, DIASM_t , similar to that of Heapy, Webster, Love, Von Maydell, and Robertson (1976). It expresses average root zone soil moisture contents between 0.06 and 15 bars tension (the model soil moisture boundaries) linearly such that at 0.06 bars tension the available water is 1.0, and at 15 bars tension the available water is 0. Plant water stress is defined as occurring when DIASM_t is less than 0.6. The reduction in daily degree days of equation (2) is accomplished by equations (3) and (4). A_t of equation (3) linearly reduces the daily degree days when DIASM_t is less than 0.6. The concept of reducing the daily degree days during water stress is based on the fact that a

plant undergoing moisture stress cannot completely use input radiant energy.

$$(3) A_t = \text{DIASM}_t + 0.4$$

$$0 \leq A_t \leq 1$$

A_t = Correction term on day t

DIASM_t = daily index of available soil moisture
on day t

$$(4) \text{CDEGDAY}_t = \text{DEGDAY}_t \times A_t$$

when $\text{DIASM}_t < 0.6$

$$0 \leq \text{CDEGDAY}_t \leq \text{DEGDAY}_t$$

CDEGDAY = degree days corrected for water stress
on day t

Degree days as corrected for water stress are accumulated by subpopulation. Accumulated degree days for each subpopulation are started on that subpopulation's first model defined emergence day. Equation (5) calculates accumulated degree days for the large plants.

$$(5) \text{LDD}_t = \text{LDD}_{t-1} + \text{CDEGDAY}_t$$

LDD_t = accumulated degree days on day t. Accumulation is from day 1 of emergence.

LDD_{t-1} = accumulated degree days on the previous day.

For medium plants the calculation is:

$$(6) \text{MDD}_t = \text{MDD}_{t-1} + \text{CDEGDAY}_t$$

MDD_t = accumulated degree days on day t . Accumulation is from day 2 of emergence.

MDD_{t-1} = accumulated degree days on the previous day.

For small plants accumulated degree days are summed in equation (7).

$$(7) \text{SDD}_t = \text{SDD}_{t-1} + \text{CDEGDAY}_t$$

SDD_t = accumulated degree days on day t . Accumulation is from day 6 of emergence.

SDD_{t-1} = accumulated degree days on the previous day.

The accumulated degree days of equations (5), (6), and (7), along with soil structure parameters are used to predict leaf areas by population prior to flowering. The leaf areas, accumulated degree days, and soil structures used in developing the leaf area predictive equations came from 1977 data of navy bean growth on Hillsdale sandy loam and Charity clay. The data used was from beans kept irrigated as needed on the Hillsdale sandy loam, and from beans grown on three different soil structures on Charity clay. The beans grown on Charity clay received some supplementary irrigation. Soil structures used in developing the equations were defined as excellent, good, or poor. The numbers 156, 144, or 72, which are the field observed vertical

cross sectional rooting areas (square inches) at flowering of beans grown on the three soil structures were used to define the soil structures during model development. Soil structure on the Hillsdale sandy loam was assumed to be excellent. In developing the predictive leaf area equations for the three subpopulations, average leaf areas were obtained by averaging leaf areas of the three largest, four intermediate, and three smallest plants of each set of ten plants cut. Eighty-four sets of data were used for each equation. Equation (8) predicts leaf areas for large plants.

$$(8) \text{ LPLA}_t = -1230 + (9.6 \times 10^{-7} \times \text{DDL}_t^{3.34}) + 8.6 \times D$$

LPLA_t = large plant leaf area on day t

D = soil structure term

Correlation coefficient $R^2 = 0.93$

The equation to predict medium plant leaf areas is:

$$(9) \text{ MPLA}_t = -838 + (3.0 \times 10^{-6} \times \text{DDM}_t^{3.1}) + 5.88 \times D$$

MPLA_t = medium plant leaf area on day t

Correlation coefficient $R^2 = 0.90$

Small leaf areas are predicted by equation (10).

$$(10) \text{ SPLA}_t = -446 + (7.8 \times 10^{-6} \times \text{DDS}_t^{2.84}) + 3.16 \times D$$

SPLA_t = small plant leaf area on day t

Correlation coefficient $R^2 = 0.67$

Flowering

The three model subpopulations begin flowering at the same time. When accumulated degree days of equation (11) equals or exceeds 700, the day prior to flowering has been reached.

$$(11) \text{ FDD}_t = \text{FDD}_{t-1} + \text{DEGDAY}_t$$

FDD_t = accumulated degree days on day t . Accumulation is from day one of emergence and is used to determine when flowering starts.

FDD_{t-1} = accumulated degree days on the previous day.

DEGDAY_t = daily degree days with no correction for moisture stress.

Equation (11) accumulates degree days from day one of emergence with no correction for moisture stress. The leaf areas of the three subpopulations on the day prior to start of flowering are used in equations (12), (13), and (14) to calculate the number of flowers blooming daily for each subpopulation.

$$(12) \text{ LFLOWER} = (5 \times 10^{-3}) \times \text{LPLA}_f$$

LFLOWER = number of flowers blooming daily on large plants

LPLA_f = large plant leaf area on the day $\text{DD4}_t \geq 700$

$$(13) \text{ MFLOWER} = (5 \times 10^{-3}) \times \text{MPLA}_f$$

MFLOWER = number of flowers blooming daily on medium plants

$MPLA_f$ = medium plant leaf area on the day $DD4_t \geq 700$

$$(14) \text{ SFLOWER} = (5 \times 10^{-3}) \times \text{SPLA}_f$$

SFLOWER = number of flowers blooming daily on small plants

$SPLA_f$ = small plant leaf area on the day $DD4_t \geq 700$

The factor 5×10^{-3} was chosen during model verification to provide sufficient flowers for the model to accurately predict yields.

Davis (1943) found that maximum air temperature is the most important climatic factor affecting pod set. Although he found correlation between percent set of pods and minimum relative humidity, he concluded that air temperature was far more important. His study showed that approximately 57 percent of the blossoms will set if the average maximum temperature for any two successive days during the blooming period does not exceed 75°F. For each degree of temperature above 75°F, a reduction of approximately 2 percent in pod set results. From his data he developed a simple equation to predict the percent of flowers blooming on a given day that will set pods. The equation uses the maximum air temperatures of the day of bloom and the following day. Equation (15) is the Davis equation.

$$(15) \text{ PSET}_t = (1.8 \times \text{AVMAXT}) + 192$$

PSET_t = percent of flowers that bloomed on day
t-1 that will set pods

AVMAXT = average of the maximum air temperatures of
day t-1 and day t.

Correlation coefficient = $-.3078$

Equation (15) is used in equations (16), (17), and
(18) to calculate daily the number of flowers that success-
fully become pods in each subpopulation.

$$(16) \text{ LPOD}_t = \text{LFLOWER} \times \text{PSET}_t$$

LPOD_t = pods formed on large plants on day t

$$(17) \text{ MPOD}_t = \text{MFLOWER} \times \text{PSET}_t$$

MPOD_t = pods formed on medium plants on day t

$$(18) \text{ SPOD}_t = \text{SFLOWER} \times \text{PSET}_t$$

SPOD_t = pods formed on small plants on day t

The pods per plant for the three subpopulations are then
accumulated during flowering by equations (19), (20), and
(21).

$$(19) \text{ LPODSUM}_t = \text{LPODSUM}_{t-1} + \text{LPOD}_t$$

LPODSUM_t = sum of pods on large plants on day t

LPODSUM_{t-1} = sum on the previous day

$$(20) \text{MPODSUM}_t = \text{MPODSUM}_{t-1} + \text{MPOD}_t$$

MPODSUM_t = sum of pods on medium plants on day t

MPODSUM_{t-1} = sum on the previous day

$$(21) \text{SPODSUM}_t = \text{SPODSUM}_{t-1} + \text{SPOD}_t$$

SPODSUM_t = sum of pods on small plants on day t

SPODSUM_{t-1} = sum on the previous day

Subhadrabandhu (1976) found with greenhouse experiments that the bean variety Seafarer has a short and highly concentrated flowering period of 6 days. With other varieties, Michelite and Black Turtle Soup, flowering period is longer and less concentrated, lasting 15 to 18 days. Our model defines flowering as occurring for a minimum of 5 and a maximum of 11 days for the bean variety Sanilac, which is similar to Seafarer. Termination of flowering between the boundaries of 5 and 11 days depends on moisture stress. This is accomplished through a cumulative equation which sums the results of equations related to daily amount of plant water stress, the number of days the plant has been stressed, and the number of days the plant has flowered. Equation (22) describes a curve which makes water stress effects increasingly severe as DIASM decreases below 0.6.

$$(22) \text{STRESS}_t = 15 \times \ln \left(\frac{1}{((\text{DIASM}_t \times 100) + 1.)} \times 1000 \right)$$

$$\text{DIASM}_t < 0.6$$

$STRESS_t$ = plant water stress on day t during
flowering

Equation (23) counts the number of days that plants have
been water stressed.

$$(23) \quad SDAYS_t = SDAYS_{t-1} + 1$$

$SDAYS_t$ = total number of flowering days plant has
been stressed on day t

$SDAYS_{t-1}$ = number of stress days from the previous
day

Equation (24) uses the result of (23) to express the
increased tendency of plants to stop flowering as number of
days with water stress increases.

$$(24) \quad CDAYS_t = e^{(SDAYS_t \times 0.4)}$$

$CDAYS_t$ = expression of water stress on flowering
day t related to the number of days the
plant has been stressed.

The tendency of plants to stop flowering as they approach
the end of the flowering period is expressed in equation
(25).

$$(25) \quad FDAYS_t = FDAYS_{t-1} + 2$$

$FDAYS_t$ = measure of accumulating number of flower-
ing days on day t, starting with day 6

$FDAYS_{t-1}$ = measure of flowering days on the previous
day

Equation (25) counts day 6 as 2, day 7 as 4, etc. The values of equations (22), (24), and (25) are summed daily as equation (26).

$$(26) \text{ ALLSTRESS}_t = \text{STRESS}_t + \text{CDAYS}_t + \text{FDAYS}_t$$

ALLSTRESS_t = daily sum of water stress equations
during flowering

Equation (27) accumulates the daily stress sums during periods of water stress.

$$(27) \text{ SUMSTRESS}_t = \text{SUMSTRESS}_{t-1} + \text{ALLSTRESS}_t$$

SUMSTRESS_t = accumulated sum of water stresses
on day t during flowering

SUMSTRESS_{t-1} = accumulated sum of water stresses
from the previous stress day

If two consecutive days with no stress (DIASM_t greater than or equal to 0.6) occur, the cumulative sum of stresses, SUMSTRESS_t , is reset to 0. Plant water stress ends flowering if SUMSTRESS_t is greater than 550.

Pod Filling

The day following the end of flowering is defined as day 5 of pod filling, because pods begin to fill immediately after being set. Pod weight during pod filling is calculated daily for each subpopulation as a function of pod filling day, total pods, and soil structure. Reduction in the rate of increase of pod weight during plant water

stress is simulated by reducing the pod filling day term. Equations (29) and (30) reduce the pod filling day term of equation (28) according to two linear equations which are discontinuous.

$$(28) \text{ DAYADD}_t = 1$$

$$0.6 \leq \text{DIASM}_t \leq 1$$

$$(29) \text{ DAYADD}_t = (3.2 \times \text{DIASM}_t) - 1.12$$

$$0.35 \leq \text{DIASM}_t < 0.6$$

$$(30) \text{ DAYADD}_t = 1.4 \times \text{DIASM}_t$$

$$0 \leq \text{DIASM}_t < 0.35$$

DAYADD_t = value by which accumulated pod filling days will be increased on day t

Equation (31) accumulates the pod filling day term.

$$(31) \text{ tp}_t = \text{tp}_{t-1} + \text{DAYADD}_t$$

tp_t = pod filling day term on day t

tp_{t-1} = pod filling day term on the previous day

In reducing the pod filling day term during water stress, equations (29) and (30) both reduce the rate of increase in pod weight, and simulate the hardening of plants to stress. Model runs showed that DIASM_t values in the range 0.59 to 0.35 occurred most often during pod filling with plants that had adequate water during most of vegetative

growth and flowering. Stresses in the range 0.59 to 0.35 had severe effects on these plants because they were not hardened to stress. In contrast, plants repeatedly stressed during the season were more likely to have $DIASM_t$'s in the range 0.35 to 0.0 during pod filling. These plants were hardened to stress and were damaged relatively less despite lower values of $DIASM_t$. The model makes stresses in the 0.59 to 0.35 range have severe effects, and those in the 0 to 0.34 range of $DIASM_t$ have less severe effects on the pod filling day term.

Equations (32), (33), and (34) use the pod filling day term, the total number of pods accumulated during flowering, and soil structure to predict dry bean weight per representative subpopulation plant during pod filling. The soil structure term D is the same as that used in leaf area calculations. Two hundred ninety eight sets of data were used to derive the single equation expressed in equations (32), (33), and (34). The correlation coefficient for the equation was $R^2 = 0.71$. Pod weights for large plants are calculated as:

$$(32) \text{ LPODWT}_t = -16.28 + 0.43 \times tp_t + 0.04 \times \text{LPODSUM}_f + 0.07 \times D$$

LPODWT_t = weight of pods on large plants on day t

tp_t = pod filling day term on day t

LPODSUM_f = final number of pods on large plants
 D = soil structure term (the same as equations (8), (9), and (10))

Equation (33) calculates pod weights for medium sized plants.

$$(33) \text{ MPODWT}_t = -16.28 + 0.43 \times \text{tp}_t + 0.04 \times \text{MPODSUM}_f + 0.07 \times D$$

MPODWT_t = weight of pods on medium plants on day t
 MPODSUM_f = final number of pods on medium plants

The pod weights of small plants are calculated by equation (34).

$$(34) \text{ SPODWT}_t = -16.28 + 0.43 \times \text{tp}_t + 0.04 \times \text{SPODSUM}_f + 0.07 \times D$$

SPODWT_t = weight of pods on small plants on day t
 SPODSUM_f = final number of pods on small plants

Pod filling is defined as lasting for 30 days.

Yield

Yield calculations are made on the final pod filling day. Total yield is the sum of the products of the number of plants per subpopulation, and the respective pod weights per representative subpopulation plant. Final predicted yields are expressed at 16 percent moisture, as are actual bean yields in Michigan.

The equations used to calculate final yield are listed as equations (35) through (39). Equation (35)

calculates the final plant stand from the number of seeds planted and the final percent emergence as observed in the field.

$$(35) \text{ PLANTPOP} = \text{SEEDPOP} \times \text{FEMERGE}$$

PLANTPOP = final plant stand/hectare

SEEDPOP = number of seeds planted/hectare

FEMERGE = percent final emergence

Equations (36), (37), and (38) calculate the number of plants in the subpopulations of large, medium, and small plants.

$$(36) \text{ LPOP} = \text{EMERGE}_1 \times \text{PLANTPOP}$$

LPOP = number of large plants/hectare

EMERGE_1 = percent emergence on day 1

$$(37) \text{ MPOP} = (\text{EMERGE}_5 - \text{EMERGE}_1) \times \text{PLANTPOP}$$

MPOP = number of medium plants/hectare

EMERGE_5 = percent emergence on day 5

$$(38) \text{ SPOP} = \text{PLANTPOP} - (\text{LPOP} + \text{MPOP})$$

SPOP = number of small plants/hectare

Final yield is calculated by equation (39).

$$(39) \text{ TOTAL YIELD} = \text{LPOP} \times \text{LPODWT}_f + \text{MPOP} \times \text{MPODWT}_f + \text{SPOP} \times \text{SPODWT}_f$$

$LPODWT_f$ = final pod weight of large plants

$MPODWT_f$ = final pod weight of medium plants

$SPODWT_f$ = final pod weight of small plants

The final pod filling day in the model is defined as the 30th day of pod filling.

Soil Moisture and Evapotranspiration

The soil moisture model assumes that the root zone of the navy bean plant extends from the soil surface to a depth of 45 cm. It also assumes that there are no layers which impede soil water movement. The model root zone is divided into 18 blocks. Each model block can hold water between the soil moisture contents of 15 and .06 bars tension. All soil moisture contents are calculated as percent by weight. Necessary user supplied model inputs are soil moisture percentage by weight at 15 and .06 bars tension, and bulk densities of soil block zones 1 through 6, and 7 through 18.

Additions of water to the soil moisture model come as rainfall or applied irrigation. The water added for a specific day is the sum of rainfall and irrigation minus pan evaporation (U.S. Weather Bureau, Type A pan). The model adds moisture to each soil block from the surface downwards until the block reaches the moisture content of .06 bars tension, or until all added water has been used. Water in excess of setting all blocks to the moisture content of .06 bars tension is assumed lost to the profile.

Actual water loss in the field is due to both evaporation and transpiration. The soil moisture model simulates evaporation from the soil surface until full plant canopy is reached, but for the remainder of the season calculates all water loss as being due to transpiration. Water loss from the soil moisture model occurs when pan evaporation exceeds rainfall and/or irrigation. All water losses from the soil are calculated from pan evaporation.

During emergence and before a full plant canopy is developed, the model simulates evaporation by immediately drying the block of surface soil to the moisture content of 15 bars tension. After complete canopy, defined as being reached on the forty-second day following the end of emergence, evaporation is no longer simulated and the soil surface block is not immediately dried to the moisture content of 15 bars tension. By ceasing simulation of evaporation after full canopy, the model simulates shading of the soil surface by the canopy. (The value 42 is the average number of observed days between the end of emergence and the start of flowering. Full canopy generally occurs by flowering.) Equation (40) calculates the difference between pan evaporation and rainfall plus irrigation, while equation (41) calculates the remaining water that can be lost from the soil profile after drying soil block 1 to the moisture content of 15 atmospheres.

$$(40) \text{ NWATLOS}_t = \text{PE}_t - (\text{R}_t + \text{I}_t)$$

for $PE_t > (R_t + I_t)$

$NWATLOS_t$ = net water loss on day t

PE_t = pan evaporation on day t

R_t = rainfall on day t

I_t = irrigation on day t

$$(41) \quad RWATLOS_t = NWATLOS_t - WLOS_1$$

$RWATLOS_t$ = remaining water available for loss on day t

$WLOS_1$ = water lost on day t when drying soil block 1 to the moisture content of 15 bars tension

If $NWATLOS$ is less than $WLOS_1$, soil block 1 is dried as much as possible. When $RWATLOS_t$ is greater than zero, it is multiplied by a transpiration factor S_t to determine the total amount of water to be removed from the rest of the soil profile.

The model defines the uncorrected transpiration factor US_t to be 0.2 prior to and during the ten day emergence period (equation (42)).

$$(42) \quad US_t = 0.2 \text{ prior to and during emergence}$$

US_t = uncorrected transpiration factor on day t

Using the leaf area index calculated in equation (43), the model increases the uncorrected transpiration factor to a

maximum of 0.8 during vegetative growth or flowering
(equation (44)).

$$(43) \text{ LAI}_t = \frac{(\text{LPOP} \times \text{LPLA}_t) + (\text{MPOP} \times \text{MPLA}_t) + (\text{SPOP} \times \text{SPLA}_t)}{10^8}$$

LAI_t = leaf area index on day t
 10^8 = number of cm^2 per hectare

$$(44) \text{ US}_t = (0.33 \times \text{LAI}_t) + 0.2 \text{ after emergence and through flowering}$$

$$0.2 \leq \text{US} \leq 0.8$$

The plant populations used in equation (43) are from equations (36), (37), and (38), and the leaf areas are from equations (8), (9), and (10). The upper boundary US_t value of 0.8 is reached when $\text{LAI}_t = 1.8$. During pod filling the model simulates senescence by decreasing US_t back to 0.2.

Corrections are applied to US_t if evaporation is occurring from the soil surface (prior to full plant canopy), or if the plants are water stressed. US_t is decreased when the soil surface has a higher moisture content than that of 15 bars tension, because transpiration decreases with the increasing humidity from evaporation of water from the soil. Equations (45) through (48) accomplish the reduction in US_t for moisture in the soil surface prior to full plant canopy.

$$(45) \quad W_R = \frac{W_1 - B_1}{B_3 - B_1}$$

W_R = soil water ratio on day t

W_1 = moisture content of soil block 1 on day t

B_1 = moisture content of soil block 1 at 15 bars
tension

B_3 = moisture content of soil block 1 at .06 bars
tension

$$(46) \quad CT1_t = (0.8 \times W_R) + 0.2$$

$CT1_t$ = correction term 1 on day t

$$(47) \quad CT2_t = (CT1_t / LAI_t) \times 0.05$$

$CT2_t$ = correction term 2 on day t

LAI_t = leaf area index on day t

$$(48) \quad CS_t = US_t - CT2_t$$

CS_t = corrected transpiration factor on day t

Equation (46) makes evaporation from the soil surface most important as the moisture content of soil block 1 approaches 0.06 bars. $CT2_t$ of equation (47) relates the correction to leaf area index so that it is greatest when the plants are small.

US_t is reduced at all plant growth stages when the plants are water stressed. Both reduction in available soil water and closing of stoma during water stress result in

reduced transpiration. When $DIASM_t$ (as previously discussed) is less than 0.6, equation (49) is used to reduce US_t or CS_t . When the soil surface has moisture but the plant is stressed due to dry soil conditions at lower depths, CS_t is calculated prior to making the correction for water stress.

$$(49) S_t = ((1.33 \times DIASM_t) + .2) \times US_t$$

$$DIASM_t < .06$$

or

$$S_t = ((1.33 \times DIASM_t) + .2) \times CS_t$$

$$DIASM_t < 0.6$$

$$S_t = \text{final transpiration factor}$$

When soil water conditions indicate no need for corrections to US_t , the final transpiration factor S_t is expressed by equation (50).

$$(50) S_t = US_t$$

The model decreases US_t during pod filling to simulate plant senescence. It takes the final transpiration factor S_t of day 5 of pod filling, and uses it as the uncorrected transpiration factor for days 6 through 14 of pod filling (equation (51)).

$$(51) US_t = S_5 \text{ for pod filling days 6 through 14}$$

S_5 = final transpiration factor value from day 5
of pod filling

From days 15 through 28 of pod filling, US_t is reduced linearly according to equation (52).

$$(52) \quad US_t = S_5 - (((S_5 - 0.2)/14) \times (TF - 14))$$

TF = pod filling day

On days 29 and 30 of pod filling, US_t equals 0.2 (equation (53)).

$$(53) \quad US_t = 0.2$$

TF = 29 or 30

The correction of equation (49) is applied to the US_t 's of equations (51), (52), or (53) during water stress.

The daily transpiration factor S_t is used to determine the total amount of water to be removed from the soil profile. Prior to full plant canopy, $RWATLOS_t$ of equation (41) is multiplied by S_t to calculate the loss from soil blocks (2) through (18) (equation (54)).

$$(54) \quad WLOS = RWATLOS_t \times S_t$$

2...18

when $RWATLOS_t > 0$

WLOS = total amount of water to be lost from
2...18 soil blocks 2 through 18

S_t = final transpiration factor on day t

After full canopy, total water to be lost from the soil profile is calculated without first evaporating the soil surface to the moisture content of 15 bars tension (equation (55)).

$$(55) \text{ WLOS} = \text{NWATLOS}_t \times S_t$$

1...18

WLOS = total amount of water to be lost from
1...18 soil blocks 1 through 18

NWATLOS_t = net water loss on day t (equation (40))

Water lost from soil blocks 2 through 18 prior to full plant canopy, and from soil blocks 1 through 18 after full canopy, is removed according to a water removal scheme of block sets of four. The removal factors $R_1 = 0.3$, $R_2 = 0.25$, $R_3 = 0.25$, and $R_4 = 0.2$, are used to remove 30 percent of the total water loss from the top block, 25 percent from the next, etc. For example, if sufficient moisture to account for all water loss exists in blocks 2 through 5, 30 percent of the total loss comes from block 2, 25 percent each from blocks 3 and 4, and 20 percent from block 5. Once a block has reached the soil moisture content of 15 bars tension, the remaining water loss is reapportioned by the same factors into the next set of four blocks. If the bottom of the soil profile is reached, loss is apportioned equally between three or two blocks.

Daily Index of Available Soil Moisture

As previously discussed, the model calculates a daily index of available soil moisture from the average root zone soil moisture contents. It expresses the moisture content of each soil block linearly, such that available moisture at .06 bars tension is 1.0, and available moisture at 15 bars tension is 0. The daily index of available soil moisture, $DIASM_t$, is calculated as the average of the available moisture in each block of the root zone. The top block in the root zone is defined to be block 2, and the bottom block is determined during plant growth from the accumulated degree days, FDD_t , calculated by equation (11). By calculating $DIASM_t$ from increasingly deeper soil blocks, the model simulates root growth. The scheme used to determine the soil blocks from which $DIASM_t$ will be calculated during plant growth is as follows:

Value of FDD_t	Soil Blocks Whose Available Moistures will be Averaged to Calculate $DIASM_t$
$FDD_t < 150$	2
$150 \leq FDD_t \leq 274$	2-3
$275 \leq FDD_t \leq 299$	2-4
$300 \leq FDD_t \leq 324$	2-5
$325 \leq FDD_t \leq 349$	2-6
$350 \leq FDD_t \leq 374$	2-7
$375 \leq FDD_t \leq 399$	2-8
$400 \leq FDD_t \leq 424$	2-9

Value of FDD_t	Soil Blocks Whose Available Moistures will be Averaged to Calculate $DIASM_t$
$425 \leq FDD_t \leq 449$	2-10
$450 \leq FDD_t \leq 474$	2-11
$475 \leq FDD_t \leq 499$	2-12
$500 \leq FDD_t \leq 524$	2-13
$525 \leq FDD_t \leq 549$	2-14
$550 \leq FDD_t \leq 574$	2-15
$575 \leq FDD_t \leq 599$	2-16
$600 \leq FDD_t \leq 624$	2-17
$625 \leq FDD_t$	2-18

Model Program

The model of navy bean growth and yield has been programmed in Fortran IV and run on a Control Data Corporation 6500 computer. The model consists of a main program and six subroutines. As needed, the main program calls subroutines for emergence, plant growth until flowering, flowering, and pod filling. Each growth stage subroutine calls weather and soil moisture subroutines daily. A flow chart of the model is contained in Figure 1.

Model Use for Management Decisions

The model of navy bean growth and yield can be used to make decisions regarding management of soil structure and irrigation needs. The need to minimize crusting during emergence and to optimize soil structure for good root distribution can be demonstrated by the model using different

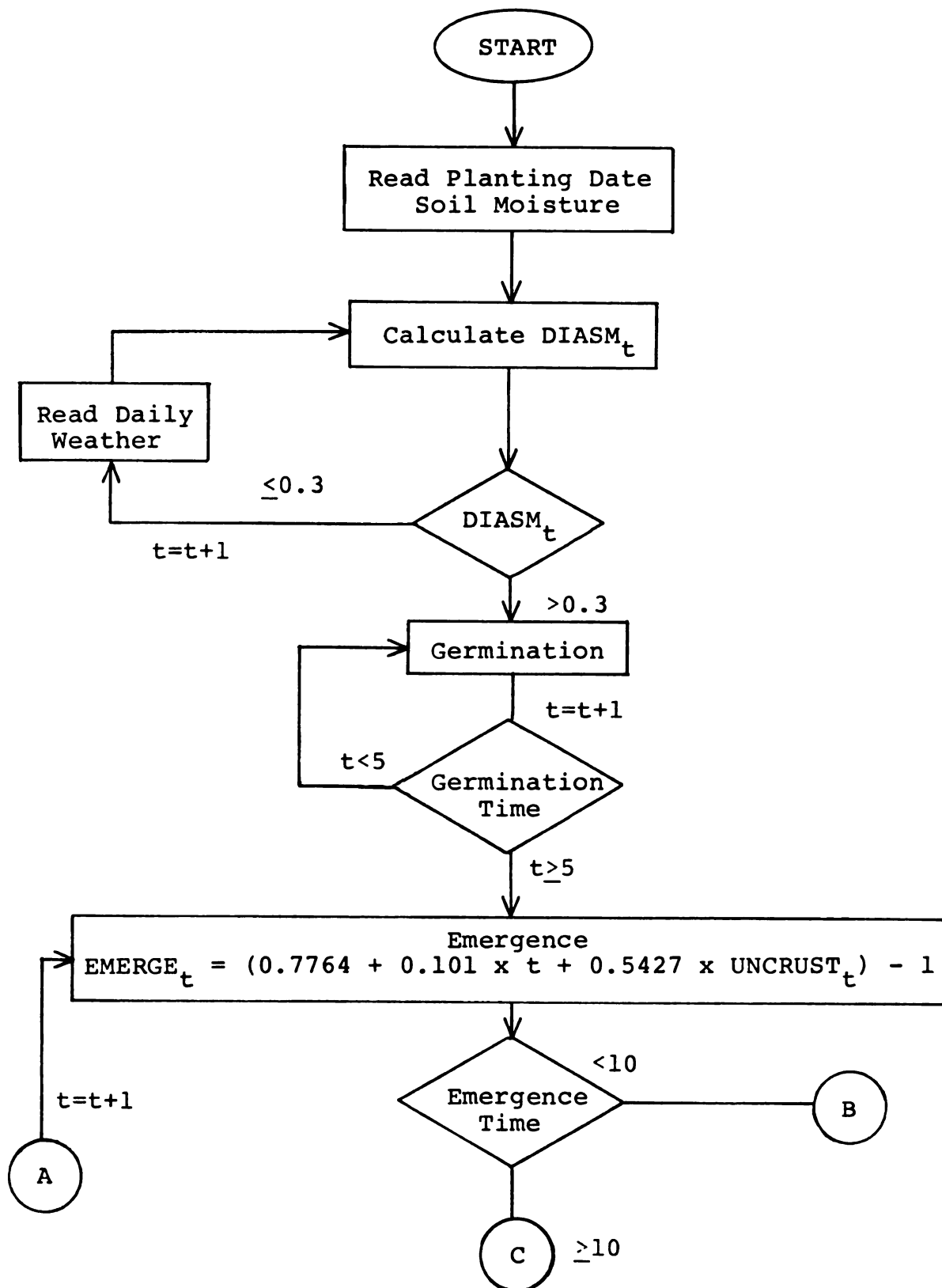


Fig. 1.--Flow Chart of Navy Bean Computer Simulation Model.

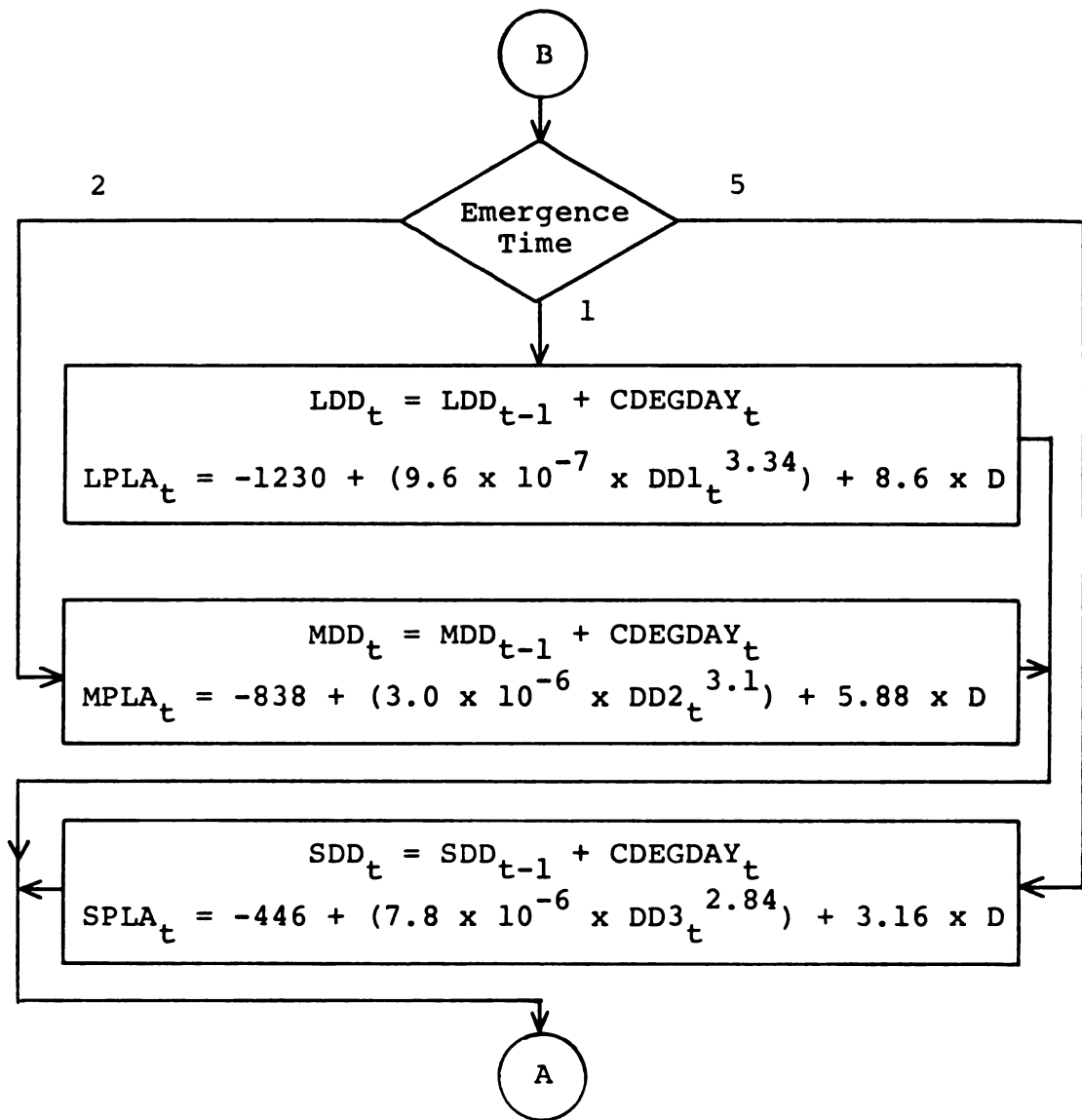


Fig. 1.--Continued.

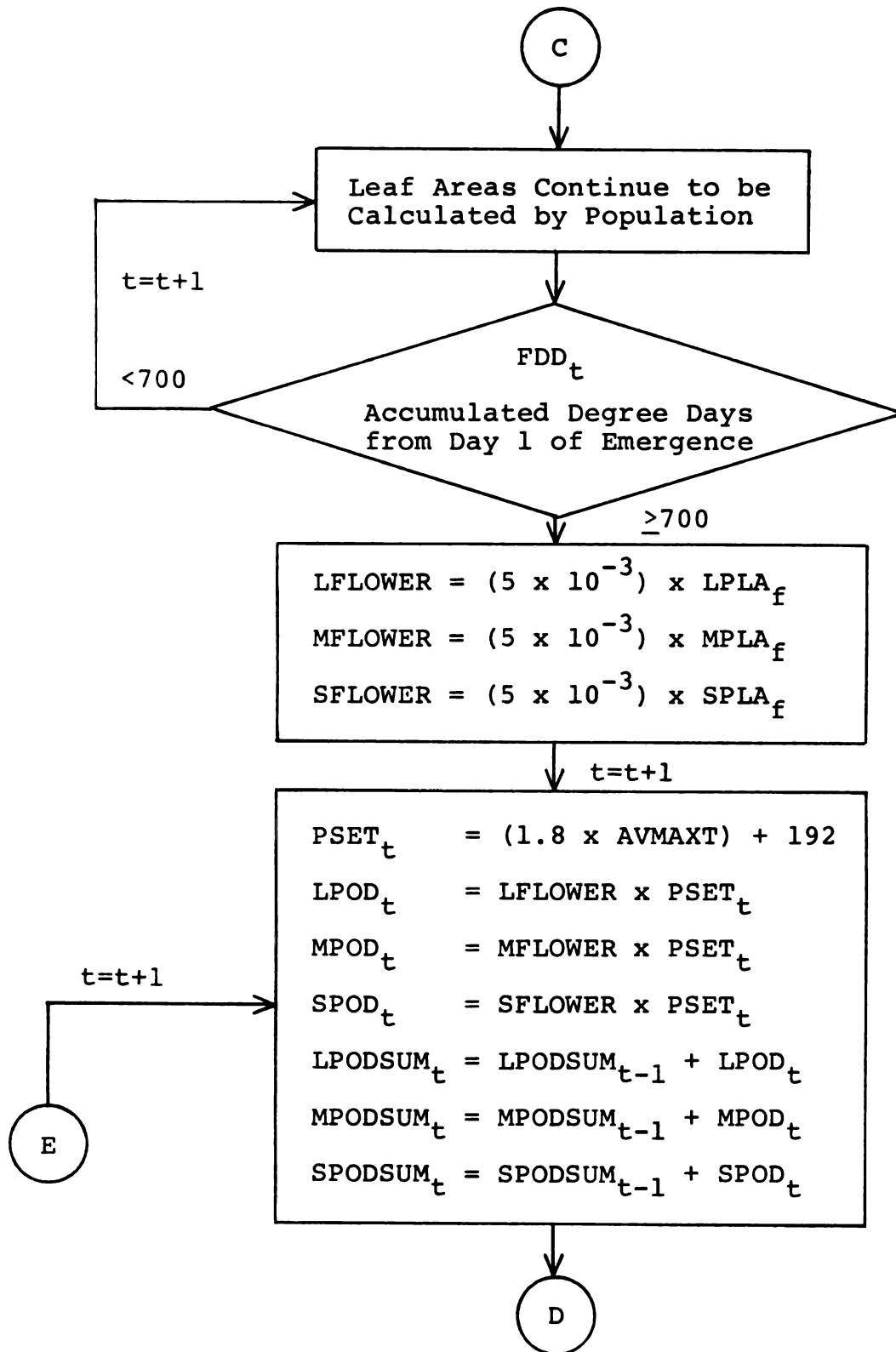


Fig. 1.--Continued.

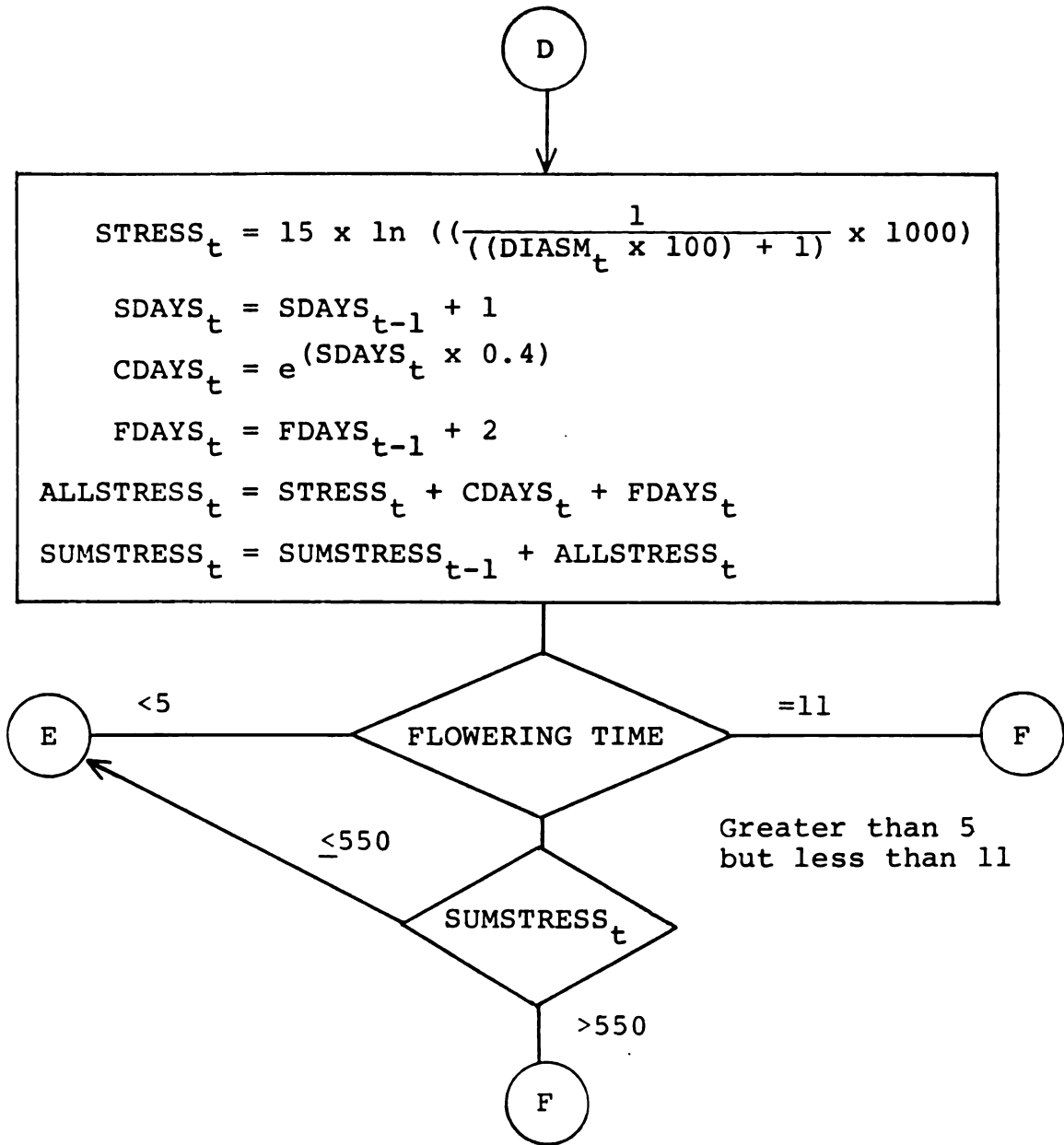


Fig. 1.--Continued.

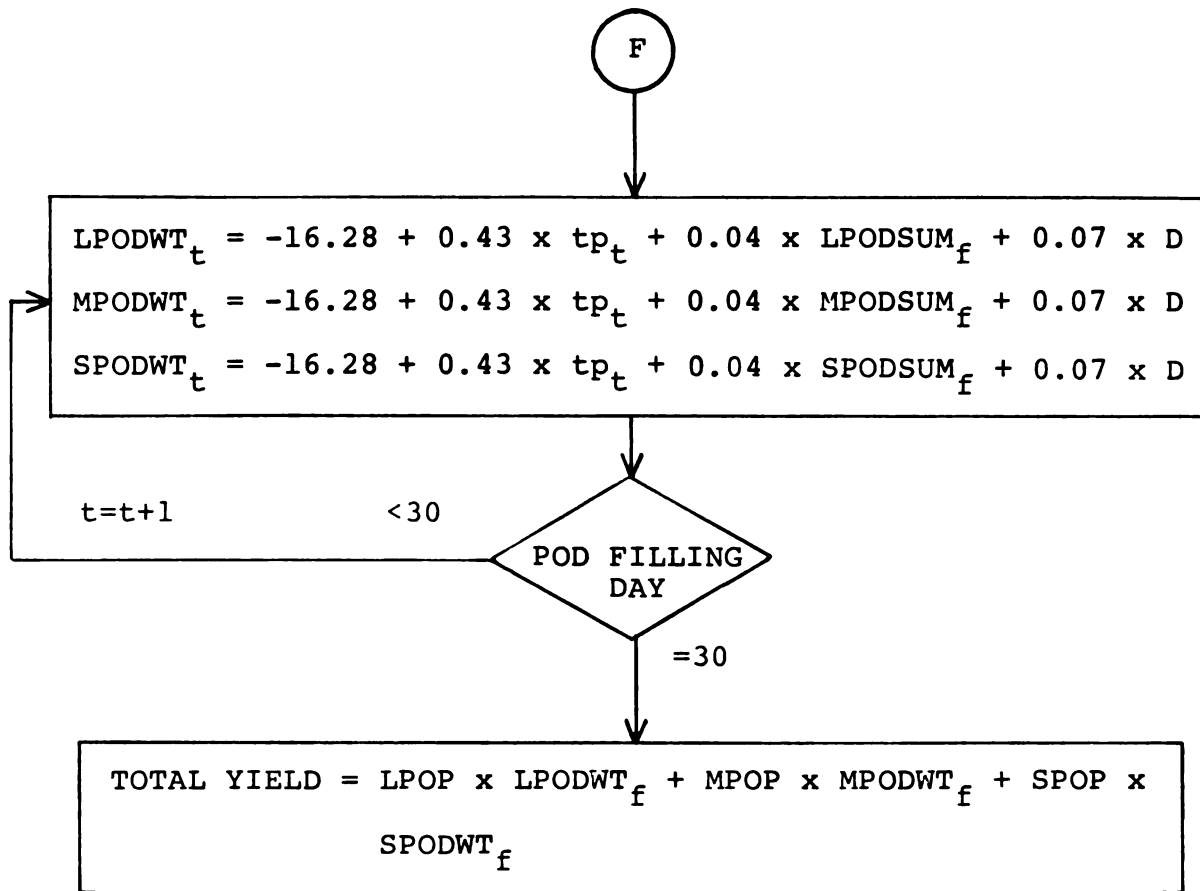


Fig. 1.--Continued.

crusting and soil structure factors. By coupling the navy bean model to a weather predictive model, the effects of crusting during emergence and poor soil structure can be evaluated under varying soil moisture regimes during the growing season. As presently programmed, the model recommends supplementary irrigation when the daily index of available soil moisture, $DIASM_t$, is less than 0.6. The assumption during model construction was that plant water stress occurs below the $DIASM_t$ value of 0.6. Future correlations between irrigations recommended by the model and actual needs by field plants will provide the basis for accurate irrigation need predictions.

Summary

A model of navy bean (*Phaseolus vulgaris*) growth and yield as a function of soil moisture and structure was developed by using multiple linear regression on field data, and by developing conceptual equations. Equations for percent emergence, plant leaf area prior to flowering, and daily pod weight during pod filling were derived from field data of navy bean growth and yield on Hillsdale sandy loam and Charity clay soils in 1977. The number of beans emerging daily, expressed as percent of the final stand, is calculated in the model as a function of emergence day and the percent of the soil surface not crusted on that day. Plant and root growth data from beans kept irrigated as needed on the Hillsdale sandy loam, and from soil structures

defined as excellent, good, or poor on the Charity clay, was used to derive equations predicting plant leaf areas prior to flowering as functions of accumulated degree days, soil structure, and plant population class (large, medium, or small). Pod weight per plant, for each population class, is calculated by the model during pod filling as a function of total pods per plant, pod filling day, and soil structure.

The model uses as input soils, plant and weather information. Needed soil measurements are bulk densities of the 0-15 and 15-45 cm soil depths, soil moisture percent by weight at .06 and 15 bars tension, soil moisture percent by weight on the planting date, the percent of the soil surface which is not crusted during emergence, and a classification of soil structure as excellent, good, or poor.

Needed plant numbers are final plant stand, which is entered in the model as number of seeds planted per hectare and percent final emergence. Daily weather values are rainfall, pan evaporation, and maximum and minimum air temperatures.

The model predicts daily plant growth from germination through final yield. Germination begins once a minimum soil moisture value has been reached. Emergence starts on the fifth day following the start of germination, and lasts for ten days. During emergence the total plant population is separated into three subpopulations defined as large, medium, or small. Separation equations predict daily leaf areas prior to flowering for the three

subpopulations. These equations use accumulated degree days starting with the first emergence day of each subpopulation and soil structure. Fifty-five degrees F° is used as the base for degree days. Soil structure is defined as excellent, good, or poor. During model development these structures were characterized by the numbers 156, 144, or 72, which are the observed vertical cross sectional rooting areas (square inches) on excellent, good, or poor soil structure on Charity clay in 1977. During vegetative growth the model reduces plant growth during moisture stress by reducing the accumulated degree day terms in the equations. Flowering in the model begins when accumulated degree days reaches a critical value. Potential flowers per day are calculated as a function of plant leaf area. Percent of flowers setting pods are determined from an equation of Davis (1943). Flowering occurs for a minimum of 5 and a maximum of 11 days, with water stress reducing length of flowering. Pod weights during pod filling are a function of pod filling day and soil structure. Pod filling occurs for 30 days. Moisture stress reduces the pod filling day term in the equations. Plant growth of each subpopulation is modeled by a single average plant. Final yield is the sum of the products of the number of plants and the average plant yield of each subpopulation.

The model includes a soil moisture submodel for evaluation of plant water stress. The soil profile is treated as 18 blocks to a depth of 45 cm. All soil moisture

calculations are made according to percent by weight. Each soil block can hold water between the moisture contents of 15 and 0.06 bars tension. Water additions are from rainfall and irrigation. Water losses are from evaporation and transpiration, and are estimated by evaporating the soil surface block to dryness prior to full plant canopy, and by multiplying pan evaporation by a transpiration factor. The factor depends on plant growth stage, leaf area index, and water stress. Plant water stress is determined from a daily index of available soil moisture ($DIASM_t$). Soil moisture contents between 0.06 and 15 bars tension are described linearly such that the moisture content of 0.06 bars has a $DIASM_t$ of 1.0, and the moisture content of 15 bars tension has a $DIASM_t$ of 0. The daily index of available soil moisture is calculated as an average of the $DIASM_t$'s for each soil block in the root zone, with root depth a function of accumulated degree days. Plant water stress in the model occurs when $DIASM_t$ is less than 0.6.

The model program is written in FORTRAN IV and consists of a main program and six subroutines. The main program drives subroutines for emergence, vegetative growth until flowering, flowering, and pod filling. These in turn call subroutines providing weather data and calculating soil moisture daily. The model can be used to predict growth and yield with different soil structure and weather conditions, and to make decisions regarding management of soil structure and irrigation needs.

References

- Anderson, C. E.; H. P. Johnson; and W. L. Powers. 1978. Water balance model for deep loess soils. Am. Soc. Agric. Engin. Trans. 21: 314-320.
- Anderson, R. L., and A. Maas. 1971. A simulation of irrigation systems: the effect of water supply and operating rules on production and income on irrigated farms. Tech. Bul. 1431. USDA-ERS and JFK School of Government.
- Baier, W., and G. W. Robertson. 1966. A new versatile soil moisture budget. Can. Jour. Plant Sci. 46: 299-315.
- Beese, F. R.; R. Van der Ploeg; and W. Richter. 1977. Test of a soil water model under field conditions. Soil Sci. Soc. Am. J. 41: 979-984.
- Black, T. A.; W. R. Gardner; and G. W. Thurtell. 1969. The prediction of evaporation, drainage, and soil water storage for a bare soil. Soil Sci. Soc. Am. Proc. 33: 655-660.
- Black, T. A.; C. B. Tanner; and W. R. Gardner. 1970. Evapotranspiration from a snap bean crop. Agron. J. 62: 66-69.
- Brun, L. J.; E. T. Kanemasu; and W. L. Powers. 1972. Evapotranspiration from soybean and sorghum fields. Agron. J. 64: 145-148, 197.
- Campbell, K. L. 1973. Hydrologic simulation of watersheds. Ph.D. dissertation, Iowa State University, Ames, IA. (Xerox University Microfilms, Order No. 73-16946, Ann Arbor, MI).
- Cowan, I. R. 1965. Transport of water in the soil-plant-atmosphere system. J. Appl. Ecol. 2: 221-239.
- Dale, R. F., and R. H. Shaw. 1965. The climatology of soil moisture, atmospheric evaporative demand, and resulting moisture stress days for corn at Ames, Iowa. J. Appl. Met. 4: 661-669.
- Davis, J. F. 1943. The effect of temperature, humidity, fertilizer, soil moisture, and leaf area on the set of pods and yield of white pea beans. Ph.D. dissertation, Michigan State University Library, East Lansing, Michigan.

- Denmead, O. T., and R. H. Shaw. 1962. Availability of soil water to plants as affected by soil moisture content and meteorological conditions. *Agron. J.* 45: 385-390.
- de Wit, C. T. 1958. Transpiration and crop yields. Institute of Biological and Chemical Research on Field Crops and Herbage, Wageningen, the Netherlands, Verse-Landbouwk, order Z. No. 64.6-5 Gravenhage.
- Dudley, N. J.; D. T. Howell; and W. F. Musgrave. 1971. Optimal intraseasonal irrigation water allocation. *Water Resour. Res.* 770-788.
- Fitzpatrick, E. A., and H. A. Nix. 1969. A model for simulating soil water regime in alternating fallow-crop systems. *Agric. Meteorol.* 6: 303-319.
- Flinn, J. C., and W. F. Musgrave. 1967. Development and analysis of input-output relation for irrigation water. *Austr. J. Agr. Econ.* 11: 1-19.
- Gardner, W. R. 1960. Dynamic aspects of water availability to plants. *Soil Sci.* 89: 63-73.
- Gardner, W. R., and D. I. Hillel. 1962. The relation of external evaporation conditions to the drying of soils. *J. Geophys. Res.* 67: 4319-4325.
- Hall, W. A., and W. S. Butcher. 1968. Optimal timing of irrigation. *Journal of the Irrigation and Drainage Division. Proceedings of the American Society of Civil Engineers* 94: 267-275.
- Hanks, R. J. 1974. Model for predicting plant yield as influenced by water use. *Agron. J.* 66: 660-665.
- Hansen, G. K. 1975. A dynamic continuous simulation model of water state and transportation in the soil-plant-atmosphere system. 1. The model and its sensitivity. *Acta. Ag. Scand.* 25: 129-149.
- Hanson, C. L. 1976. Model for predicting evapotranspiration from native rangelands in the Northern Great Plains. *Am. Soc. Ag. Engin. Trans.* 19: 471-477.
- Heady, E. O., and J. L. Dillon. 1961. Agricultural production functions. Iowa State University Press, Ames, Iowa. 667 p.

- Heapy, L. A.; G. R. Webster; H. C. Love; D. K. McBeath; V. M. von Maydell; and J. A. Robertson. 1976. Development of a barley yield equation for Central Alberta. 2. Effects of soil moisture stress. *Can. J. Soil Sci.* 56: 249-256.
- Hillel, D. I. 1975. Simulation of evaporation from bare soil under steady and diurnally fluctuating evapotranspiration. *Soil Sci.* 120: 230-237.
- Holtan, H. N. 1961. A concept for infiltration estimates in watershed engineering. USDA Agricultural Research Service ARS-41-51.
- Huggins, L. F., and E. J. Monke. 1968. A mathematical model for simulating the hydrologic response of a watershed. *Water Resour. Res.* 4: 529-540.
- James, L. G., and C. L. Larson. 1976. Modeling infiltration and redistribution of soil water during intermittent application. *Am. Soc. Agric. Engin. Trans.* 19: 482-488.
- Jensen, M. E. 1968. Water consumption by agricultural plants. Ch. 1, in T. T. Kozlowski (ed.), *Water deficits and plant growth*. Vol. 2. Academic Press, New York.
- Jensen, M. E.; J. L. Wright; and B. J. Pratt. 1971. Estimating soil moisture depletion from climate, crop and soil data. *Am. Soc. Ag. Engin. Trans.* 14: 954-959.
- Lewin, J., and J. Lomas. 1974. A comparison of statistical and soil moisture modeling techniques in a long-term study of wheat yield performance under semi-arid conditions. *J. App. Ecol.* 11: 1081-1090.
- Monteith, J. L. 1965. Evaporation and environment. *Symp. Soc. Exp. Biol.* 29: 205-234.
- Moore, C. W. 1961. A general analytical framework for estimating production functions for crops using irrigation water. *J. Farm Econ.* Vol. XLIII, No. 4. Part I. 876-888.
- Neghassi, H. M.; D. F. Heermann; and D. E. Smika. 1975. Wheat yield models with limited soil water. *Am. Soc. Agric. Engin. Trans.* 18: 549-553.

- Nimah, M. N., and R. J. Hanks. 1973a. Model for estimating soil water, plant, and atmospheric, interrelations: I. Description and sensitivity. Soil Sci. Soc. Am. Proc. 37: 522-527.
- Nimah, M. N., and R. J. Hanks. 1973b. Model for estimating soil water, plant, and atmospheric interrelations: II. Field test of model. Soil Sci. Soc. Am. Proc. 37: 528-532.
- Ritchie, J. T. 1972. Model for predicting evaporation from a row crop with incomplete cover. Water Resour. Res. 8: 1204-1213.
- Rowse, H. R., and D. A. Stone. 1978. Simulation of the water distribution in soil; measurement of soil hydraulic properties and the model for an uncropped soil. Plant and Soil 49: 517-531.
- Rowse, H. R.; D. A. Stone; and A. Gerwitz. 1978. Simulation of the water distribution in soil; the model for cropped soil and its comparison with experiment. Plant and Soil 49: 533-550.
- Saxton, K. E. 1972. Watershed evapotranspiration by the combination method. Ph.D. dissertation, Iowa State University, Ames, IA (Xerox University Microfilms, Order No. 72-26940, Ann Arbor, MI).
- Saxton, K. E.; H. P. Johnson; and R. H. Shaw. 1974. Modeling evapotranspiration and soil moisture. Am. Soc. Ag. Engin. Trans. 17: 673-677.
- Subhadrabandhu, S. 1976. Control of abscission of flowers and fruits of *Phaseolus vulgaris* L. Ph.D. dissertation, Michigan State University Library, East Lansing, Michigan.

CHAPTER IV

A LIMITED INFORMATION MODEL OF NAVY BEAN (PHASEOLUS VULGARIS) GROWTH AND YIELD AS A FUNCTION OF SOIL STRUCTURE AND WEATHER. PART II: COMPARISON OF ACTUAL AND PREDICTED GROWTH AND YIELD

Abstract

A model of navy bean growth and yield as affected by soil structure and weather was tested using 44 sets of input information. Soils information supplied to the model was bulk densities of the 0-15 cm and 15-45 cm soil depths, a soil structure factor, moisture content by weight of the soil at 15 and .06 bars tension, moisture content by weight of the soil on the planting date, and percent of the soil surface not crusted during emergence. Plant information supplied to the model was date of planting, number of seeds planted per hectare, and final percent emergence. Weather data needed for the model was rainfall, pan evaporation, and maximum and minimum daily air temperatures. The model made reasonable predictions of emergence, vegetative growth and pod weights by the end of each growth stage, and was quite

successful in predicting yields. Both plant growth and yields predicted by the model were sensitive to crusting during emergence, soil structure, and water stress. Correlation between predicted and actual yields resulted in the correlation coefficient $R^2 = 0.7$, for the equation $Y = A + BX$, where Y is predicted yield and X is actual yield ($A = -212$ and $B = 1.05$). The correlation coefficient was significant at the 1 percent level. The model can be used for evaluation of soil structure, irrigation, and other cultural practices in terms of yield using weather. As an aid in solving the problem of declining navy bean yields in Michigan, the system science approach and the model demonstrate that physical stresses are major yield limiting factors.

Introduction

The navy bean growth and yield model described in Chapter III was developed to make predictions based on limited soil and weather information. The objective was to create a model which could be used with easily obtainable input data, and which would discriminate between differing soil structure and moisture regimes so as to assist in making correct decisions regarding crop and soil management. In order to test the accuracy of the model predictions, comparisons were made with data from beans grown on both the Hillsdale sandy loam and Charity clay soils. Actual emergence data, leaf areas, pod weights, and yields were compared with predicted values. Actual and predicted emergence

curves were compared to study the effectiveness of model predictions under different crusting conditions. The ability of the model to accurately predict plant growth and pod filling according to weather data was tested by comparing actual and predicted leaf areas during vegetative growth, and pod weights during pod filling. Actual yields from 44 different situations were compared with predicted yields to study both accuracy, and overall sensitivity of yield predictions to crusting during emergence, soil structure, and weather.

Procedure

Table 1 lists the 44 sets of data used for model verification. The information used for 1977 and 1978 was specifically collected for model construction and verification. Needed model input information shown in Table 1 is bulk density, soil structure, soil moisture percent by weight at 15 and .06 bars tension, soil moisture content on the planting date, planting date, number of seeds planted per hectare, and the percent of these seeds that will emerge. Daily rainfall, pan evaporation, and maximum and minimum air temperatures were also provided to the model.

The bulk densities of Table 1 are for the soil depths 0-15 cm, and 15-45 cm. The values used in 1977 and 1978 were measured, whereas the remaining values (with the exception of the uncompacted 1972 Charity clay and the 1976 Charity clay) were estimated but were from the same farms. Soil structure factors used for model verification were

Table 1.--Input, Predicted Yield, and Actual Yield from 44 Tests of the Model of Navy Bean Growth and Yield.

Data Source	Bulk Densities		Soil Structure Factor	Soil Moisture Percent by Weight		Initial Moisture in Seed Zone Percent	Percent of Soil Surface Not Crusted During Emergence	Planting Date	Seeds Planted Per Hectare	Percent Emergence	Predicted Yield kg/ha	Actual Yield kg/ha
	0-15 cm	15-45 cm		15 Bars	.06 Bars							
Hillsdale sandy loam 1977 Always Irrigated	1.40	1.50	156	6.0	19.7	13.7	100	6-17-77	207,000	86	2,368	2,633
Hillsdale sandy loam 1977 Stress at Second Seedling (7-14-77)	1.38	1.50	156	5.1	19.5	13.5	100	6-17-77	207,000	86	2,357	2,227
Hillsdale sandy loam 1977 No Irrigation	1.40	1.51	156	4.0	18.2	12.8	100	6-17-77	207,000	86	1,888	2,009
Hillsdale sandy loam 1978 Always Irrigated	1.37	1.50	156	4.0	18.8	13.1	100	6-6-78	207,000	78	2,415	2,460
Hillsdale sandy loam 1978 Not Irrigated 7-7-78	1.37	1.50	156	4.0	18.8	13.1	100	6-6-78	207,000	78	2,366	1,900
Hillsdale sandy loam 1978 Not Irrigated 7-14-78	1.37	1.50	156	4.0	18.8	13.1	100	6-6-78	207,000	78	2,185	1,888
Hillsdale sandy loam 1978 Not Irrigated 7-21-78	1.37	1.50	156	5.0	18.8	13.1	100	6-6-78	207,000	78	2,182	1,924
Hillsdale sandy loam 1978 Not Irrigated 7-28-78	1.37	1.50	156	4.0	18.8	13.1	100	6-6-78	207,000	78	2,178	1,971
Hillsdale sandy loam 1978 Not Irrigated after 7-28-78	1.37	1.50	156	4.0	18.8	13.1	100	6-6-78	207,000	78	2,067	1,739

Table 1.--Continued.

Data Source	Bulk Densities		Soil Structure Factor	Soil Moisture Percent by Weight		Initial Moisture in Seed Zone Percent	Percent of Soil Surface Not Crusted During Emergence	Planting Date	Seeds Planted Per Hectare	Percent Emergence	Predicted Yield kg/ha	Actual Yield kg/ha
	0-15 cm	15-45 cm		15 Bars	.06 Bars							
Hillsdale sandy loam 1978 Not Irrigated after 7-7-78	1.37	1.50	156	4.0	18.8	13.1	100	6-6-78	207,000	78	1,716	1,838
Hillsdale sandy loam 1978 Not Irrigated	1.37	1.50	156	4.0	18.8	13.1	100	6-6-78	207,000	78	1,494	1,673
Charity clay 1978 Excellent Soil Structure Irrigated	1.16	1.24	156	14.5	31.5	26.2	100	5-25-78	432,000	77	2,003	2,652
Charity clay 1978 Excellent Soil Structure Not Irrigated	1.16	1.24	156	14.5	31.5	26.2	100	5-25-78	432,000	70	1,362	2,200
Charity clay 1978 Good Soil Structure Irrigated	1.24	1.34	144	14.5	31.5	26.2	100	5-25-78	432,000	78	1,979	2,101
Charity clay 1978 Good Soil Structure Heavy Irrigation 6-29-78	1.24	1.34	144	14.5	31.5	26.2	100	5-25-78	432,000	78	2,514	2,380
Charity clay 1978 Good Soil Structure Heavy Irrigation 7-19-78	1.24	1.34	144	14.5	31.5	26.2	100	5-25-78	432,000	78	2,926	3,687

Table 1.--Continued.

Data Source	Bulk Densities		Soil Structure Factor	Soil Moisture Percent by Weight		Initial Moisture in Seed Zone Percent	Percent of Soil Surface Not Crusted During Emergence	Planting Date	Seeds Planted Per Hectare	Percent Emergence	Predicted Yield kg/ha	Actual Yield kg/ha
	0-15 cm	15-45 cm		15 Bars	.06 Bars							
Charity clay 1978 Excellent Soil Structure Heavy Irrigation 8-2-78, 8-3-78	1.16	1.24	156	14.5	31.5	26.2	100	5-25-78	432,000	77	3,800	2,933
Hillsdale sandy loam Planted 6-5-74 Moderate Irrigation (Smucker)	1.1	1.4	156	7.1	19.8	13.5	100	6-5-74	247,000	85	2,529	2,972
Hillsdale sandy loam Planted 6-5-74 No Irrigation (Smucker)	1.1	1.4	156	7.1	19.8	13.5	100	6-5-74	247,000	85	1,107	1,500
Hillsdale sandy loam Planted 6-12-74 Moderate Irrigation (Smucker)	1.1	1.4	156	7.1	19.8	13.5	100	6-12-74	247,000	85	2,428	2,266
Hillsdale sandy loam Planted 6-12-74 No Irrigation (Smucker)	1.1	1.4	156	7.1	19.8	13.5	100	6-5-74	247,000	85	1,406	1,805
Hillsdale sandy loam 1975 Excessive Irrigation (Smucker)	1.1	1.4	156	7.1	19.8	13.5	100	5-28-75	247,000	85	3,349	3,242

Table 1.--Continued.

Data Source	Bulk Densities		Soil Structure Factor	Soil Moisture Percent by Weight		Initial Moisture in Seed Zone Percent	Percent of Soil Surface Not Crusted During Emergence	Planting Date	Seeds Planted Per Hectare	Percent Emergence	Predicted Yield kg/ha	Actual Yield kg/ha
	0-15 cm	15-45 cm		15 Bars	.06 Bars							
Hillsdale sandy loam 1975 Moderate Irrigation (Smucker)	1.1	1.4	156	7.1	19.8	13.5	100	5-28-75	247,000	85	3,307	3,170
Hillsdale sandy loam 1975 No Irrigation (Smucker)	1.1	1.4	156	7.1	19.8	13.5	100	5-28-75	247,000	85	1,990	2,099
Hillsdale sandy loam 1976 Excessive Irrigation (Smucker)	1.1	1.4	156	7.1	19.8	13.5	100	6-2-76	247,000	85	3,030	2,708
Hillsdale sandy loam 1976 Moderate Irrigation (Smucker)	1.1	1.4	156	7.1	19.8	13.5	100	6-2-76	247,000	85	2,999	2,834
Hillsdale sandy loam 1976 No Irrigation (Smucker)	1.1	1.4	156	7.1	19.8	13.5	100	6-2-76	247,000	85	1,442	1,877
Charity clay 1972 Not Compacted (Erickson)	1.07	1.35	144	14.5	31.5	11.0	60	6-8-72	247,000	85	3,428	2,658
Charity clay 1972 Compacted (Erickson)	1.4	1.4	100	14.5	31.5	11.0	55	6-8-72	247,000	85	2,856	2,598
Charity clay 1973 Shallow Tillage (Erickson)	1.24	1.34	144	14.5	31.5	11.0	95	6-15-73	247,000	93	2,225	1,926

Table 1.--Continued.

Data Source	Bulk Densities		Soil Structure Factor	Soil Moisture Percent by Weight		Initial Moisture in Seed Zone Percent	Percent of Soil Surface Not Crusted During Emergence	Planting Date	Seeds Planted Per Hectare	Percent Emergence	Predicted Yield kg/ha	Actual Yield kg/ha
	0-15 cm	15-45 cm		15 Bars	.06 Bars							
Charity clay 1973 Spring Chiseled (Erickson)	1.24	1.34	144	14.5	31.5	11.0	95	6-15-73	247,000	90	2,157	2,083
Charity clay 1973 Compacted (Erickson)	1.4	1.4	100	14.5	31.5	11.0	55	6-15-73	247,000	84	695	941
Charity clay 1974 Spring Tillage High Organic Matter (Erickson)	1.24	1.34	144	14.5	31.5	26.0	95	6-26-74	247,000	72	1,480	2,072
Charity clay 1974 Spring Tillage Low Organic Matter (Erickson)	1.24	1.34	144	14.5	31.5	26.0	95	6-26-74	247,000	82	1,633	1,988
Charity clay 1974 Compacted High Organic Matter (Erickson)	1.4	1.4	100	14.5	31.5	26.0	55	6-26-74	247,000	79	838	1,994
Charity clay 1974 Compacted Low Organic Matter (Erickson)	1.4	1.4	100	14.5	31.5	26.0	55	6-26-74	247,000	89	933	1,848
Charity clay 1974 (Smucker)	1.24	1.34	144	14.5	31.5	26.0	95	6-26-74	247,000	85	1,677	2,211
Charity clay 1975 (Smucker)	1.24	1.34	144	14.5	31.5	26.0	85	6-3-75	247,000	85	1,605	2,054

Table 1.--Continued.

Data Source	Bulk Densities		Soil Structure Factor	Soil Moisture Percent by Weight		Initial Moisture in Seed Zone Percent	Percent of Soil Surface Not Crusted During Emergence	Planting Date	Seeds Planted Per Hectare	Percent Emergence	Predicted Yield kg/ha	Actual Yield kg/ha
	0-15 cm	15-45 cm		15 Bars	.06 Bars							
Charity clay 1976 Deep Spring Tillage (Erickson)	1.24	1.34	144	14.5	31.5	26.0	95	6-10-76	247,000	76	1,494	1,383
Charity clay 1976 Deep Spring Tillage after Alfalfa (Erickson)	1.24	1.34	144	14.5	31.5	26.0	95	6-10-76	247,000	59	1,258	1,254
Charity clay 1976 Shallow Spring Tillage (Erickson)	1.24	1.34	144	14.5	31.5	26.0	95	6-10-76	247,000	78	1,520	1,677
Charity clay 1976 Shallow Spring Tillage after Alfalfa (Erickson)	1.24	1.34	144	14.5	31.5	26.0	95	6-10-76	247,000	71	1,428	1,422
Charity clay 1976 Compacted (Erickson)	1.4	1.54	100	14.5	31.5	26.0	55	6-10-76	247,000	81	861	1,049
Charity clay 1976 Compacted after Alfalfa (Erickson)	1.4	1.54	100	14.5	31.5	26.0	55	6-10-76	247,000	59	748	795

156, 144, and 100. The values 156 and 144 were the observed cross sectional rooting areas at flowering of beans grown on excellent and good soil structure on Charity clay in 1977 respectively, and were used in model construction. The value 100 was chosen during model verification to best represent compacted soil structure. Because the amount of compaction varies with soil moisture content, use of a single value to characterize compacted soil is difficult. The value 156 was used for excellent soil structure on the Charity clay in 1978, and for the Hillsdale sandy loam in all years. The value 156 (excellent soil structure) was chosen for 1978 Charity clay beans grown where the crop rotation included two years growth of alfalfa-timothy and fall deep chisel plowing. The bulk densities of the soil from these plots were less, and the yields from unirrigated treatments were greater than those from plots not including this crop rotation. Because sandy soils provide ideal structure for root growth, the value 156 was used to characterize soil structure on the Hillsdale sandy loam. Soil structure of uncompacted Charity clay in years other than 1978 was assumed to be good, so the soil structure factor 144 was used. The rationale for this was that structures of Charity clay soils which have not been renovated by two years growth of alfalfa-timothy and fall deep chisel plowing are generally only fair to good.

The values of percent soil moisture content at 15 and .06 bars tension shown in Table 1 were obtained from soil moisture curves. These curves were measured for the 1977 and 1978 Hillsdale sandy loam and Charity clay soils. The studies of Dr. Smucker listed as Hillsdale sandy loam were on an intergrade to Conover loam. Moisture contents at 15 and .06 bars for this soil were obtained from Stolzy, 1954. Moisture content on the planting date was measured in 1972, 1973, 1977 and 1978. The remaining initial moisture contents were estimated. Where moisture contents were estimated, it was assumed that the moisture content of the soil profile below 8 cm depth was at .06 bars tension, and that soil moisture decreased above this depth.

Hillsdale sandy loam was assumed to have no crusting during emergence. No crusting was observed on the Charity clay in 1978 so the percent of the soil surface not crusted during emergence was also 100. The remaining model tests of uncompacted Charity clay used 95 or less percent of the soil surface not crusted during emergence, depending on field notes and rainfall records. The percent of the soil surface not crusted during emergence on compacted Charity clay was set at 55.

The planting date was available for all data used in model tests. The number of seeds planted and the final percent emergence was available for 1977 and 1978. Where the seed population was not available, an estimated population of 40,500 seeds per hectare was used. When final

percent emergence was unknown, it was estimated to be 85 percent.

Results

Emergence

Figures 1, 2, and 3 show actual and predicted emergence for the Hillsdale sandy loam and Charity clay soils in 1977 and 1978. Actual emergence on the Hillsdale sandy loam (Figure 1) was rapid in both 1977 and 1978. In 1977 all beans had emerged by day six (day one is the first day beans emerge). In 1978 emergence was different between beans planted next to the tire tracks and beans planted in the center with no tire track on either side of the bean row. Poor seed-soil contact in the center row delayed emergence. Next to the tire track all beans had emerged by day 5, whereas the final plant stand of beans planted in the center was not reached until day 7. The 1977 predicted final emergence day came within one day of actual final emergence. The prediction for 1978 best approximates the emergence observed for beans planted in the center. Model predictions of emergence are linear whereas actual emergence is not.

Figure 2 shows the 1977 actual and predicted emergence curves for uncompacted and compacted Charity clay. Emergence was faster where the soil had not been crusted by compaction. Ninety-two percent of the final plant stand was reached by day 6 of emergence without crusting, whereas only 85 percent of final emergence had been reached by day 10

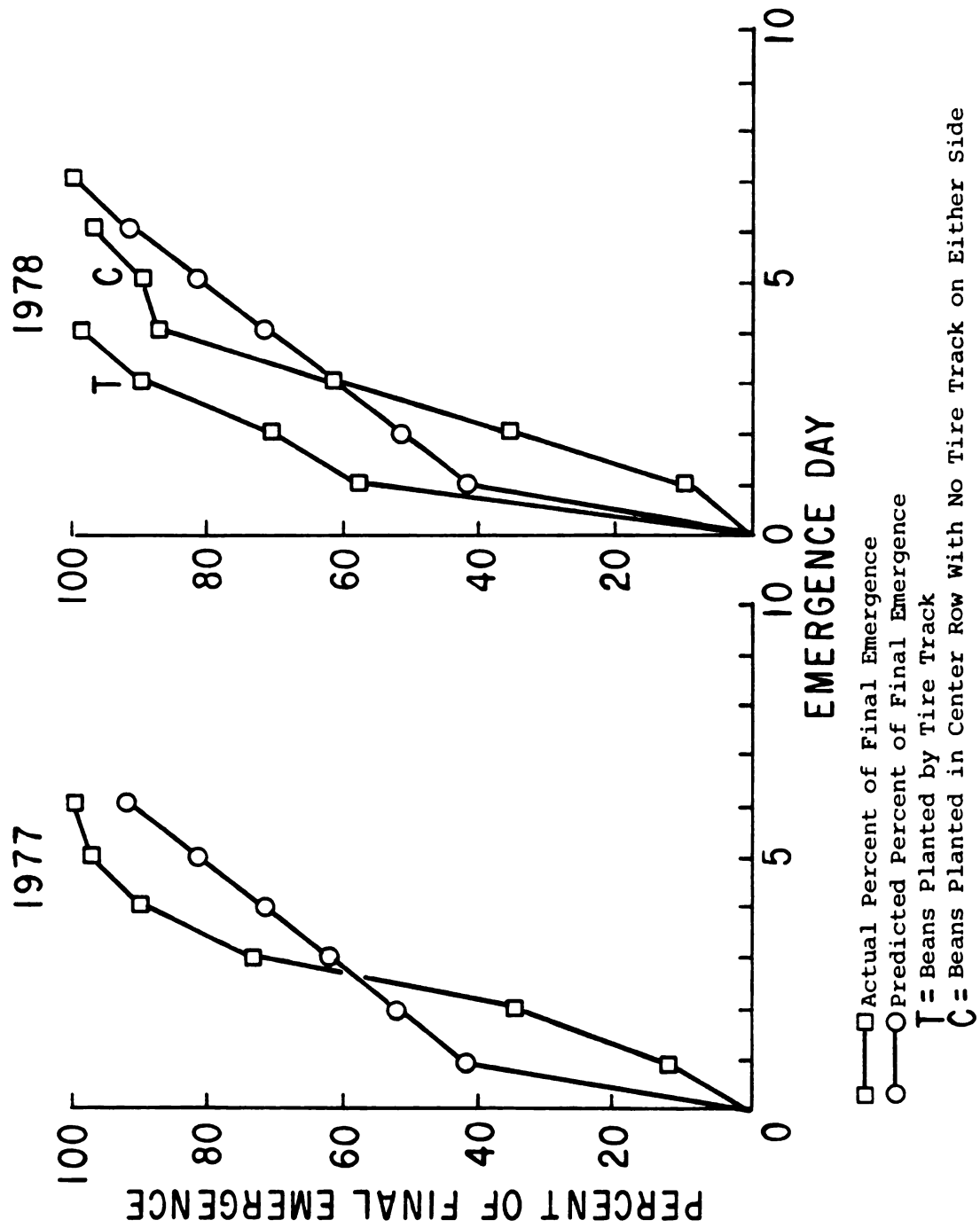


Figure 1. Actual and Predicted Emergence of Beans Grown on Hillsdale Sandy Loam in 1977 and 1978.

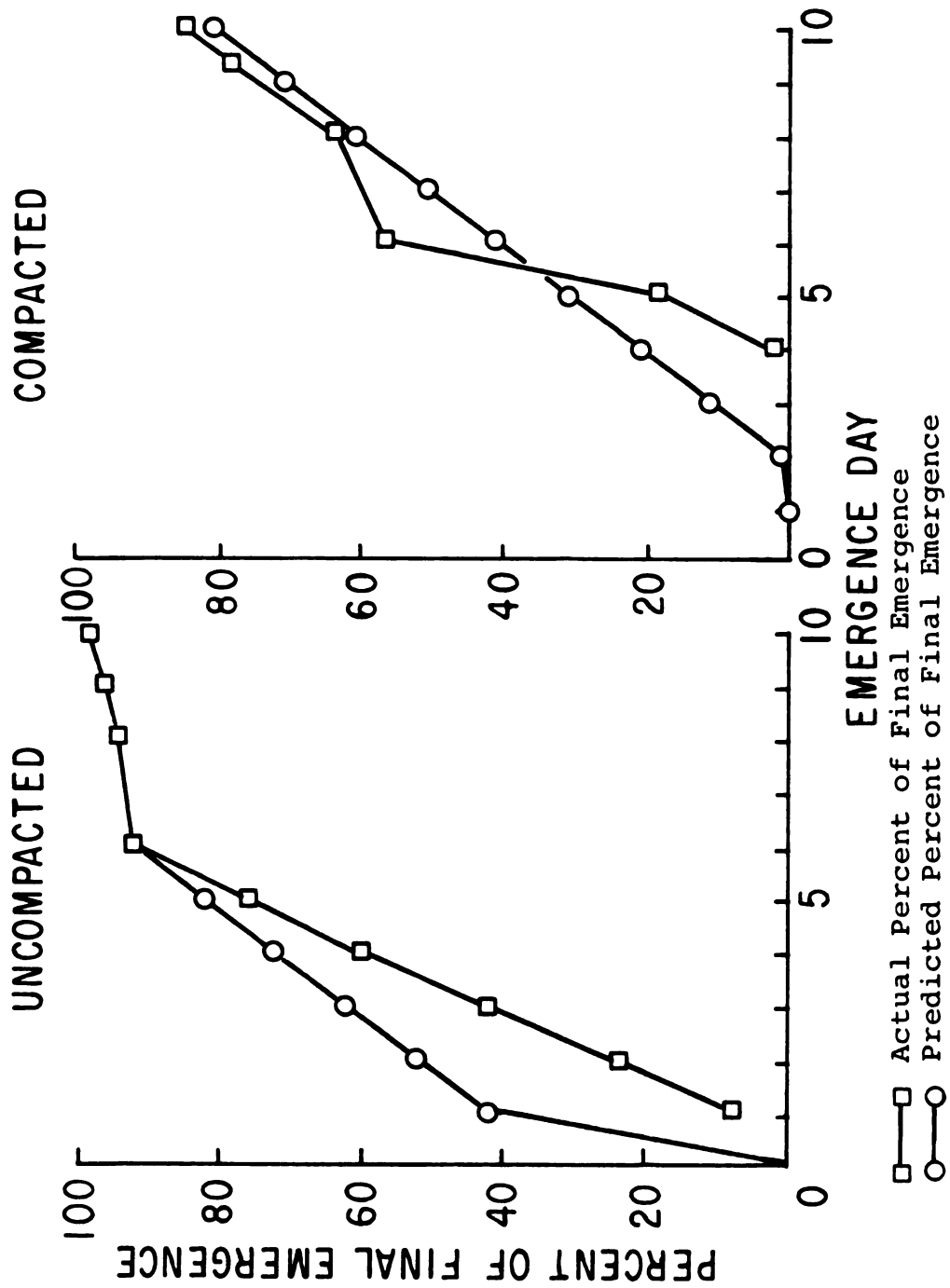


Figure 2. Actual and Predicted Emergence of Beans Grown on Uncompact and Compact Charity Clay in 1977.

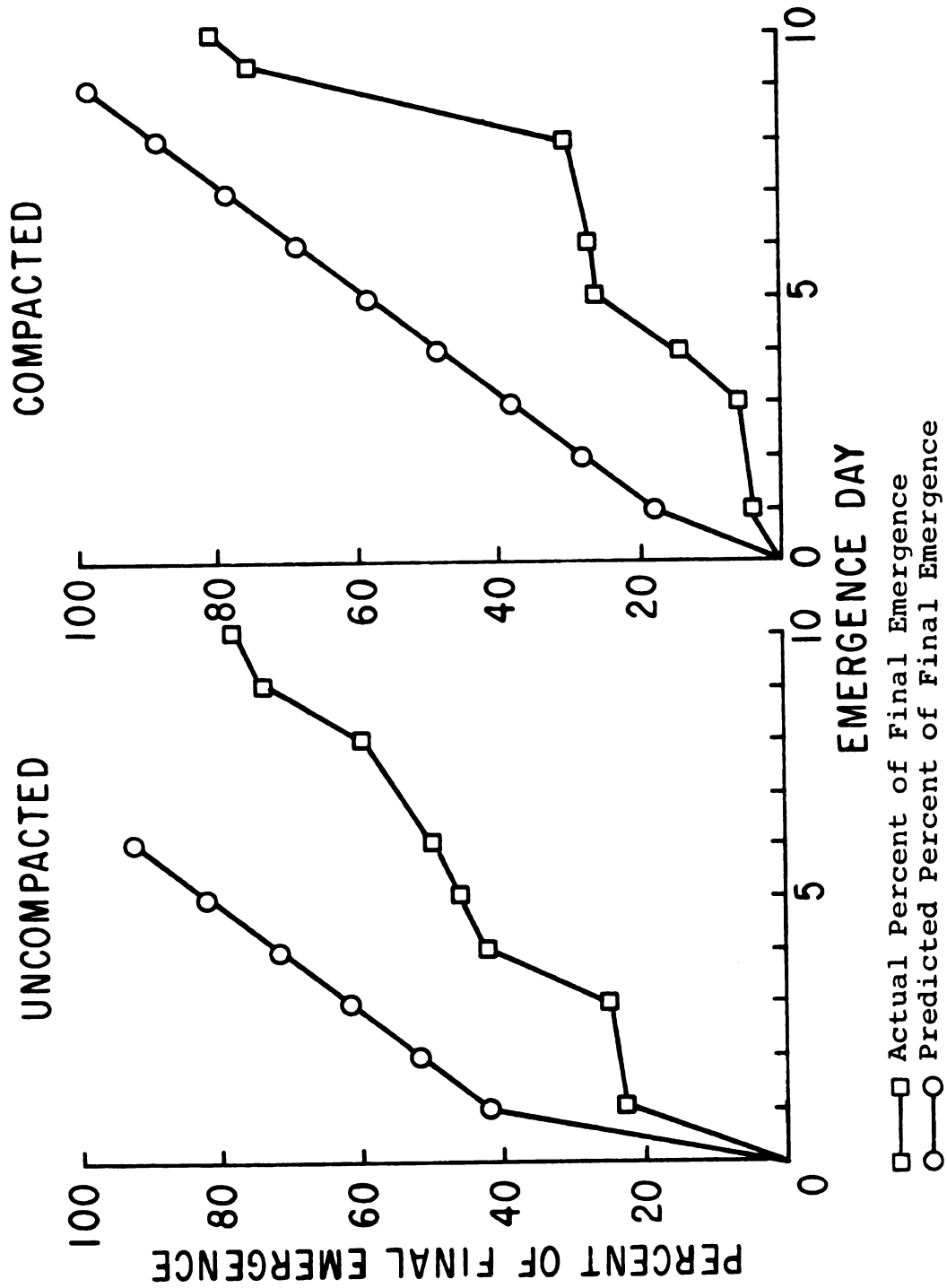


Figure 3. Actual and Predicted Emergence of Beans Grown on Uncompact and Compacted Charity Clay in 1978.

when the soil was crusted. The predicted emergence with no crusting shows faster emergence than actually occurred. The predicted emergence curve for the compacted 1977 Charity clay was calculated with the assumption that 95 percent of the soil surface was crusted. (Ninety-five percent crusting of the compacted Charity clay in 1977 was assumed in deriving the emergence equation.) The predicted emergence curve is very close to the actual emergence curve. Comparison between the actual emergence curves of Figures 2 and 1 show that emergence is faster on the sandy soil. This is because of emerging plant on the sandy soil.

Emergence from the Charity clay in 1978 was delayed by dry soil conditions. Application of supplementary irrigation on day 8 of emergence alleviated some of the problem, particularly on the compacted soil with crusting problems. The percent of soil surface not crusted during emergence was assumed to be 100 for the uncompacted soil and 55 for the compacted soil. The dry soil conditions of 1978 delayed emergence by both limiting input moisture for hypocotyl elongation and mechanically impeding the emerging plant. Better predictions of emergence by the model would result if daily values for percent of the soil surface not crusted during emergence were used according to the mechanical impedance that actually occurred in the field. The primary reason why the model is not as accurate in predicting

emergence on the Charity clay in 1978 as in 1977, is that the model does not include a soil moisture factor when calculating rate of emergence.

The model separates the total bean population into subpopulations of large, medium, and small plants based on time of emergence. With 100 percent of the soil surface free from crusting during emergence, 42 percent of the plants are large, 40 percent of the plants are medium, and 18 percent of the plants are small. The respective percentages with 55 percent of the soil surface not crusted are 18, 40, and 42. With only 5 percent of the surface free from crusting, 31 percent of the plants are medium, and 69 percent are small.

Vegetative Growth

Actual and predicted leaf areas from beans grown on Hillsdale sandy loam are shown in Figures 4, 5, and 6. Leaf areas with supplementary irrigation on the Hillsdale sandy loam were higher than without supplementary irrigation in both 1977 and 1978. Model predictions with irrigation in 1977 are accurate, but the predictions with no irrigations are not significantly different from those where irrigation was applied. A severe water stress on the afternoon of July 15, 1977 was the main cause of the difference in actual vegetative growth prior to flowering between the irrigated and unirrigated treatments. Because the model calculates soil moisture and water stress on a daily basis, it was

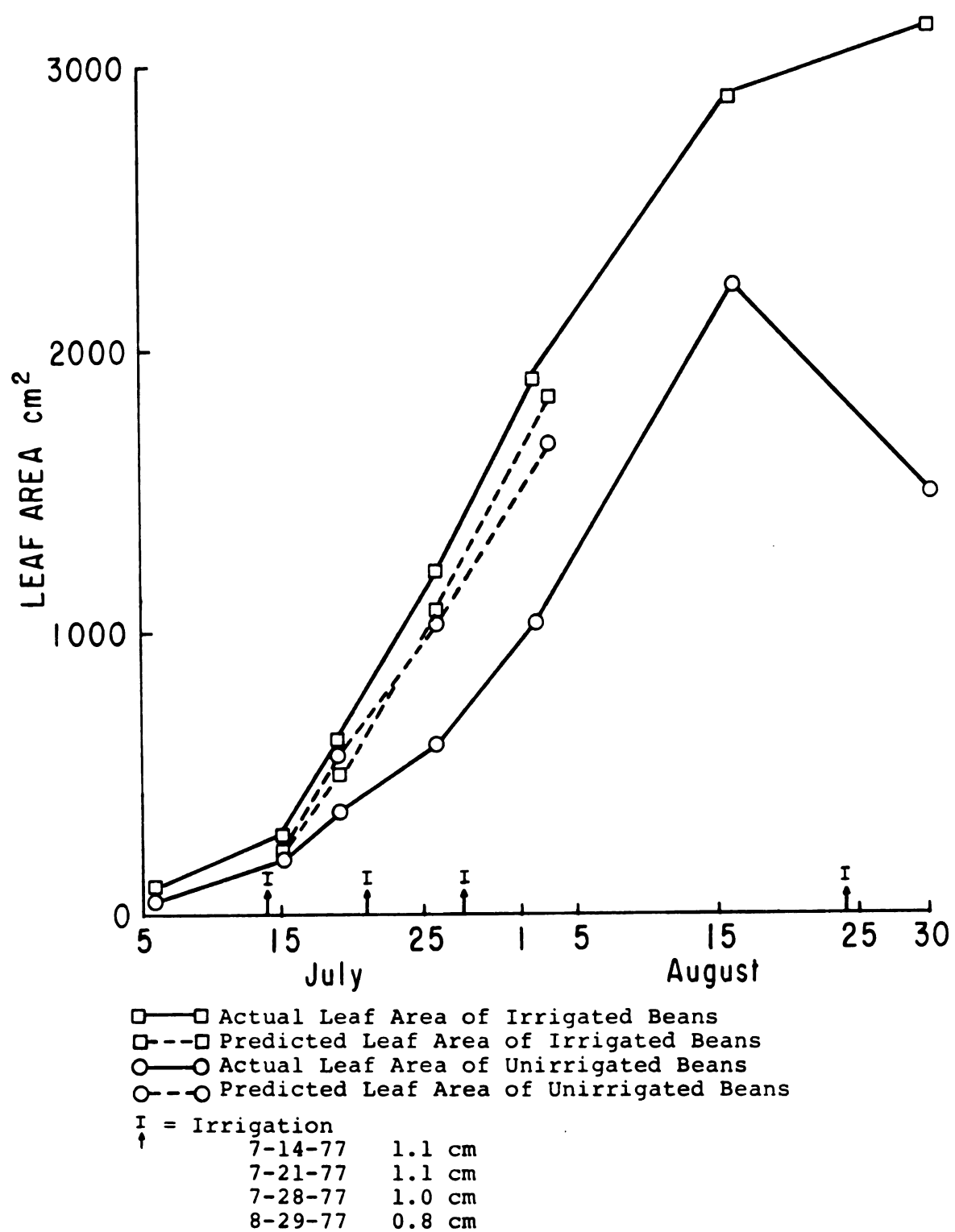
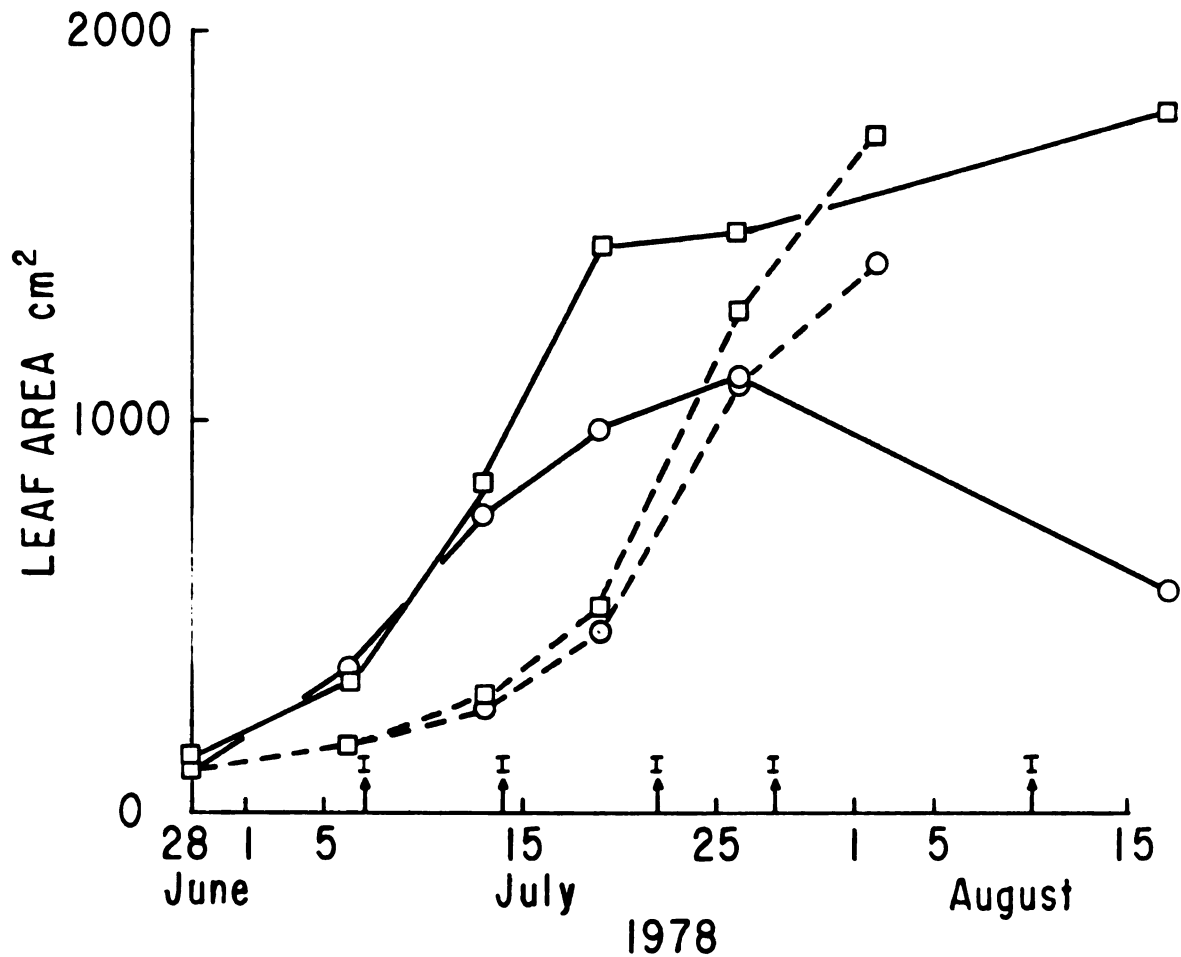


Figure 4. Actual and Predicted Leaf Areas of Irrigated and Unirrigated Beans Grown on Hillsdale Sandy Loam in 1977.



□—□ Actual Leaf Area of Irrigated Beans
 □--□ Predicted Leaf Area of Irrigated Beans
 ○—○ Actual Leaf Area of Unirrigated Beans
 ○--○ Predicted Leaf Area of Unirrigated Beans

I = Irrigation

↑	7-7-78	2.2 cm	7-28-78	1.6 cm
	7-14-78	2.5 cm	8-10-78	1.6 cm
	7-21-78	1.6 cm		

Figure 5. Actual and Predicted Leaf Areas of Irrigated and Unirrigated Beans Grown on Hillsdale Sandy Loam in 1978.

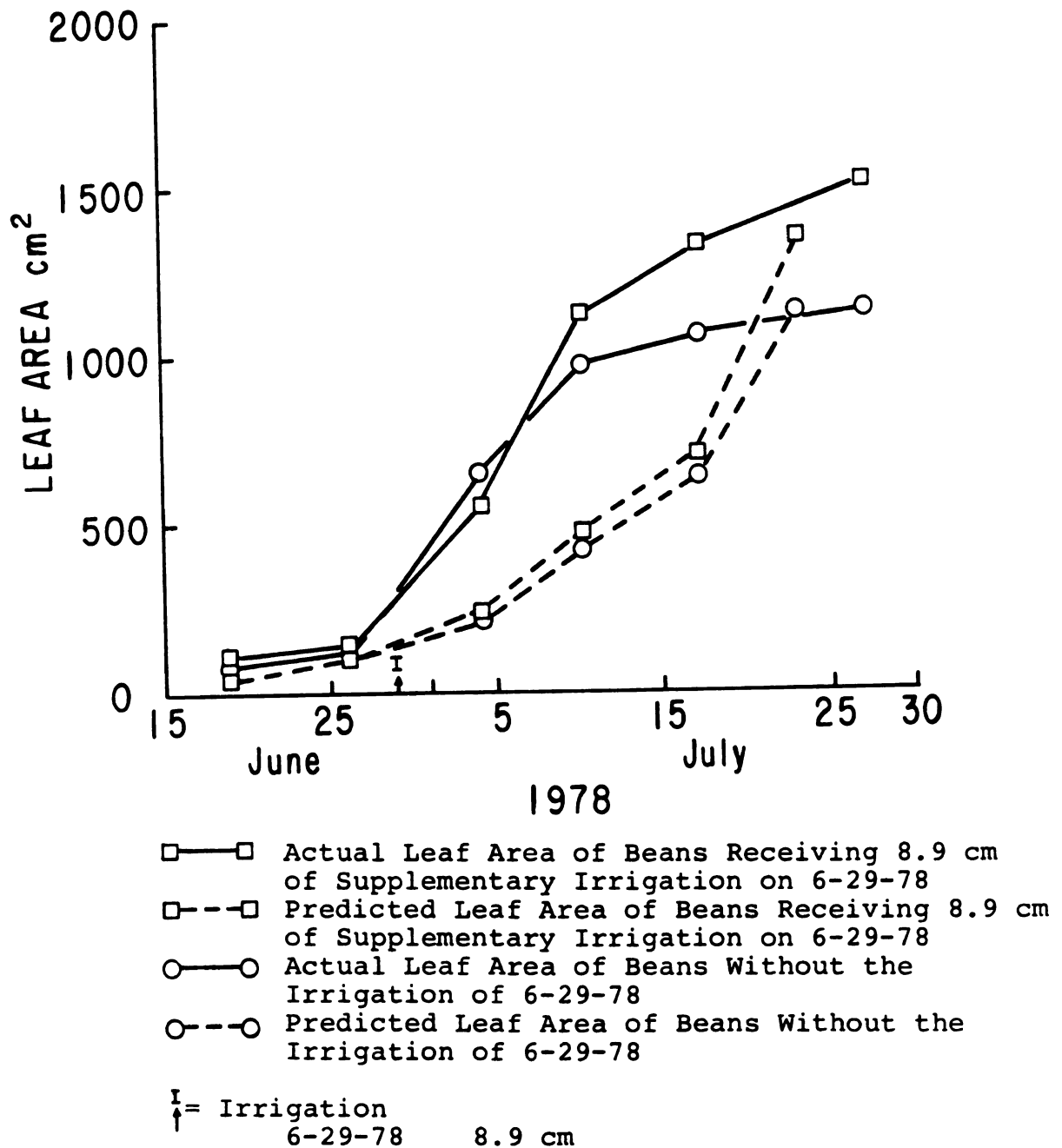


Figure 6. Actual and Predicted Leaf Areas of Beans Grown on Charity Clay With and Without 8.9 cm of Supplementary Irrigation on 6-29-78.

unable to correctly simulate the magnitude of the stress that occurred on the afternoon of July 15, 1977. Model vegetative growth (prior to flowering) ends on August 3 in 1977. August 3 was the model day when accumulated degree days from the first day of model emergence reached or exceeded the boundary value of 700.

The predicted growth curves for the Hillsdale sandy loam in 1978 (Figure 5) are quite different from the actual growth curves. The shape of the actual and predicted curves with irrigation is the same, but the model delays plant growth during July while exceeding actual growth by the final model vegetative day (August 2). The actual and predicted leaf areas without irrigation were the same on July 26, after which the plants in the field began to senesce, whereas the model plants continued to grow. The model discriminates well between irrigation and no irrigation on the final model vegetative day in 1978.

Figure 6 shows actual and predicted growth curves of beans grown on Charity clay in 1978 with and without heavy irrigation on 6-29-78. The predictions of leaf area on the final model vegetative day are quite close to the actual values. Figures 4, 5, and 6 show that because the growth equations are exponential, the predicted leaf areas are lower than actual leaf areas during early vegetative growth, but match or exceed actual leaf areas by flowering.

Pod Filling

Figure 7 shows actual and predicted pod weights of irrigated and unirrigated beans grown on Hillsdale sandy loam in 1977. The curves of actual pod weights show a significant difference between the irrigated and unirrigated treatments by the end of pod filling. The model successfully shows the difference in pod weights between the irrigated and unirrigated treatments, and makes good predictions of pod weights on the final model pod filling day. The model predicts September 8 to be the final pod filling day for the irrigated beans, and September 7 to be the final pod filling day for the unirrigated beans. The model predictions of pod weights during early pod filling are high because the model predicts more pods than actually occurred, and because the model has all pods set prior to calculating pod weights whereas in the field pod setting and filling of pods set earlier occur simultaneously. The slopes of the predicted pod weight lines are low because the model plants experienced some water stress (even when supplementary irrigation was applied). The effect of water stress during pod filling in the model is to reduce the accumulated pod filling day term. This results in predictive lines with low slopes. The slopes (AY/AX) of lines of predicted pod weights versus time from all model tests were low because the model showed most plant water stress to occur in late summer.

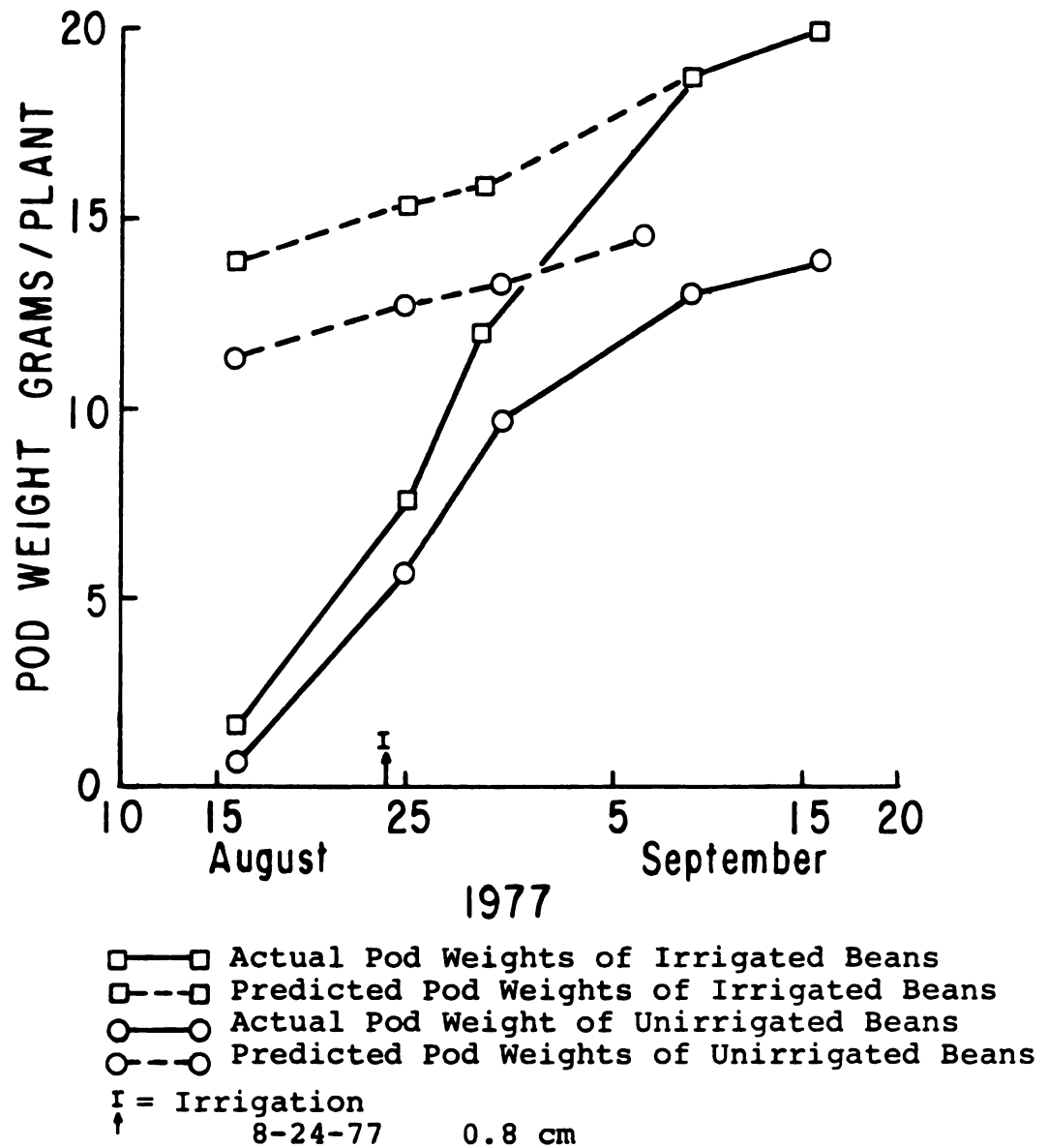
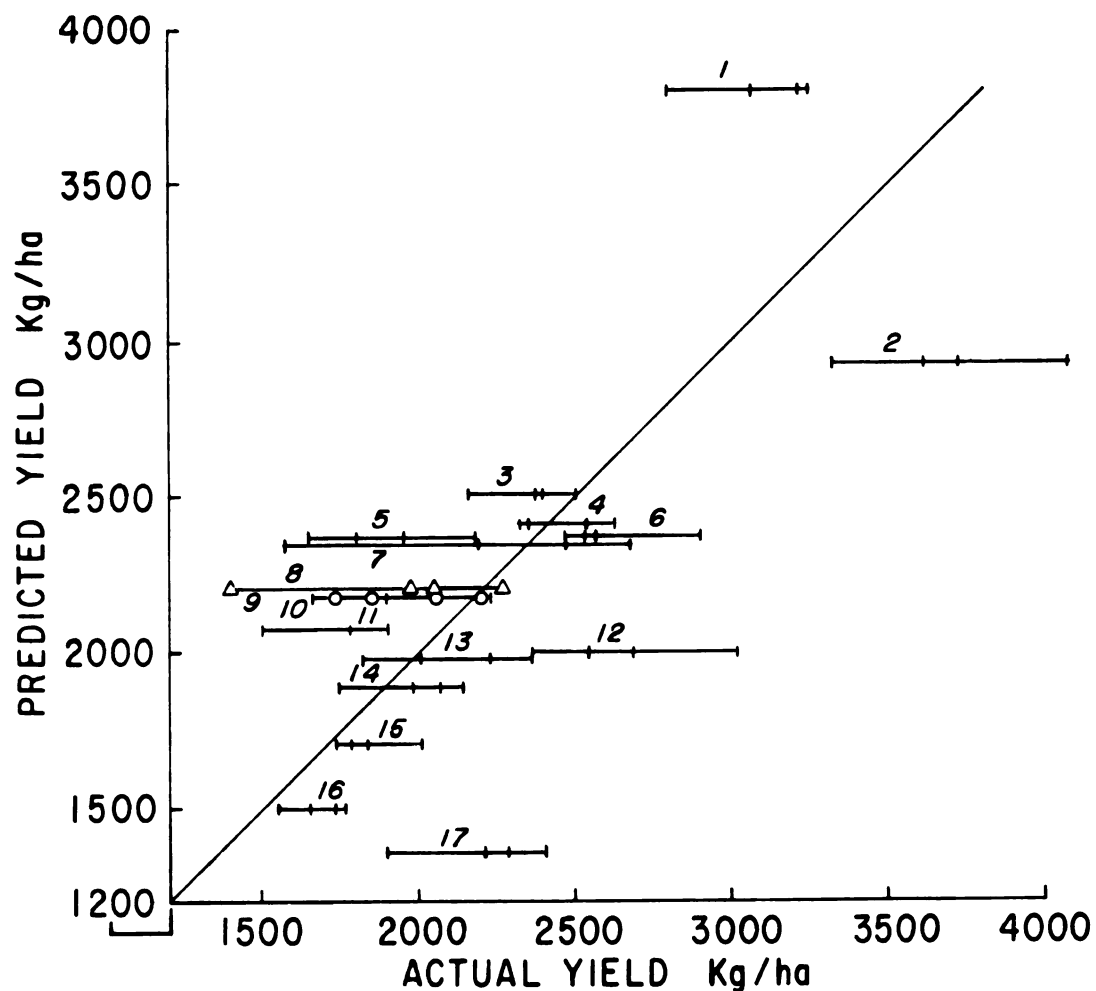


Figure 7. Actual and Predicted Pod Weights of Irrigated and Unirrigated Beans Grown on Hillsdale Sandy Loam in 1977.

Yield

Table 1 lists actual and predicted yields from the 44 sets of data used in model verification. Figure 8 shows the predicted versus actual yields by replication of beans grown on Hillsdale sandy loam in 1977 and 1978, and on Charity clay in 1978. Four replicates of each treatment were made in the field. Seven of the 17 treatments have the range of individual replicate yields crossing the one to one predicted versus actual yield line. Another four treatments are close to the one to one to one line. Of the 1978 Charity clay data shown in Figure 8, the model is least successful in predicting yields for the heavy irrigations of 7-19-78 and 8-2 and 8-3-78, and the treatments of irrigation and no irrigation on excellent soil structure. The model does not simulate the positive benefits of high humidity during flowering noted by Davis (1943), which was what occurred in the field with the heavy irrigation of 7-19-78. The heavy irrigations of 8-2-78 and 8-3-78 caused a rust infection which presumably reduced yield. The model properly discriminates between irrigated and unirrigated beans grown on excellent soil structure on the Charity clay in 1978, but makes yields too low for both. Model predictions for no irrigation on 7-7-78, and for no irrigation after 7-28-78 on the Hillsdale sandy loam are high.

Figure 9 is a plot of predicted versus actual yields (kg/ha) from Table 1. Actual yields are on the x axis and predicted yields are on the y axis. A linear regression



Charity Clay 1973

- 17. Excellent Soil Structure Not Irrigated
- 12. Excellent Soil Structure Irrigated
- 13. Good Soil Structure Irrigated
- 3. Good Soil Structure Heavy Irr. 6-29-78
- 2. Good Soil Structure Heavy Irr. 7-19-78
- 1. Excellent Soil Structure Heavy Irr. 8-2, 8-3-78

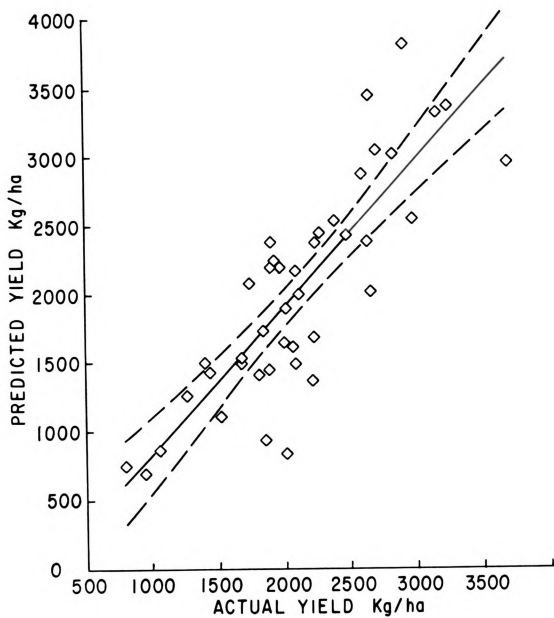
Hillsdale Sandy Loam 1977

- 6. Always Irrigated
- 7. Stress at Second Seedling
- 14. No Irrigation

Hillsdale Sandy Loam 1978

- 4. Always Irrigated
- 5. No Irr. 7-7-78
- 91. No Irr. 7-14-78
- 8X. No Irr. 7-21-78
- 10. No Irr. 7-28-78
- 11. No Irr. after 7-28-78
- 15. No Irr. after 7-7-78
- 16. No Irr.

Figure 8. Predicted Yields Versus Actual Yields by Replication of Bean Grown on Hillsdale Sandy Loam in 1977 and 1978, and Charity Clay in 1978.



$Y = A + BX$
 $A = -212$
 $R^2 = 0.70$
 $B = 1.05$
 - - - 95% Confidence Intervals

Figure 9. Predicted Versus Actual Yields of the 44 Model Verification Runs from Table 1.

equation of the form $Y = A + BX$ was obtained from this data. The correlation coefficient R^2 for the equation is 0.7, which is significant at the 1 percent level. Figure 9, and the predicted and actual values listed in Table 1 show that the model makes good yield predictions based on weather, and correctly discriminates between different water or soil structure regimes for a given year and location.

Poor yield predictions are made by the model on the compacted Charity clay in 1974. Predictions of yield from compacted soil are the most difficult because the amount of compaction depends on soil moisture at the time of compaction. The high actual yields in 1974 can be attributed to dry soil at the time of compaction. The high actual and predicted yields from the 1972 compacted Charity clay were due to heavy rainfall during pod filling. The heavy rainfall compensated for the poor soil structure in both the field and the model.

The model provides reasonable yield predictions for the data specifically collected for modeling in 1977 and 1978, and from weather data satisfactorily predicts yields of beans grown under a variety of conditions in previous years. Although some of the less successful predictions by the model are due to its simplicity, its simplicity makes it easier to use than some of the other models presently available. The accuracy of the model is also affected by such factors as soil fertility, weed competition, and plant

disease, which affect actual yield but were not included in the model.

Conclusions

The simple model of navy bean growth and yield as a function of physical stresses successfully discriminates between varying stress levels of crusting during emergence, soil structure, or drought. It makes good predictions of emergence, vegetative growth prior to flowering and pod filling by the end of each plant growth stage, and is quite successful in predicting yield. The correlation between predicted and actual yield from the 44 sets of data used in model verification is significant at the 1 percent level. The model makes good predictions for both the data collected in 1977 and 1978, and the data from previous years. Considering soil fertility differences and weed and disease problems not included as model input, the model performs outstandingly in predicting yield as a function of weather. The model can be used to show the importance of maintaining good soil structure and the effects of drought at various crop stages. It can also be used to predict when to irrigate.

Reference

- Stolzy, L. H. 1954. The effect of mechanical composition and clay mineral types on the moisture properties of soils. Ph.D. dissertation, Michigan State University Library, East Lansing, Michigan.

CHAPTER V

SUMMARY AND CONCLUSIONS

The problem of declining navy bean yields in Michigan was studied using a system science approach. The objective of the study was to determine the magnitude of the effects of physical stresses on navy bean growth and yield. Detailed plant growth measurements under different soil structure and drought stress conditions were made of beans grown on Hillsdale sandy loam and Charity clay in 1977 and 1978. Plant growth measurements collected were emergence counts, leaf areas, plant weights, rooting distributions, pod weights, and pod counts. Soil structure studies included optimum soil structure (a rotation including two years of alfalfa-timothy followed by fall chisel and moldboard plowing), average soil structure (a rotation without two years of alfalfa-timothy and chisel plowing), and poor soil structure (compacted by tractor prior to planting). Drought studies were made using supplementary irrigation during the second seedling, flowering, or pod filling plant growth stages.

A computer simulation of navy bean growth and yield was constructed using the 1977 data. Verification was made

using both 1977 and 1978 data, and additional data from other years. The computer simulation model was constructed to demonstrate the negative effects of physical stresses so as to promote better soil management. The model was constructed using field data on emergence, plant growth, and pod filling as variables in multiple linear regression analyses. Conceptual equations were developed to simulate drought stress. The conceptual equations reduce the values of terms entering the plant growth and pod filling equations or shorten the length of the flowering plant growth stage. A value for crusting during emergence, and values to characterize soil structure are used directly in the equations from multiple linear regression.

The field studies showed that navy bean growth and yield are greatly affected by crusting during emergence, soil structure, and drought stress. Crusting delays emergence and reduces total plant stand. Soil structures less than optimal result in reduced rooting distribution which in turn makes plants more susceptible to drought stress. Drought stress affects growth and yield at any plant stage, but has particularly bad effects at flowering and pod filling. Growing lush plants up until flowering through use of supplemental irrigation is not useful unless water is available during flowering and pod filling. Without supplementary irrigation our drought stresses most often occur during August (flowering and pod filling) so soil management for optimal rooting is crucial.

The computer simulation model gave yield verification with an R^2 correlation coefficient of 0.7 for the 44 sets of data used. The linear regression equation $Y = A + BX$ ($A = -212$, $B = 1.05$) was generated from predicted yield Y versus actual yield x . Verification results show that the model will accurately predict yields based on weather information, and that it discriminates well between different stress levels of crusting during emergence, soil structure, and drought. The model is not accurate in predicting emergence, vegetative growth, or pod weights at all times during the growing season. The model can be used to encourage maintenance of good soil structure, to predict when irrigation should be applied and, if coupled to a weather predictive model, to predict yield during a growing season.

The advantages and disadvantages of the model can be listed as follows.

Advantages

1. Input soils information is limited to bulk density, a soil structure factor, the moisture contents of 15 and .06 bars tension, an estimate of soil moisture on the planting date, and observed or estimated crusting during emergence.
2. Input plant information is limited to planting date and plant stand (seeds planted x final percent emergence).

3. The only input of weather information needed is daily rainfall, pan evaporation, and maximum and minimum air temperatures.
4. The model can be used to decide when to irrigate.
5. Yield predictions were good for 44 data sets tested from differing locations and years.

Disadvantages

1. Emergence, vegetative growth, and pod weights are not accurate at all times during the growing season.
2. Use of a single value to characterize soil structure can be unsuccessful on compacted soil if compaction was done on dry soil.
3. The emergence equations do not include soil moisture.
4. The model has difficulty in simulating severe short term water stresses which may occur in time intervals of less than one day.

The system science approach to the navy bean yield problem produced positive information not previously observed. Because of the goal of collecting very detailed plant information for construction of the model, it was observed that navy bean populations are not homogeneous in size but instead consist of many subpopulations with tremendous size range. The substantial number of small nonproductive plants has led to research to develop a bean planter that will space beans equidistant and provide an ideal seed bed without damaging soil structure of the root bed or bulk of the soil.

APPENDIX

ADDITIONAL INFORMATION AVAILABLE FROM THE
STUDY OF NAVY BEAN GROWTH AND YIELD
AS AFFECTED BY PHYSICAL STRESSES

APPENDIX

ADDITIONAL INFORMATION AVAILABLE FROM THE STUDY OF NAVY BEAN GROWTH AND YIELD AS AFFECTED BY PHYSICAL STRESSES

The following information may be obtained through Dr. R. K. Hubbard or Dr. A. E. Erickson of Michigan State University.

1. Field data of leaf areas, plant heights, plant weights, root weights, and pod weights from the studies conducted in 1977 and 1978.
2. A User's Manual which includes a listing of the computer program and a discussion of how to use it. The manual includes examples of input to and output from the model.

MICHIGAN STATE UNIV. LIBRARIES



31293100642788