Modeling variations in soil moisture and crop yield for an irrigated alfalfa field in southwestern Montana

by Daniel Bishop Harelson

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Agricultural Engineering
Montana State University

Abstract:
The purpose of this study was to evaluate two computer models which can be used to predict variations in soil moisture with time and space as well as crop yield. This evaluation was performed using data from a sprinkler irrigated alfalfa field on the Montana State University Red Bluff Research Ranch. FORTRAN models named SPAW and Plantgro were selected for evaluation because they differ significantly in their random access memory requirements and because they were readily available. Both models perform a water budget for a selected number of soil layers using pan evaporation to estimate evapotranspiration. Crop yields are predicted using a linear relationship between potential yield and the ratio of actual to potential transpiration. The models were calibrated using soil moisture and yield data from 1979 while similar data from 1981 was used for testing. The results of this study indicated that the SPAW model predicted soil moisture variations somewhat more acurately than the Plantgro model. However, the Plantgro model predicted crop yield more accurately than the SPAW model. Unfortunately, the results of this study were subject to doubt because model calibrations were based on very limited data and the accuracy of some of these data was uncertain. More effective use of the available data would eliminate some doubt and provide a more reasonable basis for evaluating the models in terms of the accuracy of simulated results.

MODELING VARIATIONS IN SOIL MOISTURE AND CROP YIELD FOR AN IRRIGATED ALFALFA FIELD IN SOUTHWESTERN MONTANA

by

Daniel Bishop Harelson

A thesis submitted in partial fulfillment
of the requirements for the degree

of

Master of Science

in

Agricultural Engineering

MONTANA STATE UNIVERSITY
Bozeman, Montana

March 1986

APPROVAL

of a thesis submitted by

Daniel Bishop Harelson

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style and consistency, and is ready for submission to the College of Graduate Studies.

3/31/86 — Date

Thomas L. Hanson — Chairperson, Graduate Committee

Approved for the Major Department

3/31/86 — Date

W. E. Larsen — Head, Major Department

Approved for the College of Graduate Studies

4/10/86 — Date

Henry L Parsons — Graduate Dean

STATEMENT OF PERMISSION TO USE

In presenting this thesis in partial fufillment of the requirements for a master's degree at Montana State University, I agree that the Library shall make it available to borrowers under rules of the Library. Brief quotations from this thesis are allowable without special permission, provided that accurate acknowledgement of source is made.

Permission for extensive quotation from or reproduction of this thesis may be granted by my major professor, or in his absence, by the director of Libraries when, in the opinion of either, the proposed use of the material is for scholarly purposes. Any copying or use of the material for financial gain shall not be allowed without my written permission.

Signature Daniel B. Harelson

Date 4-9-86

Acknowledgements

I would like to gratefully acknowlege the assistance and guidance provided by my thesis committee composed of Dr. Thomas L. Hanson, Chairman, Dr. William E. Larsen and Dr. Richard L. Brustkern. In addition, I would like to express my appreciation to Pamela Diedrich for generously sharing her programing expertise.

TABLE OF CONTENTS

1. Introduction.. 1

    Statement of Problem.. 1
    Literature Review.. 2

2. Background Information.. 8

    Introduction.. 8
        Spaw Model Description..10
        Plantgro Model Description..19

3. Procedure..25

    Available Data..25
    Model Calibration..29
        SPAW Calibration..32
        Plantgro Calibration..38
    Model Testing..41

4. Results..43

5. Discussion..51

    Data and Computational Requirements..51
    Analysis of Results from the Red Bluff Simulation..............52
    Sources of Error in the Red Bluff study..54
    Ease of Model Calibration and Application..58
    Suggested Program Modifications..62
    Recommendations for additional work at the Red Bluff Ranch.....63

6. Conclusions..66

References Cited..67

Appendix A..71

    Climatological Data..72
    Soils Data..75
    Crop Data..79

Appendix B..82

    Description of Program Modifications..83

LIST OF TABLES

1. Soil percent sand and clay detemined through the SPAW model....33

2. Canopy and Phenology Susceptability relationships....36

3. Field Capacity and Wilting Point as determined from Plantgro calibration....39

4. Values for the ratio of potential transpiration (PT) to potential evapotranspiration (PET)....40

5. SPAW model average percent error in predicted soil moisture....46

6. Plantgro model average percent error in predicted soil moisture....46

7. Observed Yield, SPAW Simulated crop water stress and Plantgro Simulated yield for the calibration year 1979....50

8. Observed yield and yield simulated by the Spaw and Plantgro models for the test year 1981....50

9. Precipitation data for 1979....72

10. Precipitation data for 1980....72

11. Precipitation data for 1981....72

12. Pan evaporation data for 1979....73

13. Pan evaporation data for 1980....74

14. Pan evaporation data for 1981....74

15. Soil texture by quadrant and layer....75

16. Soil moisture holding capacity at field capacity and the wilting point....75

17. Soil moisture measurements by quadrant for 1979....76

18. Soil moisture measurements by quadrant for 1980....77

19. Soil moisture measurements by quadrant for 1981....78

20. Harvest data....79

LIST OF TABLES--continued

21. Irrigation data for quadrant 1....................................78
22. Irrigation data for quadrant 2....................................79
23. Irrigation data for quadrant 3....................................79
24. Irrigation data for quadrant 4....................................80

LIST OF FIGURES

1. Control volume for the SPAW and Plantgro models.................. 9

2. SPAW model computational scheme.....................................11

3. Moisture Stress curves...15

4. Plantgro model computational scheme..................................20

5. Red Bluff Research Ranch location....................................26

6. Study site plan..27

7. SPAW Crop Canopy curve...34

8. SPAW Crop Phenology curve..35

9. SPAW simulated Soil Moisture versus Time for the calibration year and the test year.................................44

10. Plantgro simulated Soil Moisture versus Time for the calibration year and the test year...........................45

11. SPAW model Stress versus Yield......................................48

12. Plantgro model Observed Yield versus Simulated Yield..49

ABSTRACT

The purpose of this study was to evaluate two computer models which can be used to predict variations in soil moisture with time and space as well as crop yield. This evaluation was performed using data from a sprinkler irrigated alfalfa field on the Montana State University Red Bluff Research Ranch. FORTRAN models named SPAW and Plantgro were selected for evaluation because they differ significantly in their random access memory requirements and because they were readily available. Both models perform a water budget for a selected number of soil layers using pan evaporation to estimate evapotranspiration. Crop yields are predicted using a linear relationship between potential yield and the ratio of actual to potential transpiration. The models were calibrated using soil moisture and yield data from 1979 while similar data from 1981 was used for testing. The results of this study indicated that the SPAW model predicted soil moisture variations somewhat more acurately than the Plantgro model. However, the Plantgro model predicted crop yield more accurately than the SPAW model. Unfortunately, the results of this study were subject to doubt because model calibrations were based on very limited data and the accuracy of some of these data was uncertain. More effective use of the available data would eliminate some doubt and provide a more reasonable basis for evaluating the models in terms of the accuracy of simulated results.

CHAPTER 1

INTRODUCTION

Soil water is an important quantity in the hydrologic cycle since it is a water supply for plants, influences erosion and runoff and is percolated to groundwater reservoirs. The time and spatial distribution of soil water within the upper soil profile is the result of complex interactions between many variables related to current and past occurences of weather, crops and soil conditions. Computer models have been developed to provide methods for quantifying interactions between these variables so the time-depth distribution of soil water in an active soil profile can be predicted and related to crop yield. Two such computer models were examined in this study using data collected from an irrigated alfalfa field located on the Montana State University Red Bluff Research Ranch 35 miles west of Bozeman Montana.

Statement of Problem

The purpose of this study was to compare and evaluate two computer models which can be used to predict soil moisture and crop yield. The models which were selected for study differed significantly in their computational requirements. The accuracy of predicted soil moisture and yield values, the ease of calibration and application as well as computational requirements were used to provide a basis for comparing the models.

Stated in more specific terms, the objective of this study was to evaluate two computer models for use in predicting soil moisture and hay production from an irrigated alfalfa field.

To accomplish this objective, it was necessary to perform this study in the following stages:

1. Select models for study.
2. Analyze available data for the irrigated alfalfa field.
3. Make necessary modifications to the models so that they would be compatable with an AT&T 6300 microcomputer.
4. Calibrate the models to simulate changes in the time-depth distribution of soil moisture.
5. Test the capacity of the models to simulate changes in soil moisture.
6. Calibrate the models to simulate crop production.
7. Test the capacity of the models to predict crop production.

<u>Literature review</u>

A large number of computer models are available for the purpose of simulating evapotranspiration and soil water movement. A monograph published by the American Society of Agricultural Engineers (ASAE, 1982) includes a chapter outlining 75 models that could be used for this purpose or related purposes. Many of the models outlined in this publication simulate processes in addition to soil water movement and crop production. These processes include some or all of the following; flood routing, precipitation, snowmelt, infiltration, surface runoff, chemical movement and erosion yield.

A table summarizing the processes simulated and the areas where each model had been applied is included in this chapter. Following this table are abstracts and references for each of the 75 models. In addition, a second table including references for models that were under development at the time of publication is incorporated in this chapter. Another chapter which was particularly useful in this study dealt with the calibration and testing of hydrologic models. Other chapters in this monograph provide information regarding the development of approaches for modeling flood routing, precipitation, snowmelt, infiltration, surface runoff, evapotranspiration, subsurface flow, chemical movement and erosion.

The SPAW (Saxton et al., 1984) and Plantgro (Retta and Hanks, 1980) models were examined in this study because they differ in their computational requirements by an order of magnitude and they were readily available. In addition, they are frequently refered to in literature concerning computer modeling of soil moisture and crop yield. There are other computer models (Kanemasu et al., 1976; Goldstien et al. 1974) which are directly comparable to the SPAW and Plantgro models in terms of the predictions which are made. One such program is the PROSPER model developed at the Oak Ridge National Laboratory in Tennesee (Goldstien et al., 1974). This program calculates evapotranspiration using the combination equation and simulates liquid water flow using network equations. Unfortunately, documentation for this program could not be obtained while this study was in progress.

Considerable study has been devoted to the SPAW model in the past. The SPAW model has been calibrated and tested to simulate soil moisture and crop yield at study sites in western Iowa and central Missouri (Sudar et al., 1981). Corn and soybean yields were examined at these sites and the results showed that the SPAW model provided a practical and accurate approach for assessing water stress effects on crop yield. An additional study of the SPAW model tested the program for regional application to corn at 49 sites in Kansas, Missouri, Iowa and South Dakota (Saxton and Bluhm, 1982). The results of this study indicated that some local calibration of the model was required but that after a parameter set was established, crop yields could be predicted with moderate to good accuracy.

The SPAW model has also been compared with the Stockle-Campbell model (Stockle, 1983) in terms of their ability to predict winter wheat yields (Stockle and Saxton, 1984). The model comparison was based on winter wheat yields at two sites in Washington. Preliminary results of this comparison indicated that both models showed good predictive capability and might be useful for practical applications. However these results were based on calibration data only and additional work was necessary before any firm conclussions could be drawn. Additional work would involve testing the models using independent data from different years and locations.

In previous work with the Plantgro model, several variations of the model have been studied. One study tested the ability of the model to simulate corn dry matter and grain yield as well as sorghum dry matter yield (Hanks, 1974). This version of the Plantgro model differed from the one examined in this study in that the entire soil profile was represented as a single layer and evaporation was specified using a single seasonal value. Although the results of this study showed relatively good predictive capability, the model was not tested using data which were independent of the calibration year.

Another variation of the Plantgro model was studied using the modified Penman equation to evaluate evapotranspiration over the course of the growing season (Nimah and Hanks, 1973). This version differed from the one studied here in the way evapotranspiration was evaluated and in the way the movement of soil moisture was simulated. Soil moisture movement was simulated using a finite difference form of the Darcy equation for porous media flow. In addition, no attempt was made to simulate crop yield. The results of this study indicated that soil moisture movement could be simulated accurately after calibration. However, the model was not tested using data which were independent of the calibration data.

A version of the Plantgro model has also been used to simulate spring wheat grain yield (Rassmussan and Hanks, 1978). Grain yields were simulated at several sites in Utah for several years. These simulations predicted grain yield with errors of eight to thirty percent. However, the error of thirty percent was predicted for an anomolous year in terms of the length of the growing season. During this growing season, weather was warmer than normal and the planting date was significantly earlier than the planting dates of the calibration years.

The SPAW and Plantgro models have also been extended to predict soluble ion movement and the effects of salinity on yield. The SPAW model has been modified to simulate nitrate nitrogen movement and dissipation by considering additions, subtractions, storage and biological conversions represented as a time distribution (Saxton et al., 1977). In this extension of the SPAW model, the factors considered in the calculation of nitrate transport include; infiltration, soil water redistribution, percolation, plant uptake, fertilizer addition, rainfall addition, mineralization and nitrification. Although nitrate movement through diffussion was simulated, the effects of adsorption were not considered.

The Plantgro model has been extended to simulate the effects of salinity on crop yield and salt movement within the soil profile (Childs and Hanks, 1975). This extension takes into consideration effects of the irrigation amount and scheduling, irrigation water quality, initial soil salinity, crop type and uniformity of irrigation. A decreased osmotic potential was used to represent salinity effects on yield. Solute flow was modeled both in terms of bulk solution flow and solute difussion. The effects of adsorption as well as salt precipitation and dissolution were not represented.

In addition to the information described, two documents were essential to this study. These documents are the user's manuals for the SPAW (Saxton et al.,1984) and Plantgro (Retta and Hanks, 1980) models. The user's manual for the SPAW model is a publication that covers in detail every aspect of the operation of the SPAW model. The user's manual for the Plantgro model is a much smaller publication with insufficient detail. The user's manual for the Plantgro model was inadaquate because the units of measure used by the program are not clearly specified.

A paper titled "Evaluating wash tub evaporation irrigation scheduling" by Hanson (1984) provided useful information regarding previous study of the alfalfa field at the Red Bluff Ranch. In addition to discussing aspects of irrigation scheduling based on direct measurements of pan evaporation, this paper provided background information on the alfalfa field in question. This information included a summary of yield, soils and evaporation data as well as a description of the methods and materials used to plant the field.

CHAPTER 2

BACKGROUND INFORMATION

The SPAW and Plantgro models are predictive accounting procedures which produce a daily water budget for soil water within specified soil layers. These accounting procedures are governed by the major effects of weather, crops and soils. The primary purpose for developing these models was to improve predictions of infiltration, runoff, erosion and water quality. An equally important reason for developing these models was the assessment of available soil moisture throughout the growing season for agricultural crops. A number of secondary objectives can be approached through the application of these accounting procedures. These might include assesment of crop water stress effects on growth and yield, soil water influences on soluble ion distribution and the percolation of soil water for groundwater recharge. While the SPAW and Plantgro models were developed to represent a complex physical and biological system, the data requirements were restricted to those readily available through normal sources.

The diagram in Figure 1 represents the control volume considered by the SPAW and Plantgro programs to compute estimates of the soil water profile, actual evapotranspiration and deep percolation. Daily estimates of all of these quantities are made by the models to produce vertical water budgets. In the SPAW model, soil water profiles are estimated at a maximum time step of one to four hours as required to maintain computational stability. The soil profile is represented in the models by a selected number of layers and depths designed to

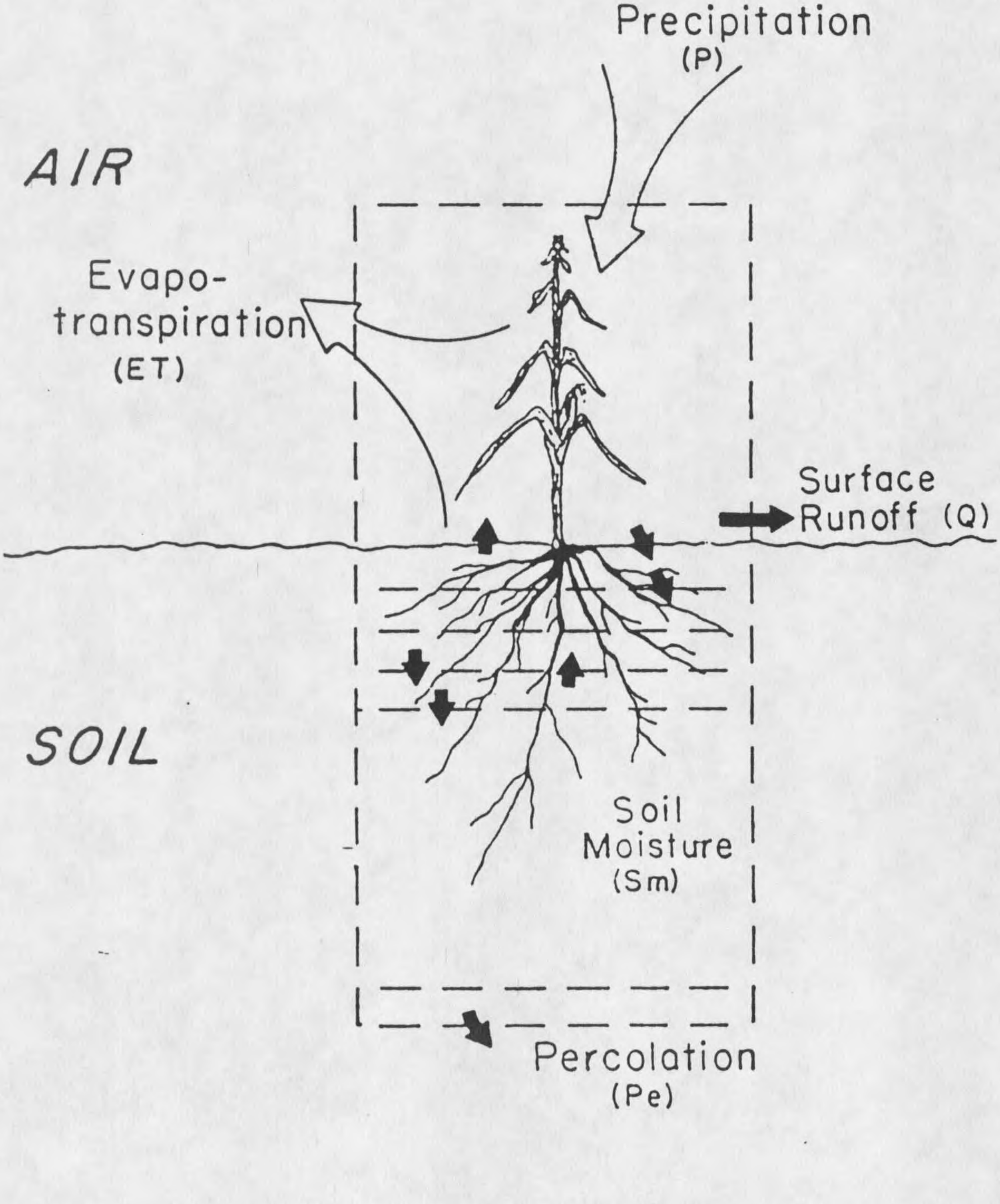

Figure 1. Control volume for the SPAW and Plantgro models.

reflect the average soil profile over the field or watershed being modeled. Each layer may be assigned a unique set of water holding characteristics and, in the case of the Spaw model, the unsaturated hydraulic conductivity of the layers can also be represented. The above ground portion of the control volume is assumed to be a uniformly distributed plant canopy.

SPAW model description

The general computational scheme used in the SPAW model is shown in Figure 2. In this computational scheme, potential evapotranspiration is determined independently and then reduced to an estimate of actual evapotranspiration. Susequent calculations divide the actual evapotranspiration into components of interception evaporation, soil water evaporation and plant transpiration. After subtracting the actual evapotranspiration from existing soil moisture by soil layers, daily infiltration is added. Then, soil water is redistributed based on a Darcian equation. A brief description of each element considered in this computational scheme follows.

Potential evapotranspiration

The potential evapotranspiration may be obtained from a variety of meteorological methods. As presented, the SPAW model estimates potential evapotranspiration from measured or estimated daily pan evaporation. The pan evaporation rates are reduced by a monthly pan coefficient to become estimates of potential evapotranspiration.

Interception

Interception of water by the crop canopy is simulated using a storage device with a maximum capacity representing potential

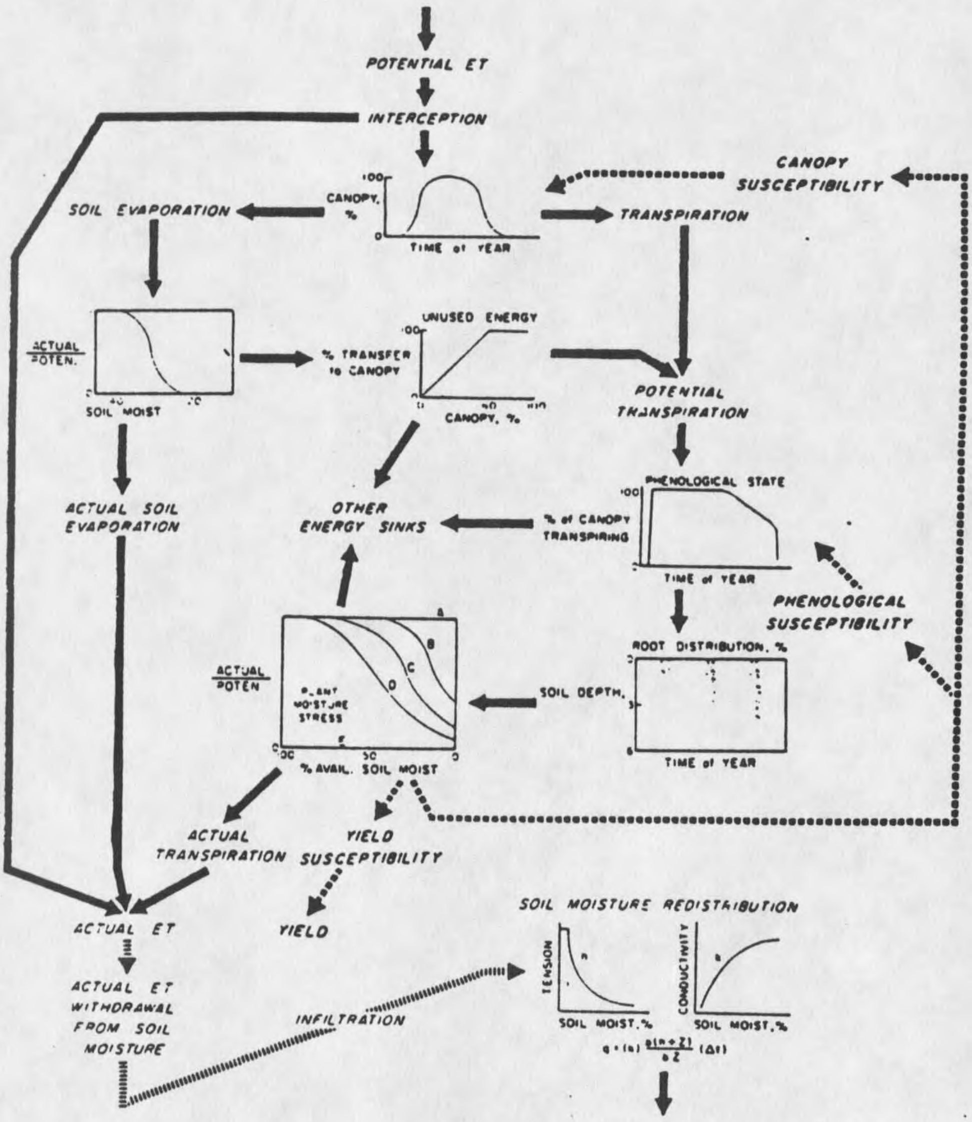

Figure 2. SPAW model computational scheme

interception. The potential evapotranspiration value is reduced by the amount of interception before transpiration and soil water evaporation are computed.

Crop canopy

Because solar radiation plays a major role in causing transpiration, the SPAW program uses crop canopy as an indicator of the proportion of the potential evapotranspiration that will be considered as transpiration from the crop canopy. Crop canopy is expressed as an annual time graph of the percentage of shaded soil. Values vary from zero for bare soils to almost 1.00 for dense canopies. Crop residues are treated as canopy cover because they provide soil shading which affects evaporation from the soil. The inability of crop residues to transpire is accounted for in the model by considering plant phenology.

For dry soil conditions with a partial canopy, there is some portion of the energy available for potential evapotranspiration which is not used for water evaporation. Unused energy heats the soil, the adjacent air and the canopy. As a result, the canopy has a second source of energy in addition to directly intercepted energy. To represent this effect, a linear relationship of canopy versus percent unused energy is incorporated into the SPAW model. When the canopy reaches sixty percent, all unused energy is captured by the canopy and it becomes part of the energy available for potential transpiration.

Plant phenology

A second annual time graph of a phenological factor is included in the SPAW model as a direct modifier of the crop canopy's ability to transpire. At times during the year when the canopy is not transpiring, the phenological factor takes on a value of zero. As the proportion of the crop canopy transpiring increases, the value of this factor approaches 1.0.

Soil water evaporation

In the SPAW program, a thin upper boundary layer is included in the soil profile incrementation. This layer has all of the functions of the other layers except plant roots are not present. In addition, water can be readily evaporated from this boundary layer and evaporation is limited only by potential evapotranspiration. Upward water movement from the second layer into the evaporative boundary layer is estimated by a Darcian equation using a small fraction of the unsaturated hydraulic conductivity for the current soil water content of the second layer. The conductivity reduction represents the fact that evaporation is by vapor flow rather than liquid flow and the effective conductivity is several magnitudes less.

Water uptake by plant roots

A simple description of a water extraction pattern with depth was programed into the SPAW model. For selected dates the percent of water to be abstracted from each soil layer is entered. Each distribution is applied to succeeding dates until a new distribution is specified to reflect root development. The entered water extraction distribution assumes that water is readily and equally available in all soil layers. Any water stress due to soil drying is considered in the crop water stress relationship.

Crop water stress

As the water supply to a plant becomes limited, physical and biological controls begin to limit the rate of transpiration. To account for this effect, several curves representing the ratio of actual to potential evapotranspiration (AT/PT) versus plant available moisture and potential evapotranspiration have been programed into the SPAW model. Several curves, shown in Figure 3, are included because a plant is more likely to attain a larger proportion of a lower potential evapotranspiration rate than it is a higher potential evapotranspiration rate. In the model, the programed curves are applied to each soil layer independently and the actual transpiration is a multiple function of the canopy, phenology and root distribution.

After estimating the daily plant actual transpiration, the SPAW program further estimates the magnitude of water stress as (1-(AT/PT)). This value is then used to calculate stress effects on canopy growth, phenologic development and yield. Stress effects on canopy and phenology are used to derive the plant status and adjustments are made to plant descriptors (canopy and phenology) for calculations on the subsequent day. These adjustments are such that prolonged water stress will severly limit plant growth or even cause plant death.

The capability to estimate how the daily crop water stress is integrated throughout the growing season to result in a final yield was also incorporated into the model. To represent the relative water stress susceptability in time and among crops, yield susceptability

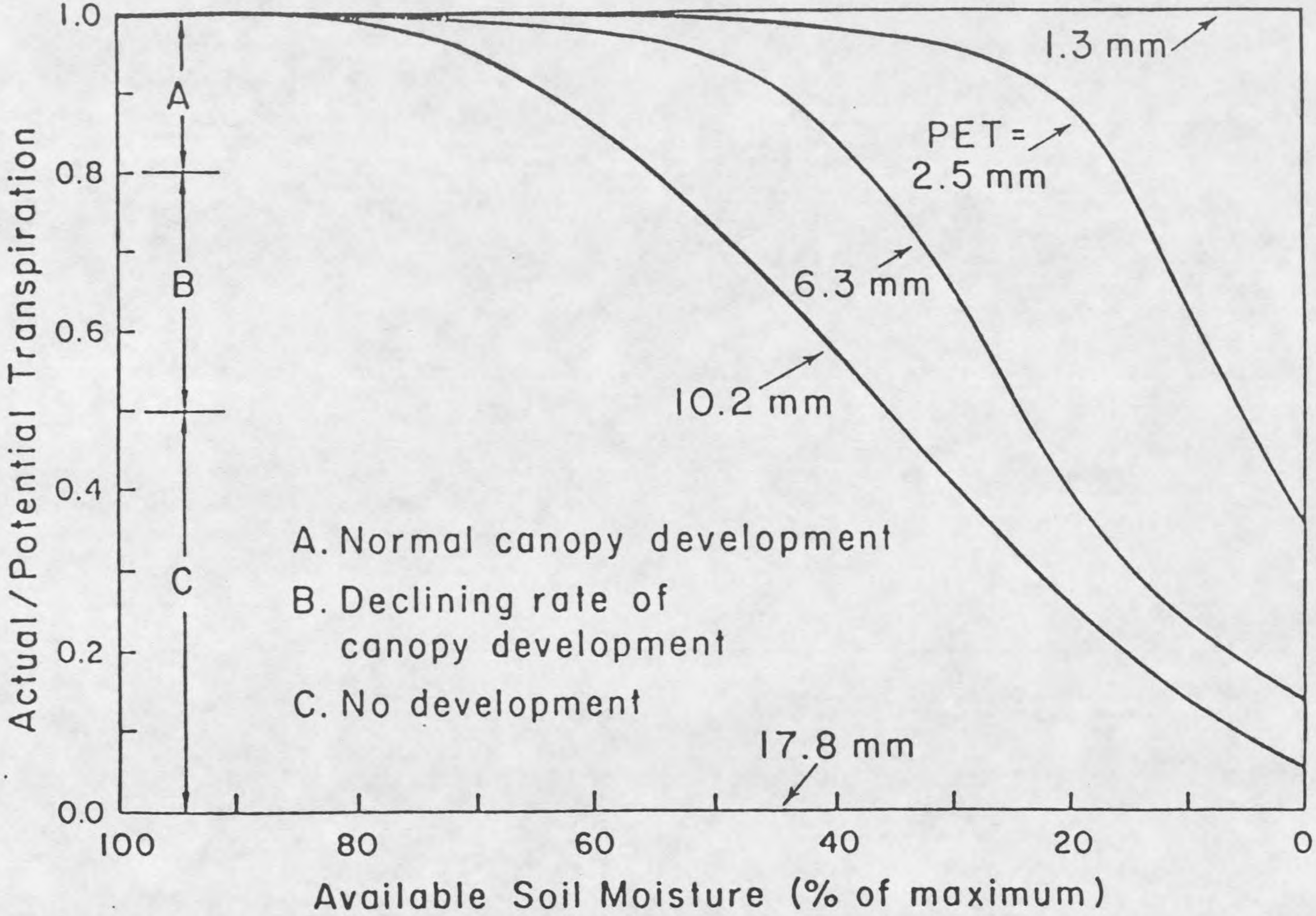

Figure 3. SPAW model moisture stress curves

relationships for particular crops must be developed and entered into the program. Yield reduction due to stress on a particular day is calculated as the product of the water stress on that day and a factor representing the susceptability of the crop to stress on the same day. The program provides relative stress indices which become meaningful only after they are correlated with observed yields from the study site or the region to derive a yield susceptability relationship.

Actual evapotranspiration

An estimate of actual evapotranspiration is obtained by adding the components of intercepted water evaporation, soil water evaporation and plant transpiration.

Infiltration

The Spaw model estimates a daily infiltration value for each day that has precipitation by one of two methods. If measured daily runoff data are available and correctly associated with a precipitation event, they are entered and infiltration is computed as precipitation minus runoff and interception. If measured data are not available, then a daily estimate of runoff is made by a modified version of the Soil Conservation Service curve number method.

The SCS curve number method estimates runoff based on a series of curves which indicate the percentage of precipitation which becomes runoff. A particular curve is selected for use based on tabulated values for various soil and crop combinations. The standard SCS method was modified in the SPAW model to utilize predicted estimates of crop canopy and soil moisture.

Daily infiltration amounts enter and move through the soil profile instantaneously in the Spaw model. Infiltrating water is added to the upper soil layers without exceeding their saturation capacity. Water is cascaded to deeper layers until adaquate storage is available for the infiltrated water. All further redistribution of water is done by the Darcian moisture redistribution routine.

Soil water redistribution

A simplified Darcian equation of water flow between soil layers was included in the SPAW program to evaluate soil water redistribution. The Darcy equation in finite difference form is:

$$q=K(\theta)\frac{(h(\theta)+\Delta Z)}{\Delta Z}(\Delta t)$$

where;

q is the estimated volumetric water flow per unit area per time step across layer boundaries ($cm^3/cm^2/hr$)

$K(\theta)$ is the mean unsaturated hydraulic conductivity of the two layers being considered. These conductivities are functions of the respective layer water contents (cm/hr).

$h(\theta)$ is the matric potential head difference between the two layers being considered as a function of their respective water contents (cm).

ΔZ is the distance between the midpoints of the layers being considered (cm).

Δt is the time increment (hr).

Many pressure and conductivity versus moisture content relationships were summarized from literature and classified by soil texture to provide a series of average relationships for estimating these when no others are available. However, there are input options to provide measured soil water characteristic data to the program or pressure and conductivity relationships can be calculated empirically by the model. Empirically calculated pressure and conductivity relationships are a function of soil texture and soil moisture. These relationships are described in a paper soon to be published in the Soil Science Society of America Journal (Saxton et al. 1986)

Summary of data requirements for the SPAW model

Weather data

Daily precipitation and irrigation amounts (cm).

Daily runoff-either observed or estimated by the model using the modified SCS curve number method.

Daily potential evapotranspiration-the model is now programed to use daily pan evaporation and monthly pan coefficients.

Crop data

Dates of planting and harvest.

Crop canopy- estimated soil shading percentage for selected dates which define a crop canopy curve.

Canopy susceptability-values to represent water stress effects on crop growth.

Crop phenology-values from 0.0 to 1.0 which describe the proportion of the canopy able to transpire on selected dates. These values and the corresponding dates describe a crop phenology curve.

Phenology susceptability-values to represent water stress effects on crop phenology.

Plant water extraction pattern-values for each soil layer for selected dates which reflect the expected water withdrawal percentage by the crop if water were readily and equally available throughout the soil profile.

Plant moisture stress curves-values describing the available soil water and evaporative demand effects on the ratio of actual to potential plant transpiration.

Yield susceptabilty-values describing the relative significance of water stress to yield throughout the crop growth period.

Soils data

Incrementation depths representing the soil profile and appropriate soil water characteristic curves for each layer. Curves can be selected from standard programed curves, user specified or calculated by the program.

Observed volumetric soil moisture values for each soil layer on each date entered. Used for initialization, or model calibration and varification.

Summary of output presented by the SPAW model

Daily and accumulated values of Potential and actual evapotranspiration, transpiration and soil water evaporation as well as precipitation, irrigation runoff and drainage.

Daily soil moisture values by soil layer.

Values for daily and accumulated crop water stress and yield reduction.

Plantgro model description

A simplified version of the flow chart for the Plantgro model is shown in Figure 4. This model operates by splitting evapotranspiration into its components of evaporation from the soil surface and transpiration from plants. Crop production is then predicted based on a linear relationship between transpiration and yield. Since evaporation from the soil surface does not contribute to plant growth, it is not included in the production relationship. Production estimation is based on an equation having the form;

Dry matter yield=P(AT/PT)

where;

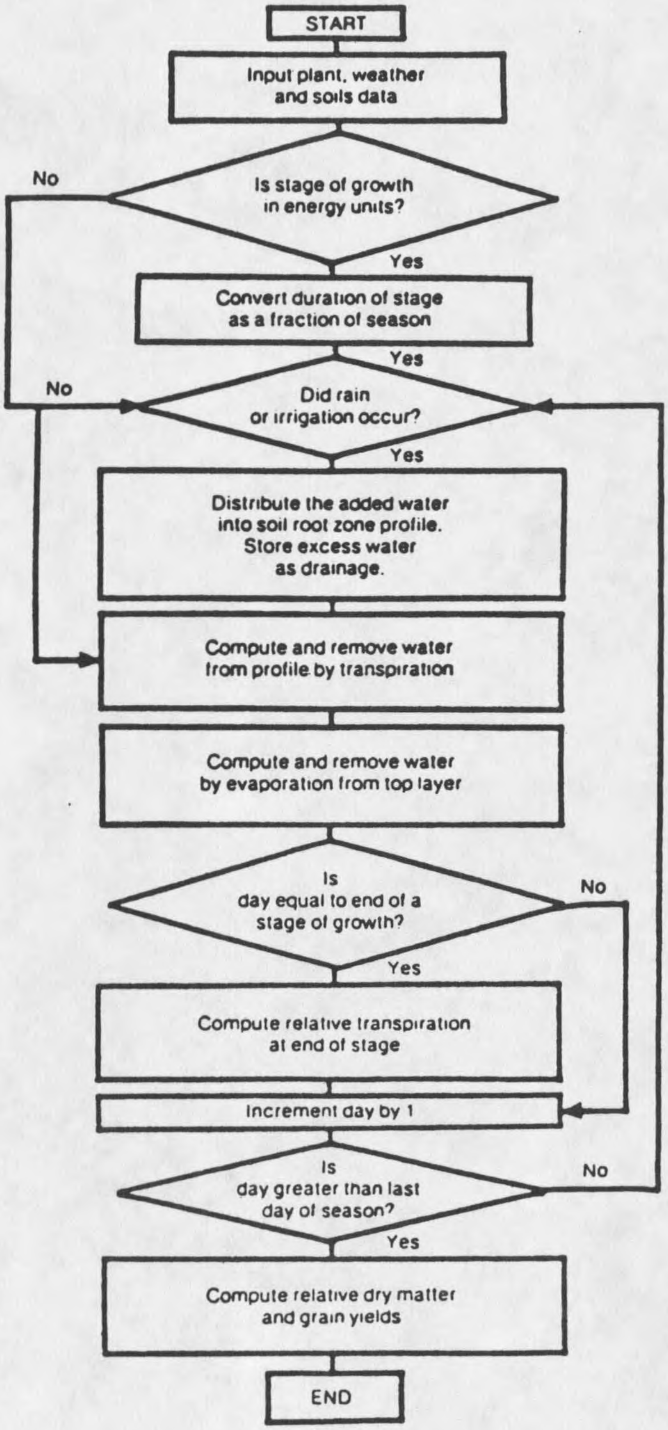

Figure 4. Plantgro model computational scheme

P is the potential dry matter yield if water is not limiting.

AT is the accumulated seasonal actual transpiration.

PT is the accumulated seasonal potential transpiration.

In addition to predicting dry matter yield, the Plantgro model also has the ability to predict grain production. Grain yield is predicted based on a relationship which accounts for the varying significance of moisture stress during different growth stages. This relationship is similar to that used to predict dry matter yield except the ratio of actual to potential transpiration is calculated for each stage of growth and raised to an appropriate power. Grain prodution is assumed to be the product of these ratios each raised to a power. Each ratio is raised to a power which represents the relative significance of moisture stress during the corresponding stage of growth.

Potential evapotranspiration is determined in the Plantgro model by multiplying observed pan evaporation by a seasonal pan coefficient. Daily values of pan evaporation or average values for several days may be supplied to the model. Potential evapotranspiration is split into its components of potential soil evaporation and potential transpiration using the following equations;

$$PT=Kt(PET)$$
$$PE=Ks(PET)=(1-Kt)(PET)$$

where;

PT is potential transpiration on a given day.
PE is potential soil evaporation on a given day.
PET is potential evapotranspiration on a given day.
Kt is the proportion of the PET that could be transpired.
Ks is the proportion of the PET that could evaporate from the soil.

The proportion factors Kt and Ks are defined by a plot of Kt values versus time. In the version of the Plantgro model used in this study, linear segments were used to join values of Kt at the begining and end of each stage of crop growth.

Actual transpiration is determined in the Plantgro model based on the amount of available water in the soil profile and the following relationships;

AT=PT if SWS/AW is greater than b
AT=PT(SWS/(AWxb)) if SWS is less than b

where;

AT is actual transpiration.
PT is potential transpiration.
SWS is the amount of available soil water in the root zone.
AW is the amount of available water in the root zone when the root zone is at field capacity.
b is the fraction of available water at field capacity below which transpiration will be limited.

Actual evaporation from the soil (AE) is estimated based on the potential soil evaporation (PE) and the length of time (t) in days since the last irrigation or precipitation event using the equation;

$AE=PE/t^{.5}$

When rain or an irrigation occurs on the day under consideration by the model, the top layer of soil is filled to field capacity first and if there is any excess, the next layer is filled. If the amount of water added exceeds the water holding capacity of the root zone at field capacity, the excess is lost as deep percolation. The depth of the root zone is estimated by the model based on a linear relationship between the depth of the root zone at maturity and the proportion of the season that has elapsed. Water is withdrawn by transpiration from the soil layers that contain roots. Evaporation only occurs from the top soil layer and this layer is allowed to lose water below the wilting point to a specified air dry moisture content. Water for transpiration is withdrawn from the soil layer with the highest moisture content. If the amount of water required for transpiration on a given day is greater than the amount of available water in the soil layer with the highest soil moisture, the difference is removed from the layer with the next highest soil moisture. With the exception of the top layer, the moisture content of the soil layers is not allowed to drop below the wilting point moisture content.

Unlike the SPAW model, the Plantgro model does not account for surface runoff or interception. A summary of the data requirements for the Plantgro model follows.

Summary of Plantgro data requirements

Weather Data

Precipitation date and amount.

Pan evaporation date and amount. The pan evaporation amount can be daily values or average values for a number of days.

Crop Data

Season length in days.

Length of each stage of crop growth in days or energy units.

Values for the proportion of the potential evapotranspiration made up of potential transpiration at the begining of each stage of growth.

Date when the maximum rooting depth is reached.

Dates and amounts of irrigation.

Soils Data

Thickness of each soil layer to be considered.

Volumetric moisture content of each soil layer when it is at field capacity (decimal percent).

Volumetric moisture content of each soil layer when it is at the permanent wilting point (decimal percent).

Estimated available moisture in each soil layer at the begining of the computation period (decimal percent).

Measured soil moisture values for initialization and model calibration and varification.

Summary of output presented by the Plantgro model

Daily and accumulated values for potential and actual evapotranspiration, transpiration and soil water evaporation as well as irrigation, precipitation and drainage.

Daily soil moistures by soil layer.

Values for the ratio of actual to potential transpiration, open soil water storage and occupied soil water storage.

Values for the grain production function at the end of each stage of growth.

CHAPTER 3

PROCEDURE

Available Data

The SPAW and Plantgro models were calibrated and tested using data collected from an irrigated alfalfa field located on the Montana State University Red Bluff Research Ranch. The Red Bluff Ranch is approximately 56 kilometers (35 miles) west of Bozeman Montana on Highway 84 as shown in Figure 5. The alfalfa field has a legal description of SW 1/4, NE 1/4 Sec. 12 T2S, R1W and covers approximately 16 hectares (36 acres). The field is located on a south facing slope at an elevation of 1490 meters (4880 ft.) and is irrigated by a center pivot sprinkler system. The field was planted with alfalfa at the begining of the 1978 growing season (Hanson, 1984) and data from the year 1979 was used to calibrate the models. Data from 1981 was used to test the ability of the models to simulate soil moisture and crop yield for periods other than the calibration period. The year 1979 was used for calibrating the models because a greater number of soil moisture measurements were made during that year than during 1981. Although data from 1980 was available, it was not used in this study because a relatively small number of soil moisture measurements were made during that year. However, these data are included in Appendix A.

The data collected during each of these years concerned soil conditions, crop status and weather conditions. For each quadrant shown in Figure 6, soil samples representing 30 centimeter (1 foot) increments in the soil profile were taken at three locations to a depth

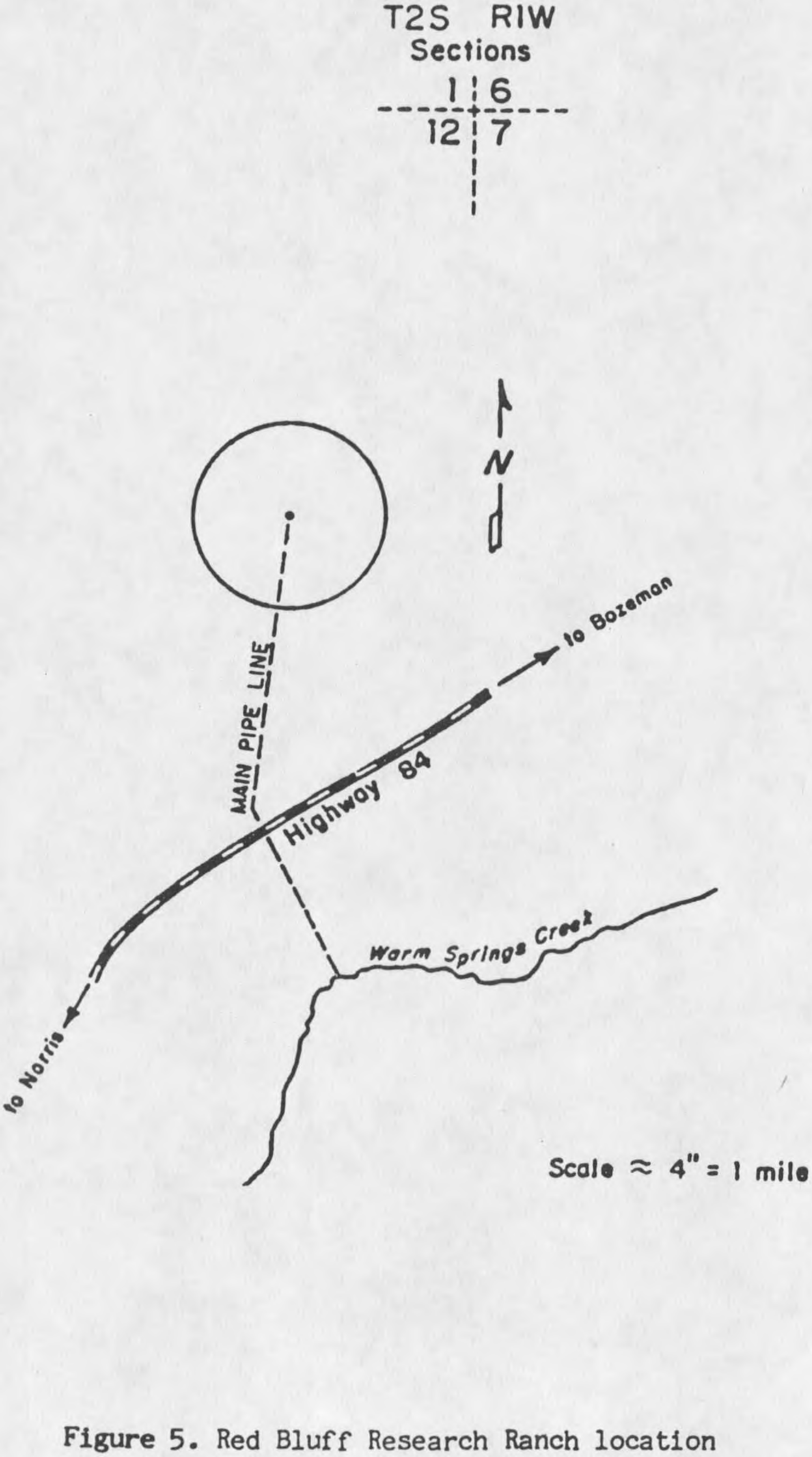

Figure 5. Red Bluff Research Ranch location

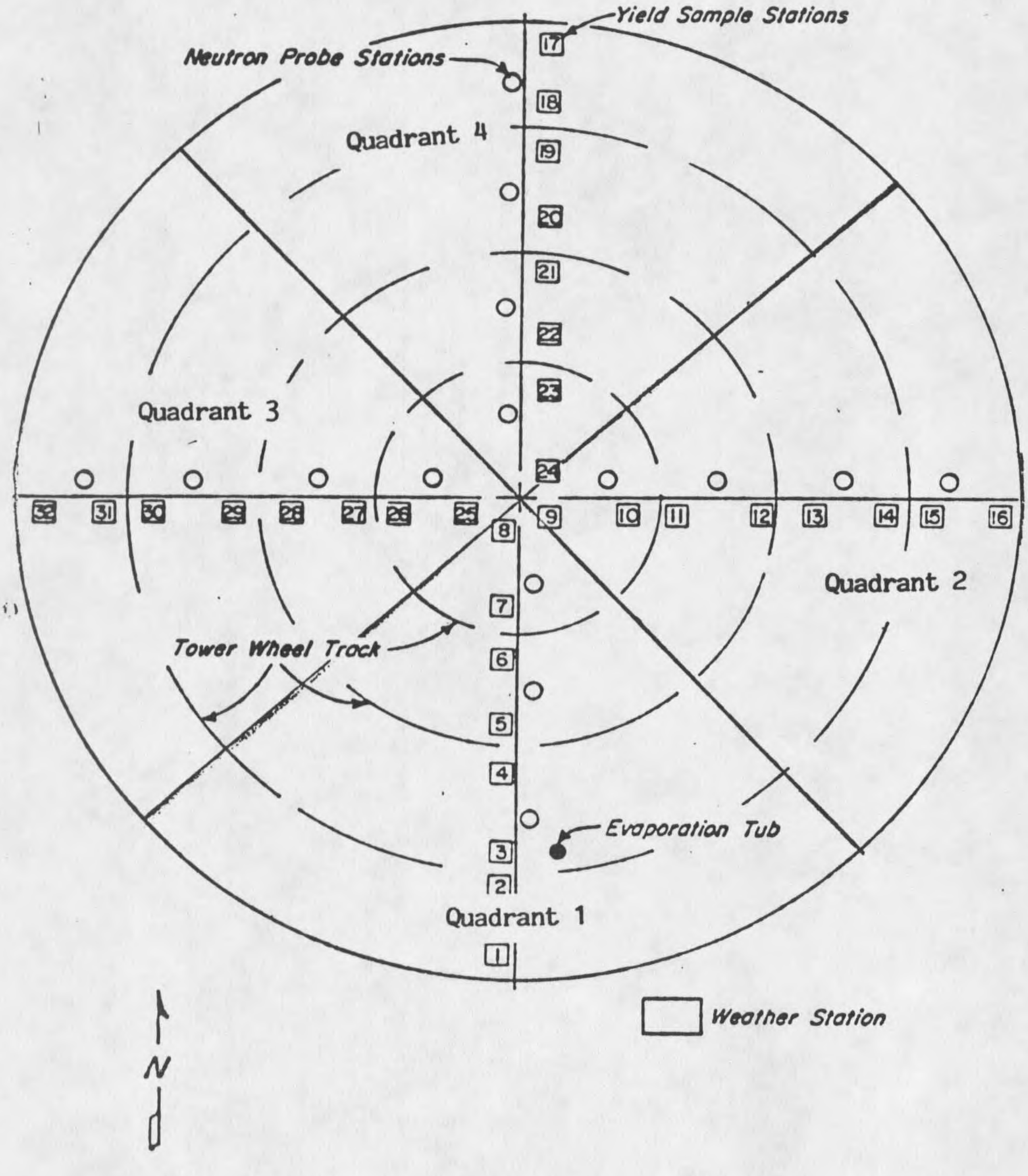

Figure 6. Study site plan

of 90 centimeters (3 feet). Textural analysis of these samples indicated a relatively uniform soil profile with a silty clay loam or silt loam texture. Soil moisture measurements were also made for each of these samples at tensions of -.3 bars (field capacity) and -15 bars (wilting point).

In addition, soil moisture measurements were made at three locations in each quadrant using a neutron probe on several dates during each of the growing seasons considered (1979 and 1981). These soil moisture measurements were made in 30 centimeter (1 foot) increments to a depth of 150 centimeters (5 feet) on each date. The average of the three measurements made at each increment of depth in each quadrant was used to represent the soil moisture distribution for a quadrant on a particular date. These average values were used to calibrate and test the models.

Data regarding the status of the alfalfa crop included the dates when harvests began, when harvests were completed as well as the yield of alfalfa produced from each harvest in each quadrant. In addition, data concerning the approximate date and amount of each irrigation were also available. Since as many as several days elapsed between the begining and end of an irrigation, it was necessary to estimate the date each quadrant recieved a given irrigation. These dates were estimated based on the recorded travel speed of the center pivot. However, the date a particular quadrant recieved an irrigation could be in error by a day or two since the starting point of the center pivot for each irrigation could not always be determined precisely from the available data.

Data concerning the weather at the site included precipitation and pan evaporation. Precipitation was measured using a recording rain gage while pan evaporation was measured using a standard Weater Bureau four foot evaporation pan. In some cases, pan evaporation values for a single day were recorded and where possible, these values were used. In other cases, accumulated pan evaporation values were recorded for a period of several days. In these cases, average daily pan evaporation values were determined by dividing the accumulated pan evaporation by the number of days over which it was accumulated. A summary of precipitation and pan evaporation data as well as the other data described in this section can be found in Appendix A.

Model calibration

For computer models to be useful in a particular situation, they must be calibrated to represent that situation. Through the calibration procedure, modeled results are made to match observed results as closely and consistantly as is justified by the precision of observed data and the intended use of the modeled results. The calibration process requires a procedure to evaluate the success of a given calibration and another procedure to adjust parameter estimates for the next calibration. The criterion for judging the adequacy of a given calibration may be subjective judgement or some statistic selected to reflect how well simulated values match observed values. The adjustment of parameters may be performed in several ways; it may be based on a subjective judgement of what parameter changes seem likely to be desirable, a set of rules derived from a sensitivity analysis of the parameters or a systematic variation of parameters (ASAE,1983).

A single statistic was selected for measuring how well the modeled soil moisture profile matched the observed soil moisture profile. The statistic used was the sum of the squared deviations of modeled soil moisture values from observed values. Smaller values for this statistic indicate a better match. The sum of the squared deviations was used in two ways: In the early stages of the calibration procedure, deviations of modeled from observed soil moisture for the entire soil profile were used. In the later stages of the calibration procedure, deviations of modeled from observed values for individual soil layers were used. Deviations for the entire soil profile were used as a measure of how well the net movement of water into and out of the soil profile was being modeled. Deviations for individual soil layers were used as a measure of how well water movement between soil layers was being modeled.

Parameter estimates for the models examined in this study were adjusted using two procedures. After initial parameter estimates for the model being calibrated were made, the model was run. From this model run, the simulated change in total soil moisture between observation dates was compared to the observed change in total soil moisture between these dates. Based on this comparison, it was possible to identify periods when the simulated evapotranspiration was either too high or too low. After identifying these periods, several parameters were adjusted to either increase or decrease evapotranspiration during the appropriate periods. When several calibration runs had been completed, appropriate parameter adjustments were no longer obvious and it was necessary to use the second calibration procedure.

In the second calibration procedure, a single parameter value was adjusted slightly and the model was run. If this adjustment reduced the sum of the squared deviations, the adjusted parameter value was recorded, the parameter was returned to its original value and a second parameter value was adjusted for the next model run. If the adjustment of the first parameter did not reduce the sum of the squared deviations, additional adjustments were performed until the sum of the squared deviations was reduced. At this point, the parameter was returned to its original value and a second parameter value was adjusted for the next model run. This process was continued until all parameter values had been adjusted and returned to their original values. When this had been accomplished, all parameter values were simultaneously set to the adjusted values which had reduced the sum of the squared deviations. This entire process was repeated until the simultaneous adjustment of parameters no longer significantly (10 percent reduction) reduced the sum of the squared deviations. Parameter values were adjusted individually and returned to their original values to prevent some parameters from being over adjusted while others would be under adjusted.

After the models had been calibrated to simulate variations in soil moisture, they were calibrated to model crop yield. Since yield measurements were available for both of two harvests during the calibration year (1979) and the test year (1981), yield calibrations were based on two simulation periods for each quadrant. Simulations of each quadrant for yield calibration were possible only because yield measurements by quadrant were available. The first simulation period used for yield calibration represented the time from the first of June until the begining of the first harvest. The second simulation period represented the time from the begining of the first harvest until the begining of the second harvest. The first of June was used as the starting date for the first simulation period because it was not possible to calibrate the models prior to this date due to a lack of soil moisture measurements during the calibration year.

Since the SPAW and Plantgro models utilize somewhat different parameters, a more detailed description of the calibration procedure for each model follows.

SPAW calibration

The operation of the SPAW model is governed by the values of several soil, crop and weather parameters. Soil conductivity and tension curves were defined using the empirical relations already briefly mentioned. These relations are dependent on the percentages of sand and clay in a soil. Table 1 contains values for these percentages in each soil layer as determined through the calibration procedure. Based on the values in this table and standard soil classification criteria (Donahue et al., 1978), all of the soil layers are classified as silty clay loams or silt loams. These classifications correspond relatively well with the soil textures determined from field measurements.

TABLE 1. Percent sand and clay determined through the SPAW calibration

soil layer	depth (cm)	percent sand	percent clay
1	0-30	26	18
2	30-60	26	19
3	60-90	24	21
4	90-120	24	22
5	120-150	24	22

Crop parameters include crop canopy, crop phenology, canopy susceptability, phenological susceptability as well as crop root distribution, crop water stress and yield susceptability . The crop canopy curve derived through the calibration procedure is shown in Figure 7 while Figure 8 shows the corresponding crop phenology curve. As shown by Figure 7, crop canopy increases linearly from the begining of the season to the begining of the first harvest. Between the begining and end of the first harvest, crop canopy decreases dramatically to reflect the effects of cutting, windrowing, baling and removal of harvested alfalfa. From the end of the first harvest, canopy again increases linearly until the begining of the second cutting where canopy again declines rapidly due to harvesting.

As shown by Figure 8, crop phenology remains relatively constant before the first harvest and between the end of the first harvest and the begining of the second. However, rapid changes in the proportion of the canopy transpiring occur during harvest periods. Although cut alfalfa making up windrows and bales would contribute to crop canopy,

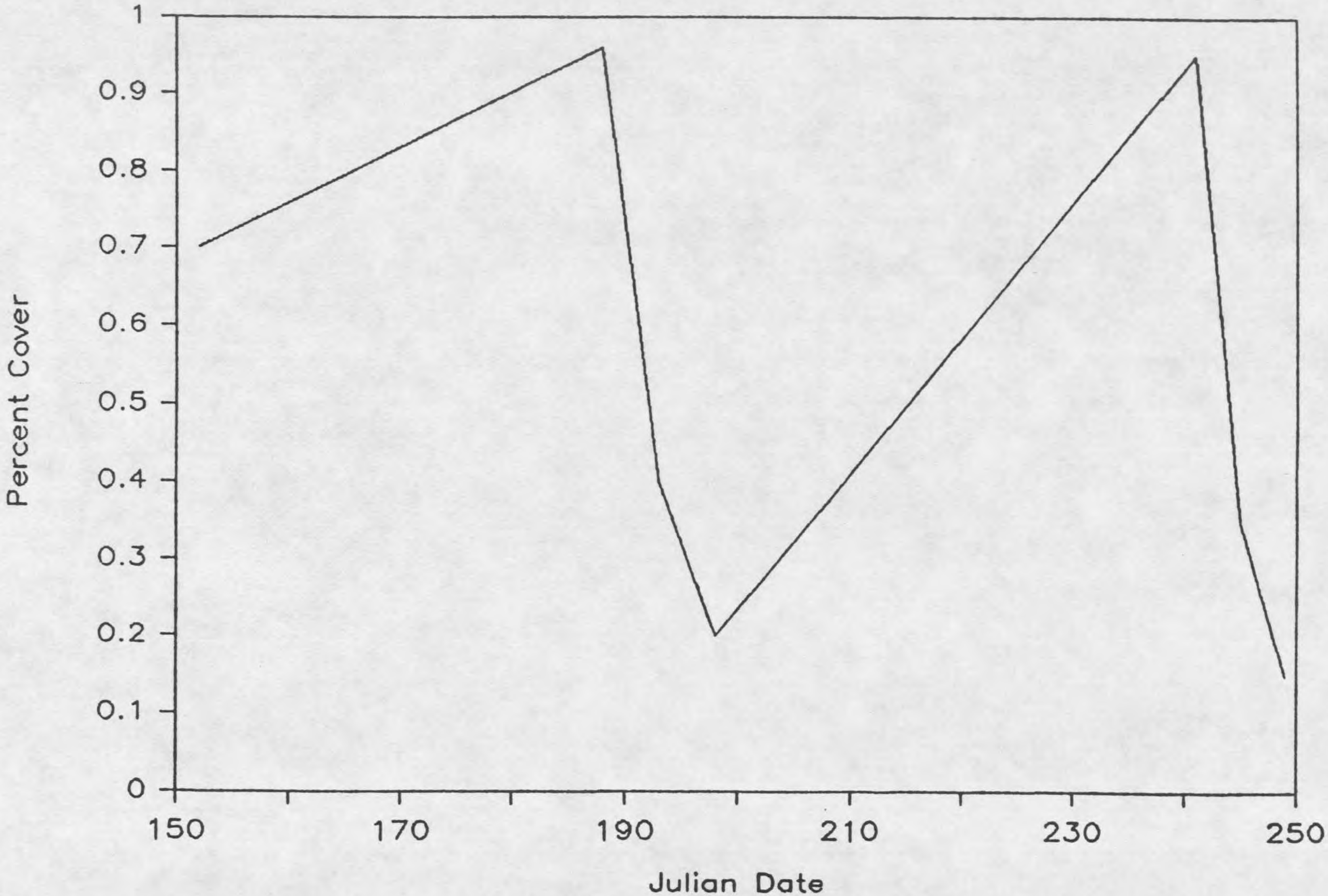

Figure 7. SPAW model crop canopy curve

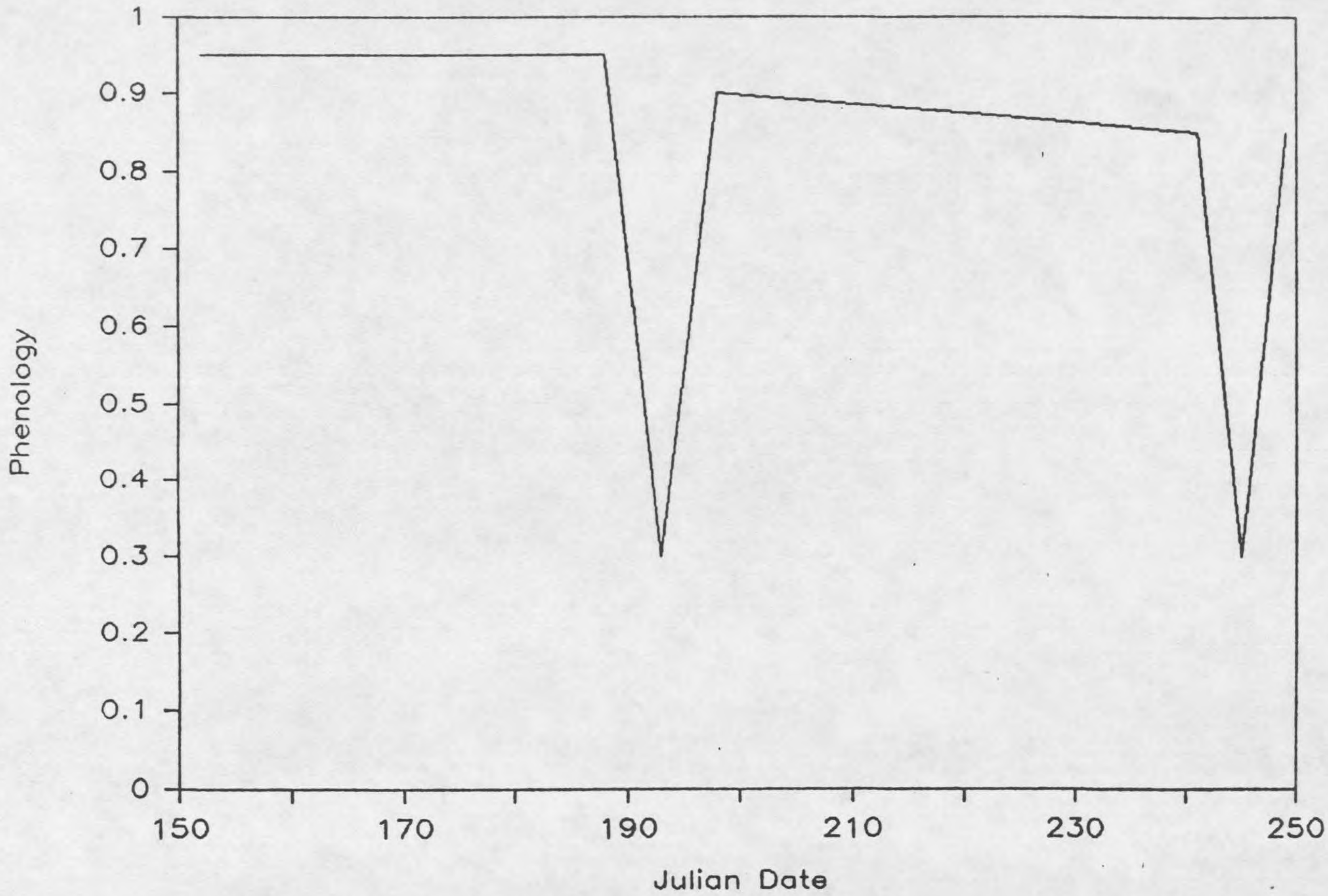

Figure 8. SPAW model crop phenology curve

it would not be able to transpire and remove water from the soil profile. This inability to transpire was reflected by a decline in phenology until the mid-point of each harvest. From the mid-point of each harvest, the proportion of the crop canopy transpiring would increase since only actively growing alfalfa would have been left on the field as harvested material was removed.

Table 2 includes values used in the canopy susceptability and phenology susceptability relationships. The ratios of actual to potential evapotranspiration (AET/PET) were selected based on a previous application of the SPAW model to the simulation of corn in eastern Washington (Saxton et al., 1984). Initial estimates of canopy growth and reduction in phenology were made based on this previous application, however, these values were slightly altered during the calibration procedure.

Table 2. Canopy and Phenology susceptability relationships

AET/PET (cm/cm)	Canopy Growth (dec. %)	Phenology Reduction (dec. %)
0.00	1.00	0.000
0.20	1.00	0.000
0.50	1.00	0.000
0.70	0.90	0.000
0.80	0.60	0.002
1.00	0.00	0.010

A constant root distribution through the growing season was assumed for this model application since the alfalfa field in question was planted a full year before the calibration year. Based on reported values (Boltan, 1962), it was assumed that the majority of the roots would be found in the first 30 centimeters (1 foot) of depth. It was further assumed that roots below 120 centimeters (4 feet) would be insignificant. Some variation in the proportion of roots in each soil layer over the course of the growing season was examined for the calibration year. However, these variations did not significantly improve the calibration. The following root distribution was based on the stated assumptions and the calibration procedure: 0 to 30 cm (1 ft.), 75 percent of the root system; 30 to 60 cm (2 ft.), 15 percent; 60 to 90 cm (3 ft.) 5 percent and 90 to 120 cm (4 ft.), 5 percent.

Although the crop water stress relationship slightly affects the simulation of soil moisture variations through its influence on canopy growth and crop phenology, its primary purpose is to provide an index which can be related to yield. For this reason, the pre-programed moisture stress curves were not adjusted until the SPAW model had been calibrated to simulate variations in soil moisture over the entire growing season. When this had been accomplished, two portions of the growing season designed to represent the portions of the season which would affect yield from either the first or second harvest were simulated seperately. Based on two simulations for each quadrant, the moisture stress curves were adjusted until low simulated stress values could be correlated with high measured yields and high simulated stress values could be correlated with low measured yields. Since moisture stress only slightly affects the simulation of soil moisture variation, the SPAW model was not recalibrated to model soil moisture changes after it was calibrated to model moisture stress.

The SPAW model calculates the amount of yield reduction based on a function of moisture stress and yield susceptability. Time did not allow for the calibration of the yield susceptability relationship. However, this parameter could be calibrated by extrapolating the yield versus moisture stress relationship to estimate the yield that could be expected if there were no moisture stress. Based on this value of potential yield and measured yield values, the yield susceptability parameter could be calibrated. The objective of this calibration would be to simulate reductions in yield corresponding to the difference between the potential yield and the measured yield.

Since recorded values for pan evaporation and precipitation were available, only pan coefficients were calibrated to define weather conditions. Since recorded soil moisture values were available only for the months of June through September, pan coefficients were calibrated only for these months. Calibration of the parameters designed to supply values for missing evaporation data was not attempted in this study.

Plantgro calibration

Plantgro calibration parameters representing soil conditions include the moisture content at field capacity, at the wilting point and the air dry moisture content of the upper soil layer. Initial estimates of the moisture content at field capacity and the wilting point were made based on measured values (Appendix A). These measured values were adjusted through the calibration procedure to obtain the values shown in Table 3. An air dry moisture content of three percent by volume was derived through the calibration procedure based on an assumed initial value of five percent.

Table 3. Field capacity and wilting point as determined from Plantgro calibration

Soil layer	Field capacity (% vol.)	wilting point (% vol.)
1	16.0	7.6
2	15.5	7.6
3	15.4	7.1
4	15.3	7.0
5	15.7	7.4

The parameters which describe crop conditions include the proportion of the potential evapotranspiration made up by potential transpiration at the beginning and end of each stage of growth, the soil moisture content below which transpiration will be limited by moisture stress as well as the depth and timing of rooting. The length of each stage of growth was selected to reflect the following periods: Stage 1 from the beginning of the simulation period to the beginning of the first harvest; Stage 2 from the beginning of the first harvest to the end of the first harvest; Stage 3 from the end of the first harvest to the beginning of the second harvest; Stage 4 from the beginning of the second harvest to the end of the second harvest and Stage 5 from the end of the second harvest to the end of the simulation period.

The values corresponding to the proportion of potential evapotranspiration made up by potential transpiration at the beginning and end of each of these stages can be found in Table 4. It was assumed that transpiration would be limited when the soil moisture dropped below fifty percent of the available moisture content This initial estimate was slightly refined through the calibration procedure.

Table 4. Values for the ratio of potential transpiration (PT) to potential evapotranspiration (PET).

Stage of Growth	(PT)/(PET) begining	end
1	0.56	0.86
2	0.86	0.17
3	0.17	0.83
4	0.83	0.14
5	0.14	0.23

The Plantgro model assumes a uniform root distribution that increases linearly in depth from the beginning of the season until it reaches a maximum depth on a particular date. Since the alfalfa field in question was planted a full year prior to the first year simulated (Hanson, 1984), it was assumed that the root distribution would have reached its maximum before the beginning of the simulation periods. To represent this assumption, it was specified in the Plantgro input files that the maximum rooting depth was reached on the first day of the growing season. A maximum rooting depth of 150 cm (5 ft.) was specified by default because the model assumes that only the portion of the soil profile containing roots is being simulated.

After the Plantgro model had been calibrated to simulate variations in soil moisture, it was calibrated to simulate yield. As with the SPAW model, the growing season was simulated in two portions to represent the fractions of the season which would affect yield from either the first or second harvest. The Plantgro model simulates yield based on a linear relationship between the potential yield and the ratio of actual transpiration to potential transpiration. To calibrate for yield, the value of the potential yield was adjusted to minimize the sum of the squared deviations of simulated yields from observed yields for all four quadrants. Since simulated soil moistures are independent of the value of the potential yield, the simulation of variations in soil moisture was unaffected by the calibration for yield.

A single pan coefficient for the entire simulation period was determined in the calibration procedure. This was the only weather parameter which was adjusted.

Model testing

The ability of each model to simulate changes in soil moisture was tested in two phases. After each model was calibrated for each of the four field quadrants using data from 1979, each quadrant calibration was tested using data from the other three quadrants. The purpose of this phase of testing was to determine if separate quadrant calibrations modeled the entire field better than a single calibration. This determination was based on the sum of the squared deviations simulated using each calibration on its corresponding quadrant and each calibration on all quadrants. The results of the first phase of testing indicated that separate calibrations for each quadrant did not necessarily produce better results than a single calibration for all quadrants. The calibration which produced the best results (minimum sum of the squared deviations) for the entire field was used in the second phase of testing. In this phase, data from 1981 was simulated for each quadrant using both models. From these simulations, the average percent deviation for all four quadrants of simulated from observed soil moistures were calculated for each layer in the soil profile. Based on these errors and plots of observed and simulated soil moisture verses time, it was possible to evaluate each model in terms of the accuracy of predicted soil moistures.

The SPAW and Plantgro models were also evaluated based on their capacity to simulate crop yield for periods other than the calibration period. The 1981 growing season was simulated in two portions which were designed to represent the fractions of the season that would affect yields from either the first or second harvest. When each portion of the 1981 growing season had been simulated for all four quadrants, the yield values predicted by each model were compared to corresponding observed yield values. The models were then evaluated based on the accuracy of the predicted yield values. In addition to the accuracy of predicted soil moistures and yields, the SPAW and Plantgro models were also evaluated based on their data, computational and calibration requirements.

CHAPTER 4

RESULTS

Figures 9 and 10 show plots of soil moisture verses time for each of the five soil layers simulated in this study. Figure 9 shows plots derived using the SPAW model and measured soil moisture values. The graphs on the left side of Figure 9 were derived using data from the calibration year 1979. The graphs on the right side of Figure 9 show plots derived using the 1979 calibration of the SPAW model and observed precipitation, irrigation and evaporation data from the test year 1981. Observed soil moisture values are shown as isolated points in these plots and in the plots shown in Figure 10. Figure 10 is similar to Figure 9 except the plots shown were obtained by applying the Plantgro model. Although the plots shown in Figures 9 and 10 represent the results from one quadrant only, similar plots were obtained for the other three quadrants.

Tables 5 and 6 include values for the average percent error in soil moisture values simulated by the SPAW and Plantgro models. The values in these tables were calculated by averaging the relative errors of simulated soil moisture values when compared to measured soil moisture values for all four quadrants. Average error figures for the calibration year were used to to reflect how precisely each model can be calibrated. Figures representing the test year are designed to show how accurately each program can simulate soil moisture during periods independent of the calibration period.

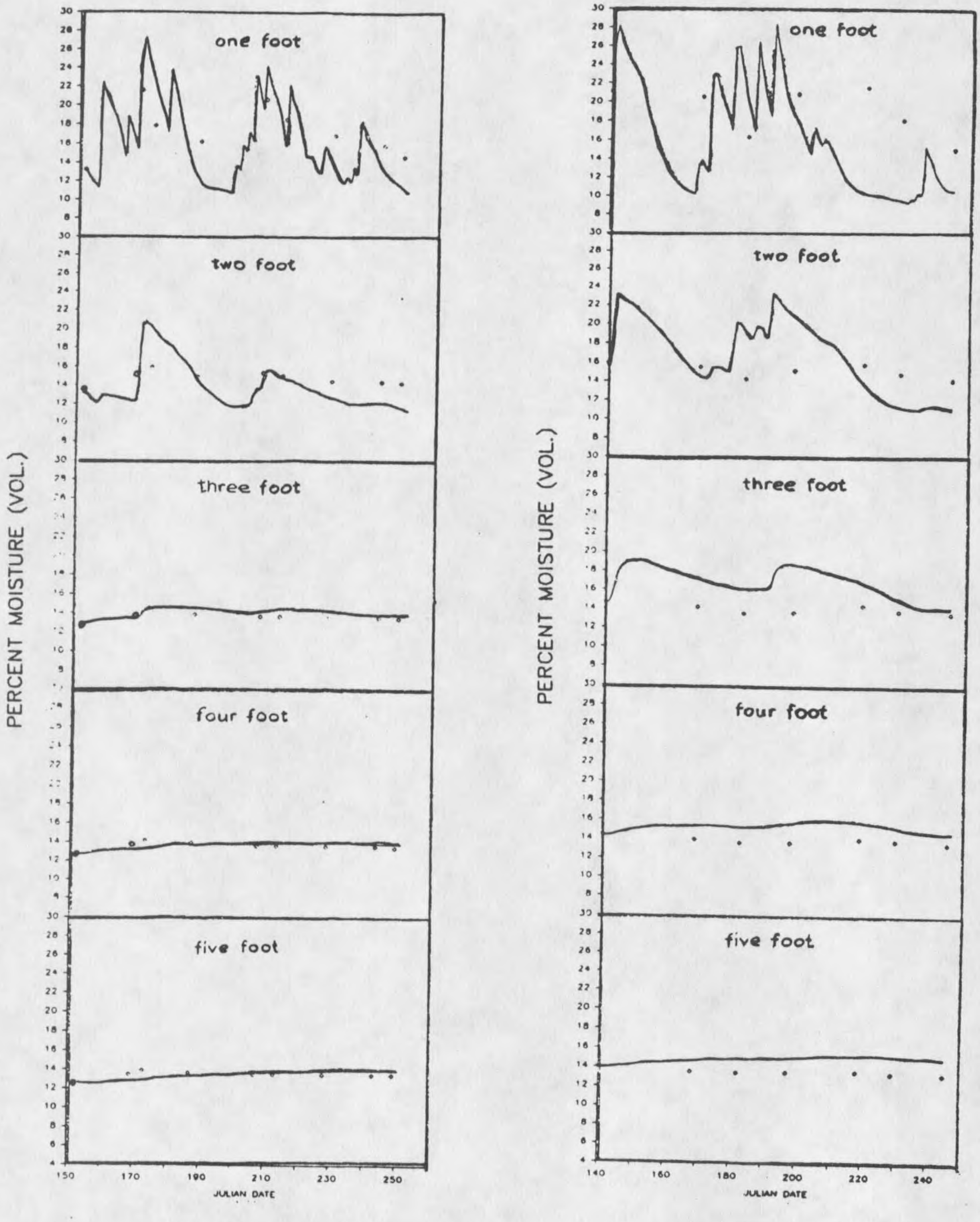

Figure 9. SPAW model simulated soil moisture versus time for the calibration year (left) and the test year (right).

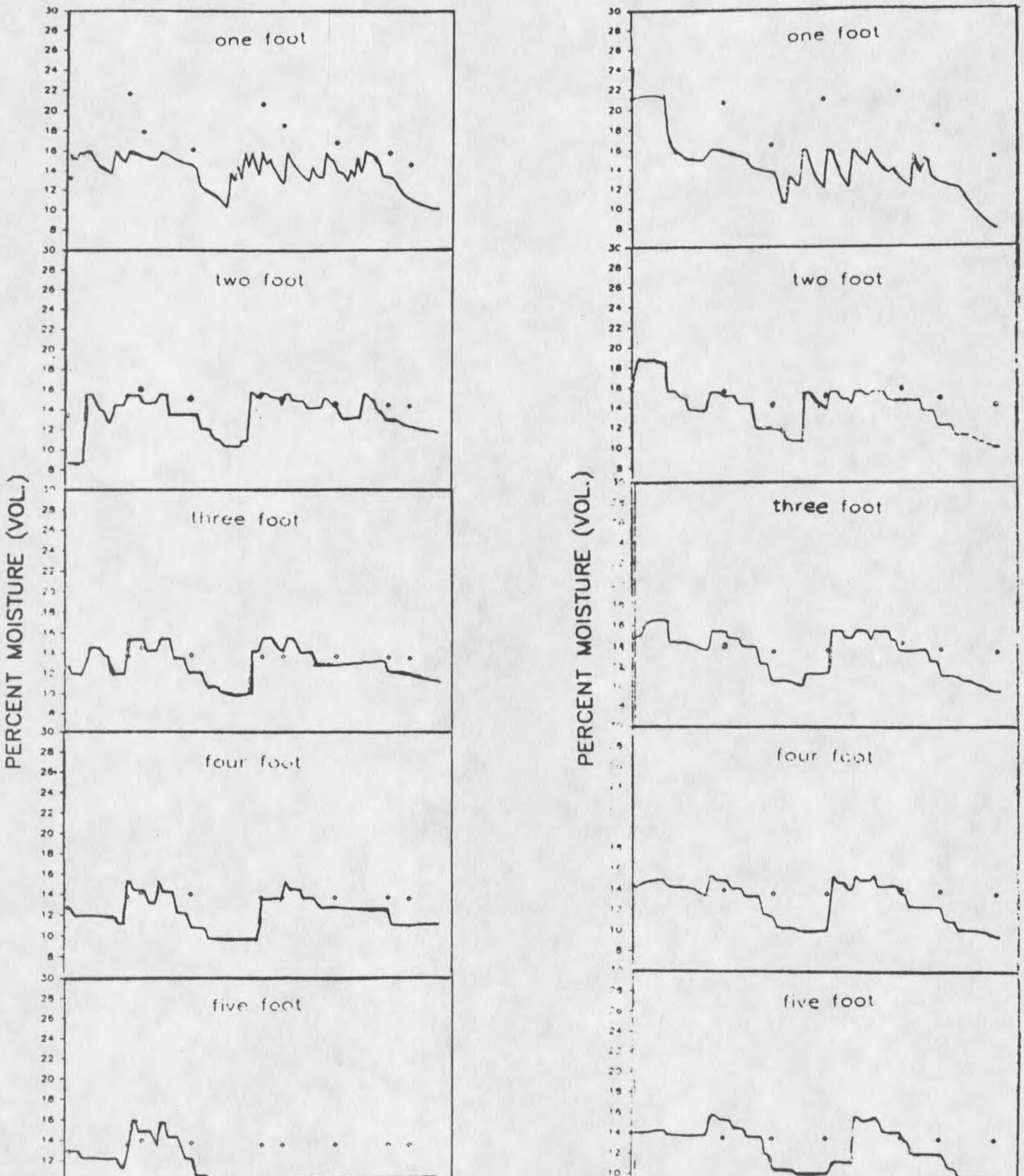

Figure 10. Plantgro simulated soil moisture versus time for the calibration year (left) and the test year (right).

Table 5. SPAW model average percent error in predicted soil moistures

Soil Layer	Calibration Year (1979)	Test Year (1981)
1	11.1	18.0
2	7.9	15.2
3	4.1	8.2
4	3.3	4.7
5	3.2	4.4
profile average	5.9	10.1

Table 6. Plantgro model average percent error in predicted soil moistures

Soil Layer	Calibration Year (1979)	Test Year (1981)
1	10.8	21.5
2	4.7	12.0
3	8.1	14.8
4	10.3	15.5
5	16.8	15.3
profile average	10.1	15.8

Based on the values for 1979 in Tables 5 and 6, it is apparent that the SPAW model can be calibrated to simulate the entire soil profile more precisely than the Plantgro model. The figures for 1981 show that, in this application, the SPAW model represents independent data more accurately for the entire soil profile than the Plantgro model. However, 1979 values show that the Plantgro model produced a calibration for simulating moisture changes in the upper two soil layers that was somewhat more precise than the SPAW model calibration. In addition, the difference in the accuracy of soil moistures predicted by each model during the test year for the upper two soil layers was relatively small. Since moisture in the upper soil layers is more important in terms of a plant's water supply than moisture in lower layers, the similarity of the results produced by each model for the upper soil layers should be considered in an evaluation of the models.

Figure 11 shows graphically the results of the SPAW calibration for yield simulation while Figure 12 shows similar results for the Plantgro model. As can be seen from these figures, both models simulate crop yield for the calibration year relatively well. A linear regression of crop water stress and yield data from SPAW simulations produced the line shown in Figure 12 with an r squared value of 0.92. A linear regression of observed yield data and yield data simulated by the Plantgro model produced an r squared value of 0.97. Observed yield values and crop water stress values simulated by the SPAW model for the calibration year can be found in Table 7 along with yield values simulated by the Plantgro model for the calibration year.

Figures 11 and 12 as well as the values in Table 8 indicate that neither model simulates crop yield very accurately for the test year of 1981. Table 8 contains values for observed yield, the yield simulated by each model as well as the relative error in yield values simulated by each model. The values in this table indicate that the Plantgro model simulated yield for the test year better than the SPAW model. However, the errors associated with both models are large enough to make yield simulations by either model for the test year of doubtful value.

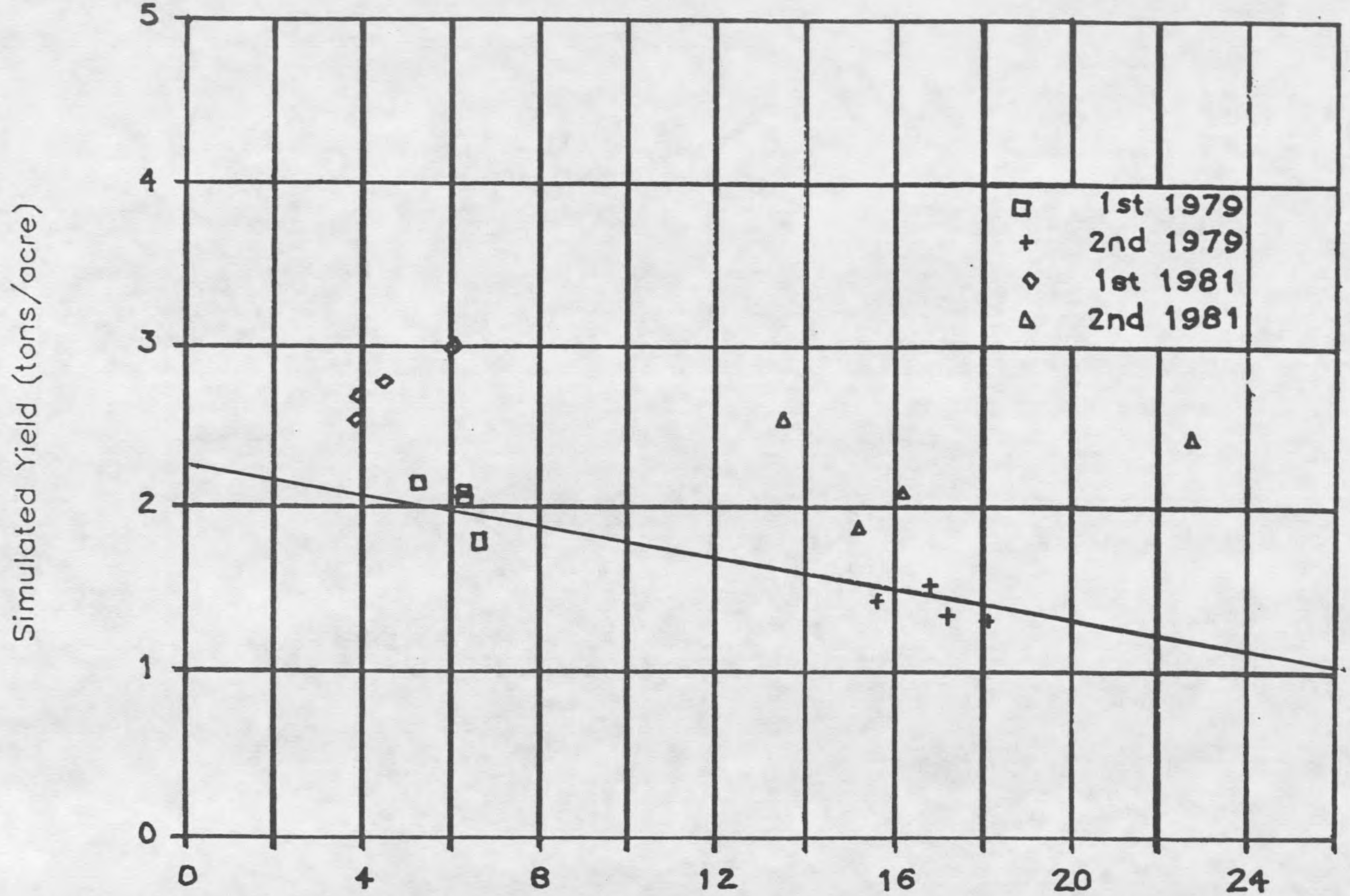

Figure 11. SPAW model stress versus yield

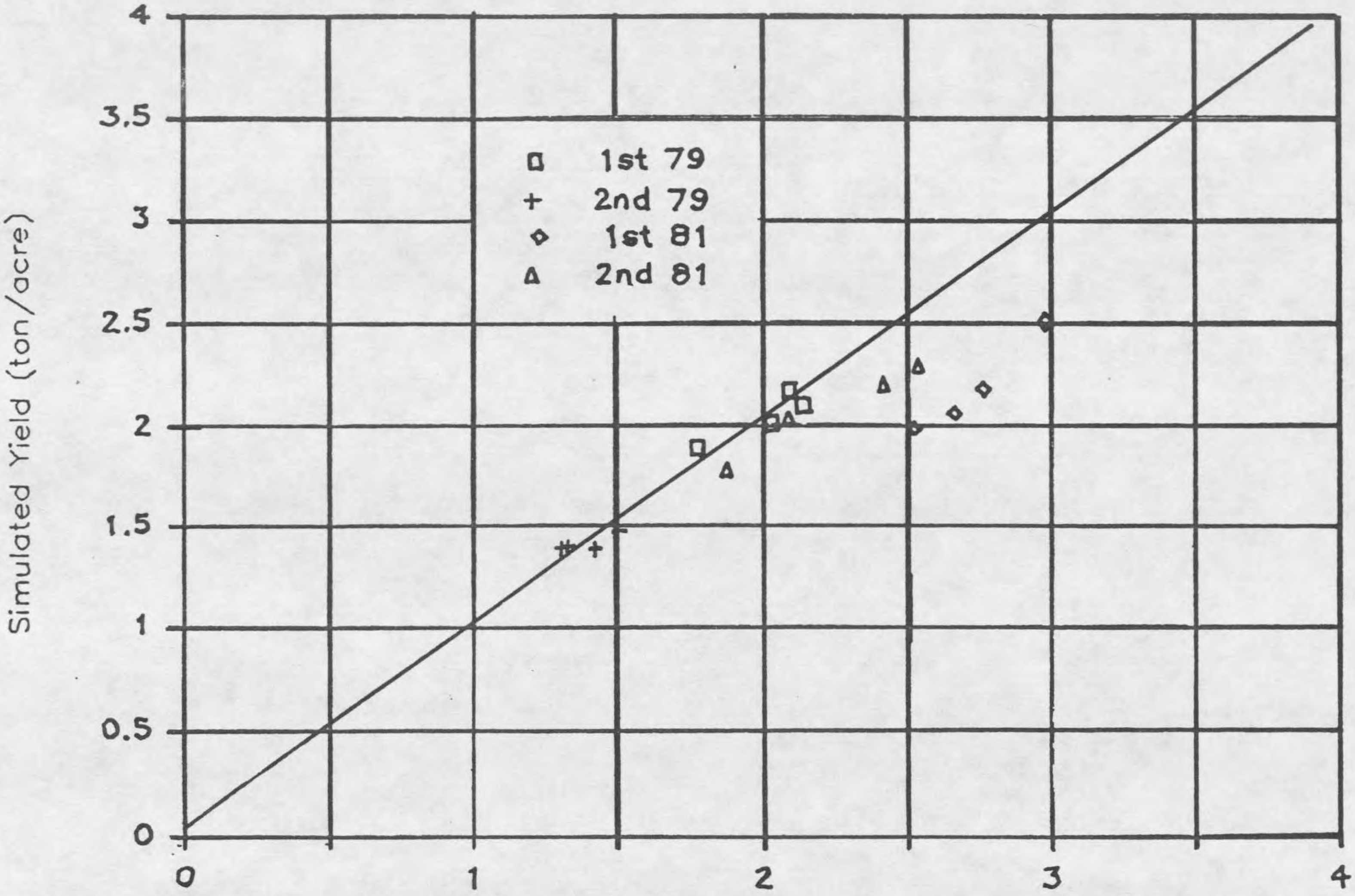

Figure 12. Plantgro model observed yield versus simulated yield

Table 7. Observed yield, SPAW simulated crop water stress and Plantgro simulated yield for the calibration year 1979.

Simulation	Observed Yield (ton/acre)	SPAW Simulated Water Stress (index)	Plantgro Simulated Crop Yield (ton/acre)
1	1.78	6.61	1.88
2	2.14	5.21	2.09
3	2.03	6.26	2.00
4	2.09	6.25	2.16
...	....	.....	....
5	1.51	16.79	1.47
6	1.31	18.07	1.38
7	1.33	17.17	1.39
8	1.43	15.59	1.38

SPAW YIELD=-0.06(STRESS)+2.36 r^2=0.92

Plantgro Yield=1.00(obs. yield)-0.01 r^2=0.97

Table 8. Observed yield and yield simulated by the SPAW and Plantgro models for the test year 1981.

Simulation	observed yield (tons/acre)	simulated yield (tons/acre)		relative error (%)	
		SPAW	Plantgro	SPAW	Plantgro
1	2.67	2.14	2.05	20	23
2	2.53	2.14	1.97	15	22
3	2.77	2.10	2.17	24	22
4	2.98	2.02	2.50	32	16
...	....	....	....	..	..
5	2.42	1.06	2.19	56	10
6	2.54	1.59	2.29	37	10
7	1.88	2.25	1.77	20	6
8	2.09	1.43	2.03	32	3
		average relative error		30	14

Simulation values one through four in Tables 7 and 8 are yield data for the first harvest of 1979 or 1981 while values five through eight are for the second harvest. Since the SPAW model provides stress values rather than yield values, the SPAW simulated yield values in Table 8 were determined from Figure 11.

CHAPTER 5

DISCUSSION

The purpose of this chapter is to evaluate the SPAW and Plantgro models in terms of their data and computational requirements, the results of their application at the Red Bluff Ranch and sources of error in this study. The ease of calibration and application, potential program improvements as well as potential future application to the Red Bluff area will also be examined.

Data and Computational Requirements

Although the SPAW model is much more elaborate than the Plantgro model, the requirements of both models for measured data are very similar. Each model requires daily values of precipitation and irrigation as well as measured evaporation. In addition, measured values of soil moisture are necessary for calibration purposes. Additional measured data such as those defining soil characteristics are helpful in obtaining initial parameter estimates, however, all other input data can be defined through the calibration procedure and subjective judgement. Subjective judgement is necessary to determine if parameter values arrived at through the calibration procedure realistically represent the physical situation.

Since the SPAW model is more elaborate than the Plantgro model, its computational requirements are correspondingly greater. The SPAW model requires a computer with approximately 132 kilobytes of random access memory (RAM) in addition to the memory required by the operating system of the computer. The operating systems of most microcomputers do not require more than about 40 kilobytes of random access memory while many operating systems require less than this amount (Adams, 1986). In contrast, the Plantgro model requires only about 10 kilobytes of RAM in addition to memory required by the operating system of the microcomputer.

Analysis of results from the Red Bluff simulation

The results of this study indicated that the SPAW model simulated soil moisture in the entire soil profile somewhat more precisely and accurately than the Plantgro model. However, the SPAW model produced much better results for the lower three soil layers while both models produced comparable results for the upper two soil layers. Although the simulated soil moistures for the upper two soil layers were comparable for both models, these results could be misleading. These results might be misleading because, based on other applications of the SPAW model (Saxton and Bluhm, 1982; Sudar et. al., 1981) it appears that additional calibration of the SPAW model could probably be performed to improve the precision and accuracy of the simulation of the upper two soil layers.

Additional calibration of the Plantgro model would probably not significantly improve the precision or accuracy of the simulation of any of the soil layers. The limited improvement is predicted because there are a smaller number of calibration parameters and the values of these parameters were thoroughly examined during the calibration process. However, the SPAW model includes a much larger number of calibration parameters and time did not allow for a complete examination of all realistically possible combinations of calibration parameter values.

The results of this study in terms of simulating variations in soil moisture might be misleading in another way due to the model testing procedure used. In the first phase of the testing procedure, seperate calibrations for each quadrant were tested. These calibrations were tested against data for all of the quadrants for both the calibration and the test year. Based on this initial testing, the calibration which produced the best simulations of all data was selected for further study. This portion of the testing procedure produced biased results because, in another situation, it might not be possible to obtain more than one independent calibration.

Better calibrations for both models could probably have been obtained in this study if the available data had been used more effectively. Data from 1980 was available, however, it was not utilized and calibrations were made based on only one year of data. The first phase of testing showed that seperate calibrations for each quadrant were unnecessary. Calibrations based on data from all four quadrants for two years would probably have been better than those that were tested. Model calibrations arrived at on this basis would have been superior to those obtained since flaws in the calibrations caused by peculiarities in data for a particular year and errors in particular field measurements would have been reduced. In addition, data from the third year of available data could still have been used for testing purposes.

In terms of yield prediction, the results of this study show that both models can be calibrated to simulate yield relatively precisely during the calibration year. However, the results also indicated that the models did not simulate yield data from non-calibration years very accurately. Yield data for a non-calibration year were probably not very accurate because the yield calibrations were based on a very limited amount of data and all of these data were from a single year. Reducing the effects of calibration flaws by using data from a number of years to produce average calibrations would probably increase the accuracy of non-calibration year yield simulations.

Sources of error in the Red Bluff study

In addition to imperfect calibrations, there were other probable sources of error in the results of this study. In some cases specific sources of error could be associated with either one model or the other. In other cases, sources of error were identical for both models and these errors did not affect the model comparison based on the precision and accuracy of modeled soil moisture results. However, errors found in only one of the models could have affected the comparison of the models based on the precision and accuracy of modeled results.

In the application of the SPAW model, error was introduced by the calibration of the crop water stress relationship. However, this error is not reflected by the soil moisture versus time plots and the average error values presented in the results section of this document. Because the SPAW model was not recalibrated to simulate variations in soil moisture after it was calibrated to simulate crop water stress, the parameter values presented here could probably be improved. The effect of the calibration for crop water stress simulation is not reflected in the soil moisture vesus time plots or the average error figures because this information was generated prior to calibrating the stress function. Although calibrating the moisture stress relationship probably reduced the accuracy and precision of the calibration presented here, it seems reasonable to assume that recalibration for soil moisture would return the precision and accuracy of the simulated soil moisture results to levels comparable to those presented.

The major source of error found in soil moisture values simulated by the Plantgro model was caused by the way in which the root distribution was specified. There was no provision in the Plantgro model for specifying a maximum rooting depth other than the full depth of the soil profile being simulated. The fact that a uniform root distribution extending throughout the soil profile was assumed probably accounts for the wide fluctuations in soil moisture values simulated for the lower soil layers. Observed fluctuations in the lower soil layers were very moderate and the assumed root distribution probably accounts for the majority of the error in results for these soil layers.

A second, though minor, source of error found in the Plantgro model but not present in the SPAW model was caused by the failure of the Plantgro model to account for interception. As it was, the Plantgro model accounted for interception indirectly by using exagerated parameter values. However, accounting for interception directly would have two advantages. Parameter values would be more realistic because it would not be necessary to exagerate them to account for interception and accounting for interception would add another calibration parameter which could be adjusted. An additional calibration parameter would probably increase the precision with which the Plantgro model could be calibrated. Although the addition of a calibration parameter would increase the time required to calibrate the model, this time increase would probably be insignificant.

The most significant source of error common to both models for the test year was introduced by the testing procedure. Error was introduced by the testing procedure because May 20 was used as the starting date for the simulations of the test year. This date was selected because the first set of soil moisture measurements were made on May 20 during the test year. Error was introduced into the test year simulations because the models were not calibrated for periods prior to June first. The models were not calibrated for periods prior to June first because soil moisture measurements were not made before the first of June during the calibration period. The effect of this source of error on the comparison of the models was probably not very significant since the period from May 20 to June first represents only a small fraction of the total simulation period for the test year (May 20-Sept. 2).

Measured data in the form of soil moisture values, the timing and amount of irrigations and pan evaporation values were also sources of potential error common to both models. There were three sources of potential error associated with the soil moisture values, however, two of these sources of error would be found in any model study of this type. Soil moisture measurements were made using a neutron probe. Unfortunately, soil moistures measured using this particular probe did not always agree well with corresponding soil moisture values measured gravimetrically. Since soil moisture measurements made using the neutron probe were checked gravimetrically only occasionally, there was some doubt as to their accuracy.

Errors associated with repressenting an area using point measurements would be present in any study of this type. Average soil moisture values were determined based on three measurements for each quadrant, however, these point measurements may or may not have accurately reflected moisture conditions in an entire quadrant. In addition, soil moistures measured using a neutron probe were converted from a weight basis to a volumetric basis using point measurements of soil bulk density. Here again there was some question as to the accuracy of extrapolating point measurements to represent the bulk density in an entire quadrant.

Data concerning irrigations could have introduced error into the simulations in three ways. Due to a lack of data, it was not always possible to determine the precise date a particular quadrant received a given irrigation. Some error could be attributed to this source, however, the timing of all irrigations was known accurately within a day or two. A second source of possible error in irrigation data was the assumption that irrigation water was applied uniformly over a particular quadrant. Since all irrigation systems are imperfect, this source of error would be present in any modeling situation where water is applied by an irrigation system. Although the SPAW model did account for interception, a third source of error was introduced by failing to account for irrigation losses due to factors such as wind drift and spray evaporation.

Errors introduced by pan evaporation measurements were caused by uncertainty in the time distribution of evaporation. In some cases, evaporation measurements were recorded for periods of up to several days. An arithmetic average of these measurements was used to arrive at daily evaporation values for periods when daily values were not recorded. If daily measurements of evaporation had been used, some error would probably have been eliminated. However, errors introduced by averaging evaporation measurements were probably not as significant as those introduced by uncertainties in soil moisture measurements and the timing of irrigations.

Ease of Model Calibration and Application

The SPAW and Plantgro models simulate the same physical processes but each model has advantages over the other in terms of their calibration. Based on the simulations performed here, the SPAW model produced results that were somewhat more accurate than those produced by the Plantgro model. However, considerably more time and effort was required to calibrate the SPAW model (six minute run time) than was required to calibrate the Plantgro model (45 second run time). Adding to the time and effort required to calibrate the SPAW model was the fact that the SPAW model includes a much larger number of parameters which required calibration.

The large number of calibration parameters incorporated into the

SPAW model was both an advantage and a disadvantage. A more precise calibration of the SPAW model was possible because there were a large number of calibration parameters which could be fine tuned. This 'fine tuning' was accomplished by altering parameters which the SPAW model is less sensitive to after a good rough calibration was obtained by adjusting sensitive parameters. The large number of calibration parameters found in the SPAW model was a disadvantage in that the overall effects of some parameter changes were not always obvious. It took a great deal of time to determine which parameter changes were appropriate because additional model runs were required to test inappropriate parameter alterations.

In contrast, the Plantgro model has a relatively small number of parameters which was also both an advantage and a disadvantage. A limited number of calibration parameters was an advantage in that a calibration that had little potential for improvement was arrived at in a relatively short period of time. In addition, even if appropriate parameter changes were not obvious, potential changes in all parameters could be examined without spending an excessive amount of time waiting for computed results. Although results from the Plantgro model were sensitive to changes in different parameters to varying degrees, the limited number of calibration parameters was a disadvantage in that they did not allow for a great deal of 'fine tuning' in a calibration.

From experience gained through working with the SPAW and Plantgro models, it was possible to draw some general conclussions regarding their sensitivity to various parameter values. The soil moisture results simulated by the SPAW model were extremely sensitive to pan coefficient values used to reduce measured evaporation to potential evapotranspiration. This model was relatively sensitive to changes in crop canopy, crop phenology and maximum interception values in terms of modeling water movement into and out of the entire soil profile. In terms of modeling the movement of water within the soil profile, the SPAW model was most sensitive to parameters that describe the soil characteristics (percent sand and clay in this study) and the distribution of plant roots within the soil profile. The SPAW model was least sensitive to variations in parameters describing canopy susceptability, phenology susceptability and the crop water stress curves.

The Plantgro model was most sensitive to variations in the value of the pan coefficient. The next most significant parameter in terms of the sensitivity of modeled results was the parameter which describes the ratio of potential transpiration to potential evapotranspiration during each stage of crop growth. The Plantgro model was not affected as much by changes in the parameters which describe the moisture content of each soil layer at field capacity and at the wilting point. However, the results from the Plantgro model were still relatively sensitive to changes in the parameters describing the ability of a soil to hold moisture at field capacity and the wilting point. The Plantgro model was least affected by changes in the parameters which describe the air dry moisture content of the upper most soil layer and the effects of moisture stress on transpiration.

The SPAW and Plantgro models differ in their ease of application in a number of respects. Because the SPAW model is much more elaborate than the Plantgro model, it took a great deal more time to become familiar with its logic and structure. It was more difficult to make program changes in the SPAW model than it was to reprogram the Plantgro model. The complexity of the SPAW model also made it difficult to anticipate the effects of the variation of some calibration parameter values. This was particularly true of parameter values associated with the effects of moisture stress (canopy susceptability, phenology susceptability and the moisture stress curves).

Although the Plantgro model was relatively easy to understand and modify, improvement in terms of its ease of application could be made. The input file required by the Plantgro model was very structured and inflexible in comparison to the input file required by the SPAW model. Input files not produced specifically for use with the Plantgro model would require major modifications before they could be used. This factor would be important if there were a large amount of precipitation and evaporation data in existing files. The flexability of the SPAW model input structure would allow existing files to be incorporated into SPAW input files with little or no modification. In addition, since there was no provision for explanitory remarks in the Plantgro input files, they were difficult to read and understand.

The relative inflexability of the Plantgro input structure became very apparent when input files were modified to calibrate the model for simulating yield. When the model was calibrated and tested for simulating yield, each growing season was modeled in two portions. In the Plantgro model, all irrigation, precipitation and evaporation data were referenced in time to the first day of the simulation period. When the first day of the simulation period was changed, it became necessary to alter a great deal of data to reflect this change. In contrast, a new starting date for a simulation period could be specified for the SPAW model by changing one value in its input file.

Program Modifications

Program modifications to the SPAW model should be designed to increase the ease of model application in several ways. The most obvious need in the SPAW model is a means to reduce the time and effort required to calibrate the model. A calibration routine which would systematically adjust parameters and evaluate the effects of adjustments could be written to make the model self calibrating. Although a calibration routine would reduce the time and effort required to calibrate the SPAW model, it would also significantly increase the random access memory (RAM) requirement of the program. Supplying pan coefficients as input data would slightly decrease the time and effort required to calibrate the model when pan coefficients are used as calibration parameters. A seperate keyword to supply irrigation data might be beneficial since it would allow the program to present irrigation data as such in its output.

Modifications could be made to the Plantgro model which would increase its ease of application and could potentially improve its ability to simulate variations in soil moisture. Similarly to the SPAW model, a calibration routine which would decrease the labor required to calibrate the model could be developed. Redesigning the input structure to utilize keywords would make the Plantgro model more flexible and would allow data with varying formats to be used. Allowing for explanitory remarks in this input structure would help to make input files more readable. It would also be desirable to reference data to a date that would not be subject to change. Modifying the program so that a maximum rooting depth other than the full thickness of the soil profile could be specified would be desirable. Reprograming the model so that water could be removed from several soil layers based on the proportion of the root system in each layer would probably be better than the programed procedure.

Recommendations for additional work at the Red Bluff Research Ranch

In addition to making the program modifications described, performing some additional work using data from the Red Bluff Ranch would be desirable. This additional work would improve the calibrations for soil moisture and yield simulation. Improving the calibrations for soil moisture simulation would probably improve the calibrations for predicting yield indirectly. Improving the calibrations for yield simulation directly would provide a more reasonable basis for testing the ability of the models to predict yield from non-calibration years. In addition, work to calibrate functions in the SPAW model which were not examined in this study would increase the versitility of the model.

The calibrations for soil moisture simulation should be improved by recalibrating the models based on data from at least two of the three years of available data and data from all four quadrants. Calibration using data from 1979 and 1981 would be superior to calibration using data from 1979 and 1980 or 1980 and 1981. Using data from 1979 and 1981 would be superior since a relatively small number of soil moisture measurements were made during 1980 and data from 1981 would extend the calibration period into May. Although a small number of soil moisture measurements were made during 1980, an adaquate number were made to test the ability of the models to simulate variations in soil moisture. If additional data are collected in the future, any further calibration of the models should be based on as many measured values of soil moisture as possible.

The calibrations for yield simulation obtained in this study were very poor since they were based on yield data from only one year. Basing calibrations for yield simulation on all available yield data would almost certainly improve these calibrations. However, these calibrations would be subject to doubt since they would still be based on a very limited amount of data. Yield calibrations for the SPAW model in other studies have been based on data from 9 to 12 years (Sudar et al., 1981; Saxton and Bluhm, 1982). This suggests that additional data should be collected to obtain a calibration for the Red Bluff Ranch. Additional collection of soil moisture data would probably not be necessary since yield calibration could be performed without additional soil moisture calibration. Calibration using data from other sites would also be desirable.

The SPAW model includes two options that were not calibrated in this study. The first of these options was the function which calculates the amount of yield reduction which would be caused by a given level of crop water stress. Calibrating this function after a good calibration for yield simulation has been obtained would allow the SPAW model to be used for evaluating a variety of irrigation scenerios at the Red Bluff Ranch in terms of yield and cost. Although this type of evaluation could be performed without calibrating the yield reduction function, it would require more effort on the part of the modeler.

The second funtion of the SPAW model not examined in this study supplies approximate values for missing evaporation data. Calibrating this option would allow the application of the SPAW model to sites where measured evaporation data are not available. Extending the application of the SPAW model to sites where measured evaporation data are not available would allow the evaluation of different irrigation practices at these sites. However, some recalibration of the model to reflect soil conditions at the site would be desirable. In addition, it would be extremely important for climatic conditions at a site where measured evaporation data were not available to be very similar to those at the Red Bluff Ranch.

CHAPTER 6

CONCLUSIONS

Both the SPAW and the Plantgro models show promise in terms of their ability to predict soil moisture distributions and crop yield. However, the results of this study should be interpereted with care since the calibrations tested were based on very limited data. In addition, there was some doubt as to the accuracy of soil moisture and irrigation data used to calibrate and test the models. The calibrations tested here could almost certainly be improved by using the available data more effectively.

The SPAW model accounts for the factors affecting variations in soil moisture more comprehensively than the Plantgro model. However, the SPAW model also requires a computer with considerably more random access memory. In addition, the SPAW model takes more time to become familiar with and it is more difficult to reprogram the model. In contrast, the Plantgro can be fully understood within a relatively short period of time. However, there is room for improvement in the way the Plantgro model accounts for some factors affecting soil moisture variations.

References Cited

Adams, Tom 1986. Personal comunication. Program Specialist II, Computing Services, Montana State University. Bozeman MT 59717.

ASAE monograph, 1983. Hydrologic modeling of small watersheds. American Society of Agricultural Engineers. St. Joseph MI.

Boltan, J. L., 1962. Alfalfa; Botany, Cultivation and Utilization. Interscience Publishers Inc. New York, NY. p 165-167.

Childs, S. W., J. R. Gilley and W. E. Splinter, 1977. "A simlified model of corn growth under moisture stress". Transactions of the ASAE. Vol. 20; No. 5, p 858-865.

Childs, S. W., and R. J. Hanks, 1975. Model to predict the effects of soil salinity on crop growth. Soil Sci. Soc. Am. Proc. 39: p 617-622.

Donahue, R. L., R. W. Miller, and J. C. Shickluna. 1978. Soils: An indroduction to soils and plant growth. Fourth Ed. Prentice-Hall Inc., Englewood Cliffs, NJ p51.

Goldstien R. A., J. B. Mankin and R. J. Luxmore, 1974. Documentation for PROSPER: A model of atmospheric-soil-plant water flow. EDFB-IBP-73-9. Oak Ridge National Laboratory, Oak Ridge TN.

Hanks, R. J., 1974. Model for predicting plant growth as influenced by evapotranspiration and soil water. Agron. J. 66:660-665

Hanson, T. L., 1984. "Evaluating wash tub evaporation pan irrigation scheduling". Montana AgResearch. Montana State University, Bozeman MT. 1(2) p 1-5.

Kanemasu, E. T., L. R. Stone and W. L. Powers, 1976. "Evapotranspiration model tested for for soybean and sorghum". Agron. J. 68(4): p757-761.

Nimah, M. N. and R. J. Hanks, 1973. Model for estimating soil water and atmospheric relations. Soil Sci. Soc. of Am. Proc. 37 p 522-532

Rasmussen, V. P. and R. J. Hanks. 1978. Spring wheat yield model for limited moisture conditions. Agron. J. 70:940

Retta, A. and R. J. Hanks, 1980. Manual for using Model Plantgro. Utah Agricultural Research Report 48. Utah State University, Logan, UT. 13p

Saxton, K. E., W. J. Rawls, J. S. Romberger and R. I. Papendick, 1986. Estimating generalized soil water characteristics from texture. Will be published in the Soil Sci. Soc. of Am. J., 50

Saxton K. E., G. E. Schuman and R. E. Burwell, 1977. Modeling nitrate dispersion and movement in fertilized soils. Soil Sci. Soc. Am. J., 41(2)p 265-271.

Saxton, K. E., H. P. Johnson and R. H. Shaw. 1974. Modeling evapotranspiration and soil moisture. Trans. Am. Soc. Agric. Engr., 17(4) p 673-677.

Saxton, K. E., P. F. Brooks, R. Richmond. 1984. Users manual for SPAW-A soil-plant-air-water model (Draft copy of August, 1984). USDA-SEA-AR, Washington State University, Pullman WA.

Saxton, K. E., G. C. Bluhm, 1982. "Regional prediction of crop water stress by soil water budgets and climatic demand". Transactions of the American Society of Agricultural Engineers. Vol. 25; No. 1, p 105-110 and 115.

Stockle, C. O., 1983. Modeling water stress effects on crop growth. M. S. thesis. Washington State University, Pullman.

Stockle C. O. and K. E. Saxton, 1984. Modeling water stress effects on winter wheat: calibration phase. Paper presented at the 1984 Pacific Northwest Regional meeting of the American Society of Agricultural Engineers. Paper no. 84-202

Sudar, R. A., K. E. Saxton, R. G. Spomer; 1981. "A predictive model of water stress in corn and soybeans". Transactions of the American society of Agricultural Engineers. Vol. 24; No. 1, p 97-102;

APPENDICES

APPENDIX A

Climatological, Soils and Crop Data

Climatological data

Table 9. Precipitation data for 1979

date	depth (cm)	depth (in)	date	depth (cm)	depth (in)	date	depth (cm)	depth (in)
6/6	0.89	0.35	6/26	0.28	0.11	8/24	0.61	0.24
6/17	0.30	0.12	7/23	0.41	0.16	8/25	0.20	0.08
6/18	4.06	1.60	7/28	0.51	0.20	8/28	0.25	0.10
6/19	0.56	0.22	8/12	0.18	0.07			
6/25	0.15	0.06	8/15	0.89	0.35			

Table 10. Precipitation data for 1980

date	depth (cm)	depth (in)	date	depth (cm)	depth (in)	date	depth (cm)	depth (in)
6/11	0.38	0.15	6/20	0.51	0.20	7/3	1.02	0.40
6/15	0.89	0.35	6/23	1.27	0.50	8/1	0.13	0.05
6/18	0.25	0.10	7/2	0.51	0.20	8/13	0.13	0.05

Table 11. Precipitation data for 1981

date	depth (cm)	depth (in)	date	depth (cm)	depth (in)	date	depth (cm)	depth (in)
5/21	3.18	1.25	6/7	0.15	0.06	7/11	0.64	0.25
5/22	2.41	0.95	6/8	0.05	0.02	7/17	0.38	0.15
5/23	0.15	0.06	6/12	0.38	0.15	7/18	1.68	0.66
5/31	0.25	0.10	6/13	2.67	1.05	8/4	0.64	0.25
6/1	0.13	0.05	6/14	0.41	0.16	8/19	0.20	0.08
6/3	1.07	0.42	7/6	1.52	0.60	8/20	0.13	0.05
6/6	0.66	0.26	7/7	0.38	0.15			

Table 12. Pan evaporation data for 1979

start date	total (cm)	total (in)	average (cm)	average (in)	start date	total (cm)	total (in)	average (cm)	average (in)
6/11	0.84	0.33	0.84	0.33	7/24	1.57	0.62	0.79	0.31
6/12	1.19	0.47	1.19	0.47	7/26	0.69	0.27	0.69	0.27
6/14	1.32	0.52	1.32	0.52	7/27	0.64	0.25	0.64	0.25
6/15	0.53	0.21	0.53	0.21	7/28	1.68	0.66	0.56	0.22
6/16	0.69	0.27	0.69	0.27	7/31	1.73	0.68	0.86	0.34
6/17	1.93	0.76	0.64	0.25	8/02	0.56	0.22	0.56	0.22
6/20	1.60	0.63	0.53	0.21	8/03	0.86	0.34	0.86	0.34
6/23	1.83	0.72	0.61	0.24	8/04	1.37	0.54	0.69	0.27
6/26	0.86	0.34	0.86	0.34	8/07	0.74	0.29	0.74	0.29
6/27	0.48	0.19	0.48	0.19	8/08	1.91	0.75	1.91	0.75
6/28	0.56	0.22	0.56	0.22	8/09	0.36	0.14	0.36	0.14
6/29	0.74	0.29	0.74	0.29	8/10	0.91	0.36	0.91	0.36
6/30	3.12	1.23	1.04	0.41	8/11	1.60	0.63	0.53	0.21
7/03	0.43	0.17	0.43	0.17	8/14	0.60	0.25	0.30	0.12
7/04	1.32	0.52	0.66	0.26	8/16	0.53	0.21	0.53	0.21
7/06	0.71	0.28	0.71	0.28	8/17	0.51	0.20	0.51	0.20
7/07	2.67	1.05	0.89	0.35	8/18	1.37	0.54	0.46	0.18
7/10	0.86	0.34	0.86	0.34	8/21	0.38	0.15	0.38	0.15
7/11	0.97	0.38	0.97	0.38	8/22	0.15	0.06	0.15	0.06
7/12	2.72	1.07	0.69	0.27	8/23	0.71	0.28	0.71	0.28
7/16	0.91	0.36	0.91	0.36	8/24	0.66	0.26	0.66	0.26
7/17	0.64	0.25	0.64	0.25	8/25	0.51	0.20	0.51	0.20
7/18	0.61	0.24	0.61	0.24	8/26	0.60	0.24	0.30	0.12
7/19	1.45	0.57	1.45	0.57	8/28	1.22	0.48	0.61	0.24
7/20	0.76	0.30	0.76	0.30	8/30	0.97	0.38	0.48	0.19
7/21	0.66	0.26	0.66	0.26	9/01	3.30	1.30	0.84	0.33
7/22	0.89	0.35	0.89	0.35	9/05	0.71	0.28	0.36	0.14
7/23	0.13	0.05	0.13	0.05					

Table 13. Pan evaporation data for 1980

start date	total (cm)	total (in)	average (cm)	average (in)	start date	total (cm)	total (in)	average (cm)	average (in)
6/11	0.81	0.32	0.41	0.16	7/19	2.06	0.81	0.69	0.27
6/13	2.03	0.80	0.51	0.20	7/22	1.98	0.78	0.99	0.39
6/17	1.98	0.78	0.66	0.26	7/24	1.68	0.66	0.84	0.33
6/20	1.85	0.73	0.46	0.18	7/26	2.13	0.84	0.71	0.28
6/24	2.06	0.81	0.69	0.27	7/29	2.59	1.02	1.30	0.51
6/27	1.42	0.56	0.36	0.14	7/31	0.69	0.27	0.69	0.27
7/01	3.81	1.50	0.53	0.21	8/01	0.81	0.32	0.81	0.32
7/08	0.91	0.36	0.46	0.18	8/02	2.82	1.11	0.94	0.37
7/10	0.91	0.36	0.91	0.36	8/05	1.80	0.71	0.61	0.24
7/11	2.36	0.93	0.79	0.31	8/08	0.76	0.30	0.76	0.30
7/14	0.30	0.12	0.30	0.12	8/09	1.78	0.70	0.89	0.35
7/15	1.42	0.55	0.71	0.28	8/11	0.74	0.29	0.74	0.29
7/17	1.57	0.62	0.79	0.31	8/12	1.32	0.52	0.66	0.26

Table 14. Pan evaporation data for 1981

start date	total (cm)	total (in)	average (cm)	average (in)	start date	total (cm)	total (in)	average (cm)	average (in)
5/28	2.59	1.02	0.51	0.20	7/23	0.76	0.30	0.76	0.30
6/04	0.56	0.22	0.28	0.11	7/24	0.58	0.23	0.58	0.23
6/06	2.18	0.86	1.09	0.43	7/25	1.24	0.49	0.41	0.16
6/08	2.64	1.04	0.26	0.10	7/28	0.89	0.35	0.89	0.35
6/18	3.51	1.38	0.43	0.17	7/29	1.78	0.70	0.89	0.35
6/26	1.27	0.50	1.27	0.50	7/31	0.61	0.24	0.61	0.24
6/27	3.43	1.35	0.86	0.34	8/01	3.73	1.47	0.74	0.29
7/01	0.71	0.28	0.71	0.28	8/06	0.66	0.26	0.66	0.26
7/02	1.42	0.56	0.71	0.28	8/07	0.66	0.26	0.66	0.26
7/04	3.05	1.20	1.02	0.40	8/08	2.46	0.97	0.81	0.32
7/07	1.68	0.66	0.84	0.33	8/11	1.55	0.61	0.76	0.30
7/09	0.33	0.13	0.33	0.13	8/13	1.37	0.54	0.69	0.27
7/10	1.88	0.74	0.94	0.37	8/15	2.46	0.97	0.81	0.32
7/12	2.04	0.80	1.02	0.40	8/18	1.47	0.58	0.74	0.29
7/14	1.68	0.66	0.84	0.33	8/20	3.84	1.51	0.64	0.25
7/16	0.66	0.26	0.66	0.26	8/26	2.79	1.10	0.94	0.37
7/17	4.72	1.86	0.94	0.37	8/29	2.59	1.02	0.86	0.34
7/22	0.91	0.36	0.91	0.36	9/01	1.96	0.77	0.99	0.39
6/02	1.22	0.48	0.61	0.24					

Soils Data

Table 15. Soil texture by quadrant and layer

Quadrant	depth 0-30cm (1 foot)	30-60cm (2 foot)	60-90cm (3 foot)
1	SCL	SCL	SCL
2	SCL	LS	SCL
3	CL	SCL	LS
4	SCL	SL	LS

Table 16. Soil moisture holding capacity at Field Capacity and the permanent Wilting point

Quadrant	depth 0-30cm (1 foot)		30-60cm (2 foot)		60-90cm (3 foot)	
	WP	FC	WP	FC	WP	FC
1	6.4	11.9	6.5	13.0	6.0	12.8
2	8.0	14.1	6.2	15.4	6.4	14.6
3	5.8	10.7	5.6	11.9	5.1	11.4
4	7.6	14.5	6.6	15.9	6.5	12.9

Table 17. Soil moisture measurements by quadrant (% vol.) for 1979

Date	quad	depth 0-30cm (1 foot)	30-60cm (2 foot)	60-90cm (3 foot)	90-120cm (4 foot)	120-150cm (5 foot)
6/01	1	13.2	13.4	12.7	12.7	12.6
6/18	1	21.6	15.3	13.7	13.8	13.5
6/22	1	17.9	15.9	14.5	14.2	13.9
7/06	1	16.2	14.9	13.8	14.0	13.7
7/26	1	20.7	15.3	13.6	13.7	13.5
8/01	1	18.6	15.0	13.6	13.7	13.5
8/16	1	16.9	14.4	13.6	13.7	13.5
8/31	1	15.8	14.3	13.5	13.7	13.5
9/06	1	14.6	14.2	13.4	13.6	13.5
6/01	2	13.9	13.8	12.9	12.7	12.7
6/18	2	15.7	14.6	13.5	13.3	13.3
6/22	2	16.6	15.7	14.1	13.3	13.3
7/06	2	15.0	14.7	13.6	13.3	13.3
7/26	2	16.7	15.0	13.4	13.2	13.2
8/01	2	16.1	15.2	13.6	13.2	13.2
8/16	2	14.7	14.6	13.5	13.2	13.2
8/31	2	13.0	14.3	13.4	13.2	13.2
9/06	2	12.1	14.1	13.3	13.2	13.2
6/01	3	13.2	13.6	12.8	12.8	12.8
6/18	3	16.3	14.2	13.4	13.4	13.5
6/22	3	17.0	15.5	14.1	13.6	13.6
7/06	3	15.4	14.4	13.7	13.6	13.6
7/26	3	16.3	14.7	13.4	13.3	13.5
8/01	3	15.2	14.9	13.8	13.4	13.4
8/16	3	14.8	14.2	13.4	13.4	13.5
8/31	3	12.8	13.9	13.3	13.3	13.4
9/06	3	12.4	13.8	13.3	13.3	13.4
6/01	4	13.0	13.6	12.9	12.8	12.8
6/18	4	18.2	14.9	13.6	13.4	13.4
6/22	4	16.3	15.4	14.3	14.1	13.7
7/06	4	15.3	14.3	13.6	13.8	13.6
7/26	4	17.6	15.0	13.3	13.4	13.4
8/01	4	16.1	15.0	13.8	13.4	13.4
8/16	4	13.6	14.0	13.4	13.3	13.4
8/31	4	12.6	13.8	13.3	13.3	13.3
9/06	4	12.1	13.7	13.3	13.2	13.3

Table 18. Soil moisture measurements by quadrant (% vol) for 1980

date	quad	0-30cm (1 foot)	30-60cm (2 foot)	depth 60-90cm (3 foot)	90-120cm (4 foot)	120-150cm (5 foot)
6/11	1	13.7	13.7	13.1	13.0	12.9
7/10	1	14.8	14.2	13.4	13.6	13.4
7/21	1	15.8	14.2	13.4	13.5	13.4
8/12	1	17.4	14.3	13.4	13.5	13.4
6/11	2	12.8	13.8	13.2	12.8	12.8
7/10	2	13.2	14.2	13.4	13.1	13.1
7/21	2	14.4	14.3	13.4	13.3	13.1
8/12	2	14.1	14.2	13.4	13.1	13.2
6/11	3	11.3	13.1	12.7	12.7	12.7
7/10	3	12.3	13.8	13.2	13.3	13.4
7/21	3	14.4	13.8	13.4	13.3	13.5
8/12	3	13.1	13.9	13.3	13.3	13.4
6/11	4	12.2	13.6	13.1	13.1	12.9
7/10	4	12.5	13.7	13.2	13.3	13.3
7/21	4	13.7	13.9	13.3	13.3	13.3
8/12	4	17.0	13.9	13.3	13.3	13.3

Table 19. Soil moisture measurements by quadrant (% vol.) for 1981

date	quad	depth 0-30cm (1 foot)	30-60cm (2 foot)	60-90cm (3 foot)	90-120cm (4 foot)	120-150cm (5 foot)
5/20	1	21.1	15.8	14.6	14.4	14.0
6/17	1	20.6	15.5	14.1	13.9	13.6
7/01	1	16.4	14.2	13.4	13.6	13.5
7/16	1	20.9	15.1	13.5	13.6	13.6
8/06	1	21.6	15.7	14.2	14.0	13.7
8/17	1	18.2	14.7	13.6	13.8	13.5
9/02	1	15.1	14.0	13.3	13.5	13.4
6/17	2	19.5	15.7	14.1	13.4	13.4
7/01	2	14.7	14.5	13.4	13.3	13.3
7/16	2	17.9	14.5	13.5	13.2	13.2
8/06	2	19.4	15.6	13.8	13.2	13.2
8/17	2	16.1	14.7	13.5	13.2	13.2
9/02	2	13.6	14.1	13.3	13.1	13.1
6/17	3	17.7	15.3	14.0	13.8	13.8
7/01	3	13.2	14.0	13.4	13.4	13.6
7/16	3	19.1	14.2	13.4	13.4	13.4
8/06	3	18.5	15.7	14.3	14.0	13.7
8/17	3	17.4	14.5	13.7	13.7	13.6
9/02	3	13.4	13.8	13.3	13.3	13.4
6/17	4	17.4	15.1	13.7	13.6	13.5
7/01	4	12.8	13.6	13.3	13.3	13.3
7/16	4	16.8	15.0	13.4	13.2	13.4
8/06	4	18.3	15.5	14.5	14.3	14.0
8/16	4	17.0	14.8	13.7	13.8	13.6
9/02	4	12.7	13.8	13.2	13.3	13.3

Crop Data

Table 20. Harvest Data

Year	Harvest	begin date	end date	Yield by quadrant (tons/acre) 1	2	3	4
1979	1	7/05	7/17	2.14	1.78	2.09	2.03
	2	8/28	9/06	1.31	1.51	1.43	1.33
1980	1	7/01	7/10	2.21	2.12	2.54	2.18
	2	8/21	8/30	1.54	1.43	1.49	1.35
1981	1	6/30	7/09	2.53	2.67	2.98	2.77
	2	8/20	9/03	2.54	2.42	2.09	1.88

Irrigation Data

Table 21. Irrigation data for quadrant 1

Year 1979 date	depth (cm)	(in)	1980 date	depth (cm)	(in)	1981 date	depth (cm)	(in)
6/04	0.58	0.23	7/10	1.88	0.74	7/10	3.66	1.44
6/06	2.92	1.15	7/12	1.88	0.74	7/17	4.29	1.69
6/14	2.18	0.86	7/16	1.14	0.45	7/24	4.42	1.74
6/19	2.82	1.11	7/22	0.76	0.30	7/29	6.20	2.44
6/27	2.74	1.08	7/23	0.76	0.30	8/10	1.63	0.64
7/17	1.52	0.60	7/24	1.14	0.45	8/13	0.97	0.38
7/19	1.52	0.60	7/26	1.14	0.45			
7/21	1.50	0.59	7/28	1.14	0.45			
7/23	2.82	1.11	7/29	1.14	0.45			
7/26	2.87	1.13	7/31	1.07	0.42			
8/02	2.79	1.10	8/05	0.94	0.37			
8/09	0.74	0.29	8/08	0.23	0.09			
8/13	0.74	0.29	8/09	0.51	0.20			
8/20	0.74	0.29	8/11	0.69	0.27			
8/22	0.71	0.28						
8/24	1.45	0.57						

Table 22. Irrigation data for quadrant 2

Year 1979 date	depth (cm)	depth (in)	1980 date	depth (cm)	depth (in)	1981 date	depth (cm)	depth (in)
6/04	0.58	0.23	7/10	1.88	0.74	7/11	3.66	1.44
6/12	2.92	0.86	7/12	1.88	0.74	7/18	4.29	1.69
6/15	2.18	0.86	7/17	1.14	0.45	7/25	4.42	1.74
6/19	2.82	1.11	7/22	0.76	0.30	8/01	6.20	2.44
6/28	2.77	1.09	7/23	0.76	0.30	8/10	1.63	0.64
7/18	1.47	0.58	7/25	1.14	0.45	8/13	0.97	0.38
7/19	1.52	0.60	7/26	1.14	0.45			
7/21	1.50	0.59	7/28	1.14	0.45			
7/24	2.87	1.13	7/30	1.14	0.45			
7/29	2.90	1.14	7/31	1.07	0.42			
8/03	2.54	1.00	8/05	0.94	0.37			
8/09	0.74	0.29	8/08	0.23	0.09			
8/13	0.74	0.29	8/10	0.51	0.20			
8/20	0.74	0.29						
8/22	0.71	0.28						
8/24	1.45	0.57						

Table 22. Irrigation data for quadrant 3

Year 1979 date	depth (cm)	depth (in)	1980 date	depth (cm)	depth (in)	1981 date	depth (cm)	depth (in)
6/04	0.58	0.23	7/11	1.88	0.74	7/13	3.66	1.44
6/12	2.18	0.86	7/13	1.88	0.74	7/19	4.29	1.69
6/16	2.59	1.02	7/17	1.14	0.45	7/27	4.42	1.74
6/26	2.59	1.02	7/22	0.76	0.30	8/03	6.20	2.44
7/18	1.47	0.58	7/24	1.14	0.45	8/11	1.63	0.64
7/21	1.50	0.59	7/27	1.14	0.45			
7/25	2.87	1.13	7/29	1.14	0.45			
7/30	2.90	1.14	7/30	1.14	0.45			
8/05	2.90	1.14	7/31	1.07	0.42			
8/09	0.74	0.29	8/06	0.94	0.37			
8/13	0.74	0.29	8/08	0.23	0.09			
8/20	0.74	0.29	8/10	0.51	0.20			
8/22	0.71	0.28						
8/25	1.55	0.61						

Table 23. Irrigation data for quadrant 4

Year 1979 date	depth (cm)	depth (in)	1980 date	depth (cm)	depth (in)	1981 date	depth (cm)	depth (in)
6/04	0.58	0.23	7/11	1.88	0.74	7/14	3.66	1.44
6/13	2.24	0.88	7/13	1.88	0.74	7/21	4.29	1.69
6/18	2.84	1.12	7/18	1.14	0.45	7/28	4.42	1.74
6/27	2.74	1.08	7/23	0.76	0.30	8/04	6.20	2.44
7/19	1.52	0.60	7/24	1.14	0.45	8/12	1.63	0.64
7/20	1.45	0.57	7/25	1.14	0.45			
7/22	2.90	1.14	7/27	1.14	0.45			
7/25	2.87	1.13	7/29	1.14	0.45			
7/30	2.90	1.14	7/30	1.14	0.45			
8/06	2.92	1.15	7/31	1.07	0.42			
8/09	0.74	0.29	8/04	0.94	0.37			
8/13	0.74	0.29	8/06	0.97	0.38			
8/20	0.74	0.29	8/09	0.51	0.20			
8/22	0.71	0.28	8/11	0.69	0.27			
8/23	1.57	0.62						

APPENDIX B

Description of Program Modifications

Before the SPAW and Plantgro models could be used on an AT&T 6300 microcomputer, it was necessary to modify the programs. Both models were modified to be more compatable with the input requirements of microcomputers and to conform with the syntax of Microsoft* FORTRAN 77. The models were modified to allow the use of several sets of data for consecutive program runs. This was accomplished through the use of counter statements which opened and closed seperate input and output files depending on the value of these counters. The models were adapted so that up to eight consecutive sets of data could be simulated.

Syntax modifications were also necessary since the programs were written in FORTRAN IV and a FORTRAN 77 compiler was used. These syntax modifications included; specifying that certain variables representing characters other than numbers were characters, format statements used as data by the SPAW model were specified as and read as character strings rather than character arrays and comment statements appearing within data and common statement continuation lines were moved outside of the data and common statements.

Program listings for the SPAW and Plantgro models can be found in the user's manuals for the respective programs. These listing are mainframe computer, FORTRAN IV versions of the models. Complete listings and additional documentation for the FORTRAN 77, IBM compatable microcomputer versions of the programs can be obtained from:

The Dept. of Ag. Engineering
409 Cobleigh Hall
Bozeman, MT 59717

* Microsoft is a trademark