A Method of Land Evaluation Using Crop Simulation Techniques

by

Constantin Onofrei

A thesis
presented to the University of Manitoba
in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy
in
Department of Soil Science

Winnipeg, Manitoba

A METHOD OF LAND EVALUATION USING CROP SIMULATION TECHNIQUES

BY

CONSTANTIN ONOFREI

A thesis submitted to the Faculty of Graduate Studies of the University of Manitoba in partial fulfillment of the requirements of the degree of

DOCTOR OF PHILOSOPHY

ABSTRACT

Onofrei, I. Constantin, Ph.D., the University of Manitoba, October, 1986. A Method of Land Evaluation Using Crop Simulation Techniques.

Major Professor: Dr. C.F. Shaykewich, Department of Soil Science.

The evaluation of land has been approached from a global, systemic standpoint, with the objective of developing a method that allows evaluation of land in the Prairie region, based on probable wheat yield distribution. The method chosen to ensure appropriate yield data was numerical simulation of the agroecosystems in the region under consideration.

Two major interrelated activities were performed: the development of a deterministic, computer model, PIXMOD, and the evaluation of the performance of the model using field data for comparison.

The model calculates the daily accumulation of aboveground net production (ANP) over a growing season, as a function of agronomic potential and the availability of three major growth factors: soil water, soil nitrate-nitrogen and soil temperature. The agronomic potential was assumed to be a function of three more stable factors: crop genetic potential, incident photosynthetically active radiation and an overall management level characteristic of the region under consideration. The so-called "constraint-free wheat yield" calculated in the study "Crop Production Potentials for Land Evaluation in Canada" was assumed to represent the agronomic potential. PIXMOD first calculates the phenological development of the crop. Based on this intermediate variable and the agronomic potential, an optimum daily growth rate is

calculated. Separate subroutines (submodels) are used to budget soil moisture content, nitrate-nitrogen and soil temperature. By using demand-supply function types, individual and composite daily limiting factors are calculated. The actual growth rate is obtained by multiplying the potential growth rate by the overall limiting factor. The ANP at maturity stage is obtained by summing the actual growth rates. Accumulated ANP is converted to grain yield using the harvest index approach.

PIXMOD was evaluated using field data from 24 site-year combinations over the 1982 and 1983 growing seasons. The experimental sites were scattered across the entire agricultural sector of Manitoba. Five major variables simulated by the model, grain, ANP, phenological development, soil water content and nitrate-nitrogen content were tested against field data. Two scenarios were assumed. One scenario (Sc. I) considered the soil physical parameters, initial conditions for soil water content and lower boundary condition of the soil profile to be known from measurements. Another scenario (Sc. II) considered the soil parameters, initial soil moisture content and lower boundary conditions of the soil profile to be information derived from the existing standard Soil Survey data. The grain yield for all site-year combinations were simulated accurately in both scenarios. Standard error of model prediction (SEP) values ranged from ± 97 to ±152 kg/ha in Sc. I and ± 225 to ± 280 kg/ha in Sc. II. The predicted phenological development was somewhat faster than the observed rate. Soil moisture content was reasonably simulated for most of the sites. Soil nitrate-nitrogen content was least accurately simulated, with the SEP being from 40 to

50% of the mean observed NO_3^--N concentrations.

The model is considered adequate for land evaluation. Run with historical weather records, i.e., stochastic input driving variables, probability density functions can be approximated for many different wheat growing conditions. By relating those functions to chosen utility functions the land can be evaluated in useful terms for land planning and optimal use.

ACKNOWLEDGEMENTS

I would like to give my thanks to the many persons and institutions that supported this project and contributed to the completion of the thesis.

The most special thanks are due to my wife, Maria Onofrei, a colleague in every line.

I would like to thank Dr. Carl Shaykewich, my thesis advisor, for his guidance, support and understanding throughout the project.

I wish to thank Dr. G. Racz, Dr. M. Cho, and Prof. C. Booy for their many helpful suggestions. I must also thank Mr. R. Smith, Dr. A. Tamburi, Dr. M. Zwarich, Dr. S. Edie, and Dr. R. Soper who served on my thesis advisory committee, and the external examiner, Dr. E. de Jong.

I would also like to thank the rest of the staff of the Manitoba Soil Survey Unit and the Department of Soil Science: Robert, Gary, Raj, Ken, Walter, Peter and Gordy for their continued help.

In addition, I would like to express my gratitude to Dr. J. Dumanski, Dr. J. van Schaik and Dr. R. de Jong of LRRI, Ottawa for their support in completion of this project.

Finally, I would like to extend my appreciation to the Land Resource Research Institute, Ottawa, for the generous fellowship provided and to the University of Manitoba for its financial support.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter 1

INTRODUCTION

The methods of land evaluation employed in studies performed in Canada as well as in other countries are, in essence, based on models aimed at describing how agroecosystems function and at predicting their output(s). Due to lack of data, appropriate information system technology and methods of analysis, the early approaches represented agroecosystems vaguely and estimated their outputs imprecisely. To some extent, the disparity between the behaviour of a real system and its representation by models has been reconciled in the most recent studies. For example, the agroecosystem that initially was considered static was represented dynamically in recent models. Some strictly empirical relationships between inputs and outputs or "black box" procedures have been replaced by descriptions of physiological, physical and chemical mechanisms. Consequently, the outputs of the agroecosystems are now described quantitatively. However, the procedures in use fail to represent the long-term behaviour of the agroecosystem correctly, with the result that the so-called long-term average output value provided by these land evaluation procedures has limited practical value. In rainfed agriculture in many parts of the world, and characteristic of the Canadian Prairie region, with large variation in yield from one year to another, the theoretical long-term average output is of limited practical use. On the other hand, much useful information for decisions related to land use alternatives can be derived from probabilistic estimates of the outputs of agroecosystems.

The purpose of this thesis was to develop a procedure that provides probable wheat yield distributions for agroecosystems of interest within the province of Manitoba and the Prairie region. The approach was based on simulation using a deterministic-mechanistic model with the stochastic input of weather variables. A physical model, Productivity IndeX MODel (PIXMOD), was developed to simulate the annual wheat growth under water stress (deficit/excess), limited soil nitrate nitrogen content and soil temperature stress. The model was tested using field data from 24 site-year combinations. A demonstration of the application of the method, or implementation, running the model for a number of soil series and years of weather records, represents the final stage in the process. However, this final stage is beyond the scope of this thesis and will not be presented.

Chapter 2

LITERATURE REVIEW

The use of simulation for land evaluation purposes is a new technique. In this chapter, a literature review is presented to provide the context for the simulation method developed for this study.

The review is organized into three parts: (i) a review of the fundamentals of land evaluation, (ii) a review of the methods used in land evaluation and (iii) conclusions.

2.1 FUNDAMENTALS OF LAND EVALUATION

Historically, land qualities were more often settled arbitrarily and land use alternatives based on trial-and-error, a time-consuming, expensive, and often ineffective method. The design of theoretically sound land evaluation methods has evolved slowly (Dent, 1983). Land evaluation, as an interdisciplinary activity, has now been undertaken in many countries.

Most of the concepts discussed below are derived from studies carried out by scientists working with the Land and Water Development Division, Food and Agriculture Organization (FAO). Additional information was derived from work done in applying simulation methods to ecological problems, and from system theory.

2.1.1 Terminology

"Land" and "land evaluation" are two key terms. In some of the most recent publications (FAO, 1984; Dent and Young, 1981; Beek, 1981a; McRae and Burnham, 1981) the term "land" refers to the definition of

Brinkman and Smyth (1973):

> A tract of "land" is defined geographically as a specific area of the earth's surface: its characteristics embrace all reasonably stable, or predictably cyclic, attributes of the biosphere vertically above and below this area, including geology, the hydrology, the plant and animal populations, and the results of past and present human activity to the extent that these attributes exert a significant influence on present and future uses of land by man.

From this comprehensive definition, two fundamental characteristics of land can be inferred. First, the land is a three-dimensional complex unit that includes the soil and extends upward into the atmosphere as well as downward into the geological substrate. Second, the unit includes both physical and biological components.

The second term, land evaluation, was defined by Dent and Young (1981) as "the process of estimating the potential of land for alternative kinds of use". Within the FAO documents (FAO, 1976), a more elaborate definition has been advanced:

> The process of assessment of land performance when used for specified purposes, involving the execution and interpretation of surveys and studies of landforms, soils, vegetation, climate and other aspects of land in order to identify and make a comparison of promising kinds of land use in terms applicable to the objectives of the evaluation.

The term "kinds of land use" has a dual connotation. In the context of FAO guidelines (FAO, 1976; FAO, 1984) this referred to either "major kinds of land use" or "land utilization types". The first term was associated with major groups of rural land use such as rainfed agriculture, annual crops, perennial crops, irrigated agriculture, grassland, forest and recreation. The second term was associated with more specific land use. For example, within the major kind of land use, rainfed agriculture, land utilization referred to a specific crop or defined combinations of crops. The definition does not identify the variable(s) to be compared for alternative land use.

2.1.2 Objectives

There are many specific reasons and associated objectives for the evaluation of rural land. Often land evaluation studies are intended either to provide useful information for land use planning (FAO, 1978) or for financial and legal assistance (Storie, 1954). However, to arrive at the specific objective of a particular land evaluation, detailed consideration must be given to the land users' needs.

The major objective of agricultural land evaluation is to estimate (Vink, 1975) the expected yield(s) of systems within the region under consideration (Beek, 1981b) and to present this information to land users in a summarized form (for example, two-dimensional maps) in which land tracts with similar expected output(s) are aggregated in distinct units.

2.1.3 System

Miller (1978) presented the basic theory of living systems common to all levels of complexity from cells to societies. The fundamental concepts relevant to system analysis in land evaluation can be summarized as follows:

(a) The natural system can be described in the context of space and time, two absolute and independent entities, as a concrete system.

(b) Two fundamental types of natural systems are identified: living and nonliving. Living systems are made up of matter and energy and are organized by information. Nonliving systems are also made up of matter and energy, but they are organized by action. Because of the known relationships between matter and energy, the joint term matter-energy is generally used in system analysis and modelling.

(c) Matter-energy and information (living system) and matter-energy and action (nonliving system) change over time. The changes are termed processes and they may progress reversibly or nonreversibly at a wide range of rates.

(d) Each system, at a given moment in time, comprises a three-dimensional space structure, a particular arrangement of components and subsystems. The term "component" refers to a distinct structural unit in the system. The term "subsystem" refers to all components which are involved in carrying out a particular process, regardless of their location in the system. Generally, there is no one-to-one relationship between subsystem and structural component with a complex system such as the agricultural system.

(e) In an agricultural area, one can always identify a hierarchy of systems; the higher-level system being made up of lower-level systems. Toward the lower end in the hierarchy, the systems are of the nonliving type (atoms, molecules). Toward the higher end of the hierarchy, the two system types, living and nonliving, coexist.

With the exception of fundamentals, the system theory developed within ecology cannot be transferred directly to agriculture, which has a much more complex basic unit. Forces of both types, natural and man-controlled, act upon the agricultural system. The other relevant differences between ecosystems and agricultural systems can be summarized as follows: Agricultural systems are guided by desirable goals (Spedding, 1984). They include modified ecosystems (plants and animals), artificially selected and reduced in diversity by excluding biological organisms vulnerable to stress (Evans, 1980). Spedding (1975) named the agricultural system an "ecosystem with purpose". Odum (1984) pointed out that ecosystems are powered only by natural energy (solar) whereas agricultural systems are powered by both natural energy and artificial sources (processed fuels and human labour). Odum also pointed out that the power density level (rate of energy flow per unit area) of an agroecosystem within an industrialized country is ten-fold or more greater than that of most natural ecosystems, mainly due to high energy and chemical subsidies.

Patten and Odum (1981) discussed the cybernetic (system function) aspect of both ecosystems and man-controlled systems (i.e., agroecosystem) and identified the main differences in the feedback mechanisms of the two system types (Figure 1). The feedback mechanism is at the core of the goal, direction, regulation and stability of a system. The authors concluded that within the natural ecosystem the feedback is internal and control mechanisms are diffuse, whereas within the agroecosystem the feedback is largely external and controlled by mechanisms concentrated with a controller. Since the controller is essential to the agroecosystem's function, the management factor cannot be neglected in the analysis of an agroecosystem's output.

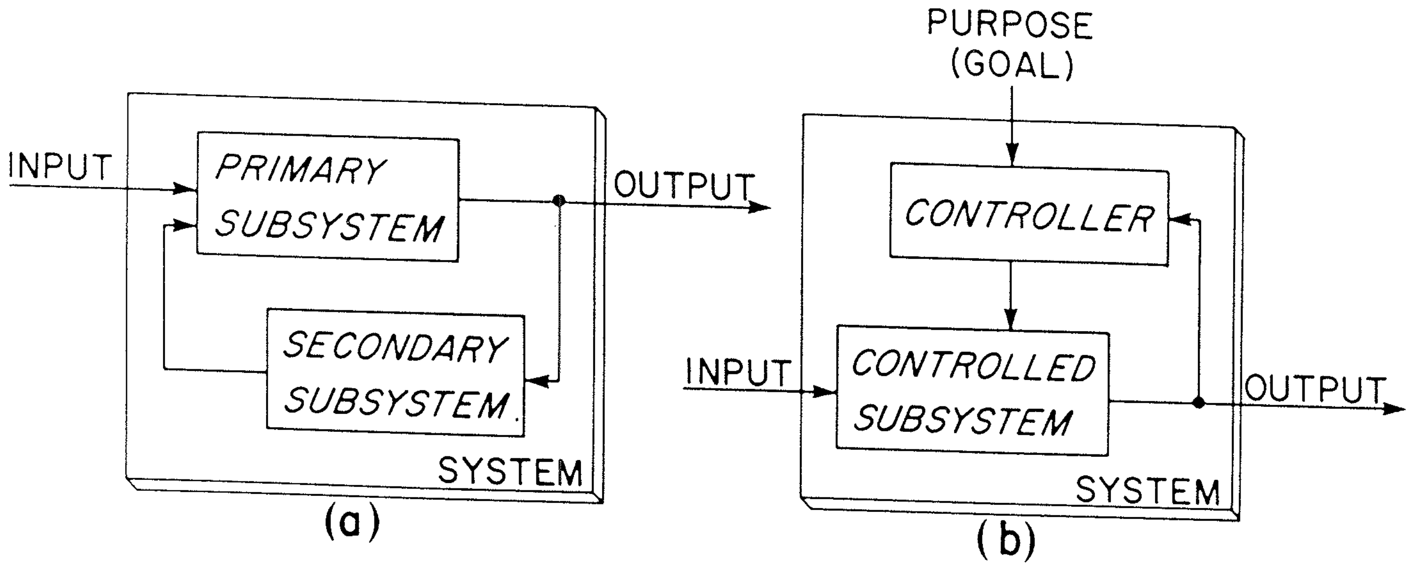


Figure 1. Feedback mechanism; (a) natural ecosystem, internally controlled, and (b) agroecosystem, externally controlled (goal oriented) (from Patten and Odum, 1981).

2.2 METHODS OF LAND EVALUATION

Although some refinements of land evaluation techniques have been made in the last decade, Dent (1983) acknowledged that most concepts and procedures remained unchanged since the 1930's when they were developed.

Physical testing of agroecosystem performance under alternative uses is not feasible over a long period of time. Consequently, all land evaluation methods were based on models that predicted the expected output(s) of agroecosystem(s) within a region under consideration. The expected outputs were expressed in terms of either attributes, rank variables or measurable variables. Both attribute(s) and rank variable(s) used in land evaluation were complex entities that avoided the conventional units used generally in science. The measurable variables were expressed in physical and/or economic units.

The physical unit was generally the amount of grain, aboveground biomass, meat, dairy product or timber, per unit area. Within FAO studies (FAO, 1976; FAO, 1984), this unit was termed "yield" to distinguish from "production", which was intended to describe the total output from the whole farm. Economic analyses were sometimes performed, but more often land evaluation was expressed in physical terms (yield).

A wide range of methods and interpretations have been suggested to solve land evaluation problems. For example, Vink (1975), FAO (1976), and FAO (1984) disregarded the capability and economic classifications and blended them within the suitability classification. Other authors replaced economic classification with "biological productivity" (Nix, 1968) or with "agricultural productivity" (McRae and Burnhan, 1981). Buol and Couto (1981) and Sanchez et al. (1982) suggested a "fertility capability classification". Riquier et al. (1964) proposed an "actual and potential productivity index". Kiniry et al. (1983) and Pierce et al. (1984) used the term "soil productivity" in their land evaluation studies. Dent and Young (1981) and Beek (1981a, 1981b) recognized capability and suitability as separate methods and for special purposes, such as project appraisals, suggested an economic analysis. Several other classifications have been proposed for major land improvements, mainly for irrigation (The Bureau of Reclamation of the U.S. Department of Interior - USBR, 1953; FAO, 1979). This diversity of land evaluation methods and the complexity of individual studies make them difficult to analyze and compare on a basis meaningful to land use planners.

Based on uncertainty in agroecosystem and its long-term behaviour, the land evaluation methods can be grouped into four broad categories: "computation", "compromise", "judgment" and "inspiration" (Table 1). The methods of interest for land evaluation are those that belong to one of computation, compromise or judgment. The last type, inspiration, associated with a trial-and-error procedure, was generally abandoned a long time ago. In the following sections the most common methods associated with each main category of land evaluation are reviewed in the order of their complexity: compromise, computation and judgment.

2.2.1 Compromise

The methods grouped in this category assumed the structure of the agroecosystem to be uncertain and its long-term output unique (certain). The solution of a land evaluation problem took the form of a compromise to accommodate different agroecosystem structures, i.e., competing land use alternatives.

Two methods that belong to this category have been frequently used in land evaluation: the Land Capability and the Parametric Approach.

Table 1. Main categories of land evaluation methods based on assumption made relative to agroecosystem structure and its long-term output.

		Agroecosystem structure: certain	Agroecosystem structure: uncertain
Agroecosystem long term output:	certain	COMPUTATION - rating - suitability	COMPROMISE - capability - parametric
	uncertain	JUDGMENT - probable yield (models)	INSPIRATION - trial & error

2.2.1.1 Land Capability

Land capability concerns the inherent capacity of land to perform at a "given level for general purposes" (FAO, 1976). The performance of an agroecosystem is established a priori within a theoretical classification system. This method has been widely used, at a national level, by numerous developed countries such the U.S.A., Canada, England and Wales (Beek, 1981a; McCormak, 1971; Olson, 1974), as well as by several developing countries such as Zambia and Nigeria, (Woode, 1981; Dalal-Clayton, 1984; Caroll, 1974).

The land capability method was based on a theoretical system developed in the early 1930's by the Soil Conservation Service of the U.S. Department of Agriculture, the system known as the USDA Land Capability System. Its original goal was to indicate the most appropriate general land use alternatives for minimizing the risk of soil erosion (Klingebiel and Montgomery, 1961). The system is hierarchical with three levels: capability units organized in classes and subclasses.

The USDA Land Capability System recognized eight classes (I to VIII) and four subclasses related to the limiting factors (erosion, excess water, soil and climate) (Beek, 1981a). The definitions of these units were expressed in terms of lists of attributes.

Although the modifications made to the original system permitted a better interpretation of the specific characteristics of the land within an individual country, they did not change the overall concept of land evaluation. Within the studies, the land tracts were aggregated into similar units based, to a large extent, on the subjective integration of soil data with other physical data (Aitken, 1983) and not on the expected yield. Additional data provide a more realistic picture of the land but this, generally, makes it more difficult to interpret the relationships between them (Neimann and McCarthy, 1979; Forrester, 1968).

In recent years, the land capability method has received more criticism than appreciation, on the grounds that the method fails to evaluate the land in physical terms (Magaldi, 1983). Boddington (1978) acknowledged the difficulties faced by land use planners in translating the evaluation classes into economic terms; this is always necessary in cost-benefit analysis, one of the most common methods employed in decisions involving land use alternatives. This explains the numerous attempts made in Canada, for example, to relate land capability classes to yield of representative crops within different regions (Patterson and Mackintosh, 1976; Peters, 1977; Kraft and Senkiw, 1979). Land capability classification can provide information that is useful only for broad planning purposes. For many other practical problems associated with land use alternatives, the method is not adequate (Beek, 1981a). Dent and Young (1981) pointed out that the land capability method does not follow any deep principles and concluded that "capability classification is an ad hoc system".

2.2.1.2 Parametric Approach

The parametric approach concerns the numerical evaluation of soil/ land factors (parameters) that are believed to influence the yield (Riquier, 1974) of the crops established in the region under consideration. According to Teaci (1970), this was the first method used in land evaluation. The approach was used at a national level in West Germany (Weiers and Reid, 1974) as well as at a regional level in California (Storie, 1954) and Alberta (Alberta Institute of Pedology, 1974).

The parametric approach was developed in the early 1920's in Germany for taxation purposes. The goal of this approach, known as "Bodenpunkte" (soil points), was a straightforward relative comparison between tracts of land. Each tract of land had points assigned to it for three groups of factors: soil conditions (maximum 90 points), climate - vegetation complex (maximum 20 points) and economics of transport (maximum 10 points). The sum of the assigned points was used in the comparisons. Weiers and Reid (1974) provided an extensive description of the system structure.

Storie (1933) developed a parametric approach, known as the Storie Index Rating (SIR), aimed at rating the agricultural value of soils in California. Initially simple, the SIR was modified and upgraded several times. The latest version (Storie, 1976) was a complex system which recognizes four major composite factors: physical profile characteristics (A), surface texture (B), slope (C) and a miscellaneous factor

(X). Each factor included 24 soil characteristics subdivided into 111 grades. The method of evaluation consisted of assigning points for individual factors to each homogeneous land unit of interest, generally assumed to be a map unit. The final SIR value was obtained by converting the value of the individual composite factor (A, B, C and X) to percentages and multiplying them together. Because the SIR considers the soil characteristics exclusively, this method evaluated soils rather than lands. With some adjustments, by including either climate characteristics (Nelson, 1963) or management factors (Leamy, 1974) or both (Riquier et al., 1964), the SIR method has been applied to evaluate the land in several regions other than California.

A wide range of opinions has been expressed on the value of the parametric method; McRae and Burnham (1981) presented a long, documented list of attributes and criticisms. For example, they noted that Storie (1954) and Weiers and Reid (1974) concluded that farmers consider this approach an equitable method to be used for taxation assessment, while McRae and Burnham (1981) pointed out that farmers' opinions on the method could be influenced by the legislation based on that method. In essence, this method presents similar shortcomings to the Land Capability Method.

2.2.2 Computation

At the International Consultation of Land Evaluation Specialists, held in Wageningen in 1972, it was concluded that information meaningful to land use planners can be provided by methods that specify rural land use alternatives (Brinkman and Smyth, 1973). By specifying land use alternatives, the structure of the agroecosystem (i.e., crop-land tract combination) and management inputs become certain, in which case the agroecosystem output can be expressed in physical terms. Several studies have been performed assuming both the agroecosystem's structure and its long-term expected output to be certain. The land evaluation method then took the form of computation. Two representative methods belong to this category: Land Rating and Land Suitability.

2.2.2.1 Land Rating

The land rating method consists of the numerical evaluation of land factors that influence the yield of a specific crop, and the overall evaluation of a homogeneous land unit (Teaci, 1970). Due to many similarities between the rating and parametric methods, especially because both express the expected output(s) of the agroecosystems in terms of points, the two methods have been considered as land evaluation methods of the same type (McRay and Burnham, 1981; Riquier, 1974). The principal difference between them is that the parametric method considers individual crop yield in the analysis. Although the agroecosystem's output within the land rating approach is expressed as a rank variable (number of points) because it was developed from observed or estimated yield value, the assigned points values can easily be converted to physical units.

Moss (1972) developed a method for rating the soils of the province of Saskatchewan. The method was based on historical wheat yields estimated for individual shipping points by the Saskatchewan Wheat Pool and the Line Elevator Companies. Three major factors were considered to affect the wheat yield: climate, soil texture and soil profile. Using a screening procedure and holding approximately constant two factors at a time, the range in yields over the province was assumed to be the result of a third factor, the variable. The Melfort association, Thick

Orthic Black silty clay soil type was selected as the standard land for the province and awarded 100 points (40 for climate, 40 for texture and 20 for profile). The climate was considered a complex factor that implicitly includes all elements relevant to yield variation. This factor was not derived from meteorological data. A predetermined relationship was assumed between the climate pattern and the major soil zones (Brown, Dark Brown, Black, Dark Gray and Gray). Within the texture factor, two subfactors were included: texture (particle size distribution) and organic matter content; each of these subfactors was subdivided into 13 and 10 levels, respectively. The profile factor included several soil characteristics (mainly genetic), which were used to differentiate between soils.

In Romania, Teaci (1970) developed a method similar to, but more complex than that of Moss (1972), called "Bonitare", i.e., the economic value of agricultural land. The method has been applied at a national level. The basic unit considered in analysis was the so-called "Ecological Homogeneous Area", EHA (Teaci and Burt, 1974). A characteristic of this method is that the points values were derived from observed yields of several crops (wheat, corn, potato, etc.) within experimental station networks and selected state farms. Correlated factors were excluded from the analysis. The effects of individual ecological and management factors on yield were calculated applying linear and curvilinear regressions to site data. For example, linear relationships have been found between yield and solum depth, humus content and slope while curvilinear (second degree polynomial) relationships were found between yield and pH, depth to the water table and climate factors. Data obtained by Teaci (1970) were comparable with those obtained by Moss (1972) and the differences in the weight factors adequately reflected the difference in conditions that prevailed in the two regions.

Although the rating method is more appropriate for evaluating land than methods of the compromise type, it presents several theoretical and practical shortcomings. First, the method does not include the effect of interaction factors on yield. Second, the yield value that can be inferred from the points value is less useful to land use planners than it might appear. The reason for this is that only the mean value over relatively long periods of time was computed. The time trend present in any crop yield (see, for example, Waggoner, 1979; Thompson, 1969; 1970; Williams et al., 1975; Pitter, 1977; Robertson, 1974; Sakamoto, 1978) has been completely ignored. Third, the data used to derive either the yield ranges (Moss, 1972) or regression coefficients (Teaci, 1970), and later, the numerical calculation of factor effect on yield have been derived from selected site records. Therefore, the evaluation of the lands within the region under consideration has been based on "representative sites" data. Several authors (Legg, 1981; Nix, 1981; Chanter, 1981) pointed out that the extrapolation of "representative" yield data in space and time, a method known in land evaluation as "extrapolation by similarity", has little practical meaning.

2.2.2.2 Land Suitability

The land suitability method has been employed in the evaluation of land for specified kinds of use (FAO, 1976), mainly in pilot studies carried out in developing countries (van den Kevie, 1976; Young and Goldsmith, 1977).

The concepts and procedures of the land suitability method were introduced by the FAO and stated in the document "A Framework for Land Evaluation" (FAO, 1976). The general goal of the FAO is to help developing countries to make rational choices between land use alternatives (Baulkwill, 1972). Because there were no land resource survey data in many developing countries, the suitability approach was designed to include all relevant phases of land evaluation: planning the study, field survey, presentation of results (classification), and post-evaluation activities. Complete and comprehensive presentations of this approach were made by Beek (1978), FAO (1976, 1984) and Dent and Young (1981).

Although land suitability aims at land use alternatives more specific than the land capability method, "kind of use" still appears as a general term. It refers either to major kinds of land use or to land utilization type. This gave rise to two different approaches.

When the major kinds of land use were considered in the analysis, the suitability method was almost identical to the capability method. Several studies have been performed based on this approach. For example, Shankarnarayan et al. (1983) evaluated the lands within an arid region in India, and Muchena and van de Weg (1982) described the application of this approach in Kenya at national, provincial and district levels. Although more elaborate schemes have been used to evaluate the land in these studies, and three degrees of suitability were recognized (highly, moderately and marginally suitable), the information provided to land use planners remained of a general nature.

Capability methods that included in the analysis the major kinds of use evaluated the land only in relative terms. Consequently, this approach provided information that was appropriate only for resource inventory.

A large number of authors (Beek, 1981; FAO, 1978; Doorenbos and Kassam, 1979; Nix, 1981; Dumanski and Stewart, 1981; Beek et al., 1983) pointed out that progress in land evaluation can be achieved when the land capability method includes the type of land utilization in the analysis. However, only two studies based on this more advanced approach have been described in the literature: The Agro-Ecological Zone Project for Africa (FAO, 1978) and Crop Production Potentials for Land Evaluation in Canada (CPPLEC) (Stewart, 1981; Dumanski and Stewart, 1983). These studies were very similar, since the Canadian study follows the concepts and procedures developed within the FAO project. Both studies were based on a simplified mechanistic model.

The CPPLEC study was aimed at predicting the yields of the most important rainfed crops in Canada as affected by the dominant climatic and soil characteristics (i.e., soil polygons based on Soils of Canada maps, 1:5,000,000). The evaluation was carried out in seven steps: (1) Input files for each polygon were generated using climate and soil inventory data. (2) Five crops (wheat, corn, soybean, phaseolus bean and potato) were selected as representative of land evaluation in Canada. (3) For each crop and polygon, the growing season length was indirectly calculated, based on either corn heat units (CHU) or degree days (DD) with $5^{o}C$ as a base. (4) "Constraint-free yield", the maximum biomass (aboveground net production, ANP), was computed, assuming all factors of growth optimum except irradiance and temperature. This phase, a model, was the core of the study. (5) In order to arrive at a so-called "anticipated yield", or "actual" (ANPa), the constraint-free yield value was corrected for three stress factors: Moisture Stress

Factor (MSF), Workability Factor (WF) and a complex soil factor, the Soil Index (SI). (6) The ANPa was converted to economic yield (P) using the harvest index approach. (7) The maximum constraint-free yield value obtained, multiplied by the appropriate harvest index was assumed to be the national standard (Ps). By dividing the economic crop yield polygon values by the national standard and multiplying by 100 a Land Suitability Value (LSV) was obtained for each polygon.

In the study, many assumptions and approximations, most of which were reasonable and theoretically sound, have been made. However, the meteorological assumptions require further discussion. The meteorological data available to this study were long-term monthly averages: maximum and minimum air temperature, incoming global solar radiation, precipitation, vapour pressure and wind speed. For prediction of constraint-free yield, only mean monthly temperature values were used. The prediction of gross biomass production was based on standardized values of photosynthetically active radiation (PAR) by latitude and month (de Wit, 1965). Both monthly solar radiation and temperature are approximately normally distributed (Joseph, 1973), and the use of Fourier series to smooth the seasonal means and standard deviations is justified. However, to compute MSF and anticipated yield, a water balance technique for which daily meteorological data were required, was employed. These data were derived from monthly means by assuming them to be normally distributed on weekly and daily bases (Stewart, 1981). Sakamoto (1981) pointed out that, with periods shorter than a month, normal distributions of meteorological data rarely exist, and the same viewpoint has been expressed by many other authors. For example, Richardson (1981) and Stern and Coe (1982) found daily precipitation data to be skewed. Furthermore, Richardson (1981) showed that radiation and temperature are simultaneously below normal on rainy days. Therefore, the predicted "constraint-free yields" are a much more reliable estimate of long term expected yields than are the "anticipated yields".

In spite of these limitations, the CPPLEC is one of the most realistic, correct and useful studies performed to evaluate agricultural land. Realistic, because this method used the observed physical data (soil characteristics and meteorological elements) to simulate the performance of agroecosystems within the region under consideration. Correct, because the simulation was performed with fixed man-controlled input (management), the outputs of different agroecosystems (polygons) were comparable and their aggregation into distinct land evaluation units was correctly made. Useful, because the expected outputs of agroecosystems of interest were predicted in physical terms, and these values could easily be converted into economic units for making decisions on land use alternatives.

2.2.3 Judgment

Many theorists (meteorologists, statisticians and economists) as well as practitioners (farmers, engineers and other land managers) have argued the imperative need for a probabilistic approach to describe meteorological phenomena and agricultural processes, an approach designed to explicitly account for uncertainty (Stern and Coe, 1982; Luttrell and Gilbert, 1976; Walker and Krenz, 1983; Grand and Matis, 1983; English, 1981; Arkin and Williams, 1983). Yields depend on the weather of a particular growing season; since the pattern of day-by-day weather varies from one growing season to another, the long-term performance of the agroecosystem is uncertain. When the structure of the agroecosystem is assumed certain and its long-term performance uncertain, the method of land evaluation takes the form of judgement. An integrated method to evaluate the land based on the probability of the agroecosystem's output has not been developed due to the lack of appropriate data. An alternative solution to this problem has been recently suggested by scientists working in the field of crop modelling (Nix, 1981; Williams et al., 1983; Ritchie, 1984). The solution involves the use of a combination of two fundmental model types: stochastic and deterministic.

2.2.3.1 Stochastic Models

Gold (1977) referred to a stochastic model as the representation of a system or process in which the output is uncertain. Ross (1980) defined the stochastic process more precisely as a collection of random variables, all defined on a common sample (i.e., probability) space. It should be noted, however, that within a stochastic process/system/model, the term stochastic does not necessarily imply a set of completely independent random values. In this latter case, the data series would be termed "white noise" (Gottman, 1981). The term "random" often implies that the data exhibit a degree of randomness.

When the long-term behaviour of the agroecosystem is of interest, the analysis focuses on data variation over many years; this collection of data is termed a time-series. To select an appropriate approach to describe agroecosystem output, three related questions must be answered. First, how do yields vary, i.e., is the long-term agroecosystem's output certain or uncertain? Second, if the yield (output) is uncertain, what are the sources associated with the uncertainty in the output? Third, if the yield is uncertain, then how can the probable yield distribution be obtained for the agroecosystem within the region under consideration?

Theoretically, any time-series generated by a complex system such as an agroecosystem can contain either a trend, a deterministic (cyclic) component, a stochastic component, or any combination of these three components. Thompson (1969), for example, reported the presence of trend and cycle components in corn yield series of five Corn Belt states. In contrast, other authors found no evidence of a deterministic component in yield data. For example, Day (1965) analyzed corn, cotton and oat yields for Mississippi and found no evidence of cyclicity. Luttrell and Gilbert (1976) analyzed twenty six yield series of corn, wheat, barley, rye and cotton recorded at national (the United States) and region (representative states) levels. Based on two tests, the Dubin-Watson parametric test and the Wallis-Moore nonparametric test, on series with the trend components removed, they concluded that the yearly deviation of crop yield from the average was random. Moreover, several series had a significant skewness. Similar results were reported for yield series obtained from a smaller area, and therefore, a more homogeneous land unit. For example, Robertson (1974) analyzed wheat yields obtained at the Swift Current Research Station over 50 years (1923 - 1972) with the trend component removed and concluded that the wheat yield variation was random. It appears that the variation of yield from one year to another contains a trend and a random component. This assumption is further supported, at least theoretically, by considerations associated with the uncertainty of the agroecosystem output.

Gold (1977) identified five sources associated with uncertainty in the output of many natural systems. At least three of them are characteristic of the functioning agroecosystem. First, there is an uncertainty of natural environmental variables (inputs of the agroecosystem) from one year to another. For example, Waggoner (1979), Richardson (1981) and Franquin (1983) all concluded that weather variables are generated by stochastic processes. Second, in some circumstances, there is uncertainty in the agroecosystem parameters. This is particularly true for soils affected by erosion. Third, even the main structure of the agroecosystem presents some uncertainty. Within annual crops, for instance, the time when the crop becomes a structural part of the agroecosystem (seeding time) is also a random event. Thus, a stochastic model would represent the long term behaviour of the agroecosystem much more correctly, and the presentation of yield in terms of a frequency distribution with all relevant parameters specified (location, scale and shape) would be a more useful description for land use planners.

The techniques involved in time-series analysis of the stochastic process/system have been described by several authors (Box and Jenkins, 1970; Ross, 1980; Gottman, 1981; Law and Kelton, 1982). Two major types of analysis have generally been employed in time-series studies: time-domain and frequency-domain. An essential feature of both types is that they assume that the observed time series is a sample (i.e., a realization) of output generated by a process/system, and the time-series presents a correlational structure. By fitting an appropriate stochastic model to observed data, it has been possible either to make limited predictions of the system output or, using a Monte Carlo approach, to generate a large number of outputs from which conclusions about expected characteristcis of the process/system could be drawn. In time-domain studies, which are generally used to analyze time-series, the most commonly used models were: (a) autoregressive (AR), known also as the Markov chain; (b) moving-average (MA); (c) combination of the autoregressive and moving-average models (ARMA); (d) the ARMA combined with an integrated term to account for a deterministic (cycle) component (ARIMA); and (e) the fractional Brownian noises (fBn's) model, appropriate for processes/systems with the so-called "infinite memory" (Mandelbrot and van Ness, 1968).

Although they constitute a powerful and appropriate method for analyzing time-series with a random component, such as yield data, stochastic models have not been used to describe crop yield variation. Such models cannot be directly used for land evaluation purposes due to a lack of the initial data needed to set up an appropriate model. Even within a region with established farming activity and relatively long yield records, it has not been possible to secure a reliable yield time--series. There are at least two reasons for that. First, most farmers use some crop rotation strategy, consequently the yield data are not continuous and equally spaced in time, conditions assumed in time-series analyses. Second, the yield records refer to a large geographical or administrative area, and this yield is, in fact, a summation of yields generated by many agroecosystems. These agroecosystems may be similar in many respects, such as structure and natural environment inputs, but they are not likely to be similar with respect to man-controlled inputs (management). Spedding (1984) pointed out that, within a given year, variation in yield obtained by individual farmers is often as large as the yield variation among years on the same farm. Based on many years of experience, Dent and Young (1981) concluded that, in a given year, within large areas, in developed countries with advanced farming, farmers typically obtain yields within ± 30 to 40% of average, a range approximately equal to "good" and "bad" years for rainfall. It is, thus, a difficult task to separate and to weight the effect of the management factor on yield records over many years, yet this is the method often employed by land use planners to correlate evaluation information provided by capability classifications with physical yield values.

An alternative to generating the probable yield distributions for the agroecosystems of interest is to simulate repeatedly a deterministic model with either historical weather records or with a synthetic set of weather inputs (Jones, 1981). Stochastic models have been extensively used in the last decade to generate synthetic weather data. Because precipitation events exhibit the highest randomness among weather variables, Markov chain models have been used to predict the sequence of days on which rain occurs (Stern and Coe, 1982). Coupled with an assumed distribution function of daily precipitation, several stochastic rainfall models, also called simulators, have been proposed. For example, Todorovic and Woolhiser (1975), Woolhiser and Pegram (1979) and Richardson (1981) used a first-order Markov chain coupled with an exponential distribution to simulate rainfall events. Ison et al. (1971) and Waymire and Gupta (1981) concluded that the use of Markov chain with the gamma distribution is a better representation for daily precipitation.

In recent years, several combinations of stochastic weather simulators with deterministic models have been used to solve problems with a practical objective. For example, Mutsaers (1979) combined a deterministic model that included a detailed water balance with a stochastic weather simulator to determine the optimum sowing date. Stern and Coe (1982) generated the probability of dry spells of 10 or more days within a region in India. Jones (1980) developed a model to generate the frequency distribution of crop yield as a function of water (rainfall probability) and optimal stomata response, a genetic drought tolerance mechanism that can be improved by breeding. Arkin et al. (1980), English (1981), Mishoe et al. (1982) and Swaney et al. (1983) combined weather data simulators with different simplified deterministic-mechanistic model types to assist farmers in making irrigation decisions. Williams et al. (1983) combined a complex weather simulator (for irradiance, temperature, precipitation, and windspeed) with a deterministic-mechanistic model to estimate the effect of soil erosion on yield of different crops.

It can be concluded that, in order to generate a frequency distribution of yield for the agroecosystems within a region, using either historical weather records or simulated weather variables as inputs, an appropriate deterministic model must be available.

2.2.3.2 Deterministic Models

A deterministic model has been defined as describing a system that does not contain random variables (Law and Kelton, 1982). Therefore, for a given set of inputs, there is a unique model output.

Deterministic models can adequately describe the agroecosystem's behaviour over short periods of time, such as one year or, more often, a growing season.

In the last two decades, considerable effort has been made to develop deterministic models that predict an annual crop yield (crop models) as a function of land characteristics. Although they included one or another of the land characteristics that affect yield, they have not been developed for land evaluation. Many simple crop models have been developed that include a single land characteristic, or describe only one process of the agroecosystem. Of considerably greater value for land evaluation, however, are models that include several relevant land characteristics that affect the agroecosystem's function, with implications for crop growth and annual yield variation. Several comprehensive reviews of deterministic models have been published in the literature. For example, Baier (1981, 1983) and Biswas (1980) reviewed agroclimate model types, Charles-Edwards (1981) and Hesketh and Jones (1980) described models developed around the photosynthesis process, Acock and Grange (1981) and Tanner and Sinclair (1983) reviewed models that emphasized water use in relation to crop production. Frissel and van Veen (1981) presented models developed to describe the nitrogen behaviour within soil-plant systems. Legg (1981), Penning de Vries and van Laar (1982), and France and Thornley (1984) described selected comprehensive models that included several relevant processes within an agroecosystem.

Crop models have been classified in many different ways. In order to present examples of deterministic crop models that have been developed, two broad categories of these models have been recognized: empirical and mechanistic, although no sharp distinction can be made between them.

2.2.3.2.1 Empirical models

The essential characteristic of an empirical model is that it displays the relationships of input-output that exist at the boundary of the agroecosystem; the agroecosystem itself is treated as a "black box". Because the input-output relationships are derived from experiments and observations, such a model was termed empirical. Since it represents the agroecosystem at a particular time, the model can also be termed "static".

The empirical crop models developed attempt to relate crop biomass of commercial yield (grain) directly to various land characteristics. Baier (1983) pointed out that the general strategy of these models was to regress samples of yield data mainly on samples of climate data within a region of interest. In such models, the general equation for yield, Y(t), as a function of predictor variable, Xi(t), is

$$Y(t) = \beta o + \sum_{i=1}^{p} \beta i Xi(t) + \varepsilon(t), \qquad t=1,\ldots,n \qquad (2.1)$$

where t is the station year, βo is the intercept, i is the predictor number, βi is the i-th regression coefficient, Xi(t) is the value of the predictor variable for station year t (i.e., the technological trend, linear or quadratic term for each land characteristic variable included in the analysis), and $\varepsilon(t)$ accounts for unexplained errors in the model for year t.

All models included meteorological elements as predictor variables, especially the temperature and precipitation. In addition, several models considered soil characteristics, either directly (Lehane and Staple, 1965; Seif and Pederson, 1978) or indirectly (Williams et al., 1975; Motha, 1979; Sakamoto, 1978).

Thompson (1969, 1970) used a multiple regression technique to regress wheat, corn and soybean yields obtained by the major producer states in the United States, on temperature and precipitation variables. Annual values for temperature and precipitation were found to be inadequate as predictor variables. Consequently, Thompson used a mean value for shorter periods (August - March, April, May, June, July). By using a large number of predictor variables, he concluded that weather and technology accounted for 80 to 92% of wheat yield variation in six states and for 98% of corn yield variation in five Corn Belt states. However, from these results, one cannot conclude that other land characteristics, such as soil properties and management inputs, were not important production factors. Because these factors generally acted on a much smaller area, the mean value of yields at state level nullified their effects. When such factors were considered in the analysis separately, they were found to be significant. For example, Lehane and Staple (1965) reported soil characteristics were significant factors in crop yield variation. Thornley (1978) reported yield variation as a result of different amounts of fertilizer applied. Pant (1979) and Thornley (1983) demonstrated that other management elements, such as plant density and planting pattern, were also major factors in yield variation.

Other empirical models, developed to assess crop production potentials, included both meteorological elements and soil properties as predictor variables. For example, Williams et al. (1975) analyzed cereal yields in relation to time trends, weather variables, and soil characteristics within the Canadian Prairie region at a crop district level. The major characteristics of soil considered were texture and moisture content prior to seeding. As another example, Pitter (1977) analyzed the wheat yield variation in Oregon by crop district and included a complex predictor variable termed the "soil type parameter" to account for soil characteristics. The models used in both studies accurately predicted the yield variation; Williams et al. (1975) reported 57 to 86% of yield variation were accounted for by the models, and Pitter (1977) reported a corresponding "coefficient of determination" of 96%. However, to include soil characteristics as major land properties, the number of predictor variables was increased to 12 by Williams et al., and to 38 by Pitter. When the number of independent variables is this large, the reliability of the above coefficient of determination decreases substantially. To illustrate this point, Sakamoto (1981a) fitted 20 years' data on California cotton yields using sixteen predictor variables, randomly selected and completely unrelated with cotton yield, and obtained an extremely high coefficient of determination (R^2 = 92%).

The use of regression techniques in crop models employed as predictive tools has several shortcomings. These are not associated with the methods themselves, but rather with their misuse. Most effort in empirical models focuses on calculation of regression coefficients (βi), i.e., fitting an appropriate model to observed data. There are three basic assumptions to be made in fitting a model described by an equation of the form of eqn. (2.1). They are as follows:

(a) $Y(t)$ are random samples from the population of interest.

(b) $Xi\,(t)$ are either:

   (i) normally distributed or

   (ii) fixed (i.e., $Xi(t)$ = constant).

(c) $\varepsilon(t)$ is normally distributed with the following properties:

   (i) mean zero,

(ii) $\varepsilon(t)$ are independent of one another, and

(iii) σ_ε^2 is independent of the value of X.

Chanter (1981) pointed out that there is no reason to draw conclusions relative to the causal connection between Y(t) and Xi(t) because the above assumptions do not imply any causal link between them. Therefore, from such an analysis, one cannot infer how much effect an individual predictor had on yield. The author also pointed out that extrapolation beyond the range of variable values used to derive the regression is not valid. No published paper based exclusively on regression has made reference to extrapolation. For land evaluation in particular, prediction for different sites is mandatory. If the restriction of extrapolation is ignored, then the regression coefficients (βi) are unreliable and their use inevitably results in error. Katz (1979) pointed out that the regression coefficients also become unreliable when there is a large correlation between the predictor variables considered in the analysis. To illustrate this, he used the equation of the variance (Var) of estimated coefficients ($\hat{\beta}_i$) (Snee, 1973):

$$\mathrm{Var}(\hat{\beta}_i) = \sigma^2/(1 - Ri), \qquad i = 1,\ldots,p \qquad (2.2)$$

where σ^2 is the error variance of the regression equation, and Ri is the multiple correlation coefficient between Xi and other predictor variables (say Xj, $j \neq i$). As the correlation coefficient Ri increases to 1, the variance of predictor approaches infinity and $\hat{\beta} i$ is no longer a reliable coefficient.

Within empirical models, many predictors are correlated. For example, there is always a degree of correlation between precipitation and temperature, and between precipitation and soil moisture content. Therefore, it is difficult to calculate reliable regression coefficients that are very sensitive to small changes in the observed predictor data and to their degree of correlation.

Sakamoto (1981a) reviewed other major limitations that might be encountered in using regression techniques for crop yield estimates. He concluded that the empirical models can be valuable tools and their usefulness depends on circumstances. For land evaluation purposes, empirical models alone are not an appropriate approach for at least two reasons: first, they fail to account for yield variation from site to site with no change in predictor variables or coefficients (Legg, 1981); second, they represent the agroecosystem as static, whereas it is dynamic in nature. However, as Waggoner (1977) pointed out, the empirical relationships are "distillations of experience in real fields". Therefore, they provide confidence in the prediction's accuracy for many appropriate practical applications.

2.2.3.2.2 Mechanistic Models

The essential characteristic of a mechanistic model is that it simulates some of the chemical, physical and physiological processes that take place within an agroecosystem. Because the processes, i.e., changes of matter-energy, information and action with time, are described according to their mechanisms, this model type is termed mechanistic or explanatory. Since a mechanistic model describes the agroecosystem as it evolves over time, it is also known as a dynamic model.

Mechanistic crop models attempt to represent as correctly as possible, processes that occur within the agroecosystem and are relevant to a specified objective. The degree of complexity varies among the models that have been developed. Penning de Vries (1982), referring to the phases of development of models, distinguished three model classes: preliminary, comprehensive and summary. Generally, each type derives from another in the order presented. Preliminary models deal with quantification and evaluation of hypotheses on the processes considered. Comprehensive models are complex models based on well-known processes described in detail. Examples of this type are models that simulate vegetative growth and include explicit descriptions of physical, chemical and physiological processes. Summary models are models that describe processes in a simplified manner; most of the physical, chemical and physiological mechanisms are implicitly recognized. Generally, these models are derived from comprehensive models from which the details have been excluded but with the theoretical, scientific bases retained. Typical examples of summary models are models in which photosynthetically active radiation (PAR) and CO_2 assimilation are computed, based on standardized functions by latitude, temperature and physiological crop parameters (FAO, 1978; Dumanski and Stewart, 1983; van Keulen et al., 1982). Although these models simplify the description of crop growth, they retain enough flexibility to predict crop growth accurately in different geographical regions (van Keulen, 1982). Since such models present the highest practical value among all model types, they are the most appropriate for land evaluation. However, Goudriaan (1982) acknowledged that summary models have to be constructed by scientists with a considerable knowledge of comprehensive models in order to arrive at a logical and correct summarization. As Penning de Vries (1982) pointed out, there is no standard "summary model" that can be used to solve all practical problems.

Mechanistic models are detailed models since they must be based on the mechanisms of processes. The relationships among terms used in describing the leading physiological processes, the carbon balance components, and biomass in crop models are presented in Table 2. Three complex and interrelated terms, gross photosynthesis (Pg), crop respiration (Rc) and net photosynthesis (Pn), are associated with the main physiological processes - the growth process. Pn is not a process but rather a useful measure of growth.

Some models are based on extrapolations of one measurement, usually the aboveground net production (ANP). The reliability of these extrapolations is a function of the accuracy of the coefficients used. The harvest index (Hi) at cultivar level seems to be the most reliable coefficient because it is genetically controlled (Donald and Hamblin, 1976). Gallagher and Biscoe (1978), for instance, found a coefficient of variation of Hi for wheat of 6% and for barley 5%. These conservative values were obtained from an experiment carried out over five years at three sites. However, Day et al. (1978) reported a variation in Hi of spring barley from 0.42 to 0.51 and related it with water stress (deficit).

The partition coefficient (Kp) of dry matter between roots and ANP is complex and dynamic. Sims and Coupland (1979) found no significant correlation between roots and ANP of grasses. Welbank et al. (1974) analyzed data for several crops and found Kp varied during the growing season but not from one year to another. Ryle and Powell (1976) worked with barley and found that an increased proportion of assimilates were transferred to roots at low irradiance. The partitioning of assimilates between roots and ANP seems to be controlled by matter-energy stress rather than by genetic template.

Table 2: Relationships among physiological processes and terms used in mechanistic crop models.

Main Physiological Process	Relation to Carbon Balance Component	Biomass Terms
		A <u>Measurements/calculations</u> (models)
1. Gross Photosynthesis (Pg)	Assimilation (Pg)	Gross Primary Production (GPP)
2. Respiration (Rc)	Consumption/Oxidation (Rc)	--
3. Net Photosynthesis (Pn)	Pg - Rc	Net Primary Production (NPP)
	Pg - (Rc + Roots)	Aboveground Net Production (ANP)
	fraction of (Pg - Rc)	Product, commercial yield (P)
		B <u>Approximations (extrapolation)</u>
		GPP = ANP +(ANP*Kp) + (ANP*Kr) NPP = ANP + (ANP*Kp) ANP = P + P[(1-Hi)/Hi] P = ANP*Hi
	where:	Kp = Roots/ANP (Partitioning coeff.) Kr = Rc/ANP (Respiration ratio) Hi = P/ANP (Harvest index)

The Kr coefficient, which represents the ratio of Rc to ANP, is not a constant either. The influence of temperature on respiration was reported by many authors (McCree, 1970; Biscoe et al., 1975). If Rc is a function of temperature then implicitly the Kr must also vary with temperature.

For prediction purposes, the crop biomass is computed through mathematical descriptions of the mechanisms of the relevant processes of crop growth as functions of time, followed by a simulation of these processes over the time period of interest. Numerous crop models have been developed, describing these processes mathematically in many different ways. The mechanistic modelling of a process or a system is much more complex than the "black box" procedure. This approach requires additional information relative to the geometry of the system, and the environmental inputs, as well as a more elaborate mathematical description of the system functioning.

Charles-Edwards (1981), for example, developed a complex model of net photosynthesis at photosynthetic site(s) and then he expanded the mathematical description to the whole leaf. In this approach the author considered the photosynthesis and the photorespiration as simultaneous processes and described them based on biochemical and physical considerations. Although models of this type describe closely the mechanism of the leaf's photosynthesis, this mathematical description has rarely been considered within the crop models developed to solve a practical problem. Charles-Edwards (1981) pointed out that his model was not fully mechanistic and numerous parameters (coefficients) had to be experimentally derived. Measurements from a field crop or even from an intact leaf do not permit any reliable test of the model on many assumptions made within this complex mathematical treatment. However, the theoretical concepts outlined in the comprehensive models constitute the basic theory for other simplified mathematical descriptions used in many mechanistic crop models.

Strictly speaking, mathematical mechanistic models have not been developed even for processes that are theoretically well documented, such as photosynthesis. Rather, each description is mechanistic to some degree. Although the descriptions that are more mechanistic are the most desirable, due to their ability to account for a wider range of environmental conditions, they are less practical. Selection of the most appropriate method that balances the mechanistic- empirical character of the model is controlled by the modelling objective.

The comprehensive models represent a rather theoretical system in which the incident solar energy is the main constraint on the living system. Within real agroecosystems, the plant/crop is always more or less under stress. Consequently, many crop models that have been developed include other processes that permit quantification of the effect of stress on growth.

Due to the large number of models and their complexity, a representative sample of published mechanistic models is presented in Tables 3 and 4. Highly theoretical models which require a large number of input variables and parameters, which makes them impracticable (Frissel and van Veen, 1981), have not been considered. Included in the sample are those models generally categorized as "statistically based crop-weather analysis models" (Baier, 1981, 1983). They have been included because they resemble mechanistic models in that they represent the system dynamics and the processes described are theoretically sound

Table 3: General information of selected samples of mechanistic crop models published in the literature.

Authors/Reference	Descriptive Full Name of Model	Abbreviated Name	Crop
de Wit et al. (1978)	BAsic CROp Simulator *	BACROS	general crop
Penning de Vries & Laar (1982)	PHOTON	PHOTON	general crop
van Keulen (1982)	Simple and Universal CROp Simulator	SUCROS	general crop
van Keulen (1975)	Simulator for growth and water use	ARIDCROP	pasture
Seligman and van Keulen (1981)	Production of Arid Pasture limited by Rainfall And Nitrogen	PAPRAN	pasture
Curry et al. (1975)	SOYabean MODel I	SOYMOD-I	soyabean
Meyer et al. (1981)	SOYabean MODel/Ohio Agr. Res. and Development Center	SOYMOD/OARDC	soyabean
Meyer (1985)	REAL time SOYabean simulator	REALSOY	soyabean
Duncan (1972)	SIMulator of COTton growth and yield	SIMCOT	cotton
McKinon et al. (1975)	Simulator Yield Model of COTton II	SYMCOT-II	cotton
McKinon and Baker (1983)	GOSsypium Simulator Yield Model	GOSSYM	cotton
Stapper and Arkin (1980)	CORN Forecasting model	CORNF	maize
Tscheschke and Gilley (1979)	CORN GROwth model	CORNGRO	maize
Weir et al. (1984)	Agricultural Research Council winter WHEAT	ARCWHEAT	wheat
Ritchie and Otter (1985)	Crop Estimation through Resource and Environment Synthesis	CERES	wheat
Holt et al. (1975)	SImulator MEDicago	SIMED	alfalfa
Baier et al. (1980)	TIMOTHY dry matter yield	TIMOTHY	timothy
Selirio and Brown (1979)	SIMulator of seasonal FOrage Yield	SIMFOY	forage
Nix (1981)	CROP EVALuation model	CROPEVAL	general crop
Williams et al. (1983)	Erosion-Productivity Impact Calculator	EPIC	general crop

* The letters used in the abbreviated name of the model have been capitalized.

Table 4: Main characteristics of selected samples of mechanistic crop models published in the literature.

MODEL NAME	Major processes considered[1]										(Δt)[3]	Main Input Variables[4]
	Ph	Re	Gr	Dev	Part	LAI	Root	Transp	Nutr	Sen		
BACROS	m[2]	m	m	–	e	e*	–	e	–	–	h	ITP
PHOTON	m	m	m	–	e	e*	–	e	–	–	min	ITP
SUCROS	–	–	sm	e	e	e	–	–	–	–	d	T
ARIDCROP	sm	sm	sm	e	e	–	–	sm	–	e	d	ITP
PAPRAN	sm	sm	sm	e	e	e	e	sm	e	e	d	ITWP
SOYMOD-I	m	m	m	e	sm	e	–	e	e	e	12 min	ITCDP
SOYMOD/OARDC	m	m	m	e	sm	e	–	e	e	e	h	ITCDP
REALSOY	m	m	m	e	sm	e	e	sm	e	e	2h	ITWP
SIMCOT	e	e	e	–	–	–	–	e	–	–	d	ITP
SIMCOT-II	e	e	e	–	–	–	–	–	e	–	d	IT
GOSSYM	e	e	e	–	–	e	e	sm	e	–	d(1/4d)	ITP
CORNF	sm	–	e	e	e	e	e	e	–	–	d	ITP
CORNGRO	sm	sm	sm	e	e	e	e	e	–	–	h	ITP
ARCWHEAT	sm	sm	sm	e	e	e*	e	–	–	–	d	ITD
CERES	–	–	e	e	e	e	e	e	–	–	d	ITP
SIMED	e	e	e	–	sm	e	–	–	–	–	d	ITDP
TIMOTHY	–	–	e	e	–	–	e	e	e	–	d	TDP
SIMFOY	–	–	e	e	–	–	e	e	–	–	d	TP
CROPEVAL	–	–	e	e	–	–	e	e	e	–	week	ITDP
EPIC	–	–	e	e	e	e	e	e	e	–	d	special file

1. Major processes: Ph - photosynthesis; Re - respiration; Gr - growth; DEV - phenological deveopment; Part - partitioning; LAI - leaf area index; Root - root expansion, activity, etc.; Transp - transpiration, water balance, water flow, etc.; Nutr - nutrient uptake; Sen - senecence.
2. Manner in which processes are described: m - mechanistic; sm - semi-mechanistic; e - empirical (e* measured).
3. Integration time.
4. Main input variables: I - irradiance; T - temperature; D - photoperiod; P - precipitation; W - windspeed; C - carbon dioxide concentration.

and in accordance with the fundamental principles contained in the more comprehensive models. Table 3 contains the general information about each model: author/reference, descriptive and abbreviated name, and the crop considered in the model. The author column does not always refer to the originator of the model but rather to the author of the paper in which some key aspects of the model have been described.

Most of the models have been developed over a long period of time. For example, the Basic Crop Simulator (BACROS) model has been developed by de Wit and co-workers over more than a decade (Penning de Vries, 1982). The Gossypium Simulator Yield Model (GOSSYM) was developed over a similar period of time (McKinon and Baker, 1983). Many models derived concepts from each other. The original forms have been reformulated, improved, expanded to include other relevant processes for new objectives or simplified to make the models more manageable for solving practical problems.

Most of the models have been developed for a specific crop. A relatively small number, either the most comprehensive or the most simplified models, were built to accommodate more than one crop. This does not mean that the model simulates simultaneously the growth of many crops, but rather that it can simulate alternative crops for alternative sets of crop parameters. In both Tables 3 and 4, the models have been grouped by schools in which they have been developed and by the specific crops considered. There are many similarities between the models developed by the same group or for the same crop. However, each model has had a different objective and, consequently, the processes incorporated in the model, the manner in which the processes have been described, and the major input variables included, were combined within each model differently. Table 4 presents the main characteristics of the models sampled. Although these presentations are brief and, to some extent, subjective descriptions of the original models, they provide an overview of mechanistic modelling activity. Four main interrelated characteristics of each model are indicated: the major processes considered, the manner in which the processes have been described, the integration time (Δt) selected, and the main input variables required to run the model.

The name of the process identified in the tables was not precisely defined, and sometimes the processes included several associated processes. The number of processes and their combinations vary widely among models, but photosynthesis, respiration and/or the growth process have been included in every model. A group of models focused on the plant/crop, assuming ample nutrients and water in the soil at all times (BACROS, PHOTON, ARCWHEAT). These models simulate "potential growth". Another group of models included processes that take place within the plant/crop and the soil (ARIDCROP, PAPRAN, REALSOY, THYMOTHY, CROPEV, EPIC). These models simulate "actual growth".

The manner in which each individual process is described in Table 4 does not necessarily coincide with the opinion expressed in the reference paper. The classification applied (m - mechanistic, sm - semimechanistic and e - empirical) was based on the perceived mechanistic/empirical character of each model. This classification helps to indicate the generality (flexibility) of the particular methods employed in describing the various processes. The comparison is relative; the mechanistic description is not fully mechanistic and the empirical description is not entirely empirical.

The integration time (Δt) generally was related with the average time considered for the instantaneous rates computed. Since all these models are solved numerically with a computer, the integration time provides some information on the precision of the solution and on the cost of running the model. The integration times vary from minutes (PHOTON, SOYMODI) to weeks (CROPEUL), with the most common integration time being one day.

The main input variables refer to five fundamental weather variables: I - irradiation; T - temperature; D - photoperiod; P - precipitation, W - windspeed, and sometimes, C - carbon dioxide concentration in the atmosphere. The specific variables considered are directly related to the processes included in the model and the manner in which these processes have been described. For example, models that described the photosynthesis process mechanistically (PHOTON, SOYMODI, BACROS, REALSOY) included irradiance as an input variable. Models that described the growth process in a simplified manner (SUCROS, SIMFOY) included only the temperature variable in relation to the main energy source. The EPIC model is a particular case of this simplified approach. The model uses a weather simulator to generate stochastically the weather input data. It requires a special, complex initial input data file, structured in a particular format.

These models cannot be directly compared in absolute terms, nor can they be fully tested with respect to every assumption included. Comprehensive models, such as PHOTON, BACROS, and REALSOY, that describe processes in detail provide the most correct mathematical description of the system considered. Because they predict only potential growth, their applicability is restricted. The models with higher potential in solving practical problems are summary types, particularly those which considered several limiting factors of growth (PAPRAN, TIMOTHY and EPIC). Mechanistic models are not without drawbacks. For a particular location and a given year, they may not be more accurate than empirical models. However, because they account for some mechanistic characteristics of the system, they can be extrapolated in space and time. Above all, mechanistic models are cheaper and faster and do not require physical land to simulate alternative uses. Paraphrasing Miller (1978), a hypothetical physical prototype of a mechanistic crop model would not be a machine that produces like an agroecosystem but rather a production machine.

2.3 CONCLUSION

The evaluation of agricultural land is of great interest in many countries. In this circumstance, land evaluation focuses on agricultural system (agroecosystem) operation, its maintenance and improvement. The agroecosystem is a complex system of a special kind in which a crop of interest and the soil are the main components. This system is driven partly by natural environment inputs, and partly by land management inputs. Within certain limits and with the exception of weather input variables, the other three elements can be combined in several different ways, combinations which are land use alternatives.

The obvious question of land use planners and managers is which alternative is the most efficient. Here, the term efficient has a complex connotation and includes political, social and economic aspects. At the base of any decision on land use is an economical analysis. According to classical economic theory, efficiency is the ratio of outputs to inputs, expressed in economic units. Since price and cost vary widely in a complex manner, land evaluation is focused on the spatial and temporal distribution of the expected yields under different constraints.

From the foregoing literature review, it is evident that a variety of methods are available to estimate expected yields. Most of them, in particular the earlier methods, are ambiguous, either because land use alternatives are loosely defined - hence, no quantitative statements can be made relative to the expected yield - or, because they assume the system to be static, so that the yield variation with time is neglected. To a large extent, these problems are associated with the lack of adequate yield data. Neither historical yield records nor experimental yield data are appropriate sets for land evaluation. The first data set is inappropriate because it was generally recorded from a large geographical area with many different land tracts, and therefore the yields are not comparable. The second data set is inappropriate because the so-called "representative" site, year and management combination has little practical meaning. The most critical component within this combined assumption is the "representative" year. By assuming this, the long term variation of the yield is disregarded.

An alternative way to generate yield data adequate for land evaluation is to simulate the system function, using an appropriate dynamic model, over a large number of years, in order to account for weather variation from one year to another. Rising costs of all inputs will affect the future location of specific crops as well as the management of inputs. Adequate judgement in land evaluation requires adequate knowledge about the yield probability distribution. This is the most useful information required by land use planners from the land evaluation process. Research on this problem is, thus, potentially of great social and economic value.

Chapter 3

MODELING ACTIVITY

The objective of this thesis is to develop a method of land evaluation that will allow the calculation of expected yield distributions for different agroecosystems within the region under consideration. From this main objective, two interrelated directions of research emerge:

1. The development of a deterministic-mechanistic model that simulates the agroecosystem short-term functioning (one growing season).
2. The evaluation of the model by comparison with real situations.

Due to the nature of the problem generally addressed by land evaluation activity, the present study has had the character of applied research. Two important limitations are related to this: (a) the system(s) under investigation exists in space, and its boundaries cannot be arbitrarily established to match all the assumptions required by the most correct theoretical treatments; (b) the solution of the problem is subject to several constraints, such as the objective of the study, current knowledge of the relevant processes, and the availability of data.

As mentioned earlier, the existing models cannot be used directly for land evaluation. However, the fundamental principles and concepts previously established constituted the basis for developing the present model. The modeling had two objectives: first, to find a practical way to represent the system of interest as correctly as possible; second, to select a new combination of the existing methods that would provide an improved, quantitative description of the system and its functioning.

3.1 SYSTEM OF INTEREST

The system of interest in land evaluation was assumed to be the agroecosystem, a complex goal-oriented system related to many other systems in an organizational hierarchy (Figure 2a).

3.1.1 Agroecosystem Identification

The agroecosystem of interest in land evaluation was defined as a relatively homogeneous three-dimensional soil tract with a uniform crop, driven partly by man-controlled inputs (farm, goal oriented system), and partly by natural environment inputs (atmosphere and geology systems). The agroecosystem defined in this way is represented in Fig. 2b. The soil and the crop were considered to be the major subsystems of the agroecosystem, with both at the same hierarchical level. The soil subsystem was composed of its main geometrical components (area and depth) and the crop was composed of two major parts (shoot and root), Fig. 2c.

The crop can only be described adequately by including biochemical and/or physiological processes, whereas the soil can be adequately described by physical and chemical processes alone.

3.1.2 Agroecosystem Specification

It was assumed that, in Manitoba and across the Canadian prairies, land evaluation can be based on the expected yield of wheat, the major crop grown in the region. Consequently, the crop specified in the model was wheat (Triticum aestivum L.).

Although the two activities, land evaluation and soil survey, are inseparably linked as one continuous process, their immediate objectives

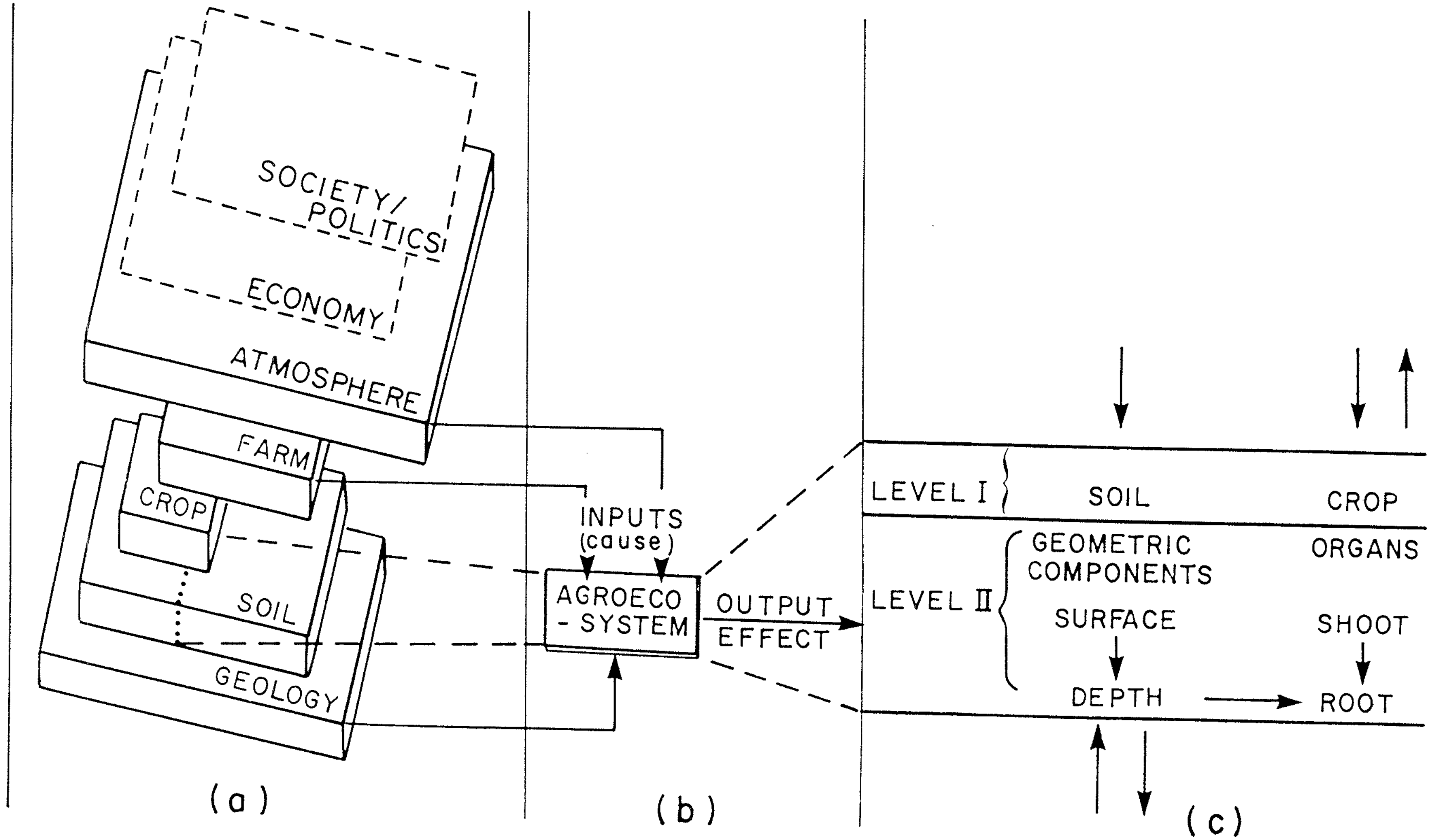


Figure 2: Agroecosystem identification; (a) system hierarchy, (b) the agroecosystem, and (c) components of the agroecosystem.

do not coincide. Wheat yield obtained on soils mapped differently may or may not be different.

Within the present study, the soil series were considered most appropriate for representing the soil subsystem of the agroecosystem. The agroecosystem is specified as a three-dimensional soil tract of the same soil series on which the wheat crop is growing.

3.2 DATA BASES

Based on the objective of the study, the agroecosystem structure and general knowledge of its functioning, the model was designed to function using four sets of available data: crop/plant data, soil data, management data and weather data. Since both the root system and the environmental inputs are dynamic, the most important soil properties are those related to matter-energy flow at the boundaries of the rooting zone and within the soil profile.

3.2.1 Soil Data

Practical, useful approximations of matter-energy flow and soil storage capacity are generally derived from texture, more precisely from particle size analysis combined with other field measurements (Cassel et al., 1983).

All soil properties used in the model were selected to match those that can be derived from the Canadian Soil Information System (CanSIS) data base and Soil Survey reports. CanSIS is a highly organized national computer file that stores a large set of soil data information. By using tailored computer programs as well as commercial software packages, most of the soil properties of interest can be taken from these data bases. Obviously, the soil subsystem parameters derived from pedon data stored in CanSIS cannot be as accurate as data measured in small field plot experiments. Nevertheless, they are the most accurate and reliable figures available from the present data that cover an area large enough to be useful for land evaluation.

3.2.2 Management Data

To obtain comparable data on yield among the agroecosystems most of the man-controlled inputs (management data) were assumed to be fixed across the region under consideration. The amount of nitrogen in the soil profile at the beginning of the growing season and seeding date were treated as variables among the agroecosystems.

In model development, the nitrogen content in the soil present "today" was assumed to reflect the past management impact on the "actual" fertility level of the soil subsystem. For implementation of the method, this information can be derived from the results of soil sample analysis performed over the last five years by the Manitoba Provincial Soil Testing Laboratory.

Past seeding dates can be derived from a Statistics Canada File. This file provides the seeding date data by year and crop district, giving one value for each entire crop district, the date when seeding "is general". It was assumed that the seeding date recorded reflected the district weather pattern for that year, but that within each crop district, seeding was also controlled by soil drainage characteristics. Considering that the date recorded for general seeding represented the time when imperfectly drained soil could be seeded, well drained soils were assumed to be seeded eight days earlier than the recorded date and poorly drained soils, eight days later than the recorded date.

3.2.3 Weather Data

Three weather variables are measured daily by the weather stations that cover the region under consideration: maximum temperature, minimum temperature and precipitation; only these three variables were used explicitly in the model. They constitute the main weather input variables. The data were taken from a weather file at the University of Manitoba, Soil Science Department, derived from a data base developed by the Atmospheric Environmental Service (AES) of Canada.

3.3 SIMULATION PROCEDURE

The general strategy used in modelling is to convert the problem (biological, physiological, physical or chemical) into a mathematical problem that can be solved with the available mathematical techniques. Although the most correct methods of solution are the analytical techniques, most of the functions that describe relevant processes within the agroecosystem are difficult or impossible to integrate in terms of elementary functions. For this reason, because even simple crop models require many calculations, the method selected is a model programmed for a computer, and the continuous functions are replaced with discontinuous functions, the differential equations are converted to difference equations and numerical integrations are substituted for analytical integrations.

The simulation procedure used in the present study was based on the so-called "state-variable approach" (de Wit, 1982a). Essential to this procedure, a widely accepted method for dynamic models, is the assumption that the state of the system can be quantified by "state variables" and the system's changes described mathematically by "rate variables" associated with the state variables. Obviously the rate variable is a result of specific processes. In this circumstance, a critical element is the selection of the integration time interval, or time step as it is often called in modelling, used to represent the process over the time span of interest.

To illustrate this point, let us assume that the process to be represented affects a state variable (Sv) whose changes with respect to time (t) are described by a differential equation such as

$$\frac{dSv}{dt} = f(Sv,t) \tag{3.1}$$

By definition,

$$\frac{dSv}{dt} = \lim_{\Delta t \to 0} \frac{\Delta Sv}{\Delta t} = \lim_{\Delta t \to 0} \frac{Sv(t+\Delta t)-Sv(t)}{\Delta t} \tag{3.2}$$

If $\Delta t \to 0$, i.e., the time interval of instantaneous rate of change (or average) is very small, then on substitution eqn. (3.1) can be approximated as:

$$Sv(t+\Delta t) \approx Sv(t) + \frac{dSv}{dt} \times \Delta t \tag{3.3}$$

That is, the state variable (Sv) at time $(t+\Delta t)$ is equal to the state variable (Sv) at time (t) one step back, plus the rate variable (dSv/dt) at time t multiplied by the integration time interval (Δt). To calculate the state variable of interest, for instance, the accumulation of wheat biomass, the procedure described above must be repeated stepwise over the time span of interest, i.e., a growing season.

One of the simplest methods of integrating equations of the form of eqn. (3.1) is the so-called Euler's forward integration equation. Although the method is not the most accurate, it is the most appropriate for solving initial-values problems coupled with discontinuous driving variables inputs. However, Euler's method is based on the Taylor series that exactly represents the value of Sv at $(t + \Delta t)$, given the value of the function and all its derivatives at t:

$$Sv(t+\Delta t) = Sv(t) + \frac{dSv}{dt}\Delta t + \frac{d^2Sv}{dt^2}\frac{(\Delta t)^2}{2!} + \dots + \frac{d^{n-1}Sv}{dt^{n-1}}\frac{(\Delta t)^{n-1}}{(n-1)!} \qquad (3.4)$$

Comparing eqn. (3.3) with eqn. (3.4), eqn. (3.3) is seen to be a Taylor series expansion of Sv about Sv(t) truncated for terms containing $(\Delta t)^2$ and higher powers of Δt. Most of the processes of interest in the agroecosystem are curvilinear. The truncated Taylor series, being linear, approximates the processes, even those that are curvilinear, by straight line segments. The error thus introduced in the solution is known as the truncation error.

Another two error types are associated with the state variable approach: round-off error and cumulative error. The first type is due to the limited number of significant digits used in arithmetic calculations. Usually this is associated with the type of computer used and the computer language employed. The second type of error is simply an error transmitted from one step to another. All these errors, particularly the truncation error, give rise to the so-called oscillation of the solution. This means that the computed state variable takes alternating values around its time trajectory with no biological, physiological, physical or chemical meaning. There are two options to solve this problem. The first, is to use a more accurate method of integration that would include higher-derivative terms in the Taylor series. This requires that the driving variables (input variables) be available on a continuous basis. A second alternative is to use a shorter time step, provided that the driving variables (inputs) are available at the same time step frequency.

Regardless of the simplicity of the model, any accurate crop model must consider several fundamental processes of the agroecosystem. First, in order to calculate the accumulated wheat biomass, one must represent photosynthesis, respiration and/or growth process. Second, in order to express the agroecosystem function in terms of commercial yield, the partitioning of assimilates among plant organs must be represented. Third, because one of the main limiting factors within rainfed agriculture is water, the transpiration process must also be considered.

Two fundamental interrelated questions have been posed. How small should the integration interval be so that the above processes can be approximated correctly using the state variable? Alternatively, which processes can be represented correctly at the time frequency (one measurement per day) of the available input data.

The answers to these questions were formulated using the so-called "time coefficient" as the reference term. This term is often used in mechanistic crop modelling with a meaning similar to relaxation time, transmission time, residence time, etc. Based on the analogy with the term relaxation time used in physics as the time required to decrease the state variable below its initial value by a factor of 1/e, de Wit (1982b) concluded that an integration time interval should be about 1/4 or less of the time coefficient values for individual process. In this case, the assumption that the rate variable of the process is constant over the integration time would hold true. Alternatively, within the framework of this study, the processes with time coefficients less than three to four days cannot be correctly approximated if the time step of one day is selected to match the input data frequency. Based on time coefficient values reported in the literature, as well as from calculations made on published experimental results, the following appropriate integration time values have been found for the main processes mentioned earlier: for photosynthesis (based on CO_2 assimilation rate), respiration and partitioning, processes that are closely related, the integration time interval should be $\leq$ 5 h; for the transpiration process, the integration time interval should be $\leq$ 20 minutes; for the growth process, the integration time interval should be $\leq$ 1.25 days.

From this preliminary analysis, the following conclusions have been drawn:

1. Within the framework of this study the wheat growth process is the most appropriate process that can be approximated correctly using the state variable approach with a time step of one day.
2. In order to include other processes (biological, physical or chemical) that require an integration time interval smaller than one day, the following options have to be used:

(a) substitution of processes with mechanisms that retain the basic concept and provide approximately the correct results,

(b) use of empirical equations derived from field experiments, or

(c) use of forcing functions based on sound assumptions.

The ability to predict agroecosystem performance is limited at present by a lack of sufficient data, rather than a lack of understanding of the important mechanisms involved, or mathematical skill.

3.4 THE MODEL: PIXMOD

The name of the model developed, Productivity IndeX MODel (PIXMOD) was related to the general objective of the study: to evaluate the land based on the productivity of the agroecosystem(s) within the region.

The objective of the model was to calculate the aboveground net production of wheat over a growing season with four major controlling factors: the supply of energy, water, nitrogen, and the soil temperature. PIXMOD is written in FORTRAN IV and can accommodate either one growing season or a series of growing seasons (years). On a main-frame computer (AMDHAL 520), the model uses 2.58 of central processing unit (cpu) time to simulate wheat growth over one growing season. On the same main-frame, 29 years require 9 cpu.

The main symbols used throughout this chapter are presented in Appendix A. The symbols, definitions and units used in the computer program are reproduced in Appendix B and the PIXMOD FORTRAN IV program is presented in Appendix C.

3.4.1 Basic Concept

The wheat crop was assumed to be described adequately by aboveground net production (B) and the associated growth rate ($\dot{b}$). The B term was used with the agronomic meaning of the biomass as it was defined in Table 2.

Since B is function of time (t), the growth rate ($\dot{b}$) can be defined as

$$\dot{b} \simeq \frac{dB}{dt} \simeq \frac{\Delta B}{\Delta t} \tag{3.5}$$

At any time during the growing season (t_x), the $B(t_x)$ can be described as accumulation of biomass:

$$B(t_x) = \int_{t_o}^{t_x} \frac{dB}{dt}\, dt = \int_{t_o}^{t_x} \dot{b}\, dt \tag{3.6}$$

If the simulation is divided into discrete intervals of one day, Δt = 1 day, the state variable approach, then $B(t_x)$ is

$$B(t_x) \simeq \sum_{i=1}^{t_x} \frac{\Delta B}{\Delta t} \times \Delta t \simeq \sum_{i=1}^{t_x} \dot{b}\,(i) \times \Delta t \qquad (3.7)$$

At the end of biological cycle (either maturity or harvest), t_x = tm, the $B(t_x)$, eqn. (3.6) or (3.7), takes the value of the cumulative above-ground net production (Bmc) obtained under certain growing conditions.

Three circumstances equivalent to three possible systems were recognized: ideal (controlled environment); agronomical optimum (optimum field experiment) and actual (agroecosystem, i.e., field conditions).

If the requirements of the living subsystem in terms of all matter-energy types are maintained at optimum over the entire biological cycle, then Bmc reaches the genetical potential value, Bmgp. In this circumstance the soil subsystem is completely disregarded, and the only system studied is a living one.

If the living subsystem is associated with a given soil subsystem and all matter-energy forms mediated by the soil are maintained at optimum over the entire biological cycle, then the depth component of the soil subsystem can be neglected. However, the area component of the soil subsystem is retained conditionally, and while all the properties of the soil surface might be maintainable at optimum, the solar radiation cannot. In addition, when the living subsystem is considered on an area basis, the management factor is operative and reflects the socio-economic conditions in the region. Due to these two limitations, the Bmc that can be obtained is always smaller than Bmgp. There is thus an agronomic potential (Bmp), a ceiling that varies from one region to another as well as from one management level to another. However, if one knows the value of Bmp and the functional dependence of the aboveground net production on the time, the value of the potential growth rate ($\dot{b}p_i$) within a given region can be derived.

Under rainfed field conditions, the matter-energy inputs required by the living subsystem cannot be maintained at optimum over the entire biological cycle. At least for some days during the growing season the actual growth rate $\dot{b}a_i$ is smaller than $\dot{b}p_i$. Therefore, the Bmc takes the value of the actual aboveground net production, Bma, so that

$$Bma < Bmp, \qquad \text{for } \dot{b}a_i \leq \dot{b}p_i \tag{3.8}$$

The difference between Bmp and Bma is considered to reflect the stress effects on $\dot{b}p(i)$ that may occur at one time or another during the growing season. The stress effect within the region under consideration is assumed to be induced by one of the following three limiting factors: supply of water ($W\ell f_i$), nitrate nitrogen ($N\ell f_i$) or soil temperature ($T\ell f_i$). All other production factors are assumed to be optimum. With the exception of episodic events (hail, insect outbreaks, etc.), the above assumptions are realistic for the Prairie region. If the requirement of the living subsystem for factor X is totally satisfied, i.e., $X\ell_i = 1$, then $\dot{b}a_i/\dot{b}p_i = 1$. If $X\ell_i = 0$, when the requirements of the living subsystem are at or below the threshold values for factor X, then $\dot{b}a_i/\dot{b}p_i = 0$. The actual growth rate can be written as a product of the agronomic potential growth rate and of an overall limiting factor, LF_i.

$$\dot{b}a_i = \dot{b}p_i \times LF_i = \dot{b}p \times g(W\ell_i, N\ell_i, T\ell_i) \tag{3.9}$$

These procedures can be written as simple functions in one of the following forms:

$$LF_i = W\ell_i \times N\ell_i \times T\ell_i \tag{3.10}$$

$$LF_i = \text{AMIN}\ [T\ell_i, (W\ell_i \times N\ell_i) \tag{3.11}$$

$$LF_i = \text{AMIN}\ [W\ell_i, N\ell_i, T\ell_i] \tag{3.12}$$

where the AMIN is the minimum value among the stress effects of individual factors.

Each equation implies different assumptions. Basically, eqns. (3.10) and (3.12) follow two well-known plant growth theories: Boule's Product Law and Leibig's Minimum Law, respectively. Eqn. (3.11) is a combination of both theories. Boule's Product Law fails to account for the so-called negative feedback interaction mechanism. For example, if two factors are simultaneously deficient, increasing one increases growth (eqn. 3.10). In fact, the other factor becomes even more deficient, therefore, it will tend to limit growth to an even greater extent. Eqn. (3.12) is used within the PIXMOD, i.e., it is assumed that the growth rate is increased only by improving the value of the factor in minimum supply.

Although within an individual time step the explicit interaction effect of the factors is neglected, the cumulative aboveground net production over the growing season reflects an integrated effect of all factors,

$$Bma \approx \sum_{i=1}^{tm} \dot{b}p_i \times LF_i, \qquad (3.13)$$

since on a given day, i, over the growing season any factor (W, N or T) may control the actual growth rate.

3.4.2 Potential Growth Rate

To be useful, estimates of crop potential growth rate at the level of the agroecosystem should be based on field experiments. Field experiments for this purpose are expensive and difficult because they must be performed under irrigation conditions with the soil temperature controlled. Consequently, the best available data, with biological and physiological validity, was used to arrive at a useful parametric function for potential growth rate.

It was assumed that Bmp values by regions, computed within the CPPLEC study (Stewart, 1981; Dumanski and Stewart, 1983), are reasonable approximations to the agronomic maxima for wheat crop growth. By maintaining the shape of the growth rate curve and modifying the parameters, the resulting values were used to define the probability density of the potential wheat growth. The agronomic potential of aboveground net production (Bp) is a function of time (days after seeding):

$$Bp = f(t) \quad . \qquad (3.14)$$

The $\dot{b}p$ was assumed to follow a normal distribution function, $\dot{b}p \quad N(\mu,\sigma^2)$, with maximum value, $\dot{b}pm$, when the crop first fully covers the ground, i.e., LAI = 5 (Figure 3).

At the end of the growing season, t = N days, the Bp is equal to Bmp, so that

$$Bp_{(t=N)} = Bmp = \int_{t=0}^{t=N} \frac{dBp}{dt}\, dt \simeq \sum_{i=1}^{N} \dot{b}p_i \times \Delta t \simeq 0.5\ \dot{b}pm \times N. \qquad (3.15)$$

The calculation of $\dot{b}pm$ was based on a model developed by de Wit (1965) and updated by Goudriaan and van Laar (1978). This model predicts a standard maximum gross photosynthesis rate ($\dot{b}_{gross}$) as a function of the angular height of the sun (which, in turn, is a function of latitude, declination and local solar time), the conditions of the sky, and a "standard canopy", i.e., LAI = 5. It should be noted that LAI = 5 was intended to provide some standardization of the canopy geometry. However, because the $\dot{b}_{gross}$ is computed on a per hectare basis, assuming a maximum rate of net CO_2 assimilation rate at high

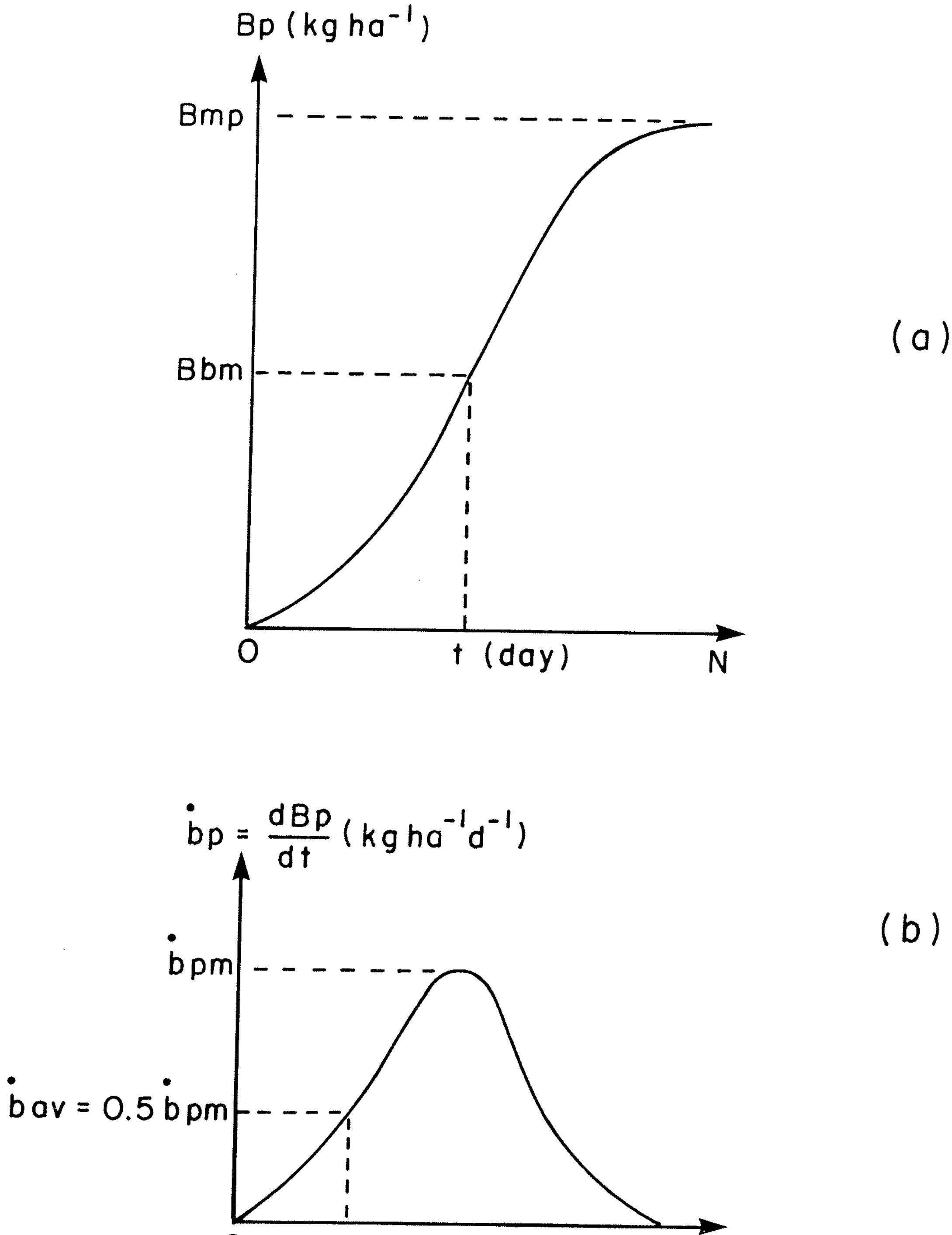


Figure 3: Typical cumulative potential aboveground net production curve (a), and potential growth rate as a function of time (b), considered in the FAO and CPPLEC studies.

light intensity of 20 kg $ha^{-1}h^{-1}$, the calculated value of $\dot{b}_{gross}$ implicitly assumes a specific density of the crop, that is, a specific management level. The value of $\dot{b}_{gross}$ was adjusted, $\dot{b}gz$, for mean daytime air temperature and LAI. This was combined with the respiration equation (McCree, 1970) where the auxiliary variable "b" in the original equation was expressed as a function of temperature (b_T). Ultimately, the maximum potential growth rate was expressed as:

$$\dot{b}pm = 0.72\ \dot{b}gz/(1 + 0.25\ b_T \times N) \ , \tag{3.16}$$

and the agronomic potential aboveground net production as:

$$Bmp = 0.36\ \dot{b}gz/[1/N + 0.25\ b_T] \ . \tag{3.17}$$

The CPPLEC study developed values of $\dot{b}mp$ and Bmp by major regions in Canada using a fixed length for the growing season and averages of the meteorological elements. Theoretically, knowing Bmp and the parameters of the potential growth rate function, μ and σ^2, one can compute $\dot{b}p_i$. Subsequently, if the value of the limiting-factors effect, LF_i, is known one can calculate the actual growth rate through eqn. (3.13). However, the parameters of the potential growth rate function cannot be used to simulate the aboveground net production in different years. This is because the length of the growing season in days varies year to year and from site to site over a much shorter distance than from one large geographical region to another. According to Sakamoto (1981b), the wheat heading date in the central region of North Dakota, for example, varied during 18 years by up to two weeks around the average date for the region. Such variations in the length of the growing season will shift the parameters of normal growth rate, so that the calculations of $\dot{b}p$ as a function of days after seeding are no longer reliable.

Although the parameters of the normal curve are not appropriate for calculating the actual growth rate, the values of cumulative aboveground net productions, Bmp, are sufficiently accurate to indicate the agronomic potentials for different regions. In order to use the Bmp value as an agronomic potential, the "ceiling", of wheat growth, implicitly accounting for the PAR variable, the aboveground net production was expressed in PIXMOD as a function of "phenological time".

Phenological time is used in this study as a specified sequence of morphological and physiological changes. It was assumed that the living subsystem can be characterized by two fundamental processes: phenological development (growth stages) and actual growth. Further it was assumed that both processes are in essence controlled genetically, interrelated and not necessarily chronological-time-dependent, but rather event-dependent. The phenological development was considered to be affected mainly by atmospheric elements (temperature and day length) whereas growth was considered to be a function of phenologic development and matter-energy supply (water, nitrogen and heat). The BioMeteorological Time Scale (BMTS) developed by Robertson (1968) is used as a submodel to describe the phenological development process.

To express the rate of crop growth as a normal probability density function of the form $f[\dot{b}p;\mu_{(BMTS)}, \sigma_{(BMTS)}]$, the two parameters, $\mu_{(BMTS)}$ and $\sigma_{(BMTS)}$, must be known. A set of selected results of previous experiments has been used in this study. The basic data set available consisted of aboveground net production records from a wheat growth experiment carried out by the Plant Science Department, University of Manitoba in 1976[1].

[1] Dr. P. McVetty, personal communication

The experiment was carried out in the field, under irrigation conditions on clay soil (Blacklake, Cumulic Regosol) at the University of Manitoba experimental sites. Four wheat varieties were used in a complete randomized block design experiment. The amount of fertilizer used was 200 kg ha^{-1} of N and 66 kg ha^{-1} of P. Although the soil temperatures were not recorded, it was assumed that the experiment was performed under nearly optimum conditions. The aboveground net production was sampled in two replicates for each variety, five times during the growing season, air dried and weighed.

Since the sampling was done on a days-after-seeding basis, the phenological time was calculated by running the BMTS submodel with weather data recorded at the Winnipeg International Airport weather station in 1976. The observed aboveground net production records were matched with the appropriate phenological time, Pd, expressed as a fraction of BMTS unit, (i.e., Pd = BMTS x 100), based on the sampling dates.

The cumulative curve of the aboveground net production (ANP) expressed as a per cent of agronomic potential (Bmp), according to phenological development, was linearized using the probit transformation (i.e., normal equivalent deviates coded by the addition of 5.0) in which the phenological development variate was replaced with its logarithmic value, P*d = ln Pd.

The parameters for the transformed data, μ^* and σ^* have been obtained using the "probit" analysis, a maximum-likelihood computer procedure, available as part of the Statistical Analysis System (SAS, 1982). The equation used by the analysis was an inverse normal distribution function of the form:

$$F^{-1}(Y) + 5 = [Co + C \times P^{*}d] \quad (3.18)$$

where F is the standard cumulative normal distribution function, Y is the probability aboveground net production, Co is the intercept, C is the slope.

The probit analysis gives the fractiles of P*d which correspond to a given cumulative ANP (fraction of the total Bmp). A plot of empirical probit at five phenological developments superimposed on the probit line is presented in Figure 4. Since the points are scattered at random about the straight line, it was considered that the logarithm of phenological development is normally distributed. The results of computation of the mean and standard deviation of transformed phenological data are presented in Table 5. After three iterations the solution converged, with a mean $\mu^{*} = 5.54005127$, and standard deviation $\sigma^{*} = 0.37452435$. Since χ^2 was small ($P > 0.10$), the 95% fiducial limits were calculated. For $\mu^{*} \approx 5.5400$, the fiducial limits were: $L_1 = 5.4963$ and $L_2 = 5.5852$. Transformed into BMTS units the fiducial interval is 0.22. Therefore, the probability that μ^{*} has a value larger than $\mu^{*} \pm$ 0.11 BMTS units is no greater than 0.05.

However, since the phenological time was transformed to the natural logarithm, the probability density function f(Pd) with the parameters μ^{*} and σ^{*} is a skewed distribution of unlimited range in both time directions. The statistical parameters μ and σ for Pd were obtained based on a set of equations developed by Chow (1954) as follows:

$$\mu = \exp[\mu^{*} + \frac{1}{2}\sigma^{*2}] \quad (3.19)$$

$$\sigma = \mu[\exp(\sigma^{*2})-1]^{1/2} \quad (3.20)$$

On substitution of μ^{*} and σ^{*} values, eqns. (3.19, 3.20) become:

$$\mu = 273.19 \text{ Pd} = 2.7319 \text{ BMTS} \quad (3.21)$$

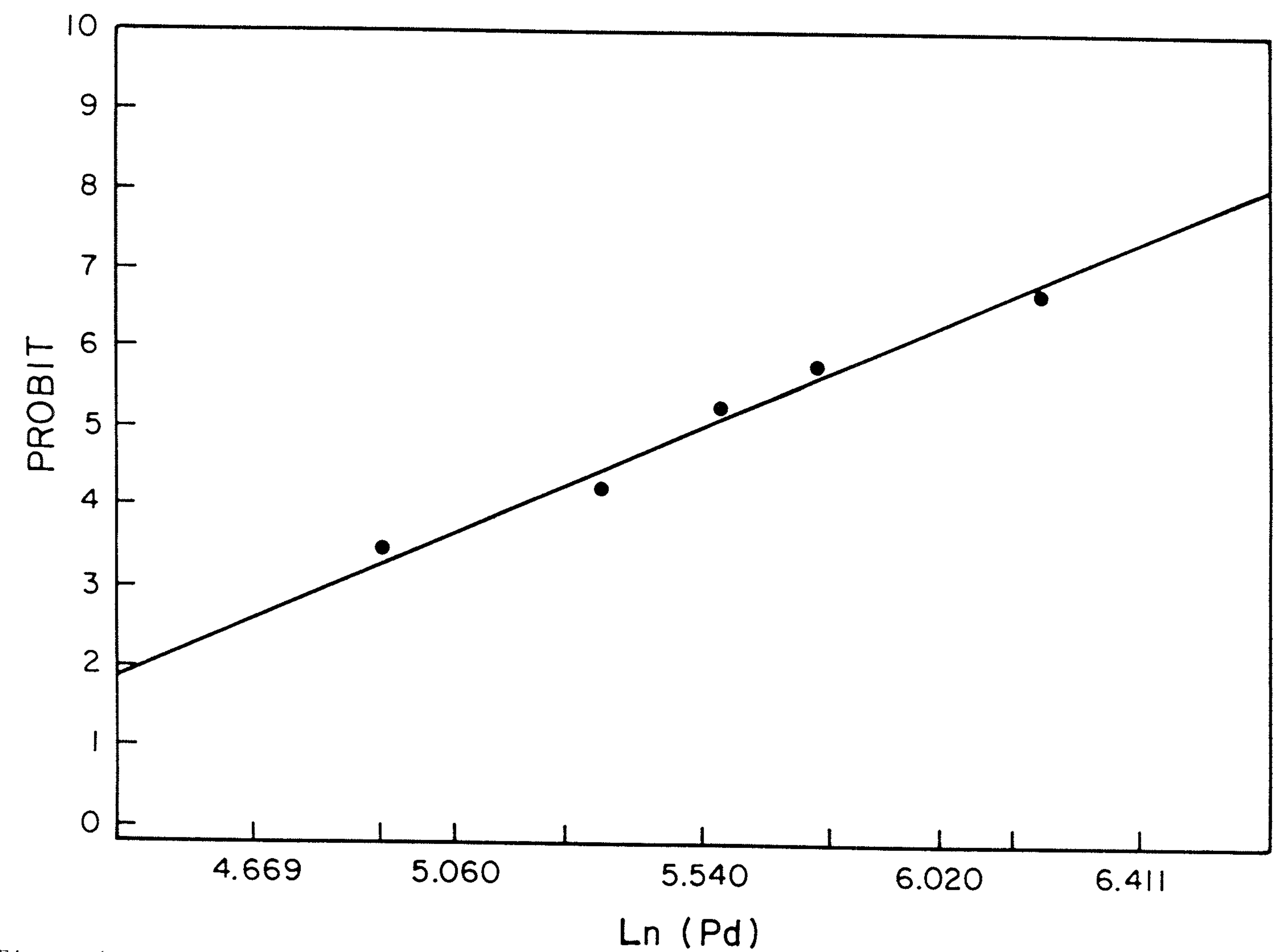


Figure 4: The empirical probit of the cumulative aboveground net production at five different phenological times (P*d = ln Pd) superimposed on the probit straight lines.

Table 5. Parameters of normal distribution function of transformed phenological development data ($P^*d \rightarrow \ln Pd$).

Iteration	Intercept	Slope	μ^*	σ^*
0	-9.05292186	2.53489046	5.54379847	0.39449436
1	-9.77019997	2.66606265	5.54007986	0.37508496
2	-9.79221193	2.67004965	5.54005125	0.37452487
3	-9.79223249	2.67005336	5.54005127	0.37452435

$$\sigma = 106.01 \text{ Pd} = 1.0601 \text{ BMTS} \qquad (3.22)$$

Using these μ and σ values and the phenological time expressed in fractions of BMTS, Pd, the normal probability density function $f[\dot{b}p(Pd)]$ is

$$f[\dot{b}p(Pd)] = \frac{1}{\sqrt{2\pi}\,\sigma} e^{-(Pd-\mu)^2/2\sigma^2}, \quad -\infty < Pd < +\infty \qquad (3.23)$$

However, the aboveground net production accumulates only between emergence and maturity (that is, between BMTS = 1 (100 Pd) and BMTS = 5 (500 Pd). Therefore, the probability distribution $f(\dot{b}p,\mu,\sigma)$ must be truncated. The degree of truncation was based on a procedure described by Hald (1952) for known truncation points.

(a) Truncation to the left (at emergence stage):

Assuming that at the emergence stage Bp = Bpo ≃ 200 kg ha^{-1}, then

$$\frac{Bp(Pd=100)}{Bmp} = 0.0495 \simeq 4.95\%, \text{ giving} \qquad (3.24)$$

$$1/(1-0.0495) = 1.0399, \qquad (3.25)$$

(b) Truncation to the right (at maturity stage):

$$\frac{Bp(Pd=500)}{Bmp} = 0.0175 \simeq 1.75\%, \text{ giving} \qquad (3.26)$$

$$1/(1-0.0175) = 1.0178\ . \qquad (3.27)$$

By multiplying eqn. (3.25) with eqn. (3.27) the truncation correction factor was obtained, ≈ 1.058, and eqn. (3.23) was corrected for the truncation:

$$f[\dot{b}p(Pd)] = 1.058 \frac{1}{\sqrt{2\pi}\sigma} e^{-(Pd-\mu)^2/2\sigma^2}, \text{ where } 100 < Pd < 500. \qquad (3.28)$$

The function $f(\dot{b}p;\mu,\sigma)$ thus becomes:

$$1.058 \frac{1}{\sqrt{2\pi}\ \sigma} \int_{Pd=100}^{Pd=500} e^{-(Pd-\mu)^2/2\sigma^2} \times d(Pd) = 1 \qquad (3.29)$$

Assuming that the accumulated ANP as a function of phenological development is a step function, then the potential growth rate can be regarded as a relative frequency, a_j, such that in (Pd, $\dot{b}p$) - coordinate system:

$$\dot{b}p(Pd)_h = \frac{a_j}{\Delta Pd_j} \qquad \text{for } Pd_j - \frac{\Delta Pd_j}{2} < Pd \leq Pd_j + \frac{\Delta Pd_j}{2} \quad , \qquad (3.30)$$

Alternatively, assuming that the accumulated ANP is represented by a continuous function, then the potential growth rate can be regarded as the probability element $\{f[\dot{b}p(Pd)] \times dPd\}$.

However, the two functions, $\dot{b}p(Pd)_h$ and $f[\dot{b}p(Pd)]$ are equivalent in the sense that frequencies, a_j, and probability element $\{f[\dot{b}p(Pd)] \times dPd\}$ are represented by the areas enclosed by equivalent corresponding curves. Consequently, the potential growth rate as a function of phenological development expressed in Pd units was approximated by eqn. (3.28), multiplied by an appropriate crop ceiling value, Bmp:

$$\dot{b}p(Pd) = 1.058 \frac{1}{\sqrt{2\pi} \times 106.01} e^{-[(Pd-273.19)^2/(2(106.01)^2)]} \times Bmp$$
$$\text{for } 100 \leq Pd \leq 500. \qquad (3.31)$$

Although eqn. (3.31) is empirical, its parameters have some biological basis, and the overall growth process as it is described is biologically plausible. For example, according to eqn. (3.31) the potential growth rate increases exponentially from emergence until shortly before heading, (μ = 2.73 BMTS units) when it reaches its maximum value. After heading, the potential growth rate declines. For determinate crop species, i.e., plants with terminal florescence such as wheat, the vegetative structure increases rapidly from emergence to heading because both the number of leaves and their size increase simultaneously (Spiertz, 1982). Around the time of flowering, close to heading as defined in BMTS (Bauer et al., 1983), the growth in vegetative structure ceases (Austin, 1981). Around the time of heading, the wheat crop canopy is fully developed and the LAI reaches its maximum value. Therefore, the growth rate also reaches its maximum value (de Wit, 1965; Goudriaan and van Laar, 1978; Kirkham and Kanemasu, 1983). The decline in growth rate after anthesis also seems to be plausible, since after this stage most of the carbon compounds from flag leaf and ears move to growing seeds (Milthorpe and Moorby, 1974), and senescence of the bottom leaves begins.

3.4.3 Model Structure

The model was constructed in modules, i.e., subroutines. The general structure of PIXMOD is presented diagramatically in the simplified flow chart (Figure 5). The model includes two supporting subroutines that have not been represented. They are standard procedures used to perform the operations of interpolation and plotting, respectively.

3.4.4 Model Operation

Each node on the main program is a principal action taken at a

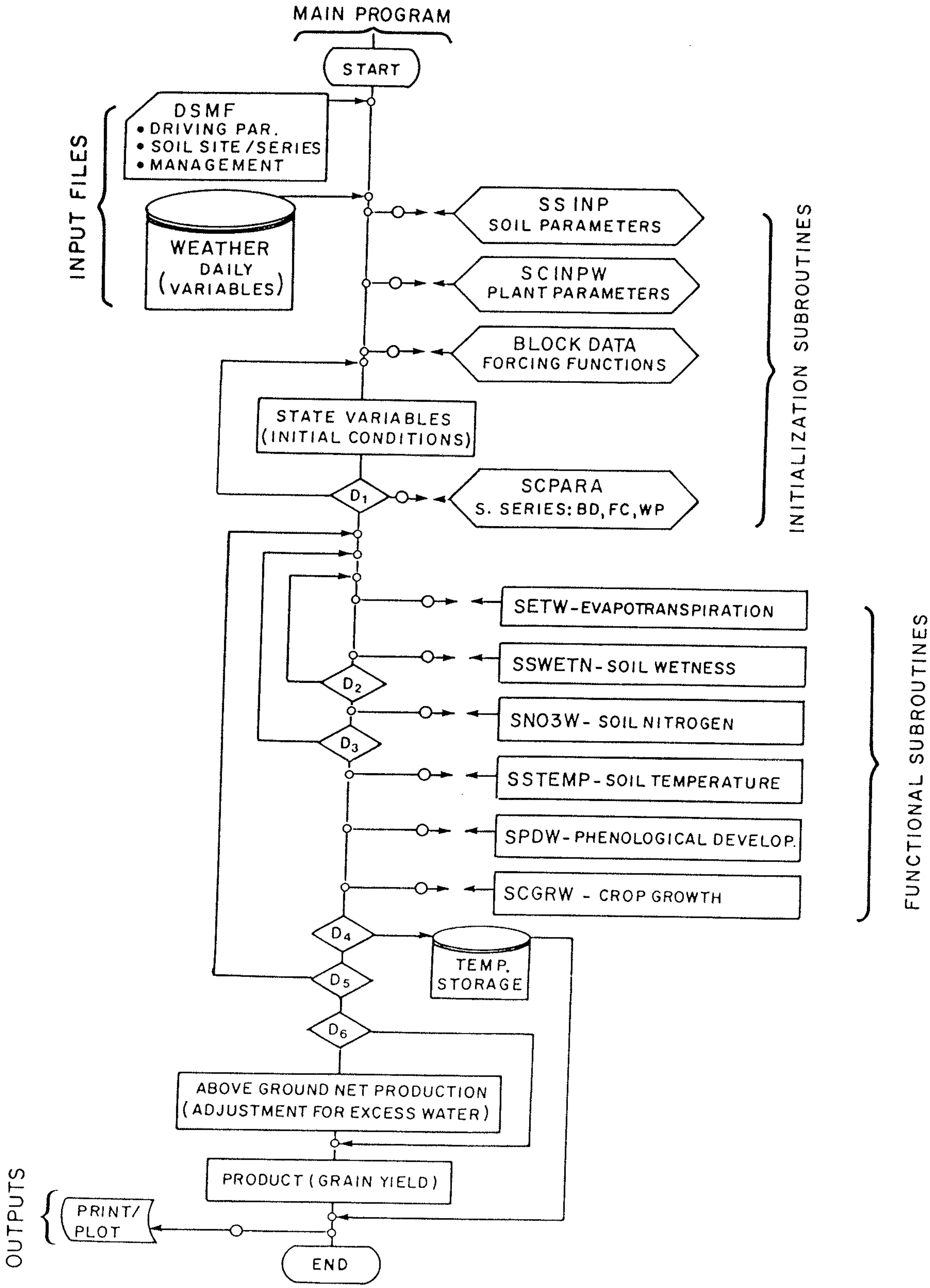


Figure 5: Simplified PIXMOD flow chart.

particular time during one run of the model. There are two types of actions performed by the model: passive actions associated with declarative statements and actions associated with executable statements.

The passive actions, represented with circles, are either input/output, read/write statements (small circles) or call statements (large circles) that activate subroutines.

The remaining actions are either computations, represented by rectangles, or logical decisions, represented by rhombs. Initialization subroutines prepare the model for a particular run. Supporting subroutines are used repeatedly to solve standard problems associated mainly with the interpolation of the functions included in the model in tabular format. The functional subroutines are associated with different functions of the agroecosystem. They perform more complex types of calculations.

The model has been developed to operate with two types of soil data input: (a) in situ measurements, appropriate for evaluation of the model and (b) data similar to that can be abstracted from the standard soil survey data (CanSIS), appropriate for applications. For easier reference, the simulation using soil field measurement data was termed scenario I (Sc. I) and simulation using derived soil data was termed scenario II (Sc. II).

The depth component of the soil subsystem was divided into j discrete layers ($j \leq 8$), each 15 cm thick. With the exception of aboveground net production, grain yield and excess water effect on the final yield, all other calculations are based on units of either length, area or volume in cm, cm^2 and cm^3, respectively.

3.4.4.1 Main Program

The main program is the controlling program. It handles input data, initializes the state variables, i.e., initial conditions, calls the appropriate subroutines, takes action for loop executions and controls the outputs. Some simple computations are also performed within the main program.

One of the major functions of the main program is to handle the order in which operations are performed. The main program starts by reading the information from the input files. This is followed by calling the initialized subroutines. Based on these data/information, a particular set of parameters and state variables are initialized and used in a particular run. All other values become dummy variables. The first decision (D1) concerns the simulation type, i.e., scenario. For Sc. I the special subroutine computation parameters (SCPARA) is bypassed. For Sc. II the main program passes appropriate data to SCPARA and receives information back. Based on this information, some parameters and initial conditions are reset to appropriate values. In the order indicated in Fig. 5, the main program calls the functional subroutines evapotranspiration (SETW), soil wetness (SSWETN), soil NO_3-N (SNO3W), soil temperature (SSTEMP), phenological development (SPDW) and crop growth (SCGRW).

The model was developed to simulate growth over a standard period of each growing season, from the 31st of March to the 1st of October. It was assumed that within Manitoba and the Prairie region, seeding does not start earlier than the end of March and the crop reaches biological maturity, i.e., BMTS = 5, before the 1st of October. The model does not include snow melting or soil thawing, due to lack of data, nor can it accommodate the effects of episodic events. However, if the seeding date is unknown, the model predicts this based on the computed daytime mean air temperature and soil moisture content. This is controlled by decision number two on the main line (D2). It was assumed that the soil temperature threshold for germination is $5^{o}C$. Because mean temperatures from a depth of 5 cm below to 200 cm above the soil surface differ only slightly (Gallagher, 1979), the air temperature is used to compute the daytime mean temperature. The condition of seeding is assumed to be reached when the temperature for three days in succession is $\geq 5^{o}C$ and soil moisture content in the first layer, i.e., 15 cm depth, is $\leq$ 90% field capacity (FC). Soil moisture content is computed by balancing the water within the first two layers, using the SETW and SSWETN subroutines.

Wheat seed germination conditions vary with cultivar (Kirkham and Ahring, 1978) and soil water potential (de Jong and Best, 1979), but this degree of detail cannot be handled with the model. After passing the seeding date, the loop controlled by D2 is no longer executed. During the growing season all operations controlled by decision D5 are executed at least once a day. The functional subroutines are called to execute particular computations, and are updated by the main program. However, to avoid oscillation in the solution of soil moisture flow, the SETW, SSWETN and SNO3W subroutines are called several times during a day with precipitation $\geq$ 2.00 cm. The number of daily iterations is directly proportional to the precipitation, and is controlled by decision D3. Detailed day-to-day computations are stored temporarily on disk. The number, type and frequency of the variable of interest to be stored, specified in the input data, are controlled by the main program

(D4). The daily loop controlled by D5 is either executed until the crop reaches maturity, which is in essence controlled by the phenological development subroutine, or up to a date specified by the user. However, if the length of time to be simulated extends beyond the maturity stage, then plant growth and associated processes (transpiration, NO_3-N uptake, etc.) are arrested at maturity and only physical processes are further simulated. This extended simulation was used for testing the model's performance. Soil moisture and NO_3-N content were measured in the field at harvest time. The harvest date lags behind maturity by eight to ten days; in order to have comparable data for water and nitrogen the SETW, SSWETN and SNO3W subroutines were updated daily until harvest time.

The stress effect due to water excess has not been represented dynamically in the model. An empirical, and to some extent speculative, adjustment of the aboveground net production is calculated based on the overall water balance during the growing season. The execution of this adjustment, controlled by decision D6, varies from one soil series to another as well as from one year to another for the same soil. In the next step the yield (grain) is computed based on the harvest index approach. Finally, the summary and/or detailed computed data within the simulation are printed and/or plotted. The model can be stopped after one run, that is, one growing season, or simulated for sequential years with standard soil parameters and historical weather records.

3.4.4.2 Input Data

The input data set contains variables, some of which do not change during one run while others do. The variables that do not change with time during one particular run become parameters. However, in the context of the whole study, they vary across the region. The input data are assembled in two files called DSMF and WEATHER.

DSMF (driving-soil-management variable file) contains special information that drives the model for a particular run and data that describe the soil subsystem and man-controlled inputs (management). During one particular run, all these variables in this file remain unchanged. There are 15 lines in the file. Each line is headed uniquely and contains a specific set of data. Although the file is short, it is very complex because it contains code commands for the parameters. Appendix D contains a sample of DSMF for the test site Winnipeg/1982 (Experimental plots, University of Manitoba), followed by a detailed description of each variable (type, format, value, units and declaration instructions). This file contains the following type of variable:

(a) Soil Data:

- Soil depth,
- Surface textural class,
- Coarse fragments (gravel) %,
- Drainage class,
- Infiltration rate,
- Water table depth,
- Incoming runoff,
- Shape and frequency of unconnected depressions,
- Slope class of depressions,
- Number of diagnostic horizons (or layers) within the soil profile,

For each identified horizon or layer:

- Centre point,
- Bulk density,

- Particle size distribution:
  - clay,
  - silt,
  - very fine sand,
  - fine sand.
- Organic carbon content,
- Field-measured volumetric field capacity (FC),
- Volumetric wilting point (WP),
- Volumetric water content at seeding time.

(b) Man-Controlled Input Data:

- Nitrate-nitrogen content before seeding by horizon/layer,
- Seeding date,
- Nitrogen fertilizer applied:
  - amount,
  - date of application,
- Harvest date,
- Agronomic-potential, ceiling for aboveground net production.

(c) Driving Variables:

- Scenario number,
- Number of variables to be stored,
- Type of variables to be stored,
- Number of variables to be plotted,
- Type of variables to be plotted,
- Number of days to run the model.

For a given run, not all DSMF data are necessary. However, the structure of the file must be complete. Some of the variables can be declared unknown. Appendix D gives the alternatives in this case.

Based on the scenario number, the main program selects the appropriate data; all other values unnecessary for the particular run become dummy variables.

The WEATHER file contains weather variables on a daily basis; 183 days/records for each growing season. Some of the variables are measured, others are computed. The frequency of these variable values must match the time step interval used in the model, one day. Appendix E contains a sample WEATHER file for the same test site as for the DSMF followed by the description of each variable within a record. The WEATHER file contains the following data:

- AES station name,
- AES station identification number,
- Year,

Daily data for:

- Precipitation,
- Maximum temperature,
- Minimum temperature,
- Solar radiation at the top of the atmosphere,
- Photoperiod.

3.4.4.3 Initialization Subroutines

Most of the parameters included in the initialization subroutines will be considered explicitly when the major equations in the functional subroutines are discussed. The initialization subroutines are only presented briefly. There are four such subroutines included in the model: SSINP, SCINPW, BLOCKDATA and SCPARA.

The SSINP subroutine groups together the soil parameters used to simulate either water flow or soil temperature. Soil hydraulic properties, essential to describe the flow of water, present the highest variability among soil characteristics (Warrick and Nielsen, 1980). At the agroecosystem level they can only be approximated roughly. Within PIXMOD they have been recognized only through three textural classes: clay, loam and sand.

SCINPW groups the crop parameters. Since the living subsystem within the agroecosystem was identified as only one crop, wheat, those parameters could be included directly in the equations used in the model. They have been grouped in a special subroutine for future consideration. For example, if better parameters are derived or if the model is expanded to include crops other than wheat, then the necessary adjustments can be made with minimum alterations to the model as a whole.

The BLOCKDATA subroutine contains all tabulated functions as arrays of various sizes. The subroutine groups heterogeneous data/information used by different functional subroutines. For example, it contains the value of hydraulic conductivity and diffusivity by soil textural class as a function of relative available water content, the optimum amount of nitrogen required by the crop at different growth stages, coefficients used within SPDW subroutine, etc. Use of the BLOCKDATA subroutine is a computer programming strategy of assigning values to the variables that have not been "declared" within the so-called "COMMON" region. "BLOCKDATA" is the key opening declaration in FORTRAN programming.

SCPARA subroutine has a distinctive role in the model. It computes a special set of parameters essential for model applications (Sc. II). This subroutine provides the critical parameters used to simulate the soil water content, which is calculated in the model based on a parametric approach. The basic parameters used to describe the upper and lower limits of water available for the plants are FC and WP. Although they are useful parameters in solving many agronomic practical problems related with optimum water management, field-measured values rarely exist. Estimating soil parameters that affect water flow through the soil and uptake by the plant is difficult, especially since these parameters often vary within the same soil series. However, many useful empirical models have been developed to allow such parameters to be estimated from more fundamental soil properties such as soil particle size distribution and organic matter and/or organic carbon content (Shaykewich and Zwarich, 1968, Clapp and Hornberger, 1978; Gupta and Larson, 1979; de Jong, 1983; Ratliff et al., 1983; Cassel et al., 1983).

The equations developed by Shaykewich and Zwarich (1968) are used in the SCPARA subroutine. The equations have been developed from 112 samples of Manitoba soils, soils that vary widely in texture and other physical and chemical properties.

The basic equations employed in SCPARA are:

$$FC(w) = 9.8708 + 0.1182(Si) + 0.2741(C) + 1.2655(OM) \quad (3.32)$$

$$WP(w) = 3.7960 + 0.0375(FS) - 0.0334(VFS) + 0.2202(C) + 0.6646(OM) \quad (3.33)$$

where:

FC(w) - Field capacity (% by weight)

WP(w) - Permanent wilting percentage (% by weight)

FS - % Fine sand (0.25 - 0.1 mm),

VFS - % Very fine sand (0.1 - 0.05 mm),

Si - % Silt (0.05 - 0.002 mm),

C - % Clay (< 0.002 mm),

OM - % Organic matter.

Since the calculations made in the model of water content are based on volumetric water content, θ, $m^3 m^{-3}$, the FC and WP, % by weight values, are converted to $m^3 m^{-3}$ units using the bulk density values ρ_b ($Mg\ m^{-3}$).

$$FC(\theta) = FC(w) \times \rho_b \tag{3.34}$$

$$WP(\theta) = WP(w) \times \rho_b \tag{3.35}$$

with ρ_b being estimated by:

$$\rho_b = 1.7756 - 0.0016(VFS) - 0.0017\ (Si) - 0.0047\ (C) - 0.0707\ (OM) + 0.008(C)\ (OM) \tag{3.36}$$

All the predictor variables used in eqns. (3.32), (3.33) and (3.36)) are given in the input data by either diagnostic horizons or layers of variable thickness. Using the interpolation subroutine, appropriate values of FC, WP and ρ_b are designated for each standard discretized layer considered in the model.

The value of FC computed within SCPARA plays a double role in the model, first, as a parameter and (under a special circumstance) as the initial condition of soil water content. When the simulation is performed for situations in which the soil moisture content at seeding time is unknown, it is set equal to FC. However, this standard assumption, $\theta(j,t=0) = FC(j)$, can be easily changed to accommodate any regional specific conditions if $\theta(j,t=0)$ can be approximated from other information.

3.4.4.4 Functional Subroutines

The functional subroutines are special components within the model. They simulate some of the processes that take place within the agroecosystem, processes relevant to the agroecosystem main output, i.e., wheat yield. In essence the functional subroutines are submodels.

Although the intention was to keep a balance with respect to the details of processes represented in PIXMOD, this was not always possible. All submodels included in PIXMOD are based on submodels developed in various disciplines. The general strategy used was either to simplify the existing comprehensive models in order to match the available data or to enhance the elementary models in order to describe a specific process. In the first case, some processes described in other models have been replaced with forcing functions, whereas in the second case simple models have been combined in order to describe adequately the processes of interest.

The subroutines are interrelated in a much more complex manner than can be represented in the simplified flow chart of Fig. 5. Some subroutines deal with processes that are related with only one subsystem of the agroecosystem, but most describe processes within both living and nonliving subsystems.

3.4.4.4.1 Evapotranspiration subroutine

Since the precipitation is an input variable, evapotranspiration is the key auxiliary variable in calculating the water available to the crop and thus in simulating the growth. In this study the evapotranspiration rate, $\dot{ET}$, is defined as the amount of water transferred daily from the soil to the atmosphere, calculated on a cropped-area basis. In general terms, $\dot{ET}$ can be considered to be functions of available energy (ξ) and soil water content (θ_s).

$$\dot{ET} = e(\xi),\ s(\theta_s)\ . \qquad (3.37)$$

If the amount of water to be evapotranspired is unlimited, i.e., θ_s is very large, then $\dot{ET}$ is only a function of the amount of energy used for evaporation. The amount of water evaporated as function of energy supply alone is termed potential evapotranspiration, $\dot{E}Tp$. If potential evapotranspiration is known, then the actual value can be written as

$$\dot{E}T = f(\dot{E}Tp, \theta_s) \quad . \tag{3.38}$$

Estimating of potential evapotranspiration is essential to calculate the actual value of water evaporated from the system. Consequently, $\dot{E}Tp$ must first be approximated even within the crop model developed for conditions of limited water supply.

3.4.4.4.1.1 Potential evapotranspiration

The estimation of potential evapotranspiration in PIXMOD is based on an equation developed by Baier and Robertson (1965). The authors used a linear multiple regression technique, on data from several locations in Canada to derive a set of equations to predict $\dot{E}Tp$.

The equation suitable for use in this study was:

$$\dot{E}Tp(\text{cm d}^{-1}) = 0.0094\{-87.03 + 0.928\ T_{max} + 0.933 \text{ range} + 0.0486\ Qo\} \tag{3.39}$$

where T_{max} is daily maximum air temperature (^{o}F), range is daily temperature range (^{o}F), Qo is solar radiation at the top of the atmosphere ($ly\ d^{-1}$).

3.4.4.4.1.2 Evapotranspiration components

Ritchie (1983) pointed out that separation of evapotranspiration components is the key factor in simulating crop growth. It is generally accepted that evapotranspiration comprises two components: evaporation ($\dot{E}v$) and transpiration ($\dot{T}r$).

$$\dot{E}T = \dot{E}v + \dot{T}r \tag{3.40}$$

Because $\dot{E}v$ and $\dot{T}r$ are related in a complex manner and are difficult to measure separately, the two terms are often considered together. Under some circumstances, for instance, when the nutrient supply is not recognized in the model or when the crop in the agroecosystem is a perennial, it may not be necessary to distinguish between $\dot{E}v$ and $\dot{T}r$. However, in this study, the nitrogen uptake is considered and the canopy and root system are dynamic features. Consequently, it was mandatory to consider the two processes separately.

Since $\dot{E}T$ is a function of ξ and θ_s [eqn. (3.38)], the two components $\dot{E}v$ and $\dot{T}r$ can also be functions of $\dot{E}Tp$ and θ_s:

$$\dot{E}v = f_1[(1-p)(ETp),\ \theta_{ss}] \tag{3.41}$$

$$\dot{T}r = f_2[p(ETp),\ \theta_{ar}] \quad . \tag{3.42}$$

where θ_{ss} is the available water content in the soil surface layer and θ_{ar} is available water content in the active rooting zone with p the fraction of soil area covered by the crop. The evaporation process is defined as water transfer from the soil surface to the atmosphere. The rate of evaporation is a function of potential evapotranspiration, soil moisture content of the surface layer and, indirectly, a function of crop characteristics, i.e., the fraction (1-p) of soil that is not covered by crop.

The transpiration process is defined as water transfer from the active root soil zone to the atmosphere. Since this water passes through the plant, the $\dot{T}r$ is controlled by ETp and the plant status (stomata reaction) as well as by the amount of water in the volume of soil accessible to the roots, and the fraction (p) of soil covered by the crop.

In PIXMOD, it was assumed that a simple shading percentage of ground cover by the crop at various stages of development (Figure 6,

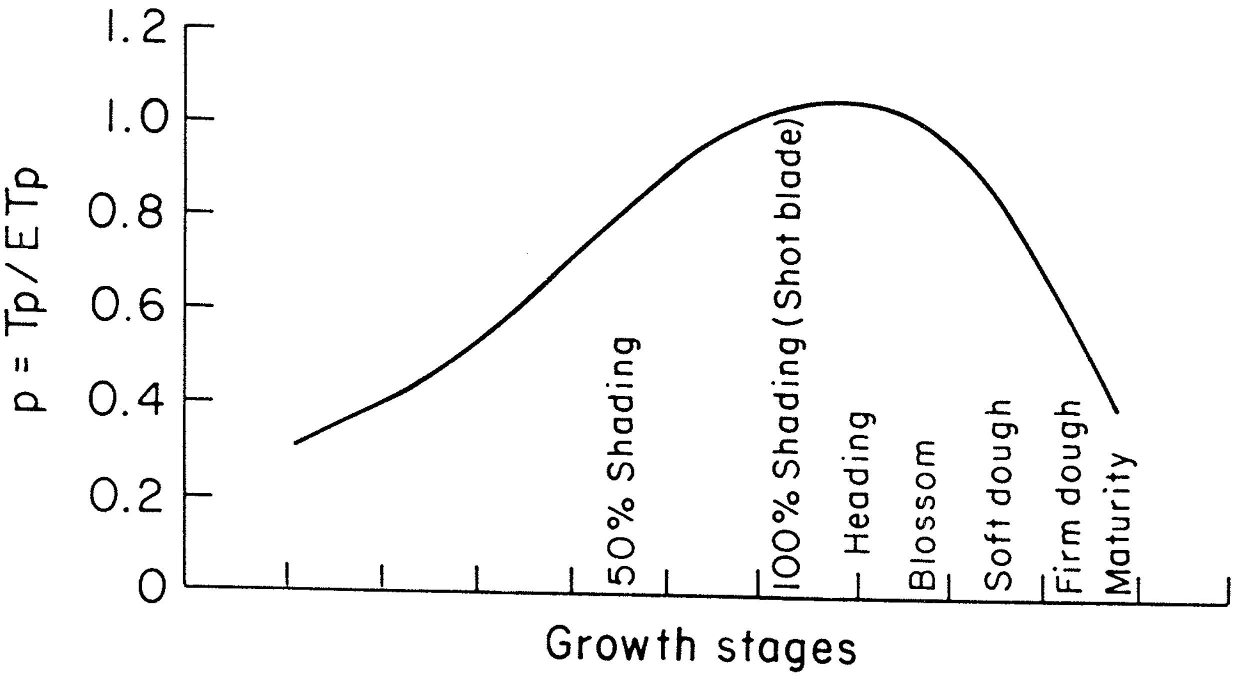


Figure 6: The partitioning factor, p, i.e., the fraction of potential evapotranspiration satisfied by transpiration at various stages of development of wheat. (After Hobbs and Krogman, 1968.)

Hobbs and Krogman (1968)) approximates reasonably the proportion of $\dot{E}$Tp accounted for by $\dot{T}$rp or the p function. It was assumed that the highest value of $\dot{T}$rp coincides with the maximum growth rate that is associated with the maximum leaf expansion. The active surface for transpiration was assumed to increase exponentially from emergence to heading (BMTS = 2.73). After heading, transpiration was assumed to decline due to leaf aging and senescence (Jones and Hesketh, 1980; Spiertz, 1982). From seeding to emergence, p is zero, therefore, $\dot{E}$vp ≃ $\dot{E}$Tp. From emergence to maturity, p is based on data tabulated in in BLOCKDATA with the phenological development (BMTS) as the predictor variable. In rainfed agroecosystems, soil moisture content is often limiting so the actual $\dot{E}$v and $\dot{T}$r are generally smaller than their respective potential value. Because the two rates are related to different agroecosystem components, $\dot{E}$v and $\dot{T}$r are computed separately.

3.4.4.4.1.3 Actual evaporation

It was assumed that evaporation takes place at the soil surface from the top 15 cm of soil. Further, it was assumed that the amount of water evaporated is controlled either by energy supply or by a combination of energy, water content and hydraulic properties of the soil. For calculating the amount of water transferred by evaporation, it is assumed that evaporation takes place in the superficial soil layer in two stages: "constant rate" and "falling rate" (Philip, 1957; Adams et al., 1976; van Bavel and Hillel, 1976). Both stages are considered in PIXMOD.

It was assumed that when the soil is moist, the actual evaporation rate ($\dot{E}$v) is controlled by the energy supply (implicitly considered within $\dot{E}$Tp) and the partitioning fraction, so that the evaporation rate is $\dot{E}vp$. When the soil moisture falls below a certain value, the evaporation rate starts decreasing below its maximum value. Both the transition point from one rate type to another, and the functional relationship between $\dot{E}v$ and $\dot{E}vp$ are controlled by the soil moisture content as well as the soil hydraulic properties. For the three textural classes (clay, loam and sand), the functional relationship $\dot{E}v/\dot{E}vp$ and relative available moisture content, θ^*_j, has been developed from the data published by Baier et al. (1972). The authors provide a set of eight curves (A through H) that relate $\dot{E}T/\dot{E}Tp$ with θ^*_j.

Based on the shape of soil-characteristic curves for Manitoba[2], the curve "D" of Baier et al. was selected as representative for clay soil, curve "G" for loamy soils and curve "H" for sandy-silty soils. For each textural class beyond the transition point from a constant to a falling rate, the following functions that estimate $\dot{E}v$ (cm d^{-1}) have been developed:

1) for clay soil,

$$\dot{E}v = \dot{E}vp \times (0.010258 \times e^{6.877143 \times \theta^*_j}), \quad \text{for } \theta^*_j < 0.66 \qquad (3.43)$$

2) for loam soils,

$$\dot{E}v = \dot{E}vp \times (0.003333 + 1.397619 \times \theta^*_j), \quad \text{for } \theta^* < 0.71 \qquad (3.44)$$

3) for sandy-silty soils,

$$\dot{E}v = \dot{E}vp \times (0.00381 + 1.968571 \times \theta^*_j), \quad \text{for } \theta^* < 0.505 \qquad (3.45)$$

where θ^*_j is the relative water content,

$$\theta^*_{i,j} = (\theta_{i,j} - WP_j) / (FC_j - WP_j) \qquad (3.46)$$

3.4.4.4.1.4 Actual transpiration

Since the soil moisture content in PIXMOD is calculated by a water

[2] Dr. C. Shaykewich, personal communication (1985).

budget technique, the actual transpiration rate was assumed to be the major sink term, S_j.

$\dot{T}r$ is calculated using a set of forcing functions coupled with simulated root penetration, and an estimate of the active soil volume element, RZ. As a first approximation, the relative water availability for transpiration was described by:

$$\theta^*_{RZ_i} = [\sum_{j=1}^{RZ/15} (\theta_{i,j} - WP_j) / \sum_{j=1}^{RZ/15} (FC_j - WP_j)] \times 100 \qquad (3.47)$$

where $\theta^*_{RZ_i}$ is the percentage of available soil moisture content in an active soil volume element, RZ is the depth of the root system (cm); all other terms have been defined previously.

Several authors (Denmead and Shaw, 1962; Aston and Lawlor, 1979; Meyer and Ritchie, 1980) reported that for a constant soil moisture content, the actual transpiration rate, $\dot{T}r$, varies with the atmospheric demand. To account for this, a new function, g, was introduced to balance $\dot{T}r$ as a function of both θ^*_{RZ} and $\dot{E}Tp$. The relationship between $\dot{T}r/\dot{T}rp$, relative transpiration rate, and available soil moisture content, θ^*_{RZ}, and atmospheric demand $\dot{E}Tp$ was derived from a function developed by Shaw (1963, Figure 7).

$$\dot{T}r = g \times \dot{T}rp \ (cm\ d^{-1}), \quad 0 \leq g \leq 1 \ . \qquad (3.48)$$

However, $\dot{T}r$ is calculated for the entire active soil volume element. In order to calculate the sink term by layer, which is essential in balancing the water and nitrate nitrogen within the subroutines, SSWETN and SNO3W the $\dot{T}r$ is partitioned among the layers of the active soil volume element.

In PIXMOD, $\dot{T}r$ and θ_j are known. The other two parameters, root system depth and percentage of roots within each layer, were estimated.

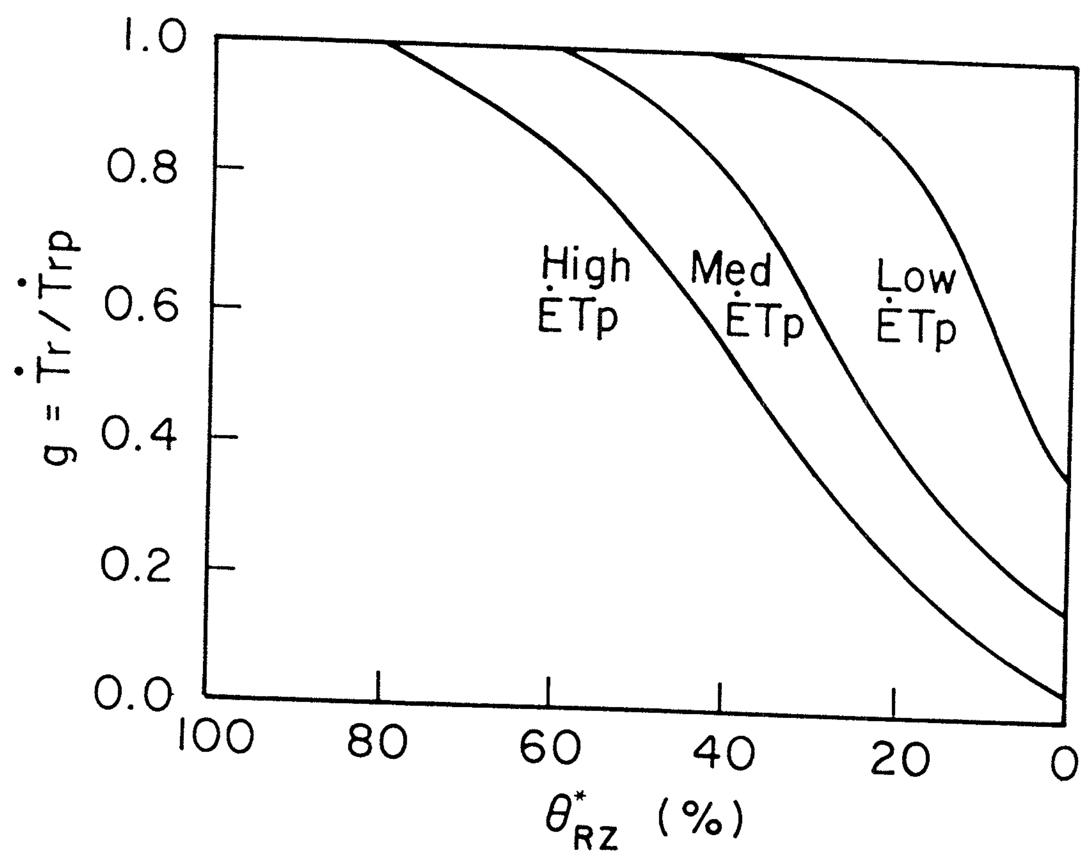


Figure 7: The relative transpiration rate, g, as function of percent of soil moisture content in the active soil volume element and atmospheric demand (after Show, 1963).

It was assumed that the vertical and horizontal expansion of the root system are correlated and that water uptake is proportional to the distribution of the roots within the active soil volume. The root density, RD, was approximated as a function of RZ from the literature data (Milthorpe and Moorby, 1974; Ellis and Barnes, 1973; Heen, 1980a; Heen, 1980b; Kirkham and Kanesmasu, 1983). The adopted pattern of water extraction by transpiration as a percentage of total transpiration rate, $\dot{Tr}$, as a function of depth (layer) is presented in Table 6. This data is included in the BLOCKDATA subroutine and is used as a dimensionless forcing function, fg. The independent variable of the fg function, the number of the active layers, anl, is represented as a (8x8) matrix. The anl values are calculated from the root depth, RZ, which in turn, is a function of phenological time. The actual transpiration rate (cm d^{-1}) from each layer is

$$\dot{Tr}_{j,i} = \dot{Tr} \times fg \qquad (3.49)$$

The largest amount of water, $\geq$ 80%, is extracted from the top 60 cm of the soil. However, the subroutine allows roots to compensate for water deficit within a layer that reached the WP value by using water from layers with adequate water supplies.

3.4.4.4.2 Soil Moisture Subroutine

Both water and oxygen deficiencies (water excess) are approximated in PIXMOD by budgetting of the water content within the soil profile during the growing season. The effect of water deficit on yield is described in some detail, whereas that of water excess is approximated.

The main function of this subroutine, SSWETN, is to budget soil water content within the rooting zone. All the calculations described in this chapter not performed within SSWETN are performed either within

Table 6. The water extraction pattern by transpiration as a percentage from the transpiration as affected by the depth of root penetration.

Depth (cm) of root penetration/layer	water extracted (percentage from total transpiration) from each layer							
0 - 15/1	100	50	40	35	35	35	35	30
15 - 30/2		50	40	35	30	30	30	30
30 - 45/3			20	20	20	15	10	10
45 - 60/4				10	10	10	10	10
60 - 75/5					5	5	5	5
75 - 90/6						5	5	5
90 - 115/7							5	5
115 - 120/8								5

the main program or in other functional subroutines.

The soil volume explored by the fully grown crop roots is defined by the maximum rooting zone, RZmax. In this study three different circumstances affecting RZmax were considered:

a) Well-drained soil subsystems with well-developed profiles,

b) Soil subsystems with shallow profiles due to bedrock, gravel deposits or other physical barriers that prevent both root penetration and the deep drainage, and

c) Soil subsystems with well developed profiles but with the water table at a depth that affects the soil moisture content within the rooting zone.

The simulation of the water available to a crop is, in essence, equivalent to simulating the water balance. The general equation that describes water balance for rainfed conditions is:

$$\Delta SMC + PREC \pm ROOF \pm DR - ET = 0 \quad , \qquad (3.50)$$

where ΔSMC is the change in content of water stored in the soil, PREC is precipitation, ROOF is runoff, DR is the drainage beyond RZmax, and ET is evapotranspiration.

Equation (3.50) is a loose description of the water balance because all the terms are rates; eqn. (3.50) does not define this but only implies it, cf. ΔSMC. In dealing with a dynamic system, where the size of the living subsystem is changing continuously, it is desirable to define more precisely the terms included in the water balance equation. The most common methods used to simulate water balance are the so-called "deterministic" and "parametric" methods (Stroosnijder, 1982). Within PIXMOD, a combination of both methods is used, although overall the water balance simulation follows the parametric approach.

3.4.4.4.2.1 Deterministic method

Within the deterministic method, the water balance problem is converted into a boundary-values problem. The simulation consists of solving the Darcy-Richards equation of water flow, including a sink term that accounts for water extraction by plant roots, i.e., transpiration, using an equation of the general form:

$$C(\psi) \frac{\partial\psi}{\partial t} = \frac{\partial}{\partial z} \left[K(\psi)\left(\frac{\partial\psi}{\partial z} - 1\right)\right] - S \quad . \tag{3.51}$$

Where $C(\psi)$ is differential moisture capacity, $C = d\theta/d\psi$, $K(\psi)$ is hydraulic conductivity and S is the sink term. Having defined the equation of flow, water balance can be converted into a transient boundary-values problem for water flow within the system of interest. However, to solve this problem one must know:

1. The agroecosystem geometry, particularly the depth dimensions of the soil subsystem, that is, the lower limit of the profile, $L\ell$, and RZmax.
2. The equation of flow.
3. The parameters that control the flow, i.e., $C(\psi)$, $K(\psi)$ and S. Obviously, to know $C(\psi)$, the relationship between ψ and θ must be known.
4. The initial conditions, i.e., $\psi(z,t = o) = \psi_o$.
5. Boundary conditions, that is, the conditions at the top and at the bottom of the profile. These can be expressed in several ways:
   a) in terms of the independent variable, i.e., $\psi(z = o,t)$ and $\psi(z = RZmax,t)$,
   b) in terms of flux, i.e., $\vec{q}(t)_u$, the flux at the soil surface and $\vec{q}(t)_{RZmax}$, the flux at the bottom of the soil volume,

c) combination of a and b; i.e., $\vec{q}(t)_u$ and $\psi(z = RZmax,t)$.

6. The method used to solve eqn. (3.51), that is, the calculation of $\psi(z,t)$.

It should be noted that the flow equation, eqn. (3.51), together with the initial conditions and the boundary conditions, contains all the elements of the water balance, eqn. (3.50).

To solve the flow equation, eqn. (3.51), it is converted into a finite-difference equation and approximated by an implicit finite-difference scheme. Deterministic simulation techniques have been used by Feddes et al. (1978) and by Belmans (1981) to simulate actual water use by crops in more complex models. The approach is physically sound and above all can provide an accurate simulation of the effect of the water table on crop growth. However, the method requires data that cannot always be measured or approximated. In addition, even if the inputs can be approximated, the number of integrations is very large so that this approach is feasible only for short simulation runs.

3.4.4.4.2.2 Parametric method

The main assumptions made in the parametric method can be summarized as follows:

1. The soil volume of interest is relatively homogeneous. Therefore, RZmax can be divided into a smaller number of layers of increased thickness compared with the depth-time diagram, where Δz must be a few cm.

2. The water stored in soil for a reasonable length of time and available to plants can be approximated by the water held by the soil within the limits FC and WP.

3. The two overall soil parameters, FC and WP, provide some

information on water flow ($\vec{q}$ and Q), as well as on the magnitude of the sink term and $\dot{E}v$. Assuming that above FC, $\vec{q}$ is high, then for one-dimensional water flow, water that enters the soil can be redistributed parametrically within RZmax so that no layer can hold more water than indicated by its FC value.

4. Each element of the water balance can be estimated separately. Therefore, the initial conditions expressed in terms of water content combined with appropriate elements of the water balance allow a separate water balance to be performed layer by layer over each time step.

Although the parametric method used to simulate matter-energy transport processes in soil divided into layers does not conform to the rigorous description used generally in soil physics, the parametric method is not a trivial solution (de Wit and van Keulen, 1975). These methods have been used successfully by van Keulen (1975) (ARIDCROP model) and Seligman and van Keulen (1980) (PAPRAN model).

The assumptions in PIXMOD related to water flow were: isothermal conditions, water moves only in liquid phase, the hydraulic head gradient is the main driving force of water flow, the pressure head represents mainly matric suction, and water flow can be adequately described by one-dimensional flow in the vertical direction.

3.4.4.4.2.3 Combined parametric-deterministic method

The calculation of water balance based on a transient boundary-values problem approach would provide information about soil moisture content over the whole range of conditions, from saturation, θs, to air-dry, θd. Although this would be a complete solution, it can be applied only to a limited number of practical agronomical problems. On the other hand, the parametric method cannot describe many of the important field conditions that inevitably exist within the large regions considered in land evaluation.

In the SSWETN subroutine, for soil moisture contents outside the range between field capacity (FC) and wilting percentage (WP), water is redistributed parametrically. For WP $\leq \theta \leq$ FC, water is redistributed using a simplified deterministic approach. The simulation procedure focuses on the water available for wheat growth. Although the redistribution of water in the range of water contents between FC and WP is slow, it was considered important for several reasons. First, the root system of the wheat crop does not explore the entire soil volume of interest, i.e., RZmax from the beginning of the growing season, so that water is not taken up simultaneously from the entire depth, and development of a potential gradient is to be expected. Second, because nitrogen is considered a limiting factor, its redistribution within the profile has been coupled with water flow. Parametric redistribution of water is too coarse a representation of nitrogen transport within the soil profile. Third, the effects of different boundary conditions at the bottom of the soil volume of interest cannot be represented without considering the water flux at that depth.

The geometry of the depth component of the three types of soil subsystem considered, the initial conditions, and the lower boundary conditions for one-dimensional flow are presented schematically in Figure 8. The soil is divided into j layers, $1 \leq j \leq 8$, of equal thickness, Δz = 15 cm. Since hysteresis is not considered in this study, initial conditions can be expressed equivalently either as

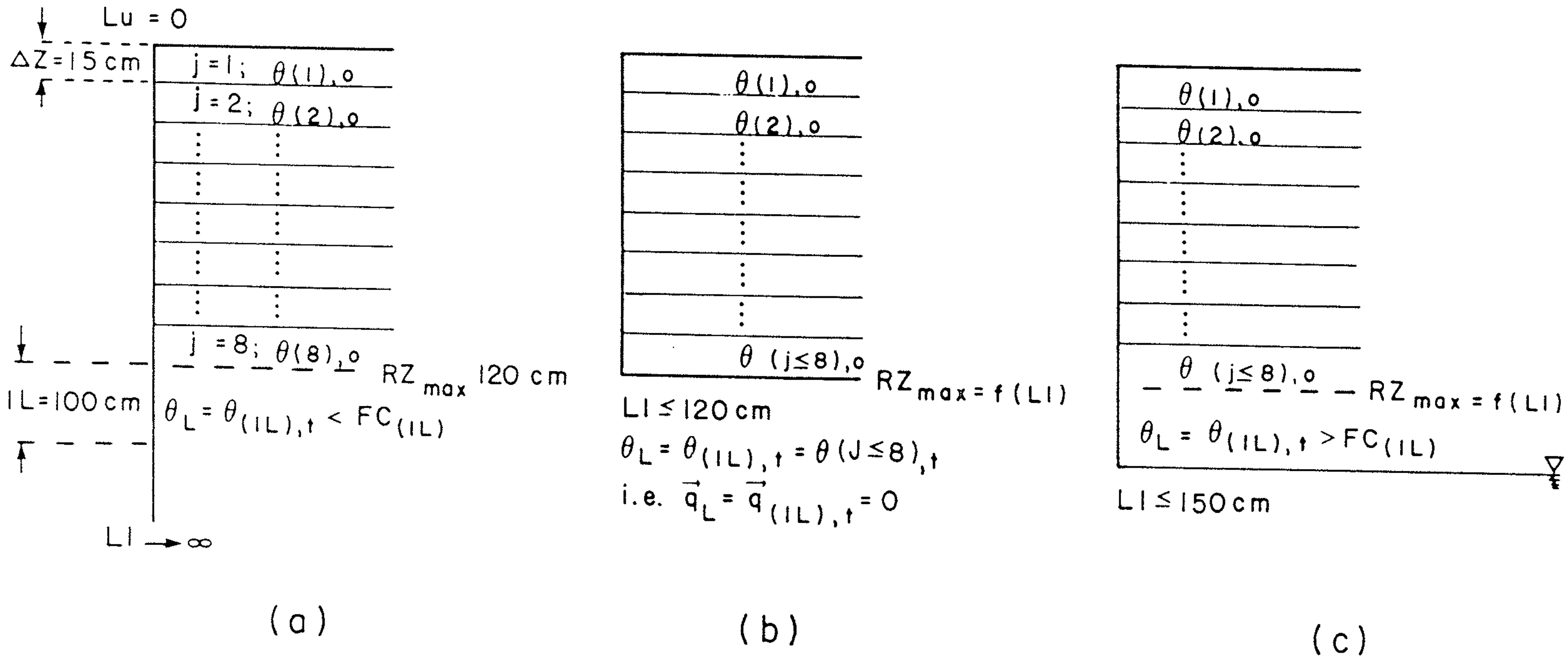


Figure 8: The geometry of the depth component of three soil subsystem types considered in the study and the initial conditions, $\theta_{j,o}$, and the lower boundary conditions, θ_{IL}, for one-dimensional flow; (a) well-developed profile, well drained, (b) profile with physical barrier and (c) profile with water table.

functions of h or ψ for each layer, designated by $\theta(z, t = 0) = \theta_{j,o}$. Upper boundary conditions, $\theta(z = 0, t) = \theta_u$, are not necessary because the elements of water balance included in the upper boundary conditions, precipitation, runoff and evaporation are measured or computed separately. In order to approximate the effect of the boundary condition on the lowest layer, an imaginary layer, IL, 100 cm thick is considered to exist beneath the last layer within the soil volume. The imaginary layer is assumed to have similar parameters, i.e., FC and WP, to the lowest layer, and it is used to approximate the lower boundary conditions, θ_L.

The case represented in Figure 8a pertains to well-drained soil subsystems (experimental site or soil series) with a well-developed profile. In this case the soil profile is of the "semi-finite" type, $Lu \leq Z < L\ell \rightarrow \infty$ and the soil element of interest has a maximum depth, i.e., RZmax = 120 cm. Within Sc. I, $\theta_{8,o}$ and $\theta_{L,o}$ are measured, so θ_L can be well approximated. For Sc. II, since θ_8 is assumed to be at FC_8, θ_L is assumed to be at 90% of its FC_{IL} so that a positive flux (outflow) from layer j = 8 is initiated.

The case represented in Figure 8b pertains to the soil subsystem with shallow profile below that is a physical barrier to water movement. In this case $L\ell \leq 120$ cm and RZmax = f(Lℓ). The $\theta_{L,t} = \theta_{j<8,t}$ and the flux out of the soil volume is zero.

The case represented in Figure 8c pertains to the soil subsystem with water table at a depth that may affect soil water content within the rooting zone. In this case, $L\ell \leq 150$ cm and RZmax = f(Lℓ). θ_L is set at θs_{IL}. Using the flow equation without gravity term the flux at the lower boundary is negative, i.e., upward.

The above information is given in DSMF file as input. For the case represented in Figure 8a, the number of layers, $n\ell$, has the standard value of 8. For the other two cases represented in Figures 8b and 8c, $n\ell = L\ell/15$ was rounded off to integer values.

For soil water contents between FC and WP the water is redistributed using a simplified deterministic procedure. Since water content between FC and WP represents an unsaturated condition, ψ is a pressure head less than zero. Assuming that the matric suction, ψ_m, is the main component of ψ, water flow equation is:

$$\vec{q} = -K(\psi)\left[\frac{\partial \psi_m}{\partial z} - 1\right]. \tag{3.52}$$

The state variable in the SSWETN subroutine is volumetric water content. Using the chain rule and assuming no hysteresis,

$$\frac{\partial \psi_m}{\partial z} = \frac{\partial \psi}{\partial \theta} \cdot \frac{\partial \theta}{\partial z} = \frac{1}{C(\theta)} \cdot \frac{\partial \theta}{\partial z} , \tag{3.53}$$

where $d\psi/d\theta$ is the reciprocal of the differential moisture capacity, i.e., $d\psi/d\theta = 1/C(\theta)$. On substitution of $\partial\psi_m/\partial z$ and $K(\theta)$ for $K(\psi)$, in eqn. (3.52) since the former relationship, $K(\theta)$, is affected by hysteresis to a much lesser extent (Topp and Miller, 1966), the flux can be written as:

$$\vec{q} = -K(\theta)\left\{\left[\frac{1}{C(\theta)} \cdot \frac{\partial \theta}{\partial z}\right] - 1\right\} . \tag{3.54}$$

The differential moisture capacity term can be implicitly represented by using the so-called diffusivity term. The hydraulic diffusivity term was defined by Childs and Collis-George (1950) as:

$$D(\theta) = K(\theta)/C(\theta) \quad . \tag{3.55}$$

Therefore, $\vec{q}$ is:

$$\vec{q} = - D(\theta) \frac{\partial \theta}{\partial z} + K(\theta) \tag{3.56}$$

For vertical flow of water, the equation from Staple (1966) is appropriate:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[D(\theta)\,\frac{\partial \theta}{\partial z}\right] + \frac{\partial}{\partial z}\,[K(\theta)] \tag{3.57}$$

Adding a sink term, S, the flow equation becomes:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[D(\theta)\,\frac{\partial \theta}{\partial z} + K(\theta)\right] - S \quad . \tag{3.58}$$

In all equations (3.56), (3.57) and (3.58) the true driving force, $\nabla\psi$, is replaced with the soil volumetric water content gradient, $\nabla\theta$. The relationship of the soil water potential to the volumetric water content is non-linear, as are the relationships of the hydraulic conductivity and the hydraulic diffusivity to the volumetric water content. However, for volumetric water contents between FC and WP, the nonlinearity is at a minimum compared with the extreme ranges.

Water balance is simulated in SSWETN in three steps. First, the redistribution of water between the centres of two adjacent layers is calculated, using eqn. (3.56) to approximate water flux. Second, the state variable is updated in each layer, and the water flow is coupled with appropriate elements of the water balance. Third, the state variable is calculated over the growing season, using a fixed time step of one day. In essence, this last step is equivalent to integrating a finite-difference equation chosen to represent eqn. (3.51) with respect to time. The solution of eqn. (3.58) is based on a simple forward difference noniterative method. Theoretically, Δt should be much smaller than one day, with a value based on the solution stability and convergence. Oscillations in the water redistribution solution have been observed during model development and screening of the simulation program. They were associated with induced steep soil moisture gradients, for example, during days with high precipitation events and low soil moisture content. To avoid this, on days with precipitation exceeding 20 mm d^{-1}, the soil moisture content is repeatedly updated within the one day time step. The number of integrations increases linearly with precipitation rates; one additional iteration for each 5 mm d^{-1} precipitation above 20 mm d^{-1}. It is assumed that the processes associated with water balance are linear in time over one day, so that the calculated rates are divided by the number of iterations per day.

The main problem in using eqn. (3.58) is to approximate $D(\theta)$ and $K(\theta)$, coefficients that are not fundamental, but derived soil "parameters". Three different textural classes were assumed to have significantly different hydraulic properties important in calculating water flow: sand, loam and clay. The values of $K(\theta)$ and $D(\theta)$ for each textural class were derived from a set of curves developed by Staple (1969), Figures 9a,b. Data points derived from these curves have been included in BLOCKDATA as a tabulated function: untabulated values are calculated by interpolation.

The runoff, ROOF, is calculated using a simple equation suggested by Duffy et al. (1975), based on the amount of daily precipitation.

$$ROOF = 0.344 \times PREC - 0.344 \quad \text{for } 2 \leq PREC\ (cm\ d^{-1}) \qquad (3.59)$$

where PREC is precipitation (cm d^{-1}), an input variable.

The soil moisture content as well as all other matter-energy entities of interest are calculated within the soil volume, i.e., RZmax, based on two fundamental assumptions:

a. within each depth interval, a soil layer, the state variables, auxiliary variables and parameters are fully homogeneous,

b. within a time step, generally one day, the flow of matter-

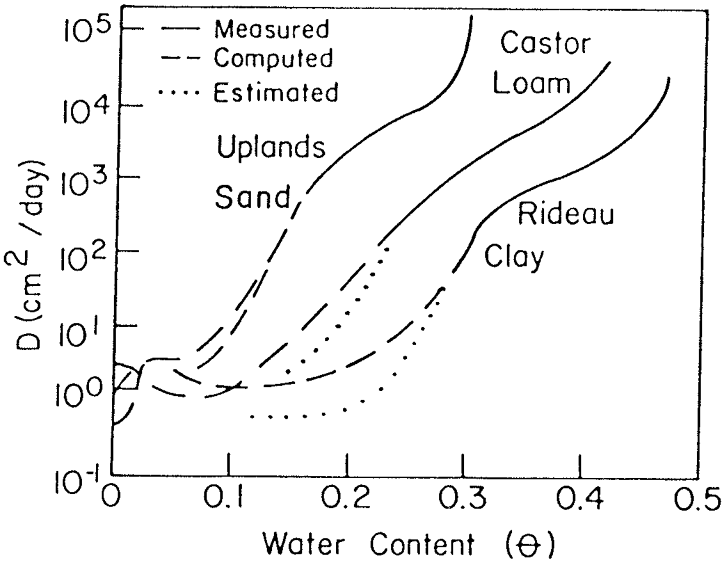


Figure 9a: Diffusivity as function of water content.

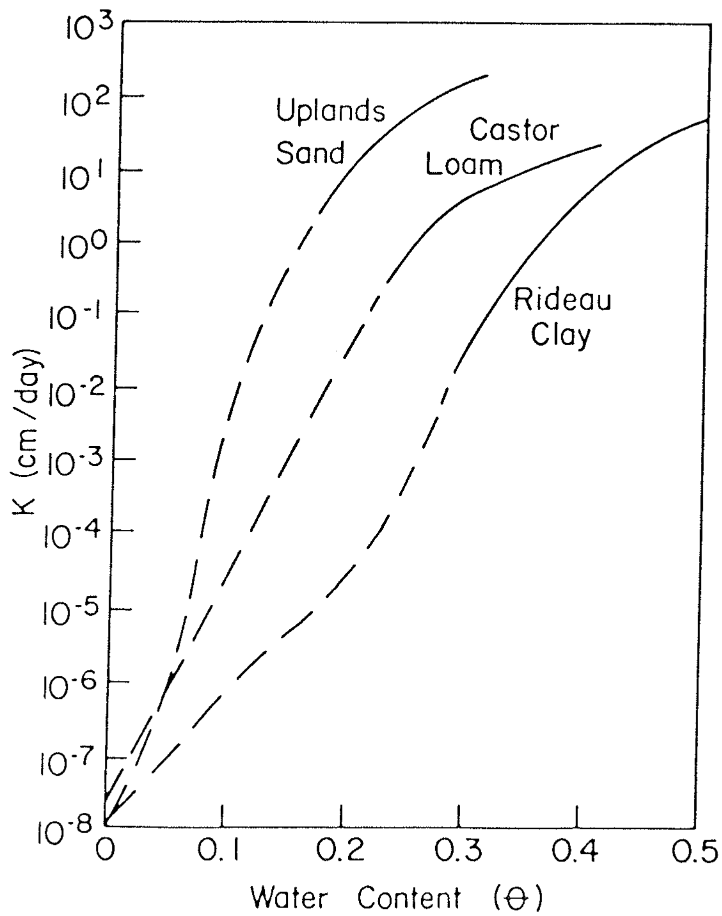


Figure 9b: Hydraulic conductivity as function of water content (after Staple, 1969, Soil Sci. Soc. Amer. Proc. 33, pg. 842, Fig. 2 and pg. 843, Fig. 3).

energy is stationary.

Having defined all the elements involved in the water balance equation, soil moisture is simulated in SSWETN in three steps.

1. First, the water redistribution within the soil volume is calculated by computing the water flux between the centres of two adjacent layers by means of eqn. (3.56). This is illustrated schematically in Figure 10. The flux equation becomes:

$$\vec{q}_j = \{\bar{D}_{j-1/2}(\theta) \times [\theta_{j-1}-\theta_j]/\Delta z_c\} + \bar{K}_{j-1/2}(\theta), \text{ for } 2 \leq j \leq 8 \quad (3.60)$$

where $\vec{q}_j$ is the flux (cm d^{-1}) at the center of layer j into the jth layer due to the gradient developed between layer j-1, and layer j, $\bar{D}$ is the average hydraulic diffusivity at the upper boundary of layer j (cm^2 d^{-1}), $\bar{K}$ is the average hydraulic conductivity at the upper boundary of layer j (cm d^{-1}), θ is volumetric water content ($cm^3 cm^{-3}$) and Δz_c is the distance between the centres of two adjacent layers (cm).

The parameters $\bar{D}(\theta)$ and $\bar{K}(\theta)$ are arithmetic averages of the respective parameters over two adjacent layers, as a function of volumetric water content.

The flux within the imaginary layer, IL, takes a value according to the lower boundary conditions of RZmax (Figure 8) as described below.

Case a - well drained soil with well-developed profile:

$$\vec{q}_{IL} = \{\bar{D}_{IL-1/2}(\theta)[\theta_{j=8} - fFC_{IL}]/\Delta Z\ell_c\} + \bar{K}_{IL-1/2}(\theta) , \quad (3.61)$$

where fFC_{IL} is a fraction of the field capacity of the imaginary layers ($cm^3 cm^{-3}$) and $\Delta Z\ell_c$ is the distance between the centre of the last layer within the RZmax, j = 8, and the imaginary layer, i.e., $\Delta Z\ell_c$ = 57.5 cm, (the subscript IL refers to the imaginary layer). All other terms and dimensions are similar to those defined for eqn. (3.60).

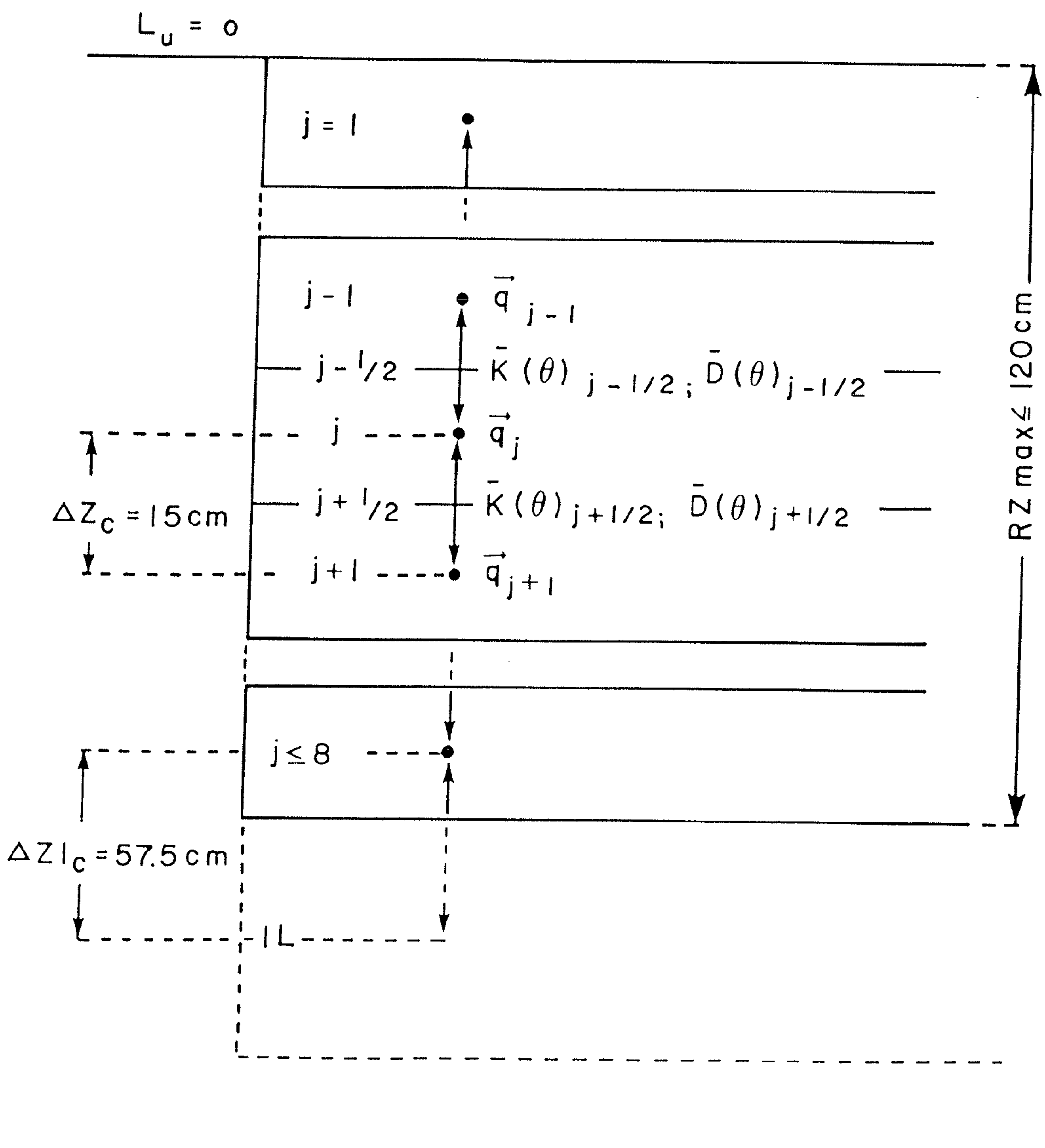


Figure 10: Geometry of the soil subsystem, depth component, used to calculate water flux between centres of two adjacent layers.

The fraction f, a dimensionless factor ($f < 1.0$), can be approximated from past experiments within the region. The experiment carried out to validate the model indicated that a value of 0.9 gives a good result.

For cases b and c, $\vec{q}$ is calculated using an equation similar to eqn. (3.60), with appropriate substitutions corresponding to the particular boundary conditions, as described below.

Case b - soil with shallow profile and physical barrier:

The flux, $\vec{q}_{IL} = 0$.

Case c - soil with water table at a depth $\leq$ 150 cm:

By replacing fFC_{IL} with a value of θ larger than FC_{IL}, for instance, with θs_{IL}, and neglecting the gravity term, $K(\theta)$, the flux, $\vec{q}_{IL} < 0$, (upward flux).

2. Second, the net flow, Qn, within an individual layer is calculated, per cm^2 of land area.

$$Qn_{(j)} = [Q_{(j)} - Q_{(j+1)}] - S_{(j)} , \qquad (3.62)$$

where $Qn_{(j)}$ is the net flow ($cm^3 cm^{-2} d^{-1}$) through the boundaries of layer j, $Q_{(j)}$ is the flow at the upper boundary and $Q_{(j+1)}$ is the flow at the lower boundary. The $S_{(j)}$ is the sink term, due to water uptake by the roots for transpiration from the entire layer (Δz,cm) ($cm^3 cm^{-2} d^{-1}$).

Based on the assumption that the fluxes at the layer boundaries are equal with the flux at the centres of two adjacent layers, eqn. (3.62) can be rewritten as:

$$Qn_{(j)} = [\vec{q}_{(j)} \times A - \vec{q}_{(j+1)} \times A] - \dot{T}r_{(j)} \quad (cm^3 cm^{-2} d^{-1}) , \qquad (3.63)$$

where $Qn_{(j)}$ is the net flow ($cm^3 cm^{-2} d^{-1}$) in layer j, $\vec{q}_{(j),(j+1)}$ is the flux at the boundary, j-1/j and j/j+1, respectively ($cm\ cm^{-2} d^{-1}$), A is the area (cm^2) and $\dot{T}r_{(j)}$ is the actual transpiration rate from eqn.

(3.49) ($cm^3 cm^{-2} d^{-1}$).

For the second-to-last layer within RZmax, the calculations of $Qn_{(j)}$ are straightforward problems because the flux values are available (eqn. (3.60) and eqn. (3.61)). $\dot{Tr}_{(j)}$ for the active soil volume (RZ), i.e., the layer containing roots, is larger than zero, whereas for the soil layer without roots it is zero. However, for the first layer, the flux term, $\vec{q}_j$, has not been calculated; $\vec{q}_j$ is replaced with $\vec{q}*$, a term calculated from water balance elements:

$$\vec{q}*_{(j)} = PREC - ROOF - \dot{Ev} - \dot{Tr}_{(j)} \quad \text{for} \quad j = 1 , \qquad (3.64)$$

where $\vec{q}*_j$ is the substituted flux element (cm d^{-1}), PREC is precipitation (cm d^{-1}) (input variable, Appendix E), ROOF is the runoff (cm d^{-1}), from eqn. (3.59), $\dot{Ev}$ is the actual evaporation (cm d^{-1}),from eqns. (3.43 to 3.45) and $\dot{Tr}$ is the actual transpiration (cm d^{-1}), eqn. (3.49).

The value of $Qn_{(j)}$ is calculated for an entire layer. Based on assumption (a), dividing $Qn_{(j)}$ by Δz, yields the net flow per cm^3 of soil, $Q*(n)_j$ ($cm^3 cm^{-3} d^{-1}$).

3. Changes in the state variable of interest, $\theta_{(j)}$, over one time step, generally one day, are calculated using an updating procedure.

$$\theta_{j,i} = \theta_{j,i-1} + Q*(n)_{j,i} , \text{ for } j=1, \ldots, n\ell \leq 8, \text{ and } i=1, \ldots , n(m) \qquad (3.65)$$

where $\theta_{j,i}$ is the volumetric water content in layer j on day i ($cm^3 cm^{-3}$) $\theta_{j,i-1}$ is the volumetric water content in layer j on the previous day. If i=1 then $\theta_{j,i-1} = \theta_{j,o}$, the initial conditions. $Q*(n)_{j,i}$ is the net flow in layer j per cm^3 of soil during the time i; $n\ell$ is the number of layers within RZmax, and n(m) is the last day of the growing season.

Once $\theta_{j,i}$ is calculated, based on input data recorded for day i+1, the calculation of the fluxes and net rates, (steps 1 and 2) is repeated and $\theta_{j,i+1}$ is recalculated. The process continues until the last day of the growing season, i.e. the day when the crop reaches maturity (BMTS = 5, Pd = 500). Soil moisture content can be estimated by layer, by active rooting zone, RZ, by different growth stages, etc. Also, any other element of water balance such as water evaporated, transpired or runoff, can be estimated over a time longer than the one day time step.

3.4.4.4.3 Soil Nitrogen Subroutine

For the present study, three fundamental aspects of the N-cycle were assumed to be important: (a) the "actual" amount of the nitrogen present in the soil during a growing season; (b) the dynamics of nitrogen, particularly the processes associated with nitrogen transformations, uptake by crop and losses beyond the rooting zone and (c) the nitrogen stress effect (lack of adequate amount) on crop growth. All these aspects are interrelated and complex; the amount of nitrogen in the soil varies widely in time and space. The nitrogen dynamics are mediated by microorganisms, but this microbiological component of the agroecosystem could not be represented in PIXMOD. The rate variables used in SNO3W subroutine are derived from the literature and local experiments. They are empirical and to some extent, speculative.

The main objective of the SNO3W subroutine is not to describe in detail the solute fluxes, but rather to provide reasonable estimates of the amount, position and distribution of the soluble nitrogen species within the soil profile during the growing season. The subroutine follows an approach described by Vithoyathil et al. (1977) and calculates a simple nitrogen balance for each soil layer, closely linked with water balance. Several assumptions were made; they can be summarized as follows:

1. From the many solute species present in soil at any time (Org.-N, NO_3^-, NH_4^+, NO_2^-, N_2, etc.) it was assumed that two ion species are the most important for plant nutrition: nitrate (NO_3^-) and ammonium (NH_4^+). The nitrogen in the soil was assumed to be represented by these two ions.
2. The nitrogen within the agroecosystem was assumed to be in only three states: "stable" in organic fraction (organic matter), mineral in the solution phase, and in dynamic (living) material (plants).
3. The total amount of nitrogen in the soil over a growing season was assumed to be a function of intrinsic properties of the soil (native organic matter content), past management (total inorganic nitrogen present in soil prior to fertilizer application) and management input (amount of fertilizer applied).
4. The nitrogen available for plant growth was assumed to be a function of two interrelated groups of processes: (a) nitrogen transformation, (b) nitrogen movement and uptake by the plant.
5. The stress effect of nitrogen on plant growth was considered to be reasonably described by a simple function of plant demand - soil supply.

The amount of nitrogen in the soil prior to the application of fertilizer as well as the fertilization rates are treated as input data. Consequently, the SNO3W subroutine focuses on the two groups of processes mentioned above: nitrogen transformation and nitrogen movement and uptake. The stress effect was programmed within the SCGRW subroutine, since this aspect is closely related to the growth process.

3.4.4.4.3.1 Nitrogen transformation

A large number of processes are related in one way or another to the nitrogen cycle. Generally, the most important processes are assumed to be mineralization-immobilization, nitrification, denitrification, volatilization and biological N_2 fixation.

Two broad categories of equations have been used to describe these processes: empirical equations and kinetic equations. The first category is particularly useful when the equations relate the nitrogen to plant uptake under a precise set of conditions (optimum or stress). For example, the results of an optimum, or highest nitrogen uptake by the crop at each phenological stage can be interpolated in time and space and used as a reference term. The equations that belong to the second category have a wider theoretical range of application since they are based on proven biochemical processes. However, since most such equations are mediated microbiologically, their practical application is limited.

The empirical equations are of the regression type. The kinetic equations that have been widely used to describe almost every rate variable associated with the N-cycle, including the nitrogen uptake by plants, can be further subdivided in three fundamental types:

(a) zero-order rate kinetics

$$dS^*/dt = K_o \tag{3.66}$$

(b) first-order rate kinetics

$$dS^*/dt = K_1(S^*) \tag{3.67}$$

(c) Michaelis-Menten rate kinetics

$$dS^*/dt = K_m \times S^*/(K_s + S^*) \quad , \tag{3.68}$$

where dS^*/dt is the substrate transformation rate, S^* is the substrate concentration, K_o, K_1, K_m and K_s are zero, first, maximum and saturation constants, respectively.

In the present study it was assumed that within the Prairie region the net mineralization, nitrification and denitrification are the most relevant processes associated with the function of the agroecosystem. The mathematical descriptions of those processes used in the SNO3W subroutine are based mainly on empirical equations.

A. Net Mineralization. According to Nyborg et al. (1976), the amount of nitrogen released from the soil during one year is about 56 kg ha^{-1} in the Prairie region. The Provincial Soil Testing Laboratories from the region make fertilizer recommendations assuming that half of this amount is released during the growing season at a constant rate. Further, they assume that all soils in the region are the same as to the properties of their more stable nitrogen content, such as organic nitrogen, and the temporal conditions, such as soil temperature and pH, that affect the net mineralization rate. Temporal soil conditions affect the net mineralization indirectly by their influence on microbiological activity, which is extremely complex, and thus difficult to represent mathematically within the framework of this study. However, the mineralization-immobilization processes are less sensitive to temporal soil conditions and more strongly related to the organic nitrogen (van Veen, 1977).

In order to differentiate between soils, the net mineralization rate was linked with the organic matter content. By using the results of past experiments carried out in Manitoba over several years on different soil series[3], the mineralization was found to be exponentially related to organic matter:

$$(NO_3 - N)m = 12.9\ e^{0.15*OM} \quad , \quad r = 0.64 \quad , \tag{3.69}$$

where $(NO_3 - N)m$ is net mineralization during the growing season (kg ha^{-1}) and OM is the organic matter content of the topsoil (%).

Assuming that the mineralization is a slow process that takes place at a constant rate during the growing season, it was expressed as:

$$\dot{N}M = 7.01 \times 10^{-4}\ e^{0.15*OM} \quad , \tag{3.70}$$

where $\dot{N}M$ is the net mineralization rate (mg-N $cm^{-2}d^{-1}$). Since most of the microbial activity takes place in the upper part of the soil profile, the mineralized nitrogen was divided equally between the first two layers, i.e., $j = 1,2$ (0 to 15 cm and 15 to 30 cm).

B. <u>Nitrification</u>. In SNO3W, it was assumed that nitrification takes place in a single step ($NH_4^+ \rightarrow NO_3^-$). This assumption is particularly appropriate for soils with approximately neutral pH, so that the oxidation of NO_2^- is rapid. Agronomical experience (Duffy et al., 1975) has shown that most of the nitrogen fertilizer applied in reduced forms nitrifies within a few weeks of application. The authors concluded that for Illinois conditions, about 80% of NH_4^+ fertilizer applied in the spring is nitrified within 20 days. Based on this conclusion, and assuming that spring temperatures are much lower in the Prairie region than in the central part of the U.S.A., it was assumed that about 80% of spring-applied NH_4^+ fertilizer would nitrify within the first 45 days of application. The nitrification rate, $\dot{N}T$, is computed in SNO3W as follows:

---

[3] Dr. G. Racz, personal communication (1985).

$$\dot{NT}(t) = 0.8 \times AFA/45 \times 0.01 \qquad t_a < t \leq t_a + 45 \qquad (3.71)$$

$$\dot{NT}(t) = 0.005 \qquad t_a + 45 < t \quad , \qquad (3.72)$$

where $\dot{NT}(t)$ is the nitrification rate (mg-N $cm^{-2}d^{-1}$), AFA is the amount of NH_4^+ fertilizer applied (kg ha^{-1}), t_a is the day of fertilizer application (t_a = 0). Since often the nitrogen fertilizer is applied at seeding time, t_a coincides with the t_o used to indicate the start of the growing season in PIXMOD. The factor 0.01 is used to convert the amount of nitrogen, from kg ha^{-1} to mg cm^{-2}. According to eqns. (3.71, 3.72) 80% of the fertilizer, regardless of the type (i.e., ammonium, sulfate, urea), is nitrified in the first 45 days at a rate that depends only upon the amount of fertilizer applied. After 45 days from the seeding date, nitrification continues at a low rate until all the fertilizer is nitrified. Since the fertilizer is often either broadcast or shallow-incorporated with the seed, the nitrification was assumed to take place only within the first layer, j = 1 (0 to 15 cm).

C. Denitrification. In SNO3W, denitrification was assumed to occur in all soil types. The denitrification rate was considered to be a function of soil moisture content and the amount of nitrate nitrogen in the soil. Theoretically, denitrification occurs at a high intensity under flooding conditions; thus, a high rate should be expected when the moisture content is close to saturation. Since the model does not simulate the water content within the profile above FC, conditions of saturation cannot be identified. The FC value is used to indicate the conditions of denitrification, not its rate. Denitrification is a function of both depth and temperature; it decreases exponentially with depth and increases linearly with temperature (Cho et al., 1979). Thus, in SNO3W, denitrification was assumed to take place only in the top layers of the profile and to be relatively constant over the growing season. Assuming that a maximum of 25 kg ha^{-1} can denitrify during a growing season at a constant rate, and that the process takes place within the first two soil layers (i.e., j = 1,2 = 30 cm), the rate of denitrification is calculated as follows:

$$\dot{DN} = 0.00136 \text{ for } \theta_{(j)} = FC_{(j)} \text{ and } NN_{(j)} \geq 0.00136,\ j = 1,2 \qquad (3.73)$$

where $\dot{DN}$ is the denitrification rate (mg-N $cm^{-2}d^{-1}$), and NN is nitrate nitrogen (mg-N cm^{-2}).

3.4.4.4.3.2 Nitrogen movement

The differential equation employed by deterministic models to describe one-dimensional flow under isothermal condition (Tanji et al., 1981) was of the general form:

$$\frac{\partial(\theta Cx)}{\partial t} = D\frac{\partial^2 Cx}{\partial z^2} + \vec{q}\,\frac{\partial Cx}{\partial z} - \frac{Cx\lambda(z,t)}{\theta} - \frac{\rho}{\theta}\frac{\partial Ex}{\partial t} + SK\ , \qquad (3.74)$$

where θ is volumetric water content ($cm^3 cm^{-3}$), Cx is concentration of mobile N species ($\mu g\ cm^{-3}$), D is apparent diffusivity coefficient ($cm^2 d^{-1}$), $\vec{q}$ is water flux (cm d^{-1}), λ is root absorption coefficient (dimensionless), ρ is soil bulk density (g cm^{-3}), Ex is concentration of N species in the exchange phase ($\mu g\ g^{-1}$) and SK is a general source-sink term ($\mu g\ cm^{-3}\ d^{-1}$).

It should be pointed out that the SK term stands for the overall result of the transformations considered to be relevant for a specific problem (mineralization-immobilization, denitrification, etc.). Also the time dimension, day (d), has been introduced only to define the terms correctly; most processes take place at faster rates. If the soil moisture contents are considered over the entire range $\theta d \leq \theta \leq \theta s$, then the problem must be converted into a transient boundary-values problem and the solution based on appropriate finite-difference equation. The solution of eqn. (3.74) using a finite difference method is even more complex and difficult than the solution of water flow equation because SK must be known almost on a continuous basis, SK(z,t). The equation used in SNO3W is a simplified version of eqn. (3.74) and follows a procedure developed by de Wit and van Keulen (1975) for the transport of salt in layered soil. This procedure has been widely used in many models with the soil profile divided into discrete layers (Kruh and Segall, 1981; van Veen and Frissel, 1981).

Equation (3.74) has been further simplified; the terms of the right hand side have been redefined as follows:

$$D \frac{\partial^2 Cx}{\partial z^2} = v_d \tag{3.75}$$

$$\vec{q} \frac{\partial Cx}{\partial Z} = v_c \tag{3.76}$$

$$\frac{Cx\lambda(z,t)}{\Theta} = S\ell m \tag{3.77}$$

$$\frac{\rho}{\theta} \frac{\partial Ex}{\partial t} = i(ex) \tag{3.78}$$

$$SK = Nt - Sn \quad , \tag{3.79}$$

where v_d is diffusion flow of the mobile ion (mg $cm^{-3}d^{-1}$), v_c is convective or central mass flow of the mobile ion (mg $cm^{-3}d^{-1}$), $S\ell m$ is the uptake of the ion by the crop (mg $cm^{-3}d^{-1}$), i(ex) is the absorption-desorption net result of the ion-exchange process (mg $cm^{-3}d^{-1}$) Nt is the net result of transformations considered (net mineralization, nitrification and denitrification) (mg $cm^{-3}d^{-1}$) and Sn is the sink term, i.e., mobile nitrogen ion uptake by the crop (mg $cm^{-3}d^{-1}$).

Eqn. (3.74) written in terms of nitrogen changes within one layer of thickness (ℓ = 15 cm) over one time step ($\partial t \simeq \Delta t$ = 1 day) is:

$$\Delta(\theta Cx) = v_d + v_c - S\ell m - i(ex) + Nt - Sn \quad (mg\ cm^{-2}d^{-1}) . \qquad (3.80)$$

Since most Manitoba soils have a high cation exchange capacity, generally between 10 and 20 cmol(+)kg^{-1} dry soil and even higher, it was assumed that any ammonium ion, NH_4^+-N, that has not been denitrified is either adsorbed on the clay surface or fixed and hence very slightly mobile. In contrast, the nitrate nitrogen ion, NO_3^--N, is not adsorbed and is quite mobile. The terms $S\ell m$ and $i(ex)$ in eqn. (3.80) have been neglected. It was further assumed that the NO_3^--N uptake is controlled by the transpiration rate, since it seems to be unaffected by the nitrate nitrogen concentration in soil solution over a wide range (Breteler et al., 1981), provided that $C_{(NO_3^- -N)}$ is larger than 0.1 m M.

Based on the assumption that there is a steady state over a time step, the calculation of NO_3^--N transport is based on the net flow within each layer as follows:

$$v_{N(j)} = v_{(j)} - v_{(j+1)} \qquad j = 1,2,\ldots \leq 8 \qquad (3.81)$$

where v_N is net flow of NO_3^--N into layer j (mg-N $cm^{-2}d^{-1}$), $v_{(j)}$ is the amount of NO_3^--N (flow) that moves from layer j-1 to j (mg-N $cm^{-2}d^{-1}$) and $v_{(j+1)}$ is the amount of NO_3^--N flow that moves from layer j to j+1. Here,

$$v_{(j)} = v_{d(j)} + v_{c(j)} , \qquad (3.82)$$

where $v_{d(j)}$ is diffusion flow (mg-N $cm^{-2}d^{-1}$) and $v_{c(j)}$ is the mass flow (mg-N $cm^{-2}d^{-1}$).

Diffusive flow is calculated in the same manner as water flow. First, it is calculated as the flux between the centres of two adjacent layers, based on Fick's first law, and then the flow is calculated at the boundaries of the layers:

$$\vec{v}_{d(j)} = D_A \times \frac{C_{j-1} - C_j}{\Delta_j} \quad , \tag{3.83}$$

where D_A is apparent diffusion coefficient ($cm^2 d^{-1}$), C is NO_3^--N concentration in layer j-1 and layer j, respectively (mg-N cm^{-3}) and Δ_j is the distance between the two centres of the adjacent layers (cm).

For the simulation performed, the D_A values are not known precisely at the level of the soil subsystems included. Therefore, it was more convenient to consider diffusion and dispersion as separate processes and to adjust the coefficients based on some properties of the soil. Assuming that the diffusion and dispersion are additive, and that the diffusion coefficient is a function of water content, θ, and tortuosity, τ, while the dispersion coefficient is a function of the flow velocity, $\vec{q}$, D_A was expressed as:

$$D_A = D_o \times \tau \times \frac{\theta_{j-1} + \theta_j}{2} + D_s \times |\vec{q}| \quad , \tag{3.84}$$

where D_o is diffusion coefficient of NO_3^--N in water ($cm^2 d^{-1}$), τ is tortuosity (the ratio of apparent diffusion pathway to the actual pathway) (dimensionless), θ is volumetric water content ($cm^3 cm^{-3}$), D_s is dispersion factor (cm) and $\vec{q}$ is water flux ($cm^3 cm^{-2} d^{-1}$).

Substituting the apparent diffusivity coefficient D_A, of eqn. (3.84), into eqn. (3.83), the diffusive flow is:

$$v_{d(j)} = \left[D_o \times \tau \times \left(\frac{\theta_{j-1} + \theta_j}{2} \right) + D_s \times |\vec{q}_{(j)}| \right] \times \left(\frac{C_{j-1} - C_j}{\Delta_j} \right) (\text{mg-N cm}^{-2} d^{-1}) \tag{3.85}$$

The mass flow within a differential soil volume element, layer, is:

$$v_{c(j)} = Q_{(j)} \times \frac{C_{j-1} + C_j}{2} = \vec{q}_{(j)} \times A \times \frac{C_{j-1} + C_j}{2} \quad (\text{mg-N cm}^{-2} d^{-1}) \tag{3.86}$$

where $Q_{(j)}$ is water flow ($cm^3 cm^{-2} d^{-1}$), $\vec{q}_{(j)}$ is water flux (cm $cm^{-2} d^{-1}$), A is cross sectional area through which flow occurs (cm^2) and C is NO_3^--N concentration ($mg\text{-}N\ cm^{-3}$).

Cracks often develop in the soil under rainfed farming conditions, particularly in soils with high clay content. These cracks have an effect on $\vec{q}$, especially in the surface layers. From a physical viewpoint, this results in nearly instantaneous flow. Since the water above FC is redistributed parametrically, the effect of cracks is implicitly recognized. However, the high flux also alters the NO_3^--N transport, i.e., the concentration of NO_3^--N in the water is much lower than it would have been if the water had been redistributed uniformly throughout the entire volume of soil. To account for this phenomenon, a dimensionless factor, less than unity, called "the leaching efficiency" ℓe (Beek and Frissel, 1973) is introduced. The actual amount of NO_3^--N transport by mass flux then becomes:

$$v_{c(j)} = \vec{q}_{(j)} \times A \times \ell e\left(\frac{C_{j-1}+C_j}{2}\right) \qquad (mg\text{-}N\ cm^{-2}d^{-1}) \qquad (3.87)$$

By substituting eqns. (3.85) and (3.87) into eqn. (3.82), the amount of NO_3^- transported, $v_{(j)}$, between two adjacent layers, j-1 and j, is:

$$v_{(j)} = \left\{\left[D_o \times \tau \times \left(\frac{\theta_{j-1}+\theta_j}{2}\right) + D_s \times |\vec{q}_{(j)}|\right] \times \left(\frac{C_{j-1}-C_j}{\Delta_j}\right)\right\} + \left\{\vec{q}_{(j)} \times A \times \ell e\ \frac{C_{j-1}+C_j}{2}\right\}$$
$$(mg\text{-}N\ cm^{-2}d^{-1}) \qquad (3.88)$$

Equation (3.88) is used to compute NO_3^--N flow from the second soil layer down to the last layer within RZmax ($j \leq 8$). For the first layer and the imaginary layer, eqn. (3.88) is modified slightly to account for the depth geometry of the soil subsystem (Fig. 10), and for the lower boundary conditions (Fig. 8). With all flow terms calculated, the net flow is computed using eqn. (3.81). The change of NO_3^--N in each layer is calculated daily using a balance technique:

$$NN_{j,i} = NN_{j,i-1} + v_{N(j),i} + Nt_{j,i} - Sn_{j,i} \qquad (\text{mg-N cm}^{-2}) \qquad (3.89)$$

$$Nt_{j,i} = \dot{N}M_{j,i} + N\dot{T}_{j,i} + D\dot{N}_{j,i} \qquad (\text{mg-N cm}^{-2}) \qquad (3.90)$$

$$Sn_{j,i} = \dot{T}r_{j,i} \times C_{j,i} \qquad (\text{mg-N cm}^{-2}) \qquad (3.91)$$

where $NN_{j,i}$ is the amount of nitrate nitrogen (mg-N cm^{-2}) in the layer j on day i, and Nt is the amount of nitrate nitrogen (mg-N cm^{-2}) yield by the transformations considered, i.e., net mineralization, nitrification and denitrification. All other terms have been previously defined.

To start the calculation at i = 0, the initial amounts of nitrate nitrogen, $NN_{j,o}$, must be known; the amount of NO_3^--N is given as input data (ppm). The conversion to the initial conditions as mass per layer is made as follows:

$$C_{j,o} = \frac{ppm_{j,o} \times 0.001 \times \rho_{b(j)}}{\theta_{j,o}}, \text{and} \qquad (\text{mg-N cm}^{-3}) \qquad (3.92)$$

$$NN_{j,o} = C_{j,o} \times \theta_{j,o} \times \Delta z \qquad (\text{mg-N cm}^{-2}) \qquad (3.93)$$

While the SNO3W subroutine does not predict precisely the amount of nitrogen within the soil profile, it does provide an approximate accounting of one of the most important crop nutrient and its effect on yield.

3.4.4.4.4 Soil temperature subroutine

Soil temperature affects all processes that take place in the agro-ecosystem regardless of their type, biological, chemical or physical, and in PIXMOD it is a correspondingly important form of matter-energy with an overall effect on crop growth. The soil temperature subroutine, SSTEMP, simulates the soil temperature at 20 cm depth.

If the temperature of the soil surface is known for steady state conditions, the heat transport in a homogeneous soil profile by molecular conduction, the relevant transport mechanism, can be described by the first law of heat conduction (Fourier's heat conduction equation). To describe the transient state, Fourier's heat conduction equation is combined with the continuity equation of energy conservation that yield an equation formally similar to Fick's second law of diffusion and the Darcy-Richards equation of water flow. The calculation of heat transport using such equations has been approached both mechanistically, i.e., numerical solution (Wierenga et al., 1970; van Bavel and Hiller, 1975) and parametrically (de Wit and van Keulen, 1975).

In order to be consistent with the solution used for water and solute transport, a parametric approach would appear to be the most appropriate solution. However, the soil surface temperature changes significantly over one day, so the time step must be kept very small even when the parametric method is adopted. For example, de Wit and van Keulen (1975) employed a time step of 10 min., i.e., about 14,400 iterations per growing season. For land evaluation problems such a large number of iterations is prohibitive. Several other problems arise in the simulation of soil temperature. For instance, the thermal conductivity (K_T), a parameter essential in the heat flux equation, is highly variable, both in space due to change in mineralogical composition of soil as well as in time over a growing season, due to changes in volumetric water content. It is difficult, if possible at all, to approximate a parametric value of K_T for a large area such as soil series from the existing data. In addition, past records of soil temperature at seeding time (i.e., the initial conditions) are not available.

In subroutine SSTEMP, both initial soil temperature and subsequent soil temperature changes are calculated using a simple approach. First, it was assumed that soil temperature at 20 cm depth has an impact on physiology of the root system and implicitly upon growth rate. Soil subsystem was divided in six thin layers, j*, of different thickness, 1, 2, 2, 5, 5 and 5 cm, respectively. It was further assumed that soil temperature is a function of the annual heat cycle produced by the sun, as well as the temperature of the "temporal" air mass that passes randomly over the soil surface.

The initial conditions, T(j*,o), are calculated assuming that soil temperature is a function of the annual cycle of solar radiation alone. The temperature at the soil surface as a function of time of the year (t) can be approximated by a sine function:

$$T(z=o,t) = \bar{T} + Ao \sin \omega t \ , \qquad (3.94)$$

where $\bar{T}$ is the average temperature of the soil surface, Ao is the average amplitude of seasonal changes in soil temperature, ω is the angular frequency (radians) and t is time.

Carslaw and Jaeger (1960) provide the solution of a heat transport equation for transient conditions using a sine function, for a homogeneous medium with semi-finite boundary conditions ($0 \leq z < \infty$).

The approximate relationship between soil temperature and soil depth at different times of the year is:

$$T(z,t) = \bar{T} + Ao \exp(-z/dd) \sin(\omega + \phi - z/dd) \ , \qquad (3.95)$$

where dd is the damping depth, $dd = \sqrt{(2D_t/\omega)}$, the depth where the temperature amplitude is 1/e x Ao and ϕ is phase.

Using an appropriate set of parameters for the Canadian Prairie region, $\bar{T} = 5.5^{o}C$, $Ao = 12.5^{o}C$, dd = 140.7 cm (Reimer, 1978), $\omega = 0.5236$ month^{-1} and $\phi = -1.964$ (Cho et al., 1979), the temperature at the centre of each soil layer is calculated by employing the following equation:

$$T(z_{j*},t_s) = 5.5 + 12.5 \exp(-z_{j*}/140.7) \sin[0.5236t_s - (z_{j*}/140.7) - 1.964] \quad (3.96)$$

where $T(z_{j*},t_s)$ is soil temperature (°C) at the centre z_{j*} (cm) of layer $j*$ at seeding time (t_s = day), calculated such that $t_s = 0$ for the 1st of January and $t_s = 6$ for the 1st of July (Cho et al., 1979).

Equation (3.96) is used only to calculate the initial soil temperature values at seeding time. The soil temperature is simulated over the growing season using an empirical set of equations (Walker, 1977). Although eqn. (3.96) simulates the heat transport correctly from a physical viewpoint, for a given depth and time of year, it predicts the same soil temperature from one year to another and from one place to another across the Prairie.

To account for variation of soil temperature from year to year and place to place the soil temperature of each layer is updated using a set of empirical equations involving the air temperature, the past temperature of the layer (one day before) as well as the temperature of the upper adjacent layers:

$$K_{j*} = z_{j*}/k_1 - k_2 \quad (3.97)$$

$$T_{j*,i} = \bar{T}a \qquad K_{j*} < 0,\ j* = 1 \quad (3.98)$$

$$T_{j*,i} = [(K_{j*} \times T_{j*,i-1}) + T_{j*-1,i}]/(K_{j*}+1),\ K_{j*} > 0,\ j = 0,..,6 \quad (3.99)$$

Here, T_{j*} is the temperature of layer $j*$ on day i (°C), K_{j*} is an empirical variable (dimensionless), z_{j*} is the depth (cm) at the centre of the soil layer $j*$, k_1 is a constant (cm), k_2 is a dimensionless constant and $\bar{T}a$ is the mean air temperature, (TMAX+TMIN)/2, (°C). The chosen values of the constants were $k_1 = 6$ and $k_2 = 0.25$ since Walker (1977) used these values and found good agreement between measured and simulated data.

Eqns. (3.97) to (3.99) imply that the temperature at the soil surface (z_{j*} = 0.5 cm) is equal to the mean air temperature. As the depth increases, the soil temperature is controlled less by the above layer temperature ($T_{j*-1,i}$) and is more dependent upon its own temperature on the previous day ($T_{j*,i-1}$). The soil temperature is an average estimate over one day, with no distinction between day and night temperatures. It is assumed that the soil temperature within the sixth layer (15 to 20 cm depth) is much more stable than the air temperature.

Since the model simulates the aboveground net production, the stress effect of each factor (including soil temperature) upon the crop growth is initiated at the emergence stage. However, the subroutine SSTEMP is activated at seeding time. It was assumed that for years and/or locations with large deviations in terms of air temperature from the average conditions in the Prairie, conditions implicitly included in eqn. (3.96), by using eqns. (3.97) to (3.99) soil temperature at emergence would be adequately adjusted and it will be more representative for a particular growing season and location. Theoretically, a better adjustment of soil temperature at 20 cm depth will be achieved for cases in which the air temperature is lower than the average because the time elapsed from seeding to emergence that is controlled by the phenological development (SPDW subroutine) will be longer.

3.4.4.4.5 Phenological Development Subroutine

This subroutine is, in essence, the BioMeteorological Time Scale (BMTS) model developed by Robertson (1968). Although by comparison with other scales (for instance, Haun's Scale) Robertson's Scale is less definitive (Bauer et al., 1983), the BMTS is the most appropriate model for this study for several reasons. First, the model uses standard available meteorological data as predictor variables. Second, the model includes the effect of all three major environmental components (maximum temperature, minimum temperature and photoperiod) on wheat development. Other models are generally based on the degree-day approach, a simple method that includes only the temperature factor. Angus et al. (1981) showed that the day length (photoperiod) strongly modified the rate of wheat development, particularly during the vegetative phase. Third, the BMTS model accounts for nonlinear effects on development of each individual environmental component. Fourth, the BMTS model integrates the influence of the three factors over short periods (growth stages) in which the major biological processes are likely to be uniform. Fifth, the BMTS model includes the effect of meteorological elements on phenological development over a time step of one day and therefore depends on weather elements rather than climate parameters.

The BMTS recognizes six phenological events (S - planting, E - emergence, J - jointing, H - heading, D - soft dough and M - maturity, i.e., biological maturity) and five biological periods or growth stages. Each period has an equal length of a BMTS unit (dimensionless). For convenience this unit was subdivided into 100 units of phenological time, Pd, so that Pd = BMTS x 100, and:

$$\sum_{i=S}^{E} Pd_{(i)} = \sum_{i=E}^{J} Pd_{(i)} \cdots = \sum_{i=D}^{M} Pd_{(i)} = 1 \text{ BMTS} = 100 \text{ Pd} \qquad (3.100)$$

$$\sum_{i=S}^{E} Pd_{(i)} + \sum_{i=E}^{J} Pd_{(i)} \cdots + \sum_{i=D}^{M} Pd_{(i)} = 5 \text{ BMTS} = 500 \text{ Pd} \qquad (3.101)$$

$Pd_{(i)}$, the fractional progress toward maturity over day i, is:

$$Pd_{(i)} = F_{P(i)}[F_{TMAX(i)} + F_{TMIN(i)}] \qquad (3.102)$$

where F_P is a function of day length, F_{TMAX} is a function of maximum temperature and F_{TMIN} is a function of minimum temperature for a particular day, i.

$$F_{P(i)} = a_1(L_{(i)} - a_o) + a_2(L_{(i)} - a_o)^2 \qquad (3.103)$$

$$F_{TMAX(i)} = b_1(T_{MAX(i)} - b_o) + b_2(T_{MAX(i)} - b_o)^2 \qquad (3.104)$$

$$F_{TMIN(i)} = d_1(T_{MIN(i)} - b_o) + d_2(T_{MIN(i)} - b_o)^2 \qquad (3.105)$$

where L is photoperiod (h), T_{MAX} is maximum air temperature measured in a Stevenson screen (^oF), T_{MIN} is minimum air temperature measured in a Stevenson screen (^oF) for the day, i, and a_o, a_1, a_2, b_o, b_1, b_2, d_1 and d_2 are coefficients characteristic of each biological period.

The three major independent variables (L, T_{MAX} and T_{MIN}) are given as input data (an example is presented in Appendix E). The temperature data are converted to ^oF in the SBMTS subroutine. The value of the coefficients ($a_o \ldots d_2$) are included in the BLOCKDATA subroutine as an 8 x 5 array.

The seeding date, either given as input data or calculated, becomes the initial condition for phenological development.

By using eqn. (3.102), the degree of maturity is computed on a daily basis. The cumulative value of the degree of maturity, $cPd_{(i)}$, is used frequently as an auxiliary variable to simulate other major physiological processes in the SCGRW subroutine.

3.4.4.4.6 Plant Growth Subroutine

The plant growth subroutine, SCGRW, integrates data and information from all other subroutines and passes back information to the functional subroutines. This subroutine makes the link between soil and crop subsystems. Five major groups of calculations are performed by SCGRW: potential growth rate, root elongation, composite limiting factor, actual growth rate and actual cumulative net production.

3.4.4.4.6.1 Potential growth rate

The potential growth rate is a straightforward calculation:

$$\dot{b}p_{(i)} = \sum_{cPd_{(i-1)}}^{cPd_{(i)}} \dot{b}p(Pd) \tag{3.106}$$

where $\dot{b}p_{(i)}$ is potential growth rate (kg $ha^{-1}d^{-1}$) of day i, $\dot{b}p(Pd)$ is potential growth rate normalized to phenological time, Pd, (kg per hectare per unit Pd) (eqn. (3.31)), $cPd_{(i-1)}$ is cumulative phenological development on the previous day (i-1) and $cPd_{(i)}$ is cumulative phenological development over day i.

3.4.4.4.6.2 Root growth

There is evidence in the literature that supports the idea that root development can be related to phenological development. For example, Brouwer (1963) pointed out that shoot and root growth are coordinated processes. Austin (1981) showed that growth of vegetative structure, therefore both shoot and root, generally ceased by anthesis. Salter and Goode (1976) and Kanemasu (1983) noted that, for determinate species, the root growth slowed or completely ceased at flowering. Consequently, root elongation is described in SCGRW by a modified form of the function proposed by Rasmussen and Hanks (1978):

$$RZ(cPd)_i = Zs + \frac{RZmax - Zs}{1 + e^{k_1 - [k_2 * (cPd)_i / cPdm]}} \tag{3.107}$$

where $RZ(cPd)_i$ is the depth of root system, or the active soil element volume (cm), Zs is the depth of sowing (cm), RZmax is the maximum rooting zone (cm), $(cPd)_i$ is the cumulative phenological development (Pd units), cPdm is the cumulative phenological development at which the root growth ceases, and k_1 and k_2 are coefficients.

The sowing depth Zs was set at 3.0 cm. Its value may vary slightly with soil properties or moisture conditions at seeding time as well as with cultivar. However, this variation has minimal impact on the calculation. It was assumed that maximum rooting depth occurred at flowering. Since the flowering stage occurs shortly after heading (Bauer et al., 1983), the cPdm value was set halfway between heading and soft dough stages, i.e., cPdm = 350, 3.5 BMTS units. The value of k_1 and k_2, the crop characteristic parameters, were taken from Rasmussen and Hanks (1978). For spring wheat they suggested $k_1 = 5$ and $k_2 = 8$. Based on the computed value of $RZ(cPd)_i$, the number of active layers, $an\ell$, is calculated followed by the calculation of $\dot{T}r_j$ and ultimately of soil moisture and nitrogen contents.

3.4.4.4.6.3 Limiting factors

The composite effect of all types of stresses included in the model is calculated using eqn. (3.12). Several terms are used in the literature to designate the undesirable effect of the lack or excess of different forms of matter-energy on crop growth: limiting effect, deficit, stress, etc. For example, Morgan (1980) and Hsiao and Bradford (1983) use pressure potential, ψ_p, to define cell wall deformation due to stress. They calculated the stress as a mechanical normal stress (normal force per surface area, which is equivalent to pressure). Hiler and Howell (1983) distinguished between "water deficit" and "water stress". The last term was used in the case of severe water deficit.

In the present study the terms limiting effect, deficit and stress are used with the same meaning: an undesirable condition of the living subsystem, the limiting factor being the factor that prevents the living subsystem from expressing its potential (Boyer, 1983).

A great number of articles has been published on the stress effects on crop yield. Since those experiments were performed under controlled environmental conditions, very little of their results can be applied to field conditions (Fisher, 1979; Jordan, 1983; Patterson, 1983). By necessity, data used in this study to express the limiting factor effect on wheat growth are composite integrated values or implicit functions. As within all practically oriented models, ARIDCROP, PAPRAN, TIMOTHY, CERES and EPIC (Tables 3 and 4, Chapter II), PIXMOD estimates of stress effects are based on simple demand-supply functions. To arrive at the overall limiting factor effect, LF, each individual limiting factor effect is calculated separately.

A. Water limiting factor. The water limiting factor is calculated in PIXMOD using an exponential equation suggested by Rickman et al. (1975) of the following form:

$$W\ell_{(i)} = 1 - e^{-3 \times \theta^*_{RZ(i)}} , \qquad (3.108)$$

where $W\ell_{(i)}$ is the water limiting effect (dimensionless, with values between 0 and unity, and $\theta^*_{RZ(i)}$ is the relative available water content in RZ, the active soil element volume.

However, eqn. (3.108) has been developed for irrigation purposes where, generally, the stress effect is never severe. For example, at $\theta^*_{RZ(i)} = 0.4$, that is, soil moisture content less than midway between FC and WP, eqn. (3.108) predicts a relatively mild stress effect, $W\ell_{(i)} \simeq 0.70$. Eqn. (3.108) is used in PIXMOD to predict the short term effect of water deficit, assuming that the growth rate can recover to its potential value on removal of the stress. This is based on evidence in the literature for growth rate recovery after a mild water stress (Begg and Turner, 1976; Fisher, 1979; Jordan, 1983).

However, prolonged and severe water stress induces a morphological change associated with cell elongation, cell division and rate of cell senescence, all of which affect the photosynthetic process and therefore, the growth rate. This is a permanent effect (Begg and Turner, 1977; Hsiao and Bradford, 1983; Hiler and Howell, 1983), since there is no mechanism for compensation, for instance, by increasing the number of leaves.

To account for this a second water limiting factor, $W\ell^*_{(i)}$, is computed based on the so-called "stress day index" approach (Hiler and Clark, 1971). The fundamental assumption behind the stress day index is that the yield decreases significantly under prolonged and severe water stress. The decrease in yield depends not only upon the degree and duration of water deficit, but is also a function of the phenological growth stage of the crop (Campbell and Davidson, 1979; Shaw, 1983; Jordan, 1983).

The general form of stress day index equation is:

$$SDI = \sum_{s=1}^{n} (SD_s \times CS_s) \ , \qquad (3.109)$$

where SDI is the stress day index, i is the growth stage, SD_s is the stress day factor (a measure of stress intensity) and CS_s is crop susceptibility index (a function of both crop species and the growth stage).

If we assume that the main environmental index that describes water deficit is the actual evapotranspiration, then the stress day index can be expressed as a function of the level of actual evapotranspiration, ET, relative to its maximum value, i.e., potential evapotranspiration, ETp:

$$SD_s = \left(\frac{ETp - ET}{ETp}\right)_s = \left(1 - \frac{ET}{ETp}\right)_s \tag{3.110}$$

where 1 - ET/ETp is the relative evapotranspiration deficit. Assuming a linear relationship between relative yield, Y/Yp, and ET/ET_p (where Yp is the potential yield), then the relative yield decrease, 1 - Y/Yp, as a function of the environmental factor selected, i.e., evapotranspiration, is:

$$\left(1 - \frac{Y}{Yp}\right)_s = CS_s \left(1 - \frac{ET}{ETp}\right)_s , \tag{3.111}$$

or

$$\left(\frac{Y}{Yp}\right)_s = 1 - CS_s \left(1 - \frac{ET}{ETp}\right)_s . \tag{3.112}$$

The crop susceptibility factor, CS_s, is thus the relative slope $[\Delta(Y/Yp)_s \,/\, \Delta(ET/ETp)_s]$, a dimensionless factor independent of ET.

Several models have been proposed to describe the relative yield function, all based on the stress day index approach. Two of these were proposed by Minhas et al. (1974):

$$Y/Yp = \prod_{s=1}^{n} [1 - (1 - (ET/ETp)_s)^2]^{\beta s} \tag{3.113}$$

and Doorenbos and Kassam (1979):

$$Y/Yp = 1 - \sum_{s=1}^{n} kys(1 - ET/ETp) , \tag{3.114}$$

where βs and kys are crop susceptibility factors whose values are functions of crop species and growth stages.

The two equations are, in essence, similar. The main difference between them consists of assumptions made relative to the overall stress effect over the growing season. For example, eqn. (3.113)implies that the stress effect is multiplicative ($\prod_{s=1}^{n}$) whereas eqn. (3.114) implies that the stress effect is additive ($\sum_{s+1}^{n}$).

The model of Minhas et al. (slightly modified) was selected to calculate the stress day index. It was assumed that the actual transpiration, Tr, is a more appropriate measure of water deficit than actual evapotranspiration. Consequently, the prolonged, severe water stress effect, $W\ell*_{(i)}$ is computed as follows:

$$W\ell*_{(i)} = [1 - (1 - \dot{T}r_{(i)}/\dot{T}rp_{(i)})^2]^{\beta s} \quad , \qquad (3.115)$$

where $W\ell*_{(i)}$ is prolonged, severe water limiting factor effect (dimensionless, 0 - 1), $\dot{T}r$ and $\dot{T}rp$ are actual and potential transpiration rates, respectively ($cm^3 cm^{-2} d^{-1}$), and βs is the wheat susceptibility factor (dimensionless) with the following values for the various growth periods (stages):

- vegetative growth, $100 \leq cPd < 200$; $\beta s = 1.5$,
- flowering and grain formation, $200 \leq cPd < 400$; $\beta s = 5.0$,
- maturation, $400 \leq cPd$; $\beta s = 0.0$.

B. Nitrogen limiting factor. In the SCGRW subroutine, the nitrogen limiting factor is calculated based on a simple demand-supply relationship. It is assumed that the rate of aboveground net production is not affected when a normal "optimum" nitrogen concentration exists in the aboveground portion of the crop. The optimum nitrogen content at different growth stages has been derived from the results obtained in an experiment carried out by Racz et al. (1965) on a black, well-drained soil, Portage Association, in 1962. The optimum fraction of nitrogen content in the aboveground net production as a function of phenological development, No(Pd), is included in the BLOCKDATA subroutine as a tabular function. Assuming that the availability of nitrogen becomes limiting when the uptake falls below 75% from optimum (Baldwin, 1976), the nitrogen limiting factor effect is calculated using an exponential equation as follows:

$$N\ell_{(i)} = e^{-\left(\frac{No(Pd) - Nu/Bm}{0.75\ No(Pd)}\right)^2} \quad , Nu/Bm < No(Pd) \qquad (3.116)$$

$$N\ell_{(i)} = 1 \quad , Nu/Bm \geq No(Pd) \qquad (3.117)$$

where $N\ell_{(i)}$ is nitrogen limiting factor effect (dimensionless, 0 - 1), No(Pd) is the optimum nitrogen fraction in the aboveground net production (kg N/kg ANP), Nu is total nitrogen uptake (kg N ha^{-1}) and Bm is aboveground net production (kg ha^{-1}).

C. Soil temperature limiting factor. The response of wheat growth to soil temperature was assumed to have an optimum value as well as lower and upper limits. The temperature stress factor effect is computed with the equation:

$$T\ell_{(i)} = e^{-[\Omega^{T_{j*,i}}((To - T_{j*,i}) / T_{j*,i})^2]} \qquad (3.118)$$

where $T\ell_{(i)}$ is the soil temperature limiting factor effect (dimensionless, 0 - 1), $T_{j*,i}$ is soil temperature, i.e., j* = 6, (20 cm depth) (^{o}K), To is optimum soil temperature (^{o}K) and Ω is a coefficient.

The optimum soil temperature value is not well defined, as can be inferred from experiments that attempted to relate growth rate to air temperature. For example, Varade et al. (1970) and Stewart and Whitfield (1965) reported an optimum of 20^{o}C. Brengle and Whitfield (1965) found that at 12.8^{o}C the wheat grew slower and produced fewer tillers than at 18.3^{o}C but at 12.8^{o}C produced about 50% more kernels per head. Macdowall (1973) working with Marquis wheat, reported two peaks for optimum growth rate at 15^{o}C and at 25^{o}C. In PIXMOD it was assumed that 15^{o}C is the optimum temperature. Setting the growth rate at a very low value, i.e., 10^{-2} at 0^{o}C (273 K), the equation (3.118) was solved for Ω. The soil temperature limiting factor effect is thus calculated using the equation:

$$T\ell_{(i)} = e^{-[1.02721^{T_{j^*,i}}((288 - T_{j^*,i}) / T_{j^*,i})^2]} , \qquad (3.119)$$

where the resulting value for Ω has been used.

Having calculated individual limiting factor effects in eqns. (3.108/3.115), (3.116/3.117) and (3.119), the composite effect of limiting water, nitrate nitrogen and soil temperature can be calculated daily using eqn. (3.12).

3.4.4.4.6.4 Aboveground net production and grain yield

The calculation of cumulative aboveground net production, Bma, is a straightforward computation. The actual growth rate $\dot{b}a_{(i)}$ is calculated first by multiplying the potential growth rate with the composite limiting factor effect. Summation of the actual growth rate over the growing season, i.e., from emergence, BMTS = 1, Pd = 100, to maturity, BMTS = 5, Pd = 500, produced the final ANP value:

$$Bma_{(Pd=500)} = \sum_{i=1,Pd=100}^{n,Pd=500} \dot{b}a_{(i)} \quad (kg\ ha^{-1}) \qquad (3.120)$$

The grain yield or product, (P), is calculated based on the harvest index approach:

$$P = Bma_{(Pd=500)} \times Hi \quad (kg\ ha^{-1}) \qquad (3.121)$$

Two implicit assumptions are behind eqn. (3.121). First, it is assumed that grain yield is determined by the total ANP accumulated over the entire growing season. Although this viewpoint is not accepted by all physiologists, there is strong evidence (Fisher, 1979; McPherson and Boyer, 1977) suggesting that grain yield is correlated with total ANP, rather than with the amount of ANP formed during the grain-filling period. Second, it is assumed that Hi is constant across the region under consideration and from one year to another. As mentioned in Chapter II, Hi is a more conservative parameter than other parameters generally used in modeling, but it is not a constant. In the present study, a Hi value of 0.38 was derived from a large data set gathered within Manitoba over several years and at many site locations.[4]

3.4.4.5 Poor Aeration Limiting Factor

To include the effect of poor aeration on yield, this condition was replaced by excess water conditions associated with the soil drainage characteristics. Excess water conditions were assumed to affect agroecosystem function in three ways (or a combination of them): (a) delay of the seeding date, (b) reduction of growth, and (c) crop losses by flooding of unconnected depressions.

The adjustment of seeding date due to imperfect or poorly drained soils has been discussed in section (3.2.2). Reduction of yield per unit area either due to water excess, WE, during the growing season or water accumulation within a small depression, WA, is calculated by adjusting the final yield, i.e., $Bma_{(Pd=500)}$ and P, grain, obtained by simulating the daily growth.

The water excess factor is calculated in PIXMOD as follows:

$$WE = \sum_{j=1}^{n\ell} (\theta'_j \times \Delta Z) + \sum_{i=1}^{m} (PREC_{(i)} - \dot{E}v_{(i)} - \dot{T}rp_{(i)}) \quad , \qquad (3.122)$$

where θ'_j ($cm^3 cm^{-3}$) is the difference between the water content in the soil layer at seeding time, WC^*_j, and WP_j (the WC^*_j in the subsurface layer of soils with water excess problem is higher than FC_j) ΔZ is the

---

[4] Dr. G. Racz, personal communication

layer thickness (cm), $PREC_{(i)}$, $\dot{Ev}_{(i)}$ and $\dot{Trp}_{(i)}$ are daily precipitation, actual evaporation and potential transpiration rate, respectively ($cm^3 cm^{-2} d^{-1}$).

The modified plant-available soil moisture content at seeding time (θ'_j) is not the most appropriate reference term to calculate the excess water factor (WE). The air-filled porosity (relative air content) is a more logical reference parameter to estimate the excess water effect on crop growth. However, to calculate the relative air content both the porosity index and the degree of saturation must be known. Calculation of the degree of saturation requires simulation of soil wetness (θ) dynamically (one day step interval) over the full range, i.e., from dry soil (θd) to completely saturated soil (θs). The parametric method employed in PIXMOD does not permit a detailed simulation of soil water content above FC value. The equations used in the model to calculate the excess water effect on wheat growth provide only a crude approximation of the effect of excess water on crop yield. More elaborate models and large data sets are needed to correctly simulate the excess water effect on crop growth based on concepts derived from classical soil physics theory.

In the model evaluation phase, the θ' are measured. For application, Sc.II, the θ' are approximated, based on calculations of saturated moisture content:

$$\theta'_{(j)} = f_{(j)} = [(\rho s - \rho_{b(j)}) / \rho s] \times \Delta z \qquad (3.123)$$

where $f_{(j)}$ is porosity ($cm^3 cm^{-3} cm$), ρs is density of solids ($g\ cm^{-3}$), taken as a constant (for most mineral soils $\rho s \approx 2.65\ g\ cm^{-3}$), and $\rho_{b(j)}$ is the bulk density by layer ($g\ cm^{-3}$), values calculated by SCPARA subroutine, and Δz is layer thickness (cm).

The adjustment of water content, $\theta^1_{(j)}$ is made for soils that are either characterized as imperfectly drained, poorly drained or soils with water table at $L\ell \leq 150$ cm (Fig. 8c). The number of layers for which $\theta^1_{(j)}$ is modified, is based on texture, drainage class and lower boundary conditions, L^ℓ, from the input data. These parameters were approximated from early spring field observations gathered over several years in Manitoba.[5]

Reduction of yield due to WE is calculated using a modified equation suggested by McBride (1984) that, in essence, is based on the Doorenbos and Kassam stress day index model, eqn. (3.114):

$$Y^*/Ys = 1 - [kys(WE - k_1)/k_2], \quad WE > k_1 \qquad (3.124)$$

where Y* is adjusted yield (kg ha^{-1}), Ys is simulated yield (kg ha^{-1}), kys is crop susceptibility factor (dimensionless) over the entire growing season kyg = 1.15 (Doorenbos and Kassam, 1979), k_1 and k_2 are coefficients, k_1 = 15 cm and k_2 = 35 cm (McBride, 1984).

Eqn. (3.124) implies:

(1) Simulated yield, Ys, is the maximum yield attainable assuming no effect due to lack of soil aeration. This is not necessarily potential yield, because other limiting factors, such as the amount of nitrogen and the soil temperature, will act on yield even when soil conditions are in optimum in terms of water and aeration.

(2) A water excess, WE, as an overall amount of water within the rooting zone during the growing season, would have a similar impact on growth as would a water deficit. The coefficient kys was thus chosen to be 1.15, as suggested by Doorenbos and Kassam (1979) for

---

[5] Dr. W. Michalyna, personal communication, 1984.

wheat, over the entire growing season.

(3) The yield decreases linearly with increasing the water excess factor, so that as WE $\rightarrow$ 45 $cm^3 cm^{-2}$ the yield becomes zero. The values of k_1 and k_2 for wheat have been calculated using as a reference the yield response to WE for corn and oats (McBride, 1984).

The crop losses were defined in this study as losses of the effective cropping areas due to small watersheds formed during the growing season in unconnected depressions. The initial assumption made was that the entire area of soil series characterized as imperfectly or poorly drained can be seeded, with some delays as compared to well-drained soils. The effective watershed area formed in any given year was assumed to be controlled by both soil subsystem parameters (depth and surface component) and precipitation events.

Soil drainage is an hydrological problem rather than a purely soil physics problem. Many data required in solving hydrological problems have to be determined at the drainage basin level. In the present study, for a quick and crude approximation of the effect of soil drainage characteristics on crop losses, the basin concept was replaced by the region concept. In this way, the emphasis was placed on the geometry of the soil surface rather than on the dynamic processes responsible for shaping the watersheds. Most of the parameters needed to calculate crop losses can be estimated from soil survey maps and field reconnaissance studies (Laliberte et al. 1982). Four major characteristics of the landscape were considered in calculating the watershed, that may form within a region: frequency (density), size, shape and slope of depressions.

The frequency is simply the average number of depressions per quarter section of land that can accumulate enough water to become a small watershed if precipitation exceeds the sum of infiltration rate and evapotranspiration. The size was expressed in terms of the cubic metres of water that can be held by the depression. In hydrologic studies, the shape of a watershed is expressed usually as an index which is a ratio of watershed length along its main stream to its average width. For a simple method of calculation, a depression was assumed to be a very shallow paraboloid of revolution. The slope class is the average microdepression slope.

Water accumulation was assumed to be either from runoff within the quarter section or as quick-return flow from neighbouring upland areas. This quick-return flow was assumed to take place on soils located on the lower slopes of the landscape.

It was assumed that during the growing season only precipitation in excess of 20 mm/d could create a watershed (ponding) that will persist long enough to asphyxiate the plant within imperfectly and poorly drained soils. For many soils with heavy texture that exhibit shrinking-swelling phenomena (Red River Valley), a 20-mm precipitation event exceeds the infiltration rate, but it was assumed that the resulting small accumulation of water for so short a period of time does not kill the plant.

Whenever a high-precipitation event occurs, the amount exceeding 20 mm is compared with the existing value of a dummy variable named COMPE and the largest value is retained.

At the end of the growing season, the value stored in COMPE, the land characteristics mentioned earlier and two soil parameters (water table depth and infiltration rate), are used to calculate the volume of water accumulated within a depression per quarter section. The actual area of the watershed projected to the horizontal plane is calculated on the basis of the effective radius of the paraboloid (rather than a cone) of revolution of known volume

$$V = 1/2\ \pi r^2 h\ , \tag{3.125}$$

where V is the volume of water accumulated in one depression (m^3), h is the vertical depth (m) and r is the radius of the circular area covered by water (m).

Since tan s = h/r (where tan s is the "slope" of the depression), then

$$\frac{V}{\tan s} = \frac{\pi r^2 h}{2h/r} = \frac{\pi r^3}{2}\ . \tag{3.126}$$

and

$$r = \sqrt[3]{\left(\frac{V}{\tan s}\right) / \frac{\pi}{2}} \quad \text{(m)}\ . \tag{3.127}$$

Based on the observed frequency of unconnected depressions, the total area lost quarter section is computed and converted to a percentage of the cropped area. This latter value is used on a proportional basis to correct the simulated Bma(Pd = 500) and P values.

3.4.4.6 Outputs

A large number of variables can be either stored, printed out, or both. During the model development and program screening phases most variables were printed out and checked.

In its final form, PIXMOD generates two output sets: (1) an extended file, and (2) a summarized file. When the model is run for evaluation purposes, i.e., Sc. I, both extended and summarized files are produced. For simulation purposes, Sc. II, only the summarized file is generated.

(1) The extended file contains two groups of information: (a) general information and (b) daily information.

(a) The general information is input data such as: plot location/ soil series, year of simulation, scenario type, boundary conditions and initial conditions. This information is useful as a means of cross reference.

(b) Daily information consists of the time (Julian day), the layer numbers, the value of the major driving variable (precipitation) as well as computed values for the major auxiliary variables such as $\dot{T}r_i$, $\dot{E}v_i$, $W\ell_i$, $N\ell_i$, $T\ell_i$, $\dot{b}p_{(i)}$, $\dot{b}a_{(i)}$, and state variables, such as Pd_i, Bma, $\theta_{j,i}$, $NN_{j,i}$ and $T_{j=6,i}$. Of particular interest are the state variables that are compared with the measured values used in the model evaluation phases.

(2) The summarized file contains general information similar to that of the extended file and an overview of the calculations performed within one growing season: for example, the date of each phenological stage (S, E, J, H, D and M), cumulative values over the growing season of the main input variable (precipitation) and auxiliary variables (ETp, Ev, Tr_j), as well as the values of the state variables at the maturity stage, Pd = 500, (Bma, P, θ_j, N_j).

In addition to all those outputs, if, during a run, a killing frost occurs (TMIN < -2^{o}C), then the grain yield, P, is set to zero, the simulation stops and the following information is printed out: Warning "FROST"; date when frost occurred (Julian day); T_{MIN}; phenological development reached by crop when frost occurred (BMTS units); "grain yield, P, equals zero".

Chapter 4

MODEL EVALUATION

The attainable accuracy of PIXMOD was assessed by comparing predicted outputs directly with the outputs of the real system at two levels: validation and verification. Although there are many different ways (with their associated terms) used to evaluate a model, validation and verification were considered to be the most appropriate criteria for this study. In the validation phase, the usefulness of the model was tested by comparing the mean grain yield observed with the predicted value.

Since the model was intended for practical application using a limited data set, the validation procedure had two goals: (a) to establish the theoretical soundness of the model, i.e., its goodness-of-fit, and (b) to establish the usefulness of the model. The model was run twice using two scenarios. Scenario I aimed at assessing the theoretical basis of the model, its accuracy. In this simulation the soil subsystem parameters were measured, and lower boundary and initial conditions were known. Scenario II aimed at assessing the applicability of the model, its plausibility for land evaluation using existing data. For this simulation only standard Soil Survey data were used as input data.

In the verification phase, an evaluation was made of several assumptions in the model. Since the processes represented in the model were continuous, the major state variables computed in the SPDW, SSWETN, SNO3W and SCGRW subroutines were compared with corresponding observed values of the variables.

The major goal of the evaluation phase was to compare the model outputs with data from real systems that were similar to the agroecosystems from the region of interest rather than to calibrate the model or perform a sensitivity analysis. It was considered essential to use field data to evaluate PIXMOD, even though it was expected that there would be a loss of measurement precision and difficulties in applying standard statistical methods when using these data.

4.1 MATERIALS AND METHODS

The model was designed to simulate wheat yields for large areas and agroecosystems in which soil subsystems are represented by soil series. A test of the model at this scale is not practical. PIXMOD was tested using experimental data from small plots. However, the small plot cannot be a perfect "scale model" of an agroecosystem. Data required for the simulation, Sc. II, was collected for each plot using the standard methods employed by the Soil Survey.

The information used to evaluate the model were obtained from field experiments carried out during the growing seasons of 1982 and 1983. Twelve sites - Bagot, Beausejour, Dauphin, Mariapolis, Roblin, Shoal Lake, Souris, Swan River, Teulon, Waskada, Winnipeg and Woodmore - were established as experimental sites in cooperation with the Plant Science Department of the University of Manitoba. The main characteristics of the field experiment were as follows:

1. The experimental sites were scattered across the entire farming sector of the province and included a wide range of characteristics of the agroecosystems represented in PIXMOD. Figure 11 represents the soil zonal map and shows the locations of the

plots used to evaluate the model.

2. A single wheat (Triticum aestivum L.) variety, Glenlea, was monitored at each site.

3. All management elements (soil tillage, seeding rates, fertilizer application rates, weed control, etc.) were uniform across the province and from one year to another. This characteristic was very useful in the evaluation of the model because the subjective management elements were eliminated. The variation of yield both in both space and time were largely controlled by the soil subsystem properties, natural environment input (particularly precipitation) and their interactions.

However, the experimental design presented two shortcomings for model testing: first, the experiments were performed on fallow plots. Fallow is not a common practice in Manitoba. On fallow plots, soil moisture at seeding time was either at, or close to, the field capacity. Therefore, the assumptions made in Sc. II as to the initial soil moisture content could not be checked. Second, the Glenlea wheat variety is not particularly representative of the varieties presently grown on the Prairies. However, since the crop data were not used for calibration, this last problem was less important.

4.2 FIELD DATA

Data collected at each site fall into two broad categories: data that describe the agroecosystem structure and environment, and data that describe the behaviour of the agroecosystem over the growing season. Data from the first category formed the input data files required to run the model. Data from the second category constituted the reference data

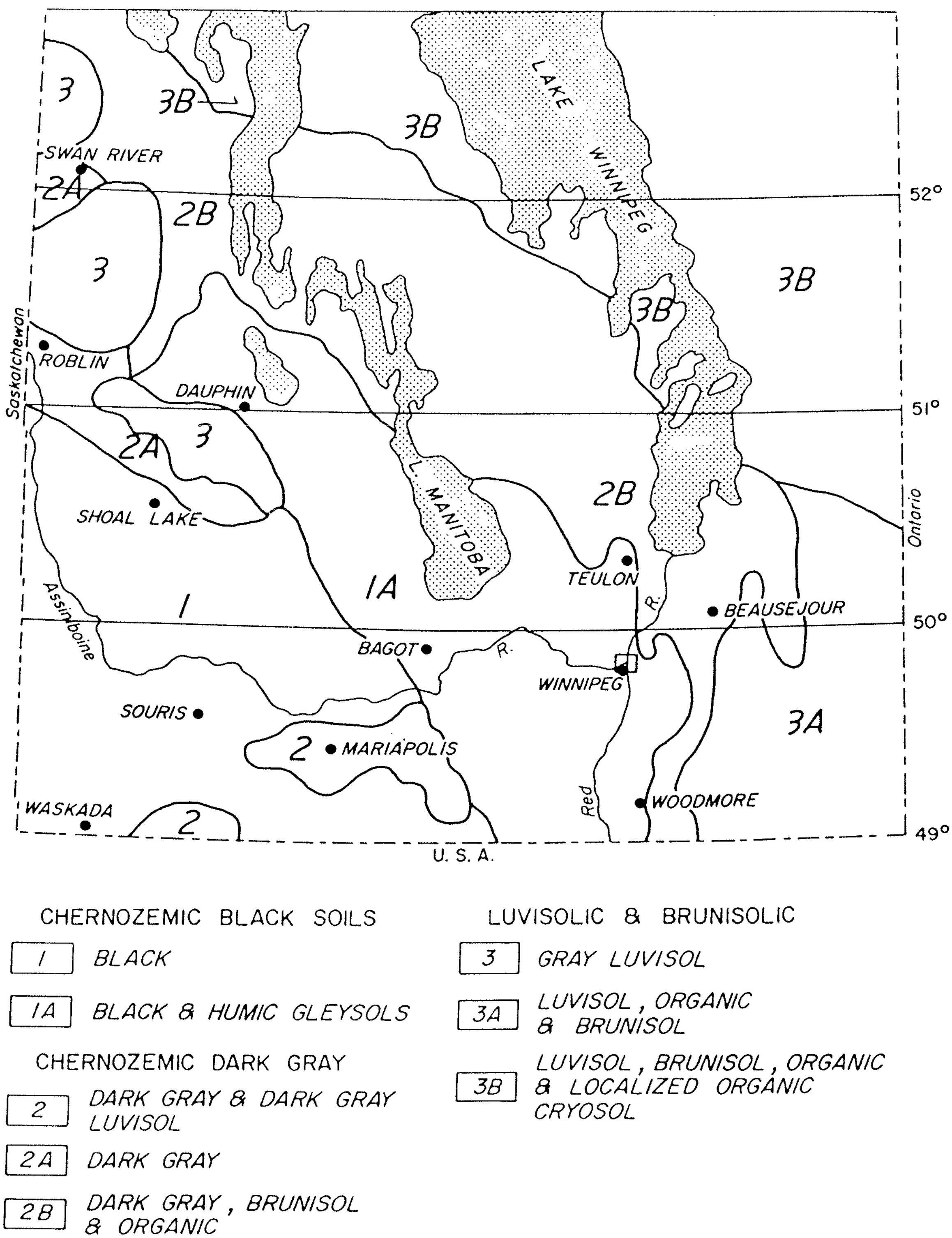


Figure 11: Soil zonal map with locations of experimental sites (•) used to evaluate PIXMOD.

for comparisons made in the validation and verification procedures.

4.2.1 Input Data Used to Simulate PIXMOD

Three types of data were collected: soil data, weather data and management data. Since most of the management variables were kept constant across the region, only seeding date varied with site-year. Soil and weather data were the major input variables collected.

Table 7 lists the 12 experimental sites used in the study, as well as general information on soil types and the nearest weather station from which most of the meteorological data were obtained for this study. Taxonomically, the soils at all sites are similar and, with the exception of the soil at Winnipeg, they all belong to the Chernozemic order. The Chernozemic A horizon in the Canadian System of Soil Classification, is similar to the "mollic" epipedon of the U.S. Soil Classification System, and is characteristic of the dark-colored and base-rich soils of the Prairie region. However, at the soil series category, criteria specific to geographic location are employed for their unique definition. The texture refers to the surface texture because some textural differences between horizons exist with each profile. However, the textural class of soil ranges from clay (Dauphin site) to loamy fine sand (Bagot and Woodmore sites).

The selection of the weather stations was based on the proximity of the weather station to an experimental plot.

4.2.1.1 Soil Data

Field and laboratory measurements performed included the following:

1. Morphological descriptions of the typical soil profiles. This was performed by using the standard procedures employed by the

Table 7: General information on experimental site location used to evaluate the model; plot legal description, soil classification, texture, and weather station from which the weather records were derived.

Site location	Legal Description	Soil: Series	Soil: Subgroup	Soil: Order	Soil: Texture	Weather Station: Name	Weather Station: ID Number	Weather Station: Lat.-Long.(degrees)
1 BAGOT	SW 6 12 9W	Willocrest	Gleyed Black	Chernozem	LFS	Macgregor	5041684	49.54 - 98.42
2 BEAUSEJOUR	SW 6 14 8W	Lakeland	Gleyed Rego Black	Chernozem	CL	Beausejour	5030160	50.07 - 96.30
3 DAUPHIN	NW 23 24 19W	Paulson	Gleyed Rego Black	Chernozem	C	Dauphin	5040680	51.06 - 100.03
4 MARIAPOLIS	NW 14 5 12W	Fifere	Orthic Dark Grey	Chernozem	L	Somerset	5012710	49.27 - 98.37
5 ROBLIN	NE 1 28 29W	Erickson	Orthic Dark Grey	Chernozem	CL	Roblin	5012473	51.23 - 101.24
6 SHOAL LAKE	NW 27 17 24W	Newdale	Orthic Black	Chernozem	CL	Strathclair	5012796	50.24 - 100.24
7 SOURIS	NE 9 8 21W	Hartney	Gleyed Rego Black	Chernozem	L	Brandon CDA	5010485	49.52 - 99.58
8 SWAN RIVER	SW 4 36 27W	Swanford	Gleyed Rego Black	Chernozem	SCL	Swan River	5042805	51.59 - 101.11
9 TEULON	NW 24 16 2E	Lakeland	Gleyed Rego Black	Chernozem	SiC	Stonewall	5022788	50.07 - 97.20
10 WASKADA	SE 4 2 2E	Bearford	Orthic Black	Regosolic	CL	Waskada	5013120	49.02 - 100.45
11 WINNIPEG	U. of M. plot	Blacklake	Gleyed Black	Chernozem	SiC	Winnipeg A	5023222	49.54 - 97.14
12 WOODMORE	NE 17 2 5E	Kittson	Gleyed Cumulic Regosol	Chernozem	LFS	Emerson	5020880	49.01 - 97.12

Soil Survey, The Canadian System of Soil Classification (Canada Soil Survey Committee - CSSC, 1978). These descriptions provided information relative to the number and thickness of horizons in the profile, as well as on lower boundary conditions. The morphological characterizations and classifications were made with substantial input from experienced pedologists.

2. Particle size analysis. These analyses were performed by using the pipette method, as described by McKeague (1981).

3. Organic carbon analysis. The organic carbon content was determined by wet oxidation (modified Wakley-Black acid titration method).

4. Bulk density, ρb, (Mg m^{-3}), ρb was determined using a method outlined by Zwarich and Shaykewich (1969).

5. Field capacity values, FC (% by weight). The measurements were taken in the field using a method described by Shaykewich and Zwarich (1968).

6. Permanent wilting points, WP, (% by weight). The water content at -15 bars (FAP) was determined by using the pressure-plate method on one-cm-thick disturbed soil samples. The WP was calculated using an equation developed by Shaykewich (1965):

$$\% \, WP = 0.021 + 0.775 \times FAP. \qquad (4.1)$$

7. Soil moisture content, $W_{(j,t=0)}$, (% by weight) at seeding time. The values were determined gravimetrically by soil sampling.

8. Nitrate nitrogen concentration, $NN_{(j,t=0)}$, (ppm) at seeding time. These analyses were determined by the Manitoba Provincial Soil Testing Laboratory using a standard method, the

"nitrate test" (Nyborg et al., 1976).

9. Water table height, $L\ell_w$, (m) at seeding time and several times during the growing season. The elevation of water level was determined in shallow well of 0.05 m diameter PVC pipe.

Bulk densities, field capacity values, soil moisture contents and NO_3-N concentration were measured in six, six, ten and two (composite) replicates, respectively. Depths of measurement were 0-0.15 m, 0.15-0.30 m, 0.30-0.60 m, 0.60-0.90 m, 0.90-1.20 m.

Statistical analyses of the bulk density and gravimetric field capacity data are presented in Appendix F and Appendix G, respectively. The mean bulk density values exhibited low variation within a plot, with few exceptions (Beausejour at 0.90-1.20 m depth and Mariapolis at 0.60-0.90 m depth); the values of the coefficient of variance (CV) for subsurface layers were less than 10%. CV values for the upper layer, 0-0.15 m depth, were higher because of large variations in soil structure. Field capacity also showed a relatively low variation, with CV near 10%, except for the Woodmore site where CV was up to 28%. This larger variation was due to the frequent variation in clay and sand content over very short distances.

Soil moisture content and nitrate nitrogen concentration in the soil presented higher variation. CV values for soil moisture content were generally between 15% and 30%.

Particle size analysis, organic carbon analysis and permanent wilting points were determined on duplicate composite samples formed from six replicates collected from bulk density and field capacity samples. These replicates were taken either at the standard depth or by horizons as they were identified morphologically.

In summary, soil subsystem properties included in the model had relatively low and medium variations, and for all practical purposes can be considered parameters of the agroecosystem.

4.2.1.2 Weather Data

The measured weather data consisted of standard daily variables: maximum temperature (°C), minimum temperature (°C) and precipitation (mm), and were taken from the Atmospheric Environment Service-station, Environment Canada File. Since the precipitation is highly variable over the Prairies, and some stations were some distance from the experimental sites, at six site locations - Bagot, Beausejour, Mariapolis, Teulon, Winnipeg and Woodmore, rainfall was measured directly on the site.

4.2.1.3 Management Data

The management data were similar for all plots. The crop was seeded in standard plots of 39 x 11 m in four replicates using a completely randomized design. The wheat was seeded in rows 0.15 m apart at a depth of 0.06 m using a seeding rate of 150 kg ha^{-1}. Each plot received 32 kg ha^{-1} (N) and 40 kg ha^{-1} (P_2O_5), broadcast at seeding time.

The only true management variable in space and time was the seeding date. This was controlled by the weather elements (temperature and precipitation) and soil conditions specific to each site-year combination.

4.2.2 Reference Data for PIXMOD Evaluation

Comparison of all variables computed by the model (state, rates and auxiliary variables) to the actual measured values was not possible.

The computed variables chosen to be compared with data from the real systems were the product (grain yield) and the major state variables: phenological development (SPDW subroutine), soil moisture content (SSWETN subroutine), nitrogen content in the soil (SNO3W subroutine) and aboveground net production (SCGRW subroutine) at different growth stages.

All phenological events could not be identified rigorously. However, based on the descriptive definitions given by Robertson (1968), the date at the beginning of each growth stage was noted and used as a time reference to measure all other variables.

Soil moisture contents and nitrogen concentrations were measured at the emergence, jointing, heading, soft dough and maturity stages at standard depths (0-0.15 m, 0.15-0.30 m, 0.30-0.60 m, 0.60-0.90 m, and 0.90-1.20 m). Moisture content was determined gravimetrically on 10 replicates taken randomly (5 in the row and 5 between rows); the results were converted to a volumetric basis ($m^3 m^{-3}$) using the appropriate ρb value. From the 10 soil samples taken for moisture content, two composite soil samples were formed for each standard depth. The NO_3-N concentrations (ppm) were determined from the composite samples by the Manitoba Soil Testing Laboratory using standard techniques.

At each growth stage, starting with the jointing stage, square metre samples of aboveground plant material were harvested in six replicates. The samples were air-dried and weighed. At harvest time, the aboveground plant material was threshed, and the grain was weighed.

Generally all the measurements were performed at each growth stage. However, due to the large volume of samples and scattered plot locations, some of the measurements were missed at some growth stages.

4.3 RESULTS AND DISCUSSION

Field data sets, soil input data and the reference data for model evaluation were analyzed statistically. Except for the phenological development, all data used for evaluation of the model were mean values.

Considerable effort was made to make all measurements accurately. In spite of this, when the raw data sets were analyzed, some of them appeared suspect. Because the sampling time was controlled by phenological development, those measurements could not be repeated; all samples have therefore been retained and used in the model evaluation.

4.3.1 Simulation Type

The model was run twice for each site-year combination, Sc. I and Sc. II.

Table 8 shows the values of the fundamental physical soil parameters used as input data for the Sc. I simulation. At Beausejour, Swan River, Teulon and Woodmore, water tables have been observed at relatively shallow depth (0.90 to 1.50 m) during the growing season. The observation of water tables was made on a discontinuous basis. Water tables fluctuated relatively rapidly. For example, at Teulon in 1983 the water table was observed at 0.70 m at the heading stage, but 17 days later, at the soft dough stage, the water table was below 2.5 m. It appeared that at all sites a so-called "perched" water table was encountered, rather than a true water table. This would explain the high fluctuation of the water table level during the growing season. However, limited information was available; field records showed only that at the four locations mentioned, the water tables rose to a depth that affected the soil moisture content in the rooting zone (1.20 m). To ensure a standard procedure from one place to another, in terms of

Table 8: Soil physical parameters used as input data in PIXMOD; simulation Sc. I.

	Site location	Depth (m)	Bulk density (Mg/m^3)	Wilting point (m^3/m^3)	Field capacity (m^3/m^3)	Available water content (m^3/m^3)
1	BAGOT	0.00 - 0.15	1.10	0.064	0.198	0.134
		0.15 - 0.30	1.25	0.084	0.208	0.124
		0.30 - 0.60	1.35	0.107	0.226	0.119
		0.60 - 0.90	1.44	0.117	0.337	0.220
		0.90 - 1.20	1.51	0.136	0.396	0.260
2	BEAUSEJOUR	0.00 - 0.15	0.84	0.147	0.319	0.172
		0.15 - 0.30	1.28	0.195	0.371	0.176
		0.30 - 0.60	1.45	0.158	0.334	0.176
		0.60 - 0.90	1.55	0.203	0.403	0.200
		0.90 - 1.20	1.39	0.245	0.459	0.213
3	DAUPHIN	0.00 - 0.15	0.60	0.167	0.318	0.151
		0.15 - 0.30	0.88	0.211	0.396	0.185
		0.30 - 0.60	0.70	0.184	0.364	0.180
		0.60 - 0.90	0.84	0.202	0.395	0.192
		0.90 - 1.20	1.11	0.213	0.400	0.187
4	MARIAPOLIS	0.00 - 0.15	0.91	0.141	0.337	0.196
		0.15 - 0.30	1.15	0.160	0.391	0.231
		0.30 - 0.60	1.17	0.169	0.363	0.194
		0.60 - 0.90	1.17	0.172	0.351	0.179
		0.90 - 1.20	1.12	0.137	0.336	0.199
5	ROBLIN	0.00 - 0.15	0.73	0.106	0.263	0.157
		0.15 - 0.30	1.21	0.150	0.339	0.189
		0.30 - 0.60	1.29	0.144	0.310	0.166
		0.60 - 0.90	1.36	0.144	0.313	0.168
		0.90 - 1.20	1.54	0.151	0.339	0.188
6	SHOAL LAKE	0.00 - 0.15	0.94	0.106	0.301	0.194
		0.15 - 0.30	1.43	0.121	0.343	0.222
		0.30 - 0.60	1.56	0.114	0.296	0.182
		0.60 - 0.90	1.66	0.148	0.349	0.200
		0.90 - 1.20	1.80	0.149	0.342	0.193
7	SOURIS	0.00 - 0.15	0.75	0.091	0.270	0.179
		0.15 - 0.	1.05	0.091	0.236	0.145
		0.30 - 0.60	1.38	0.106	0.273	0.167
		0.60 - 0.90	1.40	0.108	0.278	0.170
		0.90 - 1.20	1.38	0.110	0.314	0.204
8	SWAN RIVER	0.00 - 0.15	0.78	0.128	0.273	0.145
		0.15 - 0.30	1.15	0.147	0.299	0.152
		0.30 - 0.60	1.21	0.128	0.278	0.150
		0.60 - 0.90	1.23	0.148	0.258	0.111
		0.90 - 1.20	1.26	0.160	0.302	0.143
9	TEULON	0.00 - 0.15	0.88	0.148	0.290	0.142
		0.15 - 0.30	1.32	0.176	0.343	0.168
		0.30 - 0.60	1.31	0.156	0.314	0.159
		0.60 - 0.90	1.36	0.168	0.326	0.158
		0.90 - 1.20	1.46	0.148	0.350	0.202
10	WASKADA	0.00 - 0.15	0.96	0.130	0.290	0.161
		0.15 - 0.30	1.09	0.137	0.320	0.183
		0.30 - 0.60	1.23	0.168	0.370	0.202
		0.60 - 0.90	1.61	0.168	0.370	0.202
		0.90 - 1.20	1.61	0.161	0.320	0.160
11	WINNIPEG	0.00 - 0.15	0.85	0.222	0.349	0.126
		0.15 - 0.30	0.89	0.199	0.365	0.166
		0.30 - 0.60	0.99	0.206	0.376	0.170
		0.60 - 0.90	1.10	0.233	0.385	0.152
		0.90 - 1.20	1.16	0.196	0.383	0.187
12	WOODMORE	0.00 - 0.15	1.28	0.076	0.230	0.154
		0.15 - 0.30	1.61	0.078	0.209	0.131
		0.30 - 0.60	1.59	0.058	0.175	0.117
		0.60 - 0.90	1.71	0.053	0.239	0.186
		0.90 - 1.20	1.69	0.038	0.287	0.250

antecedant conditions of soil, all physical parameters were measured in the fall, after harvest. At the sites with a water table, the measurements of soil physical parameters were repeated during the growing season when the water table was below 2.00 m.

The fundamental physical soil properties used as input data for the Sc. II simulation are presented in Table 9. Based on these data, the SCPARA subroutine computed soil physical parameters (ρs, FC and WP), and the model was run assuming that $\theta_{j,o} = FC_j$. The computed parameter values were not equal to the measured values. However, the most critical parameter for the model is the storage capacity or maximum available water content (WAC). Table 10 shows the measured and calculated values of WAC and the model error (difference between calculated and measured value) within the standard profile to a 1.20 m depth. With the exception of Teulon and Winnipeg, the calculated values were within about 10% of measured values. At both Teulon and Winnipeg FC was remeasured in 1983. At Winnipeg the observed value was 0.230 m as compared with the 0.204 m initially measured, and the model error in 1983 less than 5%. Since the sites were not side-by-side in 1982 and 1983, the simulation in 1982 was made using the initial value observed. However, the same large difference (0.061 m) was obtained at Teulon. The error may have been induced by the regression equation used to predict soil physical parameters, but error in measurement cannot be ruled out because the measurements were based on a standard time for the soil to drain (48 - 60 hours) and not based on a repeated sampling procedure that would permit drawing some inference about the drainage process as a function of time.

Table 9: Fundamental soil physical properties used as input data in PIXMOD: simulation Sc. II.

Site location	Layer number	Depth (m)	Particle size (%)				Organic carbon (%)
			Very fine sand (0.25 - 0.1 mm)	Fine sand (0.1 - 0.05 mm)	Silt (0.05 - 0.002 mm)	Clay (< 0.002 mm)	
1 BAGOT	1	0.00 - 0.15	29	54	8	8	1.9
	2	0.15 - 0.30	23	58	8	9	0.9
	3	0.30 - 0.60	32	57	6	4	0.3
	4	0.60 - 0.90	40	57	3	0	-
	5	0.90 - 1.20	17	2	55	25	-
2 BEAUSEJOUR	1	0.00 - 0.15	8	4	28	57	4.9
	2	0.15 - 0.30	8	4	36	48	2.1
	3	0.30 - 0.60	18	3	48	28	0.6
	4	0.60 - 0.90	6	4	39	50	0.3
	5	0.90 - 1.20	2	2	29	59	0.4
3 DAUPHIN	1	0.00 - 0.15	0	0	31	67	4.5
	2	0.15 - 0.30	0	0	49	49	3.9
	3	0.30 - 0.60	0	0	49	50	2.7
	4	0.60 - 0.90	0	0	22	72	6.1
	5	0.90 - 1.20	2	2	36	54	2.4
4 MARIAPOLIS	1	0.00 - 0.15	10	9	42	27	2.6
	2	0.15 - 0.30	10	8	45	22	2.3
	3	0.30 - 0.60	10	8	42	28	0.8
	4	0.60 - 0.90	14	15	39	23	0.7
	5	0.90 - 1.20	10	7	51	23	0.3
5 ROBLIN	1	0.00 - 0.15	6	6	46	34	4.5
	2	0.15 - 0.30	6	7	44	32	0.7
	3	0.30 - 0.60	7	8	41	30	0.5
	4	0.60 - 0.90	6	9	38	30	0.5
	5	0.90 - 1.20	7	9	45	25	0.2
6 SHOAL LAKE	1	0.00 - 0.15	9	12	33	29	3.4
	2	0.15 - 0.30	9	12	32	31	1.8
	3	0.30 - 0.60	9	11	37	27	0.6
	4	0.60 - 0.90	8	10	38	28	0.4
	5	0.90 - 1.20	9	10	38	26	0.3
7 SOURIS	1	0.00 - 0.15	24	21	28	21	3.3
	2	0.15 - 0.30	25	22	27	18	0.8
	3	0.30 - 0.60	26	25	25	17	0.7
	4	0.60 - 0.90	27	25	23	17	0.6
	5	0.90 - 1.20	26	24	30	19	0.4
8 SWAN RIVER	1	0.00 - 0.15	25	4	37	34	2.7
	2	0.15 - 0.30	27	3	33	36	2.8
	3	0.30 - 0.60	28	3	35	34	1.7
	4	0.60 - 0.90	27	3	40	30	0.9
	5	0.90 - 1.20	16	1	47	41	0.8
9 TEULON	1	0.00 - 0.15	9	5	38	47	4.3
	2	0.15 - 0.30	5	3	44	46	1.3
	3	0.30 - 0.60	4	3	44	44	0.4
	4	0.60 - 0.90	0	0	53	45	0.2
	5	0.90 - 1.20	0	0	60	39	0.2
10 WASKADA	1	0.00 - 0.15	9	6	41	35	2.6
	2	0.15 - 0.30	5	10	37	36	0.7
	3	0.30 - 0.60	7	9	42	28	0.8
	4	0.60 - 0.90	10	16	45	25	0.4
	5	0.90 - 1.20	11	12	36	24	0.2
11 WINNIPEG	1	0.00 - 0.15	2	2	38	58	4.6
	2	0.15 - 0.30	1	1	39	59	2.0
	3	0.30 - 0.60	1	1	39	58	1.3
	4	0.60 - 0.90	1	1	40	58	0.9
	5	0.90 - 1.20	1	1	45	53	0.7
12 WOODMORE	1	0.00 - 0.15	22	51	6	8	3.1
	2	0.15 - 0.30	17	45	7	9	2.1
	3	0.30 - 0.60	17	50	4	6	0.0
	4	0.60 - 0.90	17	54	6	4	-
	5	0.90 - 1.20	21	48	3	1	-

Table 10: Available water content for plants in the profile of standard depth (1.20 m); measured, calculated and model error.

	Site location	Available water content (m)		Model error (m) (calculated - measured)
		Mean observed	PIXMOD estimated	
1	BAGOT	0.221	0.230	0.009
2	BEAUSEJOUR	0.238	0.261	0.023
3	DAUPHIN	0.217	0.254	0.037
4	MARIAPOLIS	0.238	0.255	0.018
5	ROBLIN	0.200	0.181	-0.018
6	SHOAL LAKE	0.241	0.244	0.003
7	SOURIS	0.212	0.237	0.025
8	SWAN RIVER	0.249	0.217	-0.032
9	TEULON	0.204	0.261	0.057
10	WASKADA	0.233	0.255	0.022
11	WINNIPEG	0.205	0.252	0.047
12	WOODMORE	0.211	0.208	-0.003

4.3.2 Criteria Used to Evaluate the Model

The ability of the model to predict accurately the main outputs of the real system was assessed in terms of the adjusted coefficient of determination $\bar{R}^2$ and the standard error of prediction (SEP):

$$\bar{R}^2 = 1 - (1-R^2)(N-1)/df \qquad (4.2)$$

$$SEP_{MO} = \pm \left[\sum_{i=1}^{N} (Y_M - Y_O)_i^2 \; / \; (N-2) \right]^{1/2} \qquad (4.3)$$

where M stands for model, O stands for mean observed value, Y stands for the entity considered in the analysis (for example, grain yield, above-ground net production, days from one phenological event to the next, etc.) and N is the number of comparisons made. Eqn. (4.3) has a form slightly different from the classical standard error of estimate used in regression analysis and the root mean square error (RMSE), since those statistics are calculated based on the overall experiment mean. In this study the comparison was based on the sum of squares of differences between the individual site-year combination predicted value (model) and actual observed value divided by N-2 degrees of freedom. (Two degrees of freedom are lost because of the two approximations involved in the analysis, averaging the observed data, and the model estimation.) Both $\bar{R}^2$ and SEP were considered important criteria for evaluating the model. $\bar{R}^2$ provided some indication of the proportion of variation of observed data explained by the model whereas the SEP gave an indication of the range of the model error expressed in the original units used to measure the observed variable. The model bias was expressed sometimes in terms of model error, the difference between predicted and observed values.

For grain yield and aboveground net production at the end of the growing season, simple linear regression equations of observed data versus PIXMOD-predicted values of the general form $Y = \beta_o + \beta_1 X$, have also been developed.

4.3.2.1 PIXMOD Validation

First, the model was validated as a whole in terms of its ability to predict the product (grain yield). Table 11 shows the observed grain yields and PIXMOD predicted values during 1982 and 1983 together with the total rainfall recorded from seeding to maturity.

Generally, 1983 was a drier year than 1982, but in the Dark Grey Zone (Roblin and Swan River sites) the reverse was true, and in the Interlake Region (Teulon site) the total amount of precipitation was approximately the same in both years. "Dry year" and "moist year" are general statements that cannot be used to characterize the weather pattern over large areas such as a province or Prairie region. The grain yields in 1983 were lower than in 1982. The observed grand mean in 1983 was lower by 563 kg ha^{-1} than in 1982, due to lower precipitation in 1983.

By combining an appropriate description of the system and its dynamic functioning with the main inputs, PIXMOD simulated successfully the wheat yield at all locations for both scenarios. The number of simulations in Sc. I was smaller than the number of simulations in Sc. II because the initial soil moisture content could not be measured for Dauphin and Shoal Lake in 1982 and simulation Sc. I could therefore not be performed.

Figures 12 and 13 show the scatter diagram of the mean observed grain yields plotted versus the value predicted by the model in Sc. I

Table 11: Mean observed grain yield and PIXMOD predicted values for 1982 and 1983 growing seasons.

Obs.	Site location	Site symbol *	Year	Precipitation from seeding to harvest (mm)	GRAIN YIELD (kg/ha) Observed (N=6) $\bar{Y}$	$S(\bar{y})$	PIXMOD prediction Sc.I	Error **	Sc.II	Error
1	I - BAGOT	B	1982	187.2	3405	279	3415	10	3460	55
2			1983	92.7	3269	213	3337	68	3481	212
3	II - BEAUSEJOUR ***	E	1982	266.6	4324	395	4459	135	4421	97
4			1983	182.9	3234	251	3109	-125	3569	335
5	III - DAUPHIN	D	1982	245.4	4760	501	-	-	4939	179
6			1983	147.4	3923	285	3943	20	4030	107
7	IV - MARIAPOLIS	M	1982	116.0	4127	261	4187	60	4534	407
8			1983	80.4	1641	169	1602	-39	1711	70
9	V - ROBLIN	R	1982	148.8	2200	83	2260	60	2230	30
10			1983	303.4	2961	147	3031	70	3226	265
11	VI - SHOAL LAKE ****	S	1982	266.3	2544	-	-	-	2524	-20
12			1983	137.3	2909	141	3189	280	3082	173
13	VII - SOURIS	U	1982		-	-	-	-	-	-
14			1983	168.8	3528	180	3652	124	3826	298
15	VIII - SWAN RIVER ***	A	1982	275.1	3835	299	3988	153	3616	-219
16			1983	365.7	3280	205	3484	204	3654	374
17	IX - TEULON ***	T	1982	270.2	3845	124	3939	94	4153	308
18			1983	233.4	3687	162	3837	150	3524	-163
19	X - WASKADA	W	1982	194.6	4176	46	4252	76	4254	78
20			1983	119.2	3414	242	3464	50	3494	80
21	XI - WINNIPEG	I	1982	227.3	4629	416	4601	-28	4757	128
22			1983	155.0	4018	318	4018	0	4050	32
23	XII - WOODMORE ***	O	1982	290.1	3473	61	3455	-18	3756	283
24			1983	185.7	2736	162	2940	204	3232	496

Note: * - Symbol used for observed mean grain yeld plotted in Figures 16 and 17.
** - Error = PIXMOD predicted value - Mean observed value.
*** - Site with observed water table at a shallow deth (0.90 - 1.50 m) during the growing season.
**** - Site with soil profile with physical barrier.

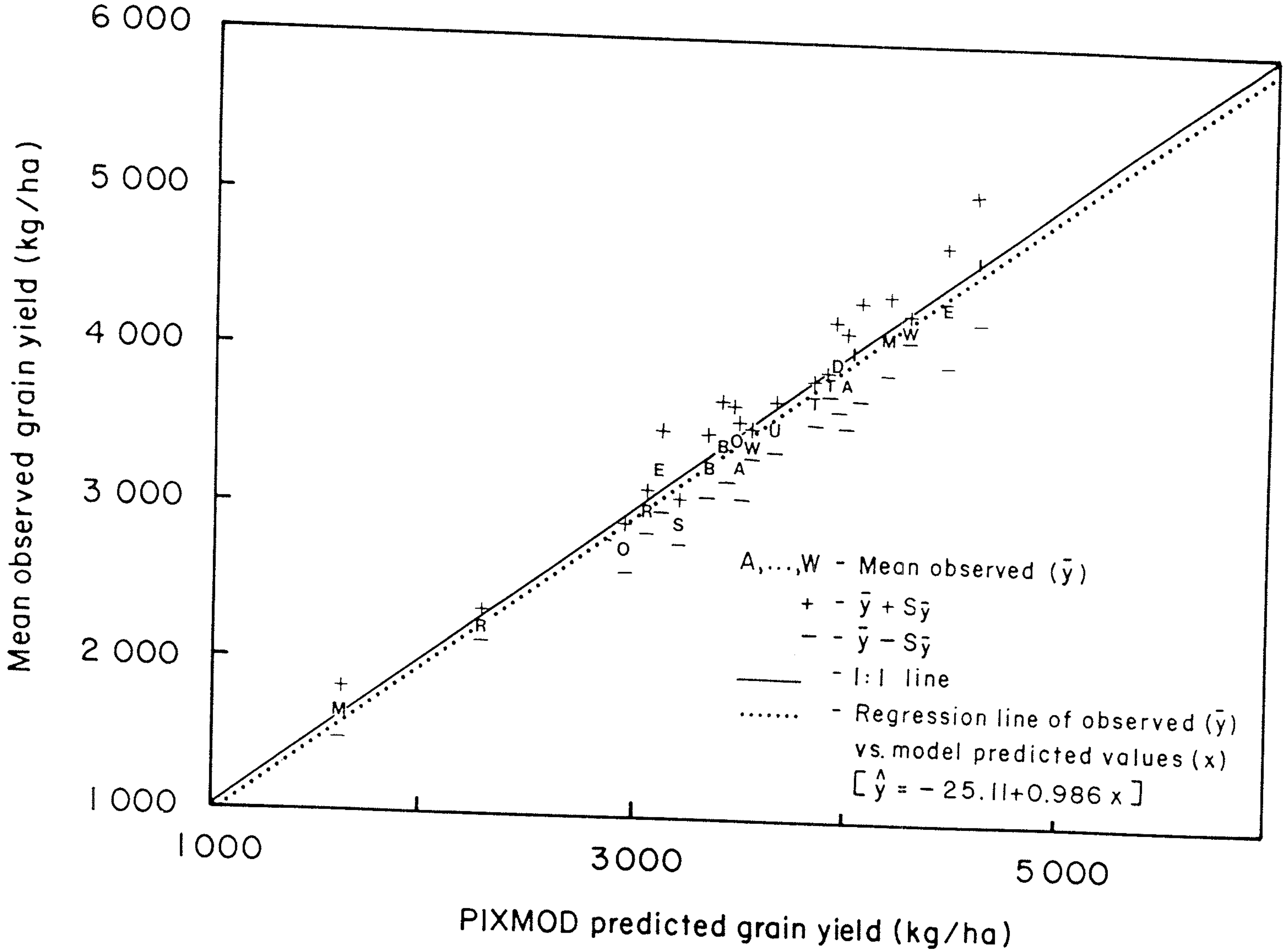


Figure 12: Scatter diagram of mean observed grain yields and PIXMOD, Sc. I, predicted values in 1982 and 1983 growing seasons at different sites used in the experiment. (See Table 11 for site symbols.)

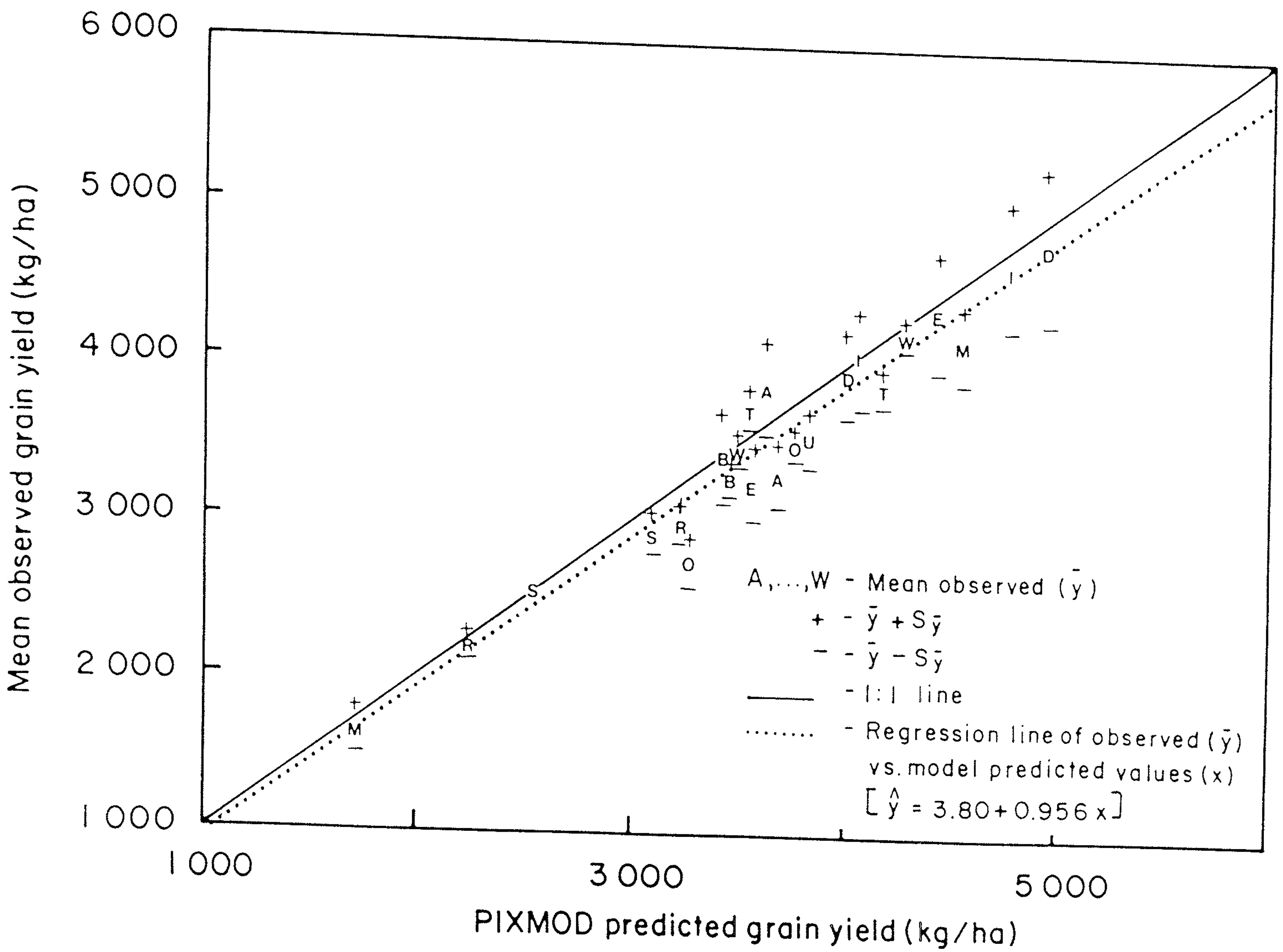


Figure 13: Scatter diagram of mean observed grain yields and PIXMOD, Sc. II, predicted values in 1982 and 1983 growing seasons at different sites used in the experiment. (See Table 11 for site symbols.)

and Sc. II, respectively. Data was plotted in the same manner in both graphs. The letters represent the observed mean grain yield at each site-year combination using the symbols of Table 11. Positive and negative signs indicate standard error ($S_{\bar{y}}$) above and below the mean, respectively. The diagonal line is the 1:1 line. Any point letter that falls below this line indicates a lower observed mean grain yield than the value predicted, the result of a positive error in the model prediction. Conversely, points that fall above the 1:1 line indicate negative error in the model prediction. However, if the 1:1 line lies within the standard error limits of the mean observed data, the PIXMOD prediction can be regarded as a correct estimation. The general agreement between observed and predicted grain yields for all site-year combinations together is indicated by the regression line of observed grain yields versus PIXMOD predicted yield (dotted line). The position of this line relative to the 1:1 regression line provides information on the overall performance of PIXMOD.

The grain yields for the 21 site-years simulated by PIXMOD in Sc. I were in good agreement with observed data. With the exception of Shoal Lake (1983), Waskada (1982) and Woodmore (1983), where the predicted value was higher than the mean observed value plus standard error, PIXMOD predicted the grain yield correctly (Fig. 12) for all the site-year combinations. The model generally overpredicted the grain yield, as indicated by the regression line.

The grain yield simulated by PIXMOD in Sc. II was also in good agreement with the observed value and followed the same pattern as in Sc. I (Table 11). Generally, the predicted grain yields for each site-year combination were higher than the observed mean values, with larger error than for Sc. I. At Swan River (1982) and Teulon (1983) the model, Sc. II, underpredicted the grain yield whereas the simulation Sc. I overpredicted the grain yield. These opposing results were due to the differences between measured and calculated soil parameters and the assumptions made in Sc. II as to the initial soil moisture content. For example, at Swan River in 1982, soil moisture content at seeding time was at the FC value. Because this is the assumption made in Sc. II, the yield simulated in this scenario should be the same as the yield simulated in the Sc. I. However, the soil parameters, and therefore the initial soil moisture content were not identical in both scenarios.

Overall, Sc. II also overpredicted the grain yield, and the regression line of observed versus predicted values falls below the 1:1 regression line. In addition, the regression line indicated that the deviations from observed were larger for higher yields (3000 to 5000 kg ha^{-1}) than for lower grain yields (1000 to 3000 kg ha^{-1}).

Table 12 summarizes the statistical results of grain yield used to validate PIXMOD. Data have been analyzed in three ways: by scenario, and for each scenario using data from all site-year combinations and each year separately. Three statistics were presented for each set of data: the SEP, the $\bar{R}^2$, and the regression equation relating observed to predicted values. For Sc. I, SEP values were low (± 125 kg/ha for all site-year combinations, ± 97 kg/ha in 1982 and ± 152 kg/ha in 1983). The absolute value of SEP provides better information about the bias of PIXMOD when it is compared with the grand mean of observed data ($\bar{\bar{Y}}$). This comparison suggested that the model predicted grain yield with an overall error of 2.5% (1982) to 4.7% (1983). The model was successful in simulating a large proportion of the observed variation in grain

Table 12: Grand mean ($\bar{\bar{Y}}$) and standard error ($S_{\bar{\bar{Y}}}$) of observed grain yield, adjusted coefficient of determination ($\bar{R}^2$), standard error of prediction (SEP) and regression equation; validation of PIXMOD.

Scenario	Year	Number of sites	Observed yield (kg/ha)		$\bar{R}^2$	+/- SEP		Regession equation of observed yield (Y) vs. PIXMOD predicted value (X).
			Grand mean ($\bar{\bar{Y}}$)	$S(\bar{\bar{Y}})$		kg/ha	% $\bar{\bar{Y}}$	
I	1982 - 1983	21	3457	155	0.98	125	3.6	Y = -25.11 + 0.986X
	1982	9	3779	237	0.99	97	2.6	Y = -10.55 + 0.987X
	1983	12	3216	182	0.96	152	4.7	Y = 27.39 + 0.956X
II	1982 - 1983	23	3474	158	0.95	243	7.0	Y = 3.80 + 0.956X
	1982	11	3756	243	0.96	225	6.0	Y = 241.09 + 0.907X
	1983	12	3216	182	0.91	280	8.7	Y = -147.87 + 0.987X

yield. The values of adjusted coefficient of determination were high (0.98 for all site-year combinations, 0.99 for the sites used in the experiment in 1983 and 0.96 for the sites used in the experiment in 1982) indicating a high correlation between the observed and predicted values. For this study, $\bar{R}^2$ was an indication that PIXMOD showed stability in accurately predicting the grain yield from one site-year combination to another.

The slopes of the regression equations developed were close to 1.00 (0.986 for pooled data, 0.987 for 1982 data and 0.966 for 1983 data). The intercepts were slightly different, being negative for 1982 (-10.55) and positive for 1983 (+27.39). Although their values were small, the T test suggested rejection of the null hypothesis, $H_o:\beta_o = 0$. Based on statistics obtained for data analyzed by individual year, it appeared that PIXMOD predicted the grain yield slightly better in 1982 than in 1983.

The summary statistics obtained from Sc. II were similar to those from Sc. I. Generally, the simulated grain yields in Sc. II were less accurate than those in Sc. I. The SEP values were higher (± 243 kg/ha for all site-year combinations, ± 225 kg/ha for 1982 and ± 280 kg/ha for 1983) and the $\bar{R}^2$ were lower (0.95 for all combinations, 0.96 for 1982 and 0.91 for 1983). Although the parameters of the regression line ($\beta_o = 3.8$ and $\beta_1 = 0.956$) for all site-year combinations indicated a good agreement between observed and predicted values, a much larger difference between those parameters was obtained analyzing each year separately ($\beta_o = 241$ and $\beta_1 = 0.907$ for 1982, and $\beta_o = -146.87$ and $\beta_1 = 0.978$ for 1983).

In summary, PIXMOD predicted the grain yield well for a wide range of growing conditions. The number of site-year combinations used to validate the model was relatively small, but the range of observed mean grain yields was large (1641 kg/ha at Mariapolis in 1983 to 4629 kg/ha at Winnipeg in 1982). Generally, the model overpredicted the grain yield, but the bias was not consistent, particularly for simulation Sc. II. This indicated that a further correction of the model prior to application is a more complex matter than a simple calibration based on field data of the type obtained in this experiment. As expected, PIXMOD predicted the grain yield more accurately when the soil physical parameters and initial soil moisture content were measured, i.e., the grain yields simulated in Sc. II were less accurate. However, the SEP values were less than ± 10% of the observed grand mean. Considering the wide range of observed yield, it can be concluded that PIXMOD predicts wheat grain yield reasonably well, even with limited data input and can provide reliable values in practical cases.

4.3.2.2 PIXMOD Verification

The most important state variables calculated by the model (phenological development, soil water content, nitrate nitrogen and aboveground net production) were analyzed in the verification phase. These state variables are the main outputs of four subroutines in PIXMOD. Because the soil water content and the nitrate nitrogen concentration depended strongly on boundary and initial conditions, only the outputs from the simulation Sc. I have been considered. Phenological development was calculated in the same manner in both scenarios and the predicted values were identical. Since the aboveground net production is the key variable in the application phase, the prediction of this variable was analyzed for both scenarios.

4.3.2.2.1 Prediction of Phenological Development - SPDW Subroutine

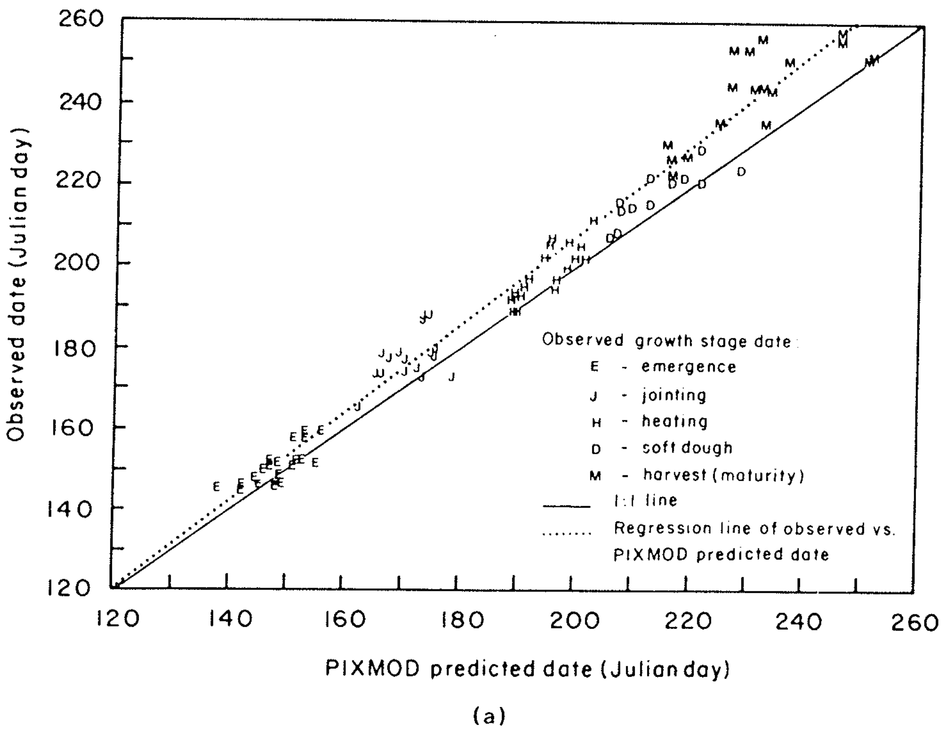
Table 13 shows the date of observed growth stages and the date predicted by PIXMOD. Growth-stage values were visual observations. The observed data at maturity represent the harvest dates rather than the biological maturity as described by Robertson (1968). The harvest dates, a management decision, were later than maturity dates by about 10 to 15 days. Since the biological maturity was not identified accurately, the harvest date was used as the reference date for maturity (M*). Using exclusively meteorological data, the model can easily be calibrated to predict the harvest date.

Figures 14a and 14b show the scatter diagram of predicted growth stages around a 1:1 line and the regression line of observed values versus model predicted values, with and without the harvest date. The predicted values fall above the 1:1 regression line. With three exceptions out of 104 observations, the BioMeteorological Time Scale consistently predicted a faster phenological development than was observed at every growth stage. The summary statistical results of the comparison of observed and predicted phenological development are presented in Table 14. When all growth stages were included, the coefficient of determination values were high ($\bar{R}^2$ = 0.97 for all year-location combinations) and remained consistent from one year to the next ($\bar{R}^2$ = 0.98 in 1982 and $\bar{R}^2$ = 0.96 in 1983). Since the bias of the model was consistently negative, the SEP defined as $[(\text{model-observed})^2/N-2]^{1/2}$ has had only a negative value. Overall, the model predicted the growth stages to be earlier than observed by 7 days. A better prediction was obtained in 1982 (SEP = -5 days) as compared with 1983 (SEP = -8 days). This is reflected also in the SEP values calculated for individual

Table 13: Date of observed phenological events (growth stages) and PIXMOD predicted dates (Julian day).

Site location	Year	Seeding Model	Seeding Obs.	Emergence Model	Emergence Obs.	Jointing Model	Jointing Obs.	Heading Model	Heading Obs.	Soft dough Model	Soft dough Obs.	Maturity Model	Maturity Obs.*
		GROWTH STAGES											
1 - BAGOT	1982	-	142	148	148	172	175	196	197	218	229	230	244
	1983	-	131	142	145	165	174	188	189	206	208	215	230
2 - BEAUSEJOUR	1982	-	140	148	147	173	173	196	196	219	228	232	244
	1983	-	136	145	147	169	179	189	193	207	216	216	227
3 - DAUPHIN	1982	-	146	155	152	179	-	201	202	227	-	245	257
	1983	-	143	151	158	173	187	195	207	216	222	226	244
4 - MARIAPOILS	1982	-	141	148	148	172	175	196	197	221	229	233	244
	1983	-	131	144	148	167	178	189	194	209	215	218	229
5 - ROBLIN	1982	-	141	147	153	173	-	199	202	226	-	245	256
	1983	-	146	153	159	173	188	195	207	218	222	229	254
6 - SHOAL LAKE	1982	-	140	147	-	173	-	200	204	229	-	251	252
	1983	-	145	153	158	175	178	198	206	221	221	233	243
7 - SOURIS	1982	-	-	-	-	-	-	-	-	-	-	-	-
	1983	-	144	151	152	174	178	195	206	216	221	226	245
8 - SWAN RIVER	1982	-	141	147	152	171	-	194	202	218	-	231	256
	1983	-	148	156	159	174	188	195	207	216	222	226	254
9 - TEULON	1982	-	141	149	148	178	173	202	211	228	224	250	251
	1983	-	130	142	147	166	179	188	193	207	214	216	227
10 - WASKADA	1982	-	145	152	153	174	-	196	195	218	-	232	236
	1983	-	141	148	152	170	178	190	194	209	215	218	229
11 - WINNIPEG	1982	-	132	138	146	162	166	189	189	212	222	224	236
	1983	-	129	141	145	166	174	188	189	207	208	216	223
12 - WOODMORE	1982	-	143	149	151	175	179	198	200	224	235	236	251
	1983	-	137	146	151	170	175	191	196	212	216	220	228

Note: * - The observed maturity date is the harvest date.



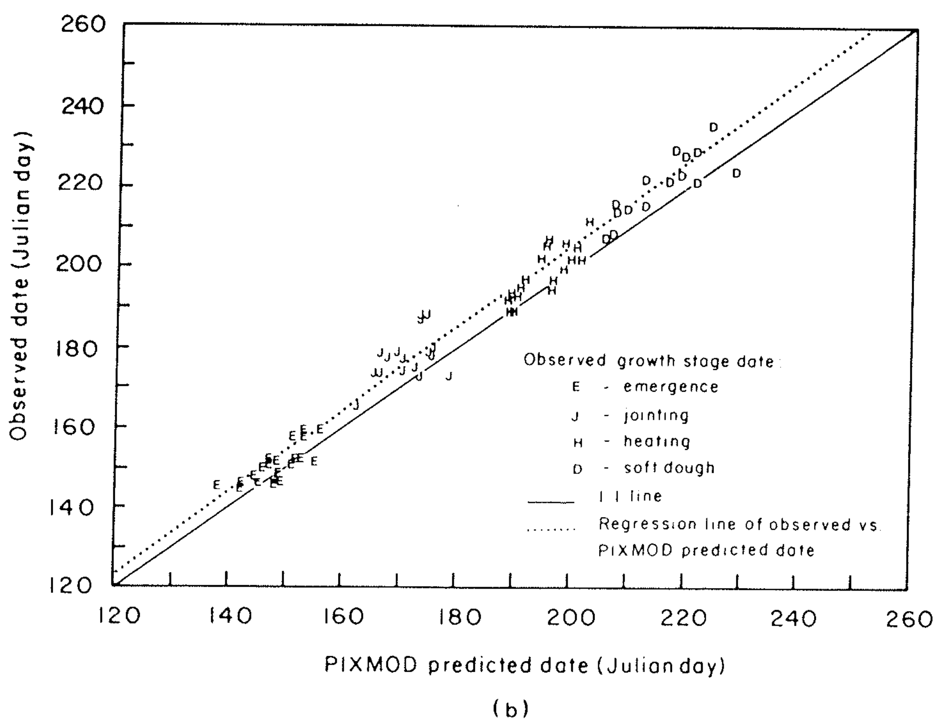


Figure 14: Scatter diagram of the date on which each growth stage was observed and the date predicted by PIXMOD for the 1982 and 1983 growing seasons; (a) including the harvest date, and (b) without harvest date.

Table 14: Adjusted coefficient of determination ($\bar{R}^2$) and standard error of prediction (SEP) of date on which phenological stages were reached for various year and growth stage combinations; verification of subroutine SPDW.

Growth stage	Year	Number of comparisons	$\bar{R}^2$	- SEP (days)
All growth stages including harvest (maturity)	1982 - 1983	104	0.97	9
	1982	44	0.98	8
	1983	60	0.96	10
All growth stages without harvest (maturity)	1982 - 1983	81	0.98	7
	1982	33	0.98	5
	1983	48	0.98	8
Emergence - E	1982 - 1983	22	0.62	4
Jointing - J	1982 - 1983	18	0.12	9
Heading - H	1982 - 1983	23	0.55	6
Soft dough- D	1982 - 1983	18	0.67	8
Emergence - E	1982	10	0.25	4
Jointing - J	1982	6	0.47	4
Heading - H	1982	11	0.69	4
Soft dough- D	1982	6	0.12	10
Emergence - E	1983	12	0.90	4
Jointing - J	1983	12	0.30	11
Heading - H	1983	12	0.89	8
Soft dough- D	1983	12	0.73	8

growth stages by year. In 1983 the daily temperature values during the growing season were higher than in 1982. It appeared that the bias of SPDW was larger in the hotter, drier year. Since the photoperiod variable employed by the BMTS model varied from one year to another within a narrow range, the temperature coefficients dominated the estimation of growth stage. Therefore, the bias toward earlier prediction than observed growth stage was due to too high a value for the temperature coefficients.

The values of SEP calculated for individual growth stages indicated that the accuracy of predicting phenological development decreased in the following order: emergence (-4 days), heading (-6 days), soft dough (-8 days) and jointing (-9 days). It is quite likely that the coefficients developed for the periods emergence to jointing and jointing to heading need further calibration. However, the absolute values of SEP are not accurate because the observed values were not as precise as other measurements. There were two reasons for this: first, the original description of the growth stages (especially of jointing and soft dough) presented an inherent difficulty in their assessment; second, the experimental sites were scattered over a large geographical area within Manitoba preventing frequent visits to the sites. Therefore, the growth stages could not be monitored precisely. An error of +3 to +5 days from observed dates should be considered to be within experimental error.

Since the bias of the model is consistent, a correction is possible, but this will require high-quality data obtained from a rigorously controlled experiment. Doraiswamy and Thompson (1982) used data acquired by the U.S. Department of Agricultural Statistical

Reporting Service, during 1978, from wheat fields in North and South Dakota, Minnesota and Montana, to modify the regression coefficients of BMTS. PIXMOD employed these coefficients for several site-year combinations. By comparison, Robertson's original values gave much better results than the new proposed coefficients.

The results of the study showed that BMTS is a reliable method available for estimating wheat growth stages in Manitoba, and probably in the entire Prairie region as well.

4.3.2.2.2 Prediction of Soil Wetness - SSWETN Subroutine

Soil water content has been related in a complex manner with soil subsystem properties, crop subsystem characteristics, and initial boundary conditions. A very large number of variables, measured at short time intervals are needed for a complete assessment of SSWETN. From the field data collected, useful information was derived on the overall performance of the subroutine and on the assumptions made for lower boundary conditions of the soil subsystem.

Since the initial conditions have been measured for the simulation Sc. I and upper boundary conditions were either input as driving variables or computed by other subroutines, the predicted water content values are mainly related to soil characteristics and lower boundary conditions. Because SSWETN was driven by input variables monitored on a calendar time basis, the reference time used in the analysis of the data was the corresponding Julian day for the observed growth stages. The standard error of prediction of soil moisture content in the rooting zone for each experimental site at emergence, jointing, heading, soft dough and maturity is presented in Table 15. The soil moisture content was predicted within acceptable limits of accuracy at the sites with

Table 15: Standard error of model prediction (SEP) of soil wetness in the rooting zone (1.20 m depth) at different growth stages over both years (1982 and 1983); verification of subroutine SSWETN.

Site location	+/- SEP AT DIFFERENT GROWTH STAGES (m^3/m^3)				
	Emergence	Jointing	Heading	Soft dough	Maturity*
1 - BAGOT	0.043	0.076	0.063	0.046	0.053
2 - BEAUSEJOUR **	0.098	0.120	0.092	0.098	0.101
3 - DAUPHIN	0.035	0.092	0.098	0.110	0.056
4 - MARIAPOLIS	0.035	0.101	0.074	0.078	0.078
5 - ROBLIN	0.064	0.030	0.054	0.025	0.021
6 - SHOAL LAKE ***	0.039	0.044	0.046	0.037	0.058
7 - SOURIS	0.133	0.166	0.181	0.163	0.174
8 - SWAN RIVER **	0.097	0.107	0.102	0.122	0.161
9 - TEULON **	0.072	0.089	0.060	0.067	0.122
10 - WASKADA	0.038	0.046	0.039	0.041	0.012
11 - WINNIPEG	0.047	0.026	0.027	0.038	0.033
12 - WOODMORE **	0.155	0.135	0.128	0.159	0.149

Note: * - Maturity stage represents the harvest date.
** - Site with observed water table at a shallow deth (0.90 - 1.50 m) during the growing season.
*** - Site with soil profile with physical barrier.

well-drained profiles (Bagot, Dauphin, Mariapolis, Roblin, Waskada and Winnipeg). The SEP varied in the range ± 0.012 to ± 0.047 m^3m^{-3} at Waskada and Winnipeg, in the slightly larger ranges ± 0.021 to ± 0.076 m^3m^{-3} at Bagot and Roblin, and ± 0.035 to ± 0.110 m^3m^{-3} at Mariapolis and Dauphin. Since the standard error of the mean observed data was within a range of ± 0.010 to 0.020 m^3m^{-3}, the standard error of prediction values were regarded as reasonably small. For example, at the Winnipeg site the predicted values of water content at the heading stage (the lowest SEP) were about ± 4% from measured available water content and at emergence (the highest SEP) about ± 14%. At Souris, a site considered to have a well- drained profile, the SEP values were higher; the bias of the model was systematically negative. The Souris site was introduced into the experiment late in the spring of 1983 and no information about water tables could be obtained. It is probable that the site had a shallow water table because the soil moisture content values determined on the samples collected at all growth stages were either close to, or even higher than the measured FC. Good results (SEP = ± 0.037 to ± 0.058 m^3m^{-3}) were obtained at Shoal Lake, simulated as a soil profile with a physical barrier (the bulk density at a depth of 0.90 to 1.20 m was 1.80, Appendix F).

The highest SEP values and therefore the largest biases in calculating the soil water content were obtained at Beausejour, Swan River, Teulon and Woodmore. These sites had fluctuating, shallow water tables. This bias was to be expected because the parametrical method employed in the model cannot accommodate computations of soil water above FC. Generally, at those sites, the mean observed values of water content were larger than the predicted values. Table 16 shows the mean observed

Table 16: Mean observed and predicted (PIXMOD Sc. I) volumetric water content at different growth stages at Beausejour site in 1983.

Growth stage	Date of sampling	Depth (m)	Mean observed (N=10) (m^3/m^3)	Model prediction (m^3/m^3)	Model error * (m^3/m^3)
Seeding **	16 May 1983	0.00 - 0.15	0.38	-	-
		0.15 - 0.30	0.51	-	-
		0.30 - 0.60	0.51	-	-
		0.60 - 0.90	0.56	-	-
		0.90 - 1.20	0.40	-	-
Emergence	27 May 1983	0.00 - 0.15	0.34	0.26	-0.08
		0.15 - 0.30	0.45	0.35	-0.10
		0.30 - 0.60	0.41	0.33	-0.08
		0.60 - 0.90	0.43	0.40	-0.03
		0.90 - 1.20	0.40	0.46	0.06
Jointing	28 Jun 1983	0.00 - 0.15	0.34	0.25	-0.09
		0.15 - 0.30	0.47	0.28	-0.19
		0.30 - 0.60	0.43	0.30	-0.13
		0.60 - 0.90	0.49	0.37	-0.12
		0.90 - 1.20	0.44	0.43	-0.01
Heading	12 Jul 1983	0.00 - 0.15	0.32	0.22	-0.10
		0.15 - 0.30	0.41	0.24	-0.17
		0.30 - 0.60	0.39	0.31	-0.08
		0.60 - 0.90	0.44	0.37	-0.07
		0.90 - 1.20	0.42	0.41	-0.01
Soft dough	04 Aug 1983	0.00 - 0.15	0.27	0.15	-0.12
		0.15 - 0.30	0.37	0.19	-0.18
		0.30 - 0.60	0.32	0.19	-0.13
		0.60 - 0.90	0.34	0.33	-0.01
		0.90 - 1.20	0.42	0.40	-0.02
Maturity ***	15 Aug 1983	0.00 - 0.15	0.26	0.15	-0.11
		0.15 - 0.30	0.34	0.19	-0.15
		0.30 - 0.60	0.32	0.16	-0.16
		0.60 - 0.90	0.35	0.32	-0.03
		0.90 - 1.20	0.36	0.40	0.04

Nota: * - Model error = (PIXMOD estimated value - Mean observed value)
** - Initial conditions.
*** - Maturity date is harvest date.

values, model predicted values, and the model error of soil moisture content at Beausejour in 1983. The mean observed values were close to FC and even higher than FC at every growth stage. At seeding time, the soil moisture content was at calculated saturation and even higher (0.51 to 0.56 $m^3 m^{-3}$) at a depth of 0.20 to 1.00 m. The high soil water content at seeding date was not induced by the water table, but by precipitation prior to seeding combined with poor percolation conditions because of a thin frost layer (approximately 0.15 - 0.20 m), observed in the field during seeding.

The adjustment of yield for water excess, although crude, appeared to be appropriate. Without considering the negative effect of water excess, the model would predict a grain yield of, for example, 3880 kg ha^{-1} at Beausejour in 1983 approximately 600 kg ha^{-1} higher than the observed value.

In summary, SSWETN performed reasonably well. The predicted values of soil moisture content were in an acceptable range of accuracy and the assumptions made for lower boundary conditions and water excess effects on yield appear justified. The errors in estimated water content were both positive and negative, but the general tendency of the model was to underpredict the soil moisture content.

4.3.2.2.3 Prediction of Soil Nitrogen - SNO3W Subroutine

The nitrogen content in the soil profile was less accurately predicted by the model than water content. Table 17 shows the standard error of prediction for each site at different growth stages. Generally, the SEP is in the range ± 40% to ± 50% from the mean observed NO_3^--N concentration in the soil profile.

The largest absolute values of SEP were obtained at the sites with

Table 17: Standard error of model prediction (SEP) of nitrate nitrogen in the rooting zone (1.20 m depth) at different growth stages over both years (1982 and 1983); verification of subroutine SNO3W.

Site location	+/-SEP AT DIFFERENT GROWTH STAGES (ppm)				
	Emergence	Jointing	Heading	Soft dough	Maturity *
1 - BAGOT	3.9	5.9	2.6	2.3	2.9
2 - BEAUSEJOUR **	7.6	5.2	2.4	2.4	3.1
3 - DAUPHIN	8.8	18.3	14.4	13.4	8.4
4 - MARIAPOLIS	10.8	9.9	13.1	6.6	7.6
5 - ROBLIN	14.1	12.1	11.0	8.8	7.9
6 - SHOAL LAKE ***	5.3	4.4	2.6	6.4	7.3
7 - SOURIS	5.9	7.1	6.7	5.8	4.2
8 - SWAN RIVER **	3.2	4.5	5.3	5.1	5.0
9 - TEULON **	16.7	13.3	15.0	18.2	18.8
10 - WASKADA	2.7	5.3	5.7	4.6	2.6
11 - WINNIPEG	9.2	18.5	18.4	14.9	14.1
12 - WOODMORE **	9.0	13.6	7.2	5.9	7.7

Note: * - Maturity stage represents the harvest date.
** - Site with observed water table at a shallow deth (0.90 - 1.50 m) during the growing season.
*** - Site with soil profile with physical barrier.

high nitrogen content in the soil prior to fertilizer application. For example, at Dauphin the mean observed value of NO_3^--N was 19.84 ppm, at Mariapolis 25.30 ppm and at Teulon, 31.90 ppm. Overall, the model predicted larger amounts of nitrogen in the soil than observed, a positive bias. With the exception of the Teulon site, the largest error was observed in the first half of the growing season, particularly at the jointing or heading stage when the model overpredicted the nitrate nitrogen content in the soil profile. This may have been the result of higher actual nitrogen uptake rates. The nitrogen uptake rates are higher at the beginning of the growing season and some of the nitrogen uptake is stored in the roots. This nitrogen is used for protein synthesis later (Vos et al., 1982). Nitrogen storage in the roots and translocation were not described in PIXMOD.

The model bias alternated between postive and negative when the nitrogen data was analyzed by discrete layers and at different growth stages (data not presented). Exceptions were observed at Winnipeg and Dauphin, where the errors were almost always positive. At both sites the clay content in the soil was high (Table 9) and probably some fixation of nitrogen took place, a process not included in the model.

In summary, SNO3W provided only a general estimation of the distribution of the nitrate nitrogen within the soil profile during the growing season. However, the pattern of changes in time from seeding to maturity and in space within the profile was approximated reasonably well for each site-year combination used in the experiment.

Further research on soil chemistry and plant nutrition are needed in order to improve the simulation of the nitrogen cycle in the agroecosystem.

4.3.2.2.4 Prediction of Aboveground Net Production - SCGRW Subroutine

Aboveground net production was the most important state variable calculated by the model; it was simulated daily by integrating the variables predicted by all the other subroutines in PIXMOD, and its value at the end of the growing season constituted the basic figure for the grain yield calculation.

In order to determine whether the accumulated daily estimates of ANP at any time were sufficiently accurate for the assessment of land evaluation based on PIXMOD, the subroutine SCGRW was verified in more detail. First, the accumulated ANP was analyzed at the end of the growing season, as predicted by the model for both scenarios for each individual site. Second, the predicted values over the growing season were analyzed at four key growth stages (jointing, heading, soft dough and maturity).

Statistical analysis results of aboveground net production field data are presented in Appendix I. The values of ANP predicted by PIXMOD, for each scenario and observed mean ($\bar{Y}$) and $S_{\bar{y}}$ for the individual site-year combinations used in the experiment (Table 18) were plotted on graphs (Figures 15a and 15b). Data for ANP were plotted in the same way as the grain yield data; the mean observed ANP have been indicated in Figure 15 by symbols (Table 18) surrounded by $\bar{Y} + S_{\bar{y}}$ and $\bar{Y} - S_{\bar{y}}$. The dotted line represents the regression line between mean observed values and model predicted values and the continuous line is 1:1 line.

Most of the predicted aboveground net production values of Sc. I were within the range of $\bar{Y} \pm S_{\bar{y}}$ (Fig. 15a). At five sites, the predicted values were slightly larger than the standard error of the

Table 18: Mean observed aboveground net production (ANP) at the end of the growing season and PIXMOD predicted value in 1982 and 1983 growing seasons.

Obs.	Site location	Site symbol *	Year	Precipitation from seeding to harvest (mm)	ABOBEGROUND NET PRODUCTION (kg/ha) Observed (N=6) $\bar{Y}$	$S(\bar{Y})$	PIXMOD prediction Sc.I	Error **	Sc.II	Error
1	I - BAGOT	B	1982	187.2	12127	483	12197	70	12357	230
2			1983	92.7	8134	475	8342	208	8703	569
3	II - BEAUSEJOUR ***	E	1982	266.6	11487	664	11733	246	11635	148
4			1983	182.9	8500	594	8182	-318	9393	893
5	III - DAUPHIN	D	1982	245.4	12980	1012	–	–	13348	368
6			1983	147.4	11093	661	11266	173	11513	420
7	IV - MARIAPOLIS	M	1982	116.0	10103	109	10213	110	11059	956
8			1983	80.4	8335	230	8009	-326	8556	221
9	V - ROBLIN	R	1982	148.8	8417	208	8692	275	8577	160
			1983	303.4	8167	342	8419	252	8960	793
11	VI - SHOAL LAKE ****	S	1982	266.3	12230	–	–	–	12137	-93
12			1983	137.3	7700	349	8391	691	8111	411
13	VII - SOURIS	U	1982		–	–	–	–	–	–
14			1983	168.8	8741	445	9131	390	9566	825
15	VIII - SWAN RIVER ***	A	1982	275.1	11100	487	11560	460	10482	-618
16			1983	365.7	9103	413	9678	575	10151	1048
17	IX - TEULON ***	T	1982	270.2	10293	453	10646	353	11225	932
18			1983	233.4	11057	243	11628	571	10680	-377
19	X - WASKADA	W	1982	194.6	9667	570	9888	221	9894	227
20			1983	119.2	9153	570	9362	209	9442	289
21	XI - WINNIPEG	I	1982	227.3	13207	772	13109	-98	13554	347
22			1983	155.0	11344	383	11350	6	11442	98
23	XII - WOODMORE ***	O	1982	290.1	10067	358	10161	94	11048	981
24			1983	185.7	8669	422	9187	518	10099	1430

Note: * - Symbol used for observed mean grain yeld plotted in Figures 16 and 17.
** - Error = PIXMOD predicted value - Mean observed value.
*** - Site with observed water table at a shallow deth (0.90 - 1.50 m) during the growing season.
**** - Site with soil profile with physical barrier.

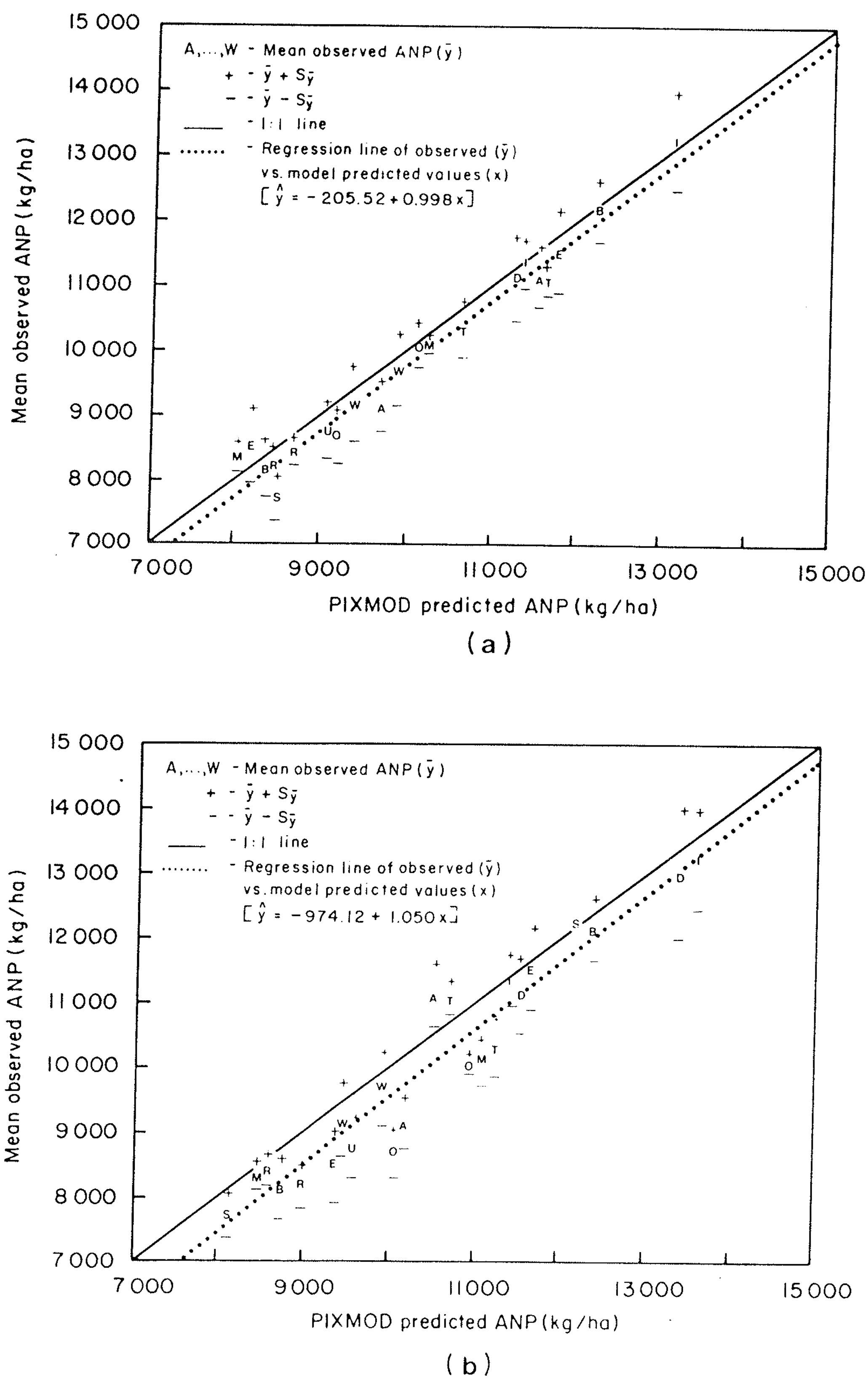


Figure 15: Scatter diagram of mean observed aboveground net production (ANP) and the PIXMOD predicted values at the end of 1982 and 1983 growing seasons at different sites used in the experiment; (a) PIXMOD predicted values in Sc. I, and (b) PIXMOD predicted values in Sc. II. (See Table 18 for site symbols.)

mean observed values. With the exception of Mariapolis in 1983, where the model underpredicted ANP with 326 kg ha^{-1}, all other predictions that fall outside $\bar{Y} \pm S_{\bar{y}}$ were positive.

All the predicted values that fell outside the $\bar{Y} \pm S_{\bar{y}}$ occurred in 1983; generally they were too high. This indicates that the model predicts less accurately for dry years. Since the predicted values for soil moisture content were generally lower than observed data, it appears that either the water stress factor was larger than calculated by the model or this was the consequence of overpredicting NO_3-N.

The values of ANP simulated by the model in Sc. II (Fig. 15b) were less accurate than those predicted in Sc. I. A larger number of predicted values fall outside the ranges of $\bar{Y} \pm S_{\bar{y}}$. With two exceptions, Swan River, 1982 and Teulon, 1983 (sites with water tables where the model underpredicted the ANP), all predicted ANP values were higher than observed. Seven out of ten overpredicted values were obtained for 1983, the year with less precipitation.

The summary statistical results of the analysis for cumulative aboveground net production at the end of the growing season is presented in Table 19. These results were different from the results for grain yield (Table 12) for two reasons. First, the grand mean observed values have different standard errors, and second, in calculating the grain yield the observed harvest index value was used, not a standard value. However, the statistical results indicated that PIXMOD predicted the ANP at the end of the growing season accurately enough for both scenarios. For the combined data, 1982 and 1983, the $\bar{R}^2$ was high (0.97 for Sc. I and 0.91 for Sc. II). The SEP values, although relatively large for Sc. II, particularly in 1983, (SEP = ± 788 kg ha^{-1}) were less than ± 10%

Table 19: Grand mean ($\bar{\bar{Y}}$) and standard error ($S_{\bar{\bar{Y}}}$) of observed aboveground net production (ANP) at the end of the growing season in 1982 and 1983, adjusted coefficient of determination ($\bar{R}^2$), standard error of prediction (SEP) and regression equation; verification of subroutine SCGRW.

Scenario	Year	Number of sites	Observed yield (kg/ha) Grand mean ($\bar{\bar{Y}}$)	Observed yield (kg/ha) $S(\bar{\bar{Y}})$	$\bar{R}^2$	+/- SEP kg/ha	+/- SEP % $\bar{\bar{Y}}$	Regession equation of observed yield (Y) vs. PIXMOD predicted value (X).
I	1982 - 1983	21	9831	333	0.97	345	3.6	Y = -205.52 + 0.998X
	1982	9	10718	476	0.99	282	2.6	Y = -713.76 + 1.048X
	1983	12	9166	367	0.93	440	4.8	Y = 342.68 + 0.971X
II	1982 - 1983	23	10072	347	0.91	682	6.8	Y = -974.12 + 1.050X
	1982	11	10061	451	0.88	628	6.2	Y = -0.62 + 0.971X
	1983	12	9166	367	0.85	788	8.7	Y =-1311.45 + 1.078X

from the observed grand mean. The regression equations were computed to provide some information on the degree of fit of the model predicted values. The technique of predicting yield used in this study was not based on regression, therefore the intercept values are less important. The slopes, which were the parameters of interest, were relatively constant for all combinations analyzed, with values close to 1.00 indicating a stability in the model's predictions when run with both types of input data.

By using the simulated ANP of Sc. I and the observed mean value at different growth stages, R^2 and ± SEP were computed for different site year and growth stage combinations. The summary statistical results of ANP analysis are presented in Table 20. For all 78 site-year-growth stage combinations, as well as for the site-growth stage combinations for 1982 and 1983, R^2 was high (0.95, 0.98 and 0.94, respectively). For the sites with the water table near the rooting zone, the predicted ANP values were adjusted for the effect of water excess at the end of the growing season. For this reason, data for these sites were not included in the analysis of aboveground net production at a given growth stage.

The accuracy of estimating ANP increased as the growing season progressed, i.e., SEP decreased. At the jointing stage, the coefficient of determination was low (R^2 = 0.19), with the model consistently overpredicting the ANP for every site-year combination. The model error at this stage was high (SEP = ± 1319 kg/ha). Generally, the model predicted a cumulative biomass of about twice the observed value. There are two probable reasons for this overprediction. First, because the SPDW subroutine predicts a faster phenological development than actually takes place, particularly at the jointing stage (SEP = -9 days),

Table 20: Coefficient of determination (R^2) and standard error or model prediction (SEP) of aboveground net production for different year-growth stage combinations and for each site location used in the experiment.

Number of sites/ location	Year	Growth stage (grand mean)	Number of comparisons	R^2	+/- SEP (kg/ha)
21	1982 - 1983	J,H,D, and M*	78	0.95	1201
9	1982	J,H,D, and M*	30	0.98	1334
12	1983	J,H,D, and M*	48	0.94	1143
21	1982 - 1983	J (Y = 1104) **	18	0.19	1319
21	1982 - 1983	H (Y = 5186)	21	0.47	1597
16	1982 - 1983	D (Y = 9045)	18	0.80	1169
21	1982 - 1983	M*(Y = 9706)	21	0.98	312
1 - BAGOT	1982 - 1983	J,H,D, and M*	8	0.98	1037
2 - BEAUSEJOUR	1982 - 1983	J,H,D, and M*	8	0.98	1067
3 - DAUPHIN	1982 - 1983	J,H,D, and M*	4	0.99	952
4 - MARIAPOLIS	1982 - 1983	J,H,D, and M*	8	0.96	1197
5 - ROBLIN	1982 - 1983	J,H,D, and M*	6	0.89	1602
6 - SHOAL LAKE	1982 - 1983	J,H,D, and M*	4	0.97	1388
7 - SOURIS	1982 - 1983	J,H,D, and M*	4	0.92	1669
8 - SWAN RIVER	1982 - 1983	J,H,D, and M*	6	0.97	1525
9 - TEULON	1982 - 1983	J,H,D, and M*	8	0.94	1332
10 - WASKADA	1982 - 1983	J,H,D, and M*	6	0.84	1643
11 - WINNIPEG	1982 - 1983	J,H,D, and M*	8	0.98	790
12 - WOODMORE	1982 - 1983	J,H,D, and M*	8	0.95	1261

Note: * - Maturity date is the harvest date.
** - At jointing stage (J) the model predicted always higher value then the mean observed.

simulated root growth was faster, the volume of soil explored was larger, and consequently, the limiting water factor was underestimated. Second, the model did not correctly predict the effect of one or more of the limiting factors for the interval between emergence and jointing. However, the R^2 value improved gradually as the simulation progressed toward the maturity stage so that at heading the R^2 was 0.47, at the soft dough stage 0.80 and at maturity, 0.98. The SEP decreased in the same manner, from jointing to maturity. Although the absolute values of SEP were similar at jointing, heading and soft dough, they decreased from 100% of the grand mean at jointing to about 14% at the soft dough stage. Pooled ANP data from both growing seasons and all growth stages were analyzed for each site. The coefficient of determination values were relatively high and similar from site to site. The SEP varied from 790 kg/ha (at Winnipeg) to 1669 kg/ha (at Souris). It appeared that overall, the model prediction of wheat above ground net production was simulated reasonably well at every location.

4.3.2.2.5 Detailed prediction at three selected sites

Data used to verify the outputs of the major subroutines were not fully dynamic because collection of field data at one-day time steps is not practical. Due to the heterogeneity of the soil properties, as well as because the measurement of most variables of interest requires use of a sampling method without replacement, changes in the state variables over such short time intervals are practically impossible to measure and interpret. Even though quantitative comparisons between the model predicted values and observed data could not be made on a continuous basis, useful information about PIXMOD performance was derived from inspection of the curves of accumulated daily estimates of two major variables in the system, the soil water content and ANP, coupled with discrete measurements.

Detailed outputs of PIXMOD for soil moisture content and aboveground net production are presented graphically for three sites with well-drained soils of different textures: Bagot (loamy fine sand), Mariapolis (loam), and Winnipeg (silty clay). The simulated values used in all the graphs were derived from the model outputs. Examples of PIXMOD daily simulation outputs (1982) for the sites mentioned above, are presented in Appendix J.

For each location-year combination, the precipitation recorded at the site during the growing season, mean observed soil moisture content at each phenological event and PIXMOD Sc. I continuously estimated values are presented in Figures 16 and 17 for Bagot, in Figures 18 and 19 for Mariapolis and in Figures 20 and 21 for Winnipeg. The model predicted the soil moisture content reasonably well for all three textural classes and variations in precipitation. Most of the mean observed values were close to the continuously estimated values. The best agreement between observed and simulated values was obtained for the silty clay soil at Winnipeg, and next best for the loamy fine sand soil at Bagot. The error was higher on loam soil at Mariapolis, particularly for 1983 (Fig. 19) between the depths of 0.30 m and 1.20 m. Since the simulated values for 1982 (Fig. 18) were in good agreement with the mean observed values for all depths, it appeared that the error in the predicted values was not induced by incorrectly estimating the soil physical properties that affected the water flow. The error was probably induced by inadequate representation of the root system adaptation to particular soil moisture conditions. In 1983, for

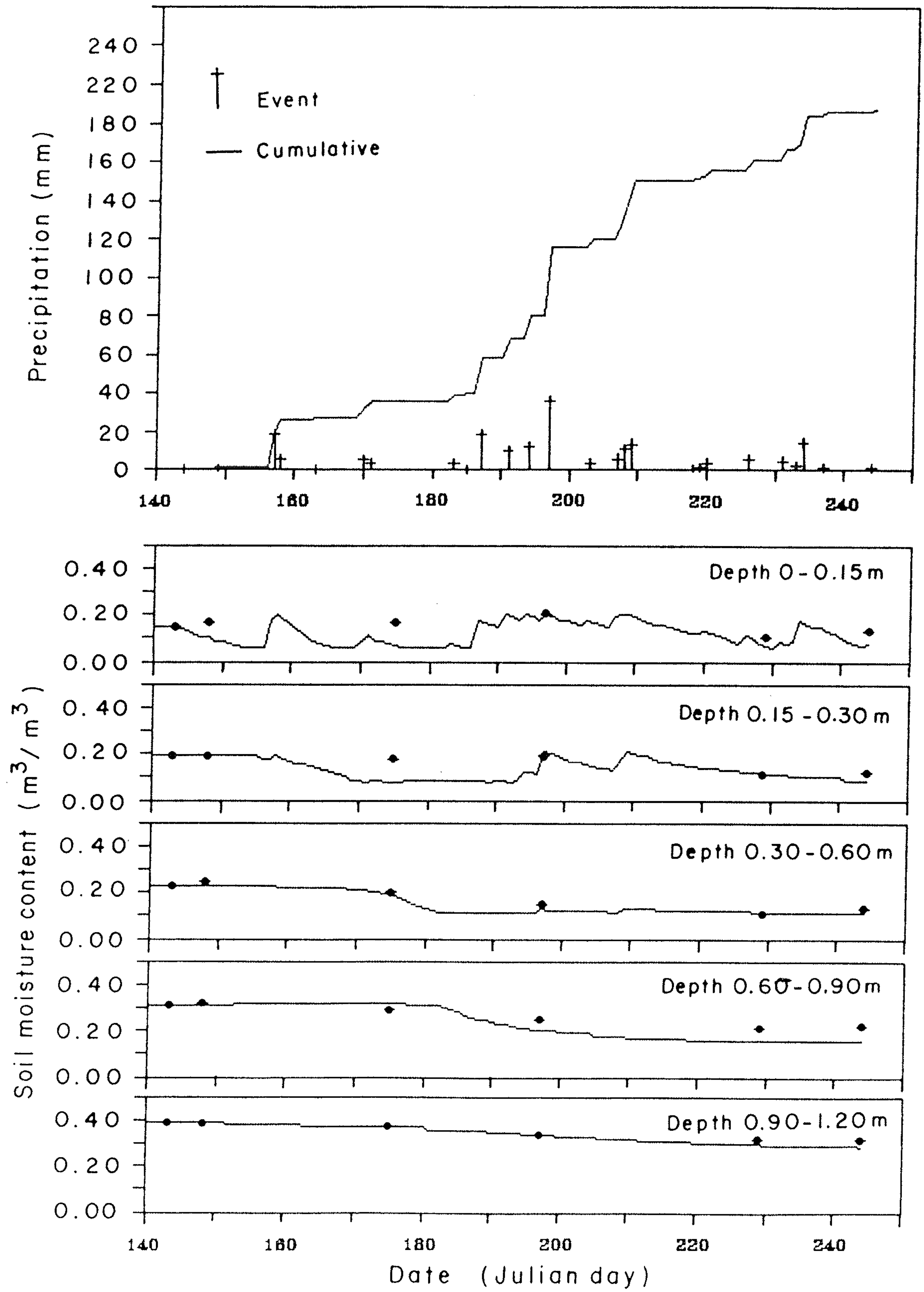


Figure 16: Precipitation (uppermost graph), mean observed soil moisture content (•), and PIXMOD, Sc. I, continuous estimated value (——) versus time at Bagot site in 1982 growing season.

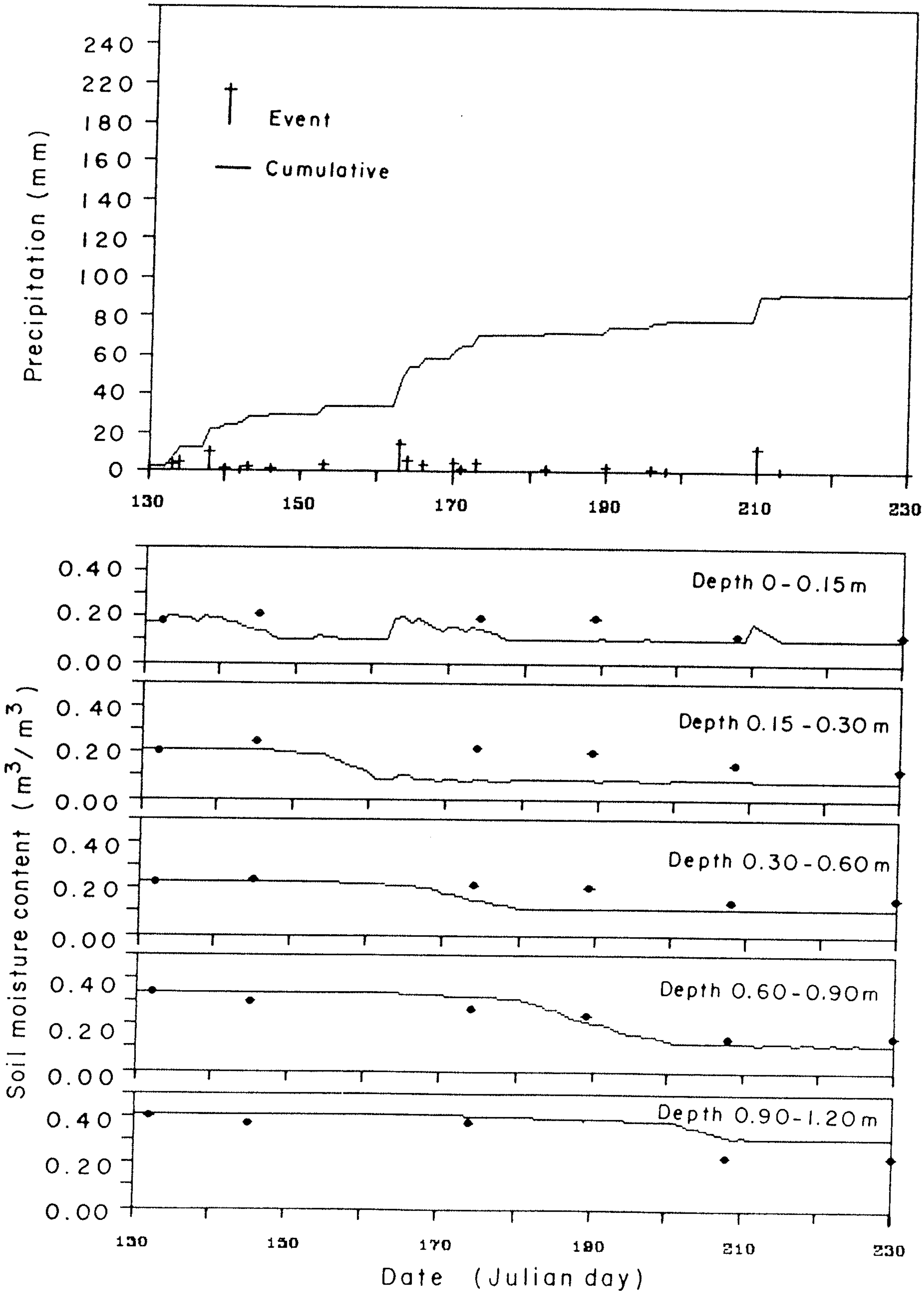


Figure 17: Precipitation (uppermost graph), mean observed soil moisture content (•), and PIXMOD, Sc. I, continuous estimated value (——) versus time at Bagot site in 1983 growing season.

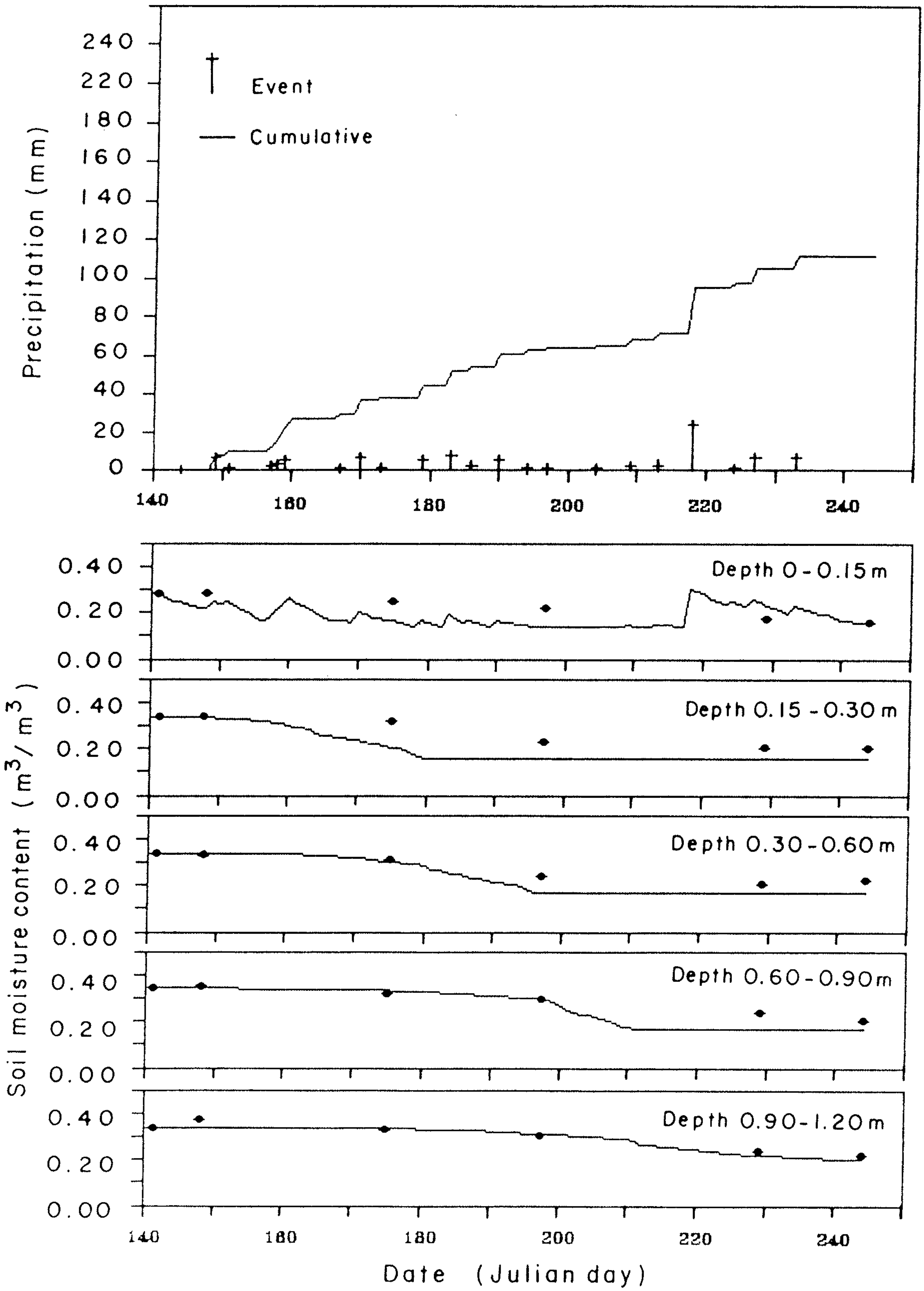


Figure 18: Precipitation (uppermost graph), mean observed soil moisture content (•), and PIXMOD, Sc. I, continuous estimated value (——) versus time at Mariapolis site in 1982 growing season.

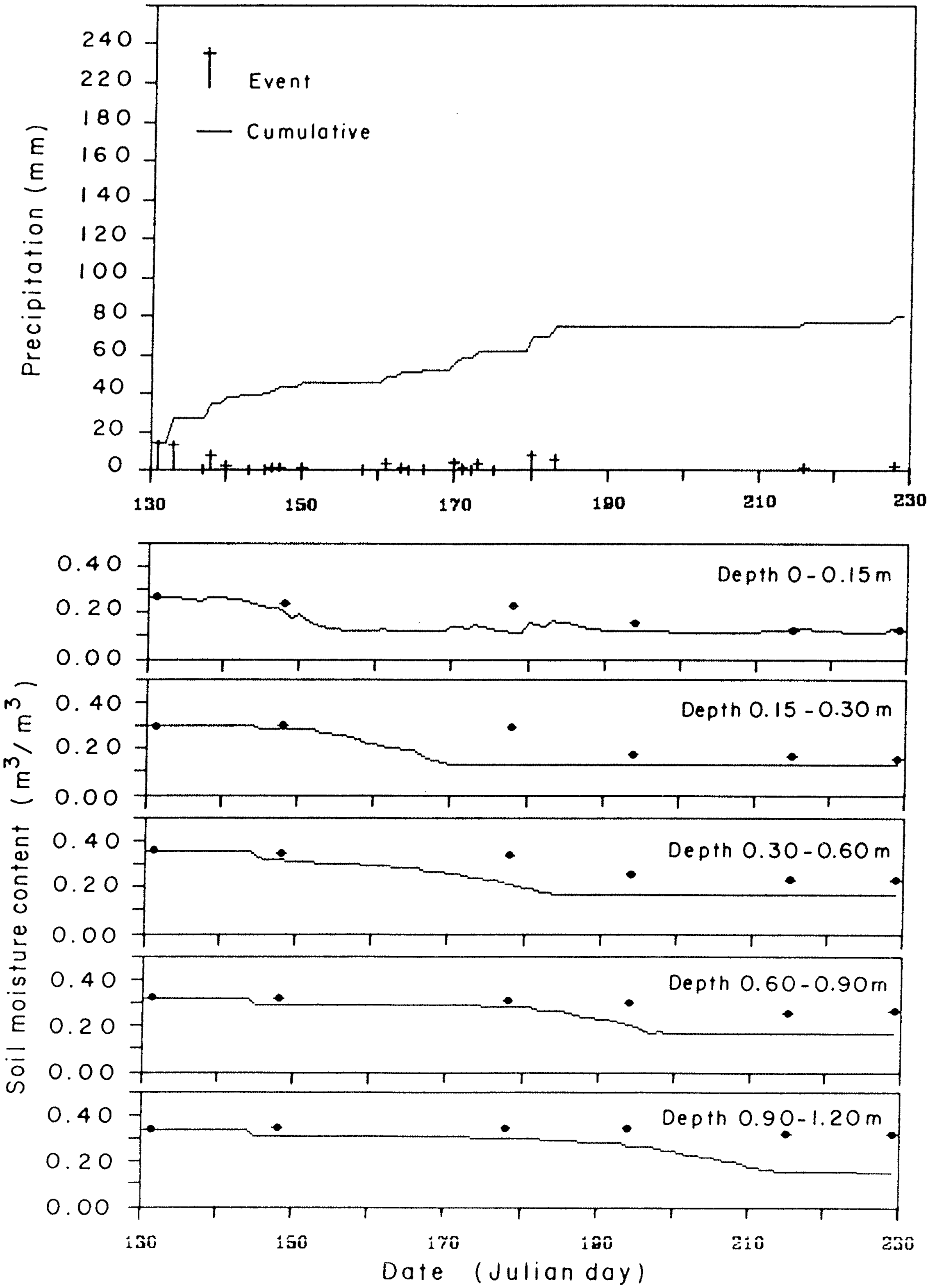


Figure 19: Precipitation (uppermost graph), mean observed soil moisture content (•), and PIXMOD, Sc. I, continuous estimated value (——) versus time at Mariapolis site in 1983 growing season.

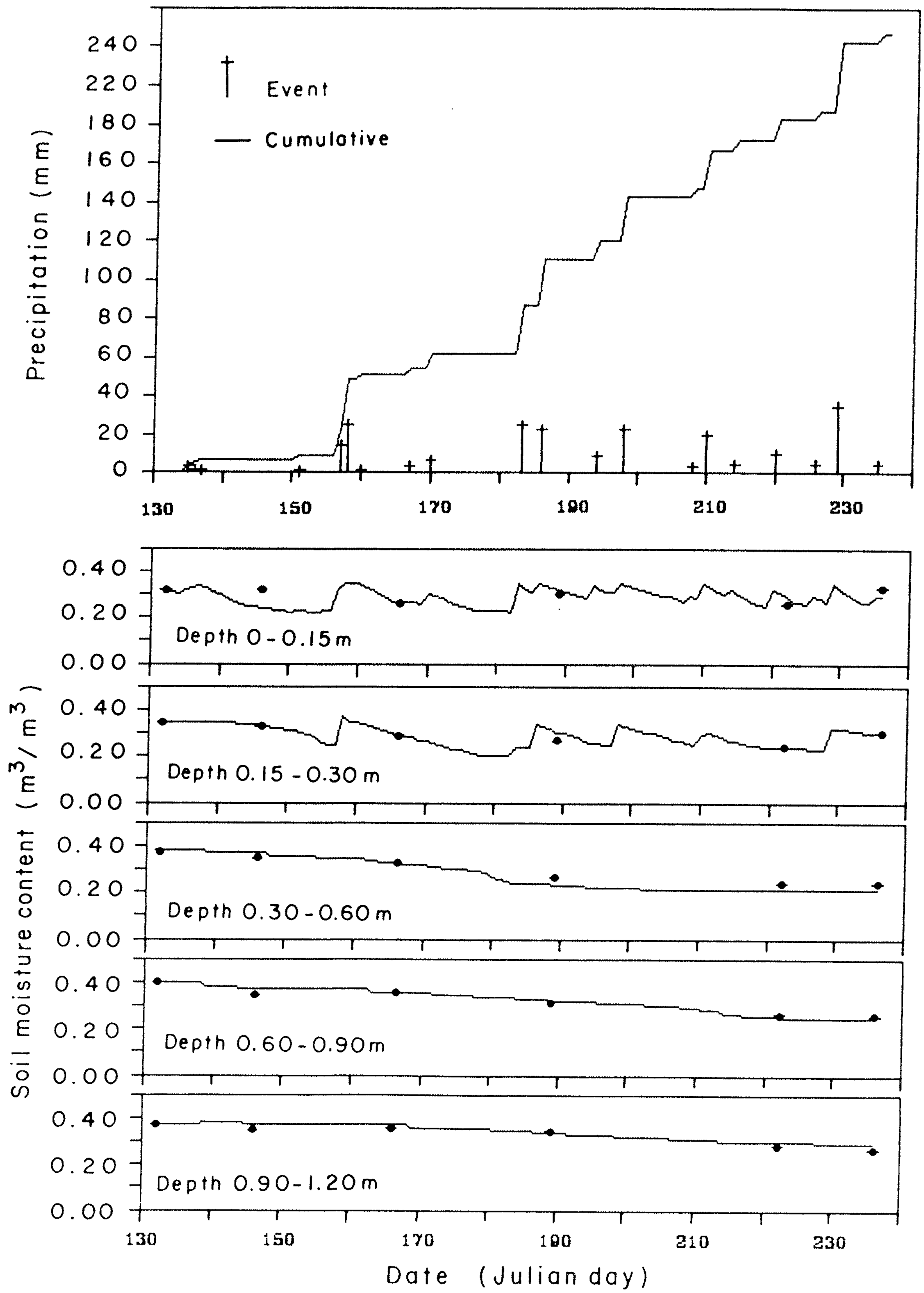


Figure 20: Precipitation (uppermost graph), mean observed soil moisture content (•), and PIXMOD, Sc. I, continuous estimated value (——) versus time at Winnipeg site in 1982 growing season.

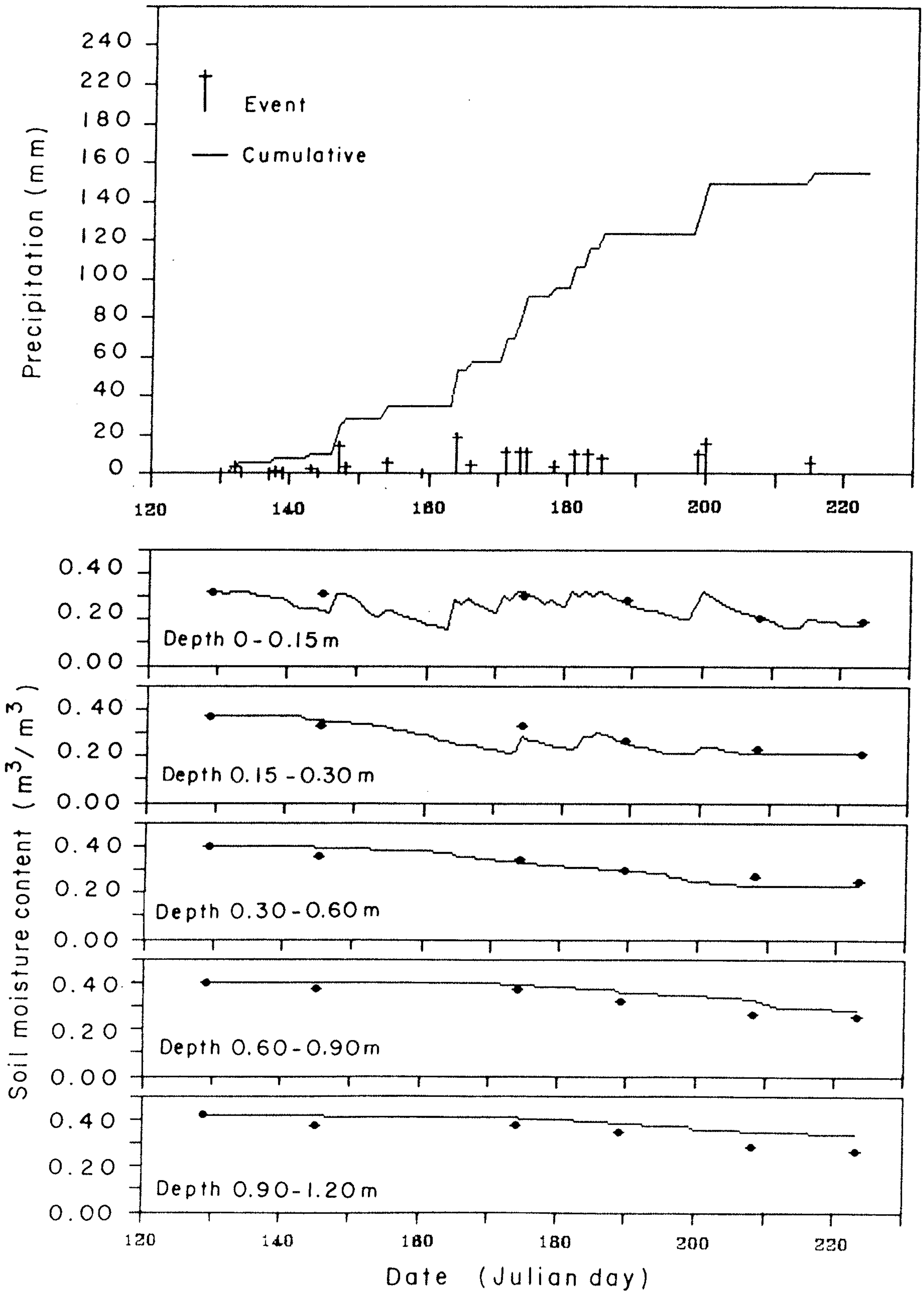


Figure 21: Precipitation (uppermost graph), mean observed soil moisture content (•), and PIXMOD, Sc. I, continuous estimated value (——) versus time at Winnipeg site in 1983 growing season.

instance, 63 mm of precipitation (about 77% of the total for the growing season) occurred before jointing. It might be possible that the roots developed at a shallow depth and failed to take up water from the theoretical maximum rooting zone (1.20 m deep) assumed by the model. On both sandy and loamy soils the model seemed to underestimate the soil moisture content to a depth of 0.30 m. This was most evident at Bagot for 1983 (Fig. 17) and at Mariapolis for 1982 (Fig. 18). Since the model also underestimated the soil moisture content at the emergence stage, this suggested that the model overpredicted the amount of water evaporated. The water lost by evaporation, expressed as % of transpiration, was predicted by PIXMOD as follows: at Bagot 24% in 1982 and 17% in 1983, at Mariapolis, 27% in 1982 and 20% in 1983 and at Winnipeg about 18% in both years. Generally, the PIXMOD estimate of water lost by evaporation was well correlated with the entire amount of precipitation, the frequency of precipitation events, and their distribution over the growing season, as well as with the hydraulic properties of the soil. More elaborate field experiments are required to evaluate this prediction, and therefore, no precise statement can be made on the evaporation estimates.

The PIXMOD simulation of soil wetness seemed to be well correlated with other processes, however. For example, water content simulated for a depth of 0.60 m changed rapidly in response to upper boundary conditions (precipitation, evapotranspiration) and to the water uptake by the root system that is the most dynamic within this depth range. The water in the profile from 0.60 m to 1.20 m was simulated as being more stable. The water content at this depth started to decrease approximately at the jointing stage. It decreased fairly steadily (at different rates from one location to another and from one year to another), and became stable again between the soft dough stage and maturity, an interval during which the root activity decreases and even ceases. This seemed to be a realistic representation of the field condition because the deep horizon of well-drained soil profile in the Prairie region acts as a reservoir that is recharged with water mainly from precipitation during the fall and winter (de Jong and Cameron, 1980).

The continuous prediction followed observed soil moisture content fairly closely for every site-year combination, indicating that the model is sensitive to both the soil physical properties and the natural environment inputs (precipitation and energy).

The continuously predicted aboveground net production (ANP) values from PIXMOD (Sc. I 1982, 1983) and the mean observed ANP data versus phenological development are presented in Figure 22 for Bagot, in Figure 23 for Mariapolis and in Figure 24 for Winnipeg. In all three figures the cumulative PIXMOD ANP estimates are represented by a continuous line, and the mean observed values are indicated by letters for each growth stage. Generally, the curves of cumulative ANP showed good agreement between model simulated values and mean observed data. For all site-year combinations the estimate was better for the heading, soft-dough and maturity stages; the continuous curves either passed through the range of $[(\bar{Y}+S_{\bar{y}}) - (\bar{Y}-S_{\bar{y}})]$, symbolized in the graphs by " + " $\bar{Y}+S_{\bar{y}}$ and " - " $\bar{Y}-S_{\bar{y}}$ around the mean value, or close to these values. The best fit was obtained for Bagot, in 1983 (Fig. 22b), and Mariapolis, in 1982 (Fig. 23a) where the simulated curves passed through $\bar{Y} \pm S_{\bar{y}}$ ranges at all growth stages except the jointing stage. As the

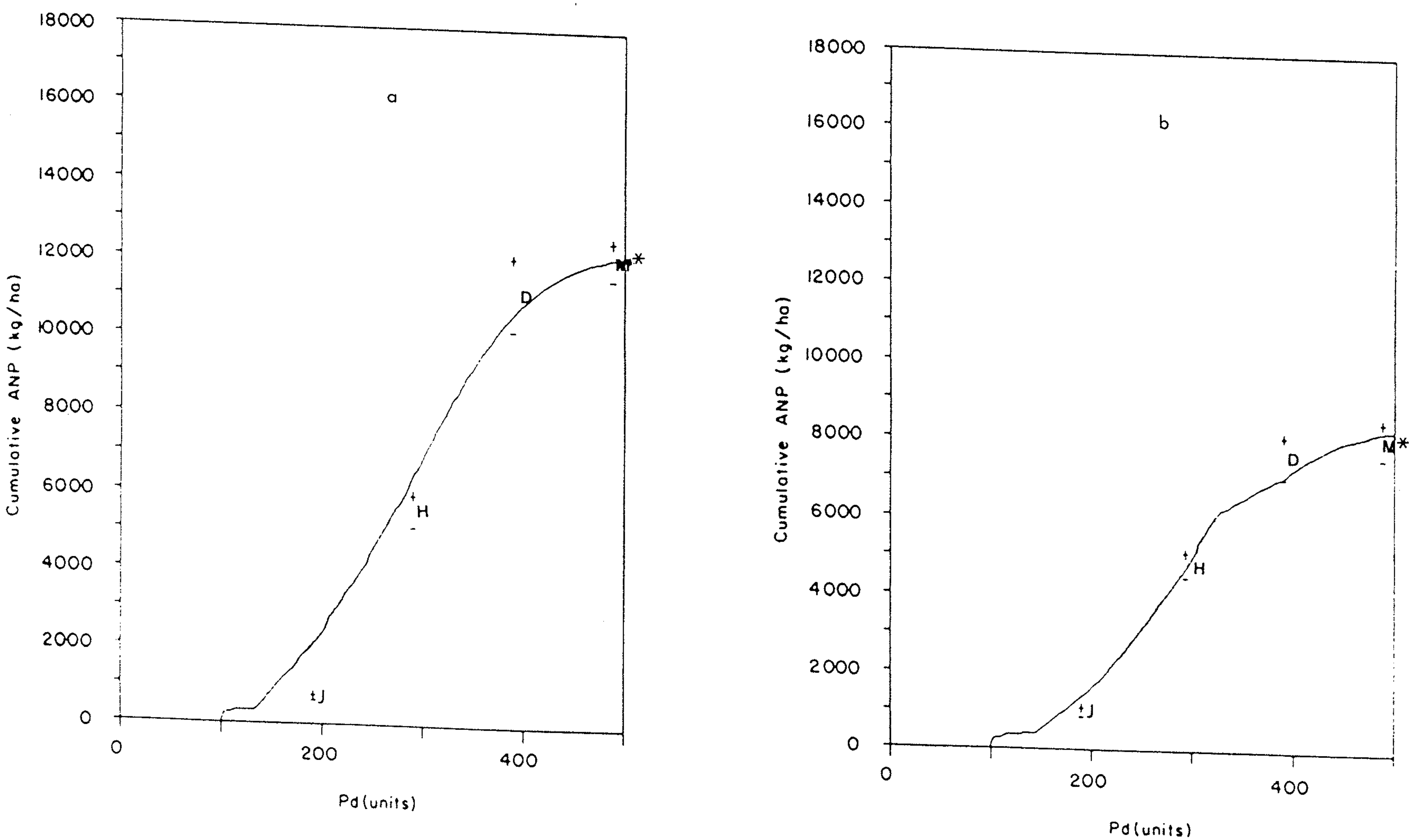


Figure 22: PIXMOD Sc. I, continuous prediction (—) of aboveground net production (ANP), and mean observed value at jointing (J), heading (H), soft dough (D) and maturity (M*) at Bagot site in (a) 1982, and (b) 1983.

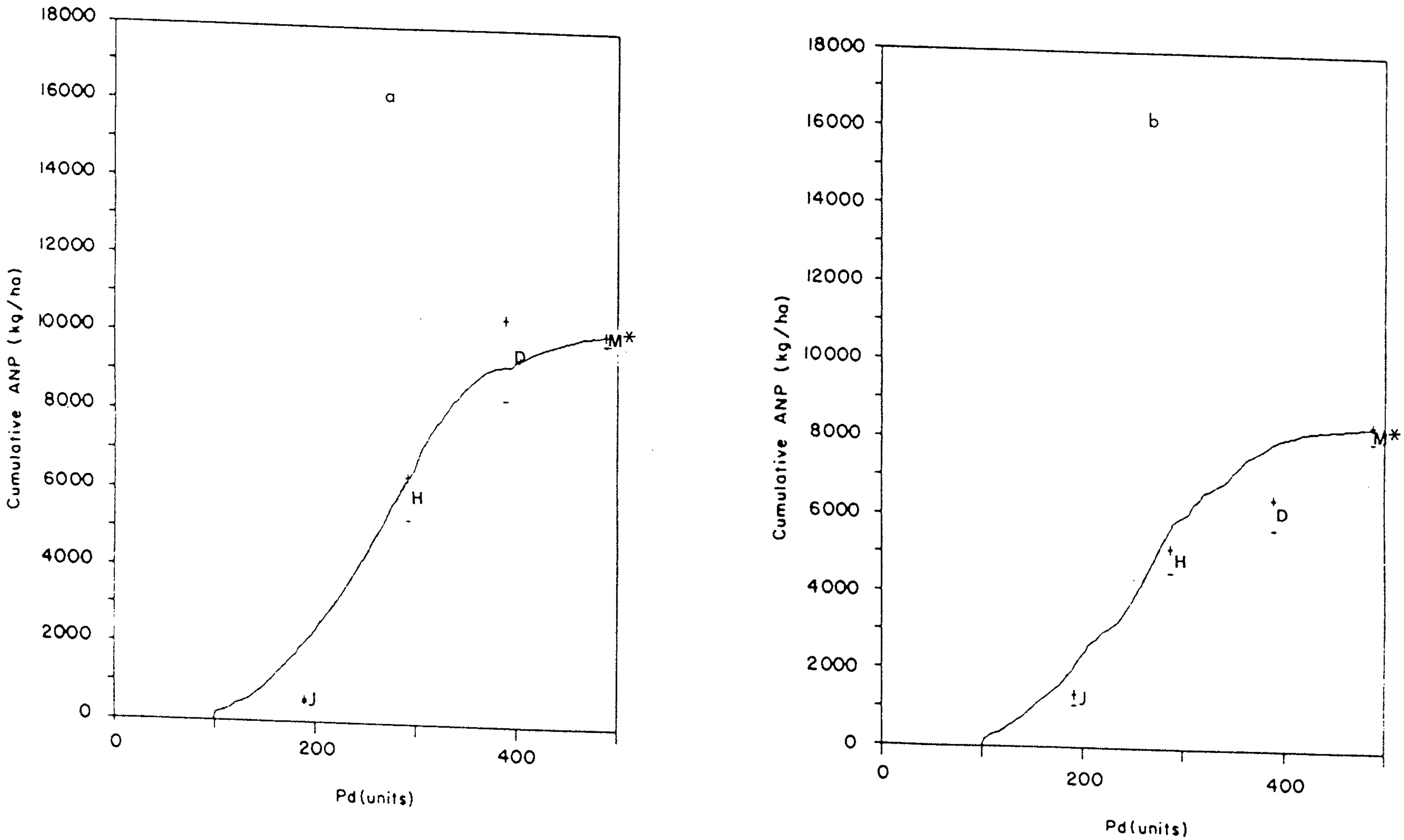


Figure 23: PIXMOD, Sc. I, continuous prediction (——) of aboveground net production (ANP), and mean observed value at jointing (J), heading (H), soft dough (D) and maturity (M*) at Mariapolis site in (a) 1982, and (b) 1983.

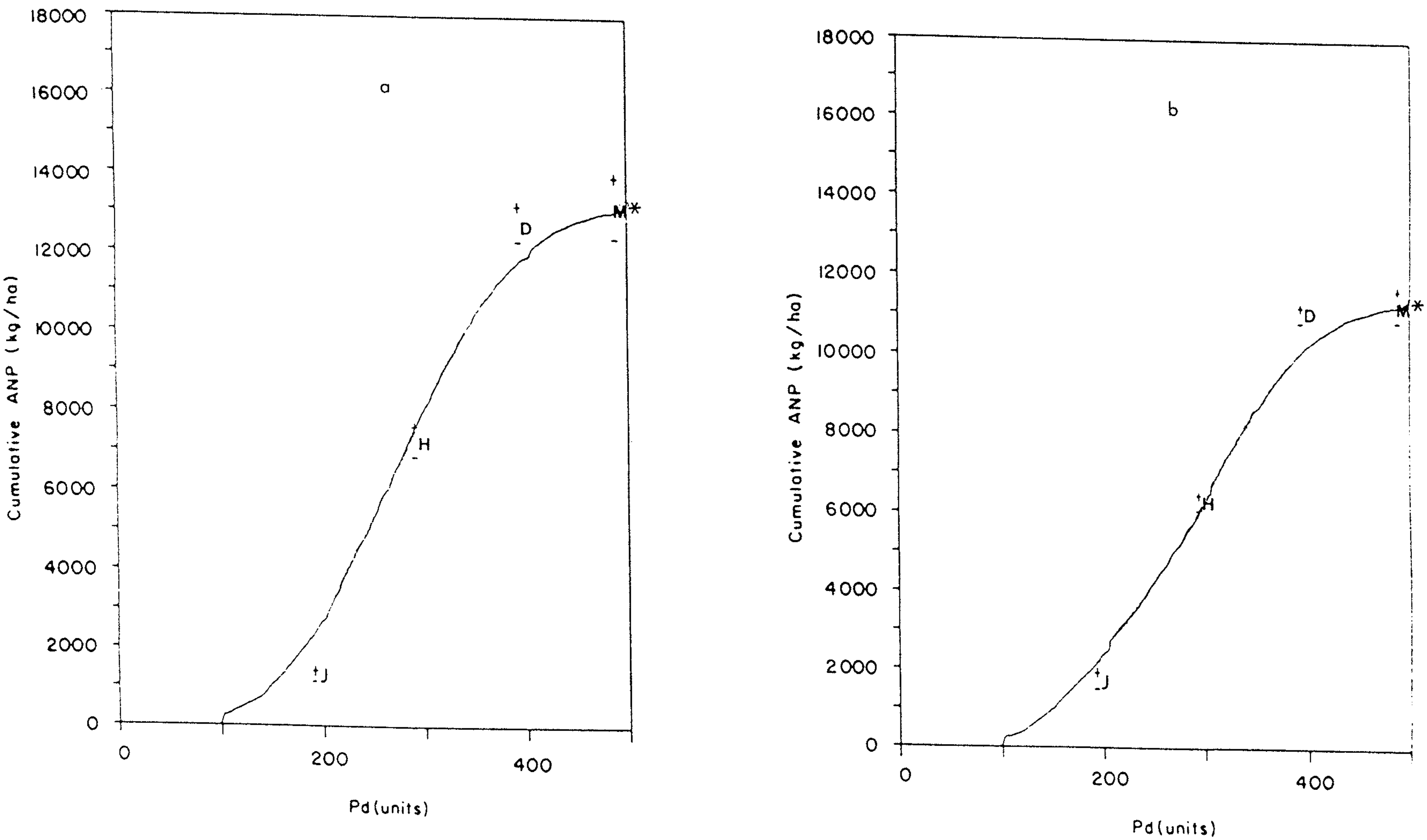


Figure 24: PIXMOD, Sc. I, continuous prediction (—) of aboveground net production (ANP), and mean observed value at jointing (J), heading (H), soft dough (D) and maturity (M*) at Winnipeg site in (a) 1982, and (b) 1983.

summary statistical results (Table 20) showed, the least accurate prediction was made at the jointing stage. In addition to the probable reasons for overprediction mentioned in the previous chapter, it is possible that the initial parameters of the normally distributed curve of ideal growth rate (eqn. 3.31) were in error. A calibration of the model based on the observed data set is not appropriate because data required for fitting the ideal growth rate must be derived from irrigated experiments. However, the model's continuous prediction of ANP seemed to be a reasonable approximation of wheat cumulative aboveground net production. The shape of the curves is different from one place to another and from one year to another, indicating that PIXMOD presents a reasonable degree of generality and that the simulated cumulative ANP values were reliable.

The application of PIXMOD for land evaluation assessments depends to a large extent on the ability of the model to predict accurately the wheat ANP using a limited data set as in Sc. II. Aboveground net production values (observed and simulated, both scenarios) accumulated from each phenological event to the next, are shown for Bagot in Figure 25, for Mariapolis in Figure 26 and for Winnipeg in Figure 27. In all three figures, the accumulated ANP from emergence to jointing, from jointing to heading, from heading to soft dough and from soft dough to maturity are presented in stacked bar graphs. The predictions in Sc. II were slightly higher than those of Sc. I, but differences between Sc. II and Sc. I were in narrow ranges. The absolute value of error varied from one site-year combination to another, with the same pattern for both scenarios. For example, at Bagot (Fig. 25) both scenarios underpredicted the accumulated ANP between jointing and heading in 1982

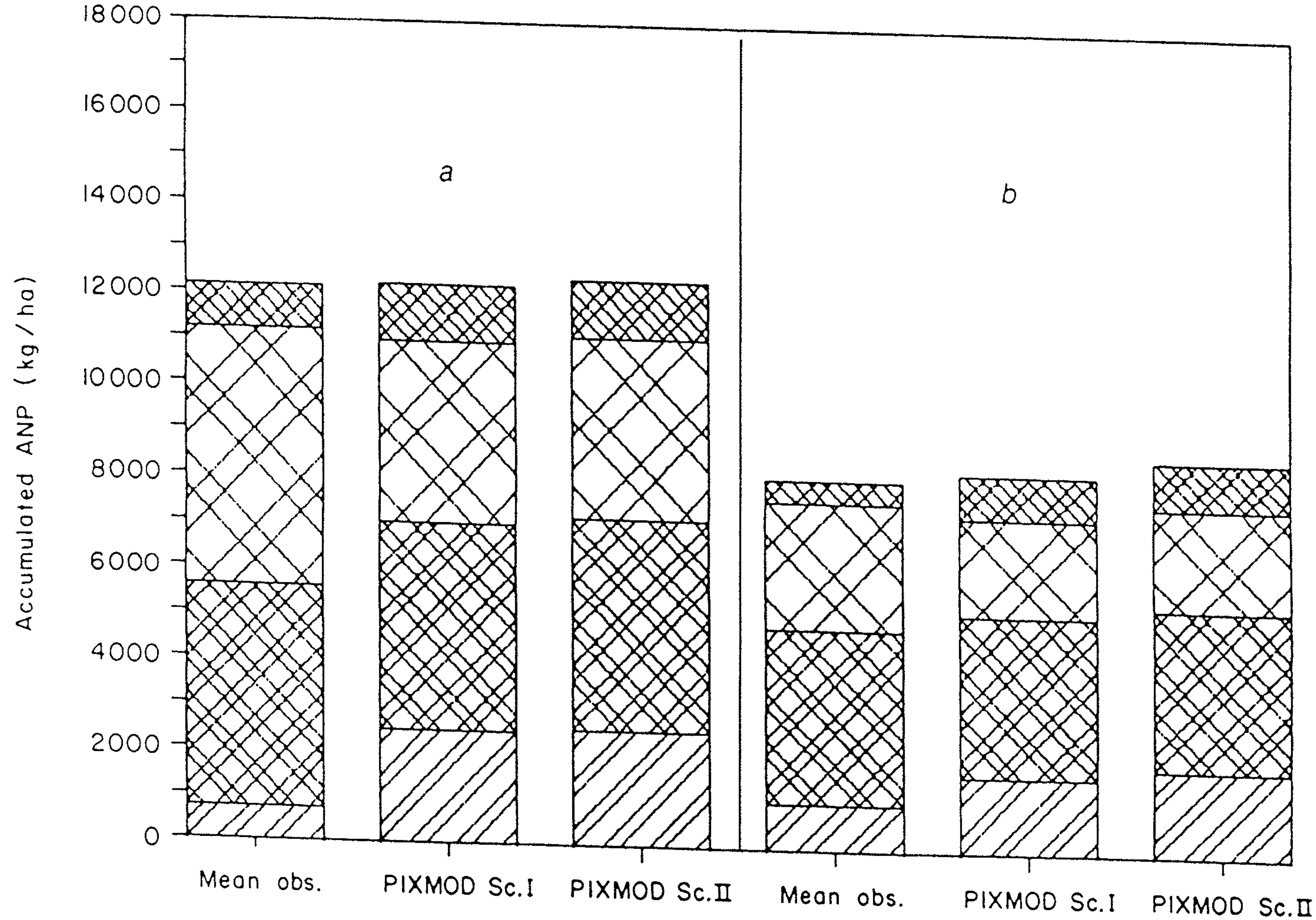


Figure 25: Accumulated aboveground net production (ANP) from one growth stage to the next ([hatched] from emergence to jointing, [cross-hatched] from jointing to heading, [open cross-hatched] from heading to soft dough, and [dense cross-hatched] from soft dough to harvest/maturity) observed and PIXMOD predicted values in Sc. I and Sc. II at Bagot site: (a) in 1982, and (b) in 1983 growing seasons.

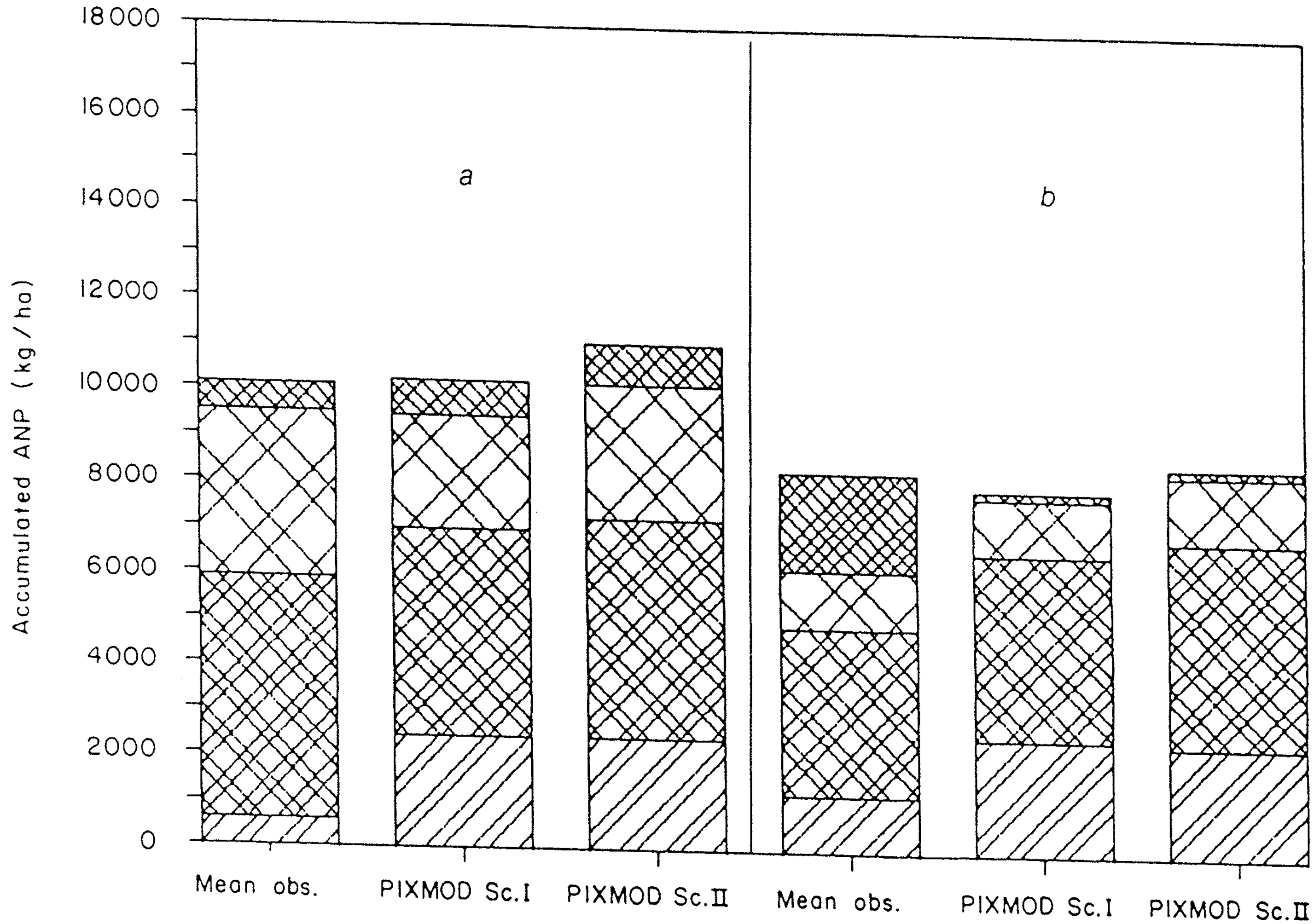


Figure 26: Accumulated aboveground net production (ANP) from one growth stage to the next (from emergence to jointing, from jointing to heading, from heading to soft dough, and from soft dough to harvest/maturity) observed and PIXMOD predicted values in Sc. I and Sc. II at Mariapolis site: (a) in 1982, and (b) in 1983 growing seasons.

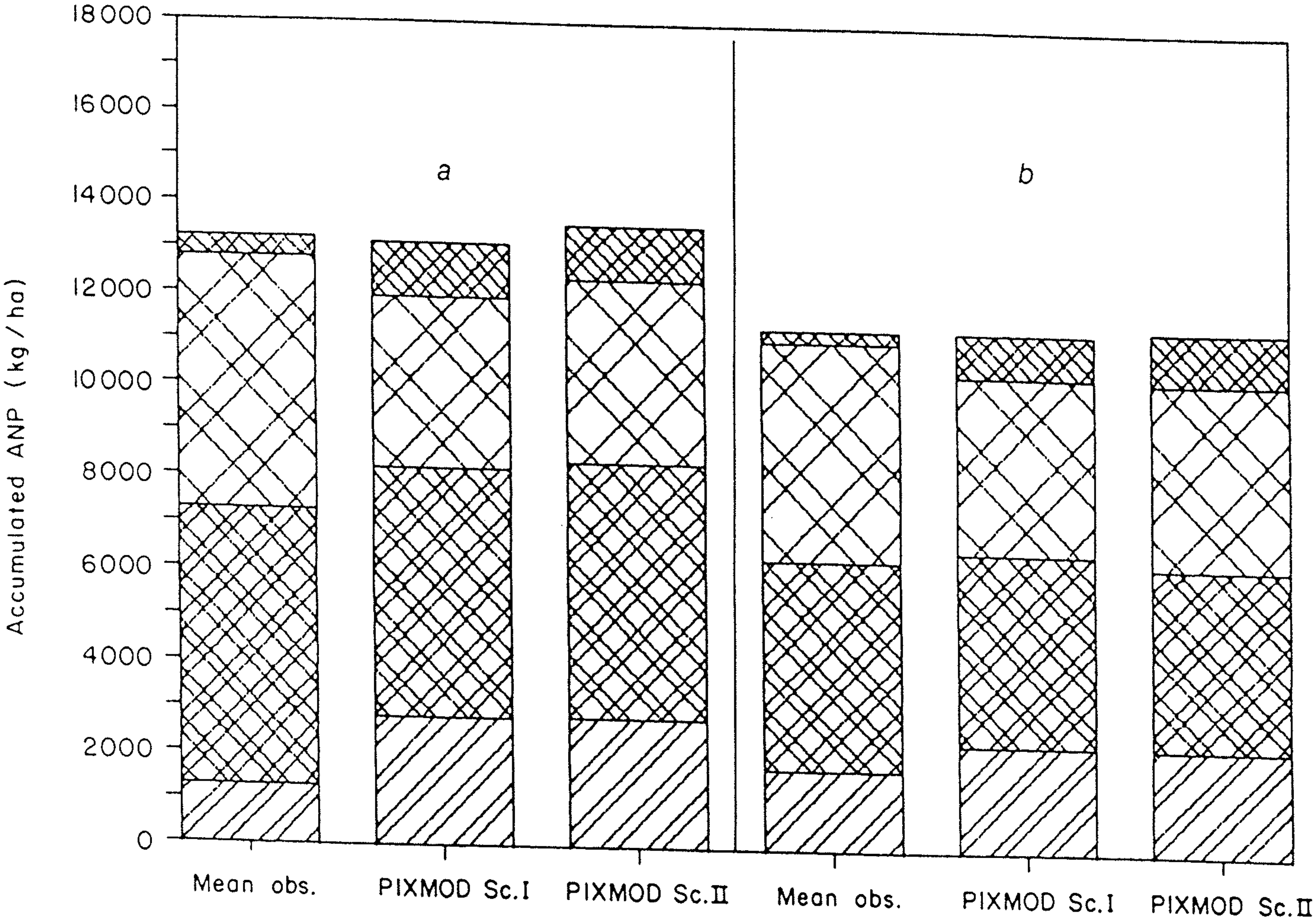


Figure 27: Accumulated aboveground net production (ANP) from one growth stage to the next (from emergence to jointing, from jointing to heading, from heading to soft dough, and from soft dough to harvest/maturity) observed and PIXMOD predicted values in Sc. I, and Sc. II at Winnipeg site: (a) in 1982, and (b) in 1983 growing seasons.

by approximately 1650 kg/ha; at Mariapolis (Fig. 26) the largest error was between soft dough and maturity in 1983, about 1800 kg/ha. At Mariapolis this error could be the result of the error for the soil moisture content estimate (Fig. 19) because the model underestimated the soil wetness for the second half of the growing season. At Winnipeg site, except for the accumulated ANP from soft dough to maturity, all other estimated values were close to the observed data.

It may be concluded that the estimates made by the model in Sc. II were not accurate enough for the individual growth stage intervals. However, because the accumulated ANP values were well approximated either for jointing-heading, heading-soft dough or both intervals, and because the growth rate was largest during these stages, the ANP accumulated at the end of the season was estimated reasonably well. The reason for the good prediction of the aboveground net production at maturity stage is that errors in individual stages tended to cancel each other. For example, at Bagot in 1982, the overpredicted value for the emergence-jointing interval was compensated for by an underprediction for heading-soft dough period.

In summary, the application of PIXMOD cannot be recommended to assist the farmers in making decisions during the current growing season, but the simulated yields are accurate enough to simulate wheat yields under different growing conditions and to compare different agroecosystems within a region of interest.

Chapter 5

CONCLUSION

The present study has approached the problem of land evaluation from a system standpoint, with emphasis on the dynamic interactions among major components of the agroecosystem and the stochastic environmental factors. Two interrelated activities have been performed. The first involved the development of a deterministic dynamic model that simulated wheat growth over a growing season. The second activity involved the evaluation of the model performance using field data, to enable a direct comparison between the outputs of a real system and the outputs of the model.

A computational procedure was described to simulate wheat growth under rainfed conditions in Manitoba and the Prairie region where soil wetness, nitrogen content in the soil and temperature were assumed the major factors that controlled the production of wheat. The model developed, PIXMOD, employed the method known as "the state-variable approach", and was based on two model programs, the first described by de Wit and van Keulen (1975) and the second by Vithayathil et al. (1977). The models were modified to accommodate the constraints under which PIXMOD must operate: the objective of the study, the knowledge about the relevant processes of the agroecosystem, and the availability of data.

PIXMOD has been developed to simulate aboveground net production using a time step of one day. The basic physiological processes, photosynthesis and respiration, were considered implicitly. The model now in use in Canada (Crop Production Potentials for Land Evaluation in Canada) was adopted, since it accounted for the genetic and adaptive potentials of wheat growth as well as for the photosynthetically active radiation (PAR) constraints. The variation of yield from place to place and from year to year was assumed to be the result of differences in soil subsystem properties, stochastic weather elements, and their interaction. Consequently, attention was focused on phenological development and growth rate as the major physiological processes, and on physical and chemical processes that controlled the most relevant factors limiting crop growth in the region: soil water content, nitrogen availability and soil temperature. Data used to develop the model were derived from the literature and from experiments performed in Canada, particularly in the Prairie region.

To evaluate the model, field experiments with measurements of boundary and initial conditions of the most critical variables included in PIXMOD, periodic harvesting of aboveground net production and soil sampling, have been performed across the agricultural sector of Manitoba over the growing seasons of 1982 and 1983. Briefly the evaluation results were:

1. The model predicted most of the state variables of the agroecosystem reasonably well. Particularly good agreement was obtained for the observed grain yield, and the aboveground net production at the end of the growing season.
2. Phenological development of the wheat crop estimated by the biometeorological time scale (BMTS) was predicted to be earlier than was observed, by approximately seven days. However, the BMTS is still the most reliable model available for estimating wheat growth

stages in the Prairie region.

3. Agreement between simulated soil wetness and that measured at jointing, heading, soft dough and maturity was good, with a few large deviations observed at some locations. The results suggested that, in order to predict soil moisture content accurately, knowledge about the lower boundary conditions of the rooting zone and about the soil initial conditions is as important as data on the soil storage capacity for water and soil hydraulic properties. The negative impact of excess water on yield, while based on "intelligent guesses" rather than a rigorous physical approach, was found to be justified in many instances.
4. The predicted value for nitrogen content was a rough approximation. The nitrogen content was not well simulated, whereas the grain yield and total ANP were still simulated fairly well. This seemed to be the result of compensating effects during the growing season, rather than the model's insensitivity to the amount of nitrogen initially present in the soil or to the amount of fertilizer applied.
5. The test results showed that the model predicted grain yield and aboveground net production reasonably accurately, even with limited data (Sc. II). This suggested that the existing standard Soil Survey data can be used to approximate fundamental soil properties and to provide input data for PIXMOD.
6. Although the performance of the model was satisfactory compared with the behaviours of the real system, a number of weak points were identified. First, the morphology of the root system was not well represented. The forcing function used for the water extraction pattern, although based on some experimental results, is still

largely speculative. The only realistic variable considered in the model that changed the pattern of the root system was the physical barrier at the bottom of the profile. Second, the effective area lost due to excess water was calculated based on information provided by expert pedologists rather than on experimental data. Third, although the model was developed independently of data collection, these two activities proceeded in parallel and some interaction was unavoidable. The interaction was mainly related to addition of processes in the model that were neglected initially, rather than adopting curve-fitting procedures. Nevertheless, further validation of the model using fully independent data set is recommended.

Finally, PIXMOD should be considered a first stage in the development of an operational model for land evaluation. However, the study showed that PIXMOD, by using soil and management data coupled with historical weather records, can be used to simulate wheat yields under different growing conditions. The simulated yield can be analyzed to arrive at probable wheat yield distributions for the agroecosystems identified in the Prairie region. These data can be reformatted in any desired level of probability. The expected wheat yields can be transformed into productivity indices or, by including cost/price factors, they can be converted into profit indices, a basis on which the land within the Prairie region can be easily evaluated.

REFERENCES

Acock, A and Grange, R.I. 1981. Equilibrium models of leaf water relations. In Mathematics and Plant Physiology. Rose, D.A. and Charles-Edwards, D.A. (eds.) Academic Press, London. p. 29-47.

Adams, J.E., Arkin, F.G. and Ritchie, J.T. 1976. Influence of row spacing and straw mulch on first stage drying. Soil Sci. Soc. Am. J. 40:436-442.

Aitken, F.J. 1983. Relationships between yield of sugar cane and soil mapping units, and the implications for land classification. Soil Survey and Land Evaluation 3(1):1-8.

Alberta Institute of Pedology. 1974. A comparison of the Canada Land Inventory (CLI) for agricultrual land evaluation and the Sloric Rating System. Alberta Institute of Pedology, University of Alberta, Edmonton.

Angus, J.F., Mackenzie, R., Morton, R. and Schofer, W.C. 1981. Phasic development in field crops II. Thermal and photoperiodic responses of spring wheat. Field Crops Res. 4:269-283.

Arkin, F.G., Maas, J.S. and Richardson, W.C. 1980. Forecasting grain Sorghum yields using simulated weather data and updating techniques. Transactions of the ASAE 23(3):676-680.

Arkin, F.G. and William, Jr., D.A. 1983. Making weather- and climate-dependent crop-management decisions. In Agroclimate Information for Development, Cusack, D.F. (ed.) Westview Press, Boulder, Colorado. p. 128-139.

Aston, M.J. and Lawlor, D.W. 1979. The relationship between transpiration, root water uptake, and leaf water potential. J. Exp. Bot. 30:169-181.

Austin, B.R. 1981. Crop characteristics and the potential yield of wheat. J. Agric. Sci. Camb. 98:447-453.

Austin, B.R. 1980. Genetic improvements in winter wheat yields since 1900 and associated physiological changes. J. Agric. Sci. Camb. 94:675-689.

Baier, W. 1981. Crop-weather analysis models. In Application of Remote Sensing to Agricultural Production Forecasting, Berg, A. (ed.), A.A. Balkema, Rotterdam. p. 105-118.

Baier, W. 1983. Agroclimatic modeling: an overview. In Agroclimate Information for Development. Cusac, F.D. (ed.), Westview Press, Boulder, Colorado. p. 57-82.

Baier, W. and Robertson, G.W. 1965. Estimating latent evaporation from simple weather observations. Can. J. Plant Sci. 45:276-284.

Baier, W., Dyer, J.A. and Sharp, R.W. 1979. The versatile soil moisture budget. Tech. Bull. No. 87, Agrometeorol. Sec. LRRI, Ottawa.

Baier, W., St.Pierre, J.C. and Lovering, J.H. 1980. Analysis of environmental factors affecting timothy yields. Agric. Meteorol. 22:319-339.

Baldwin, J.P. 1976. Competition for plant nutrients in soil; a theoretical approach. J. Agric. Sci., Cambridge 87:341-356.

Bauer, A., Smika, D. and Black, A. 1983. Correlation of five wheat growth stage scales used in the Great Plains. Advances in Agricultural Technology, Agricultural Research Service, USDA AAT-NC-7.

Baulkwill, W.J. 1972. The land resources division of the overseas development administration. Trop. Sci. 14:305-322.

van Bavel, C.H.M. and Hiller, D. 1975. Calculating potential and actual evaporation from a bare soil surface by simulation of concurrent flow of water and heat. Agric. Meteorol. 17:453-476.

Begg, J.E. and Turner, N.C. 1977. Crop water deficits, Adv. Agron. 28:161-217.

Beek, K.J. and Frissel, M.J. 1973. Simulation of Nitrogen Behaviour in Soil. Pudoc, Wageningen.

Beek, K.J. 1978. Land evaluation for agriculture development. ILRI Pubn. 23. International Institute for Land Reclamation and Improvement, Wageningen.

Beek, K.J. 1981a. From soil survey interpretation to land evaluation. Part 1. From the past to the present. Soil Survey and Land Evaluation 1(1):6-12.

Beek, K.J. 1981b. From soil survey interpretation to land evaluation. Part 2. From the past to the present. Soil Survey and Land Evaluation 1(1):23-30.

Beek, K.J., Huizing, H.G.J., de Man, H.W. and de Vos, H.J. 1983. Agroclimate information requirements for land evaluation purposes. In Agroclimate Information for Development. Cusack (ed.), Western Press, Boulder, Colorado. p. 155-161.

Belmans, C., Wesseling, G.J. and Feddes, A.R. 1981. Simulation model of the water balance of cropped soil providing different types of boundary conditions (SWATRE). Nota ICW 1256, Wageningen.

Biscoe, P.V., Scott, K.R. and Monteith, J.L. 1975. Barley and its environment. III. Carbon budget of the stand. J. Appl. Ecol. 12:269-293.

Biswas, A.K. 1980. Crop-climate models: a review of the state of the art. In Climatic Constraints and Human Activities. Ausubel, J. and Biswas, A.K. (eds.), Pergamon Press, New York, N.Y. p. 75-92.

Boddington, M.A.B. 1978. The classification of agricultural land in England and Wales: a critique. Rural Planning Services, Ipsden, Oxfordshire.

Box, E.P.G. and Jenkins, G.M. 1970. Time Series Analysis Forecasting and Control, Holden-Day, San Francisco.

Boyer, S.J. 1983. Environmental stress and crop yields. In Crop Reactions to Water and Temperature Stress in Humid Temperature Climates. Raper, Jr., C.D. and Kramer, P.J. (eds.), Westview Press, Boulder, Colorado. p. 3-7.

Brengle, K.G. and Whitfield, C.J. 1969. Effect of soil temperature on the growth of spring wheat with and without wheat straw mulch. Agron. J. 61:377-379.

Breteler, H., Greenwood, J.D., Petterson, I., Russell, S.J., Sauerbeck, D., van Dorp, F., van Keulen, H. and van der Meer, G.H. 1981. Soil-plant relations. In Simulation of Nitrogen Behaviour of Soil-Plant Systems. Frissel, J.M. and van Veen, J.A. (eds.), Pudoc, Wageningen. p. 45-47.

Brinkman, R. and Smyth, A.J. (ed.). 1973. Land evaluation for rural purposes. Publ. 17. Intern. Inst. Land Reclam. and Improvement (ILRI), Wageningen.

Brouwer, R. 1963. Some aspects of the equilibrium between overground and underground plant parts. (IBS) p. 31-39.

Buol, S.W. and Couto, W. 1981. Soil fertility - capability assessment for use in humid tropics. In Characterization of Soils in Relation to their Classification and Management for Crop Production, Greenland, D.J. (ed.), Oxford University Press, Oxford, p. 254-261.

Campbell, A.C. and Davidson, H.R. 1979. Effect of temperature, nitrogen fertilization and moisture stress on growth, assimilate distribution and moisture use by Manitou spring wheat. Can. J. Plant Sci. 50:603-626.

Caroll, D.M. 1974. The soils of the Maiduguri-Bama area. Soil Survey. Bull. Samaru No. 40.

Carslaw, H.S. and Jaeger, J.C. 1960. Conduction of heat in solids. Oxford. Univ. Press, London.

Cassel, K.D., Ratliff, F.L. and Ritchie, T.J. 1983. Models for estimating in-situ potential extractable water using soil physical and chemical properties. Soil. Sc. Soc. Am. J. 47:764-769.

Chanter. 1981. The use and misuse of linear regression methods in crop modelling. In Mathematics and Plant Physiology. Rose, D.A. and Charles-Edwards, D.A. (eds.), Academic Press, London. p. 253-267.

Charles-Edwards, A.D. 1981. The Mathematics of Photosynthesis and Productivity. Academic Press, London.

Childs, E.C. and Collis-George, N. 1950. The permeability of porous materials. Proc. Roy. Soc. Series A. 201:392-405.

Cho, C.M., Sakdinan, L. and Chang, C. 1979. Denitrification intensity and capacity of three irrigated Alberta soils. Soil Sci. Soc. Am. J. 43:945-950.

Chow, V.T. 1954. The log-probability low and its engineering applications. Proc. Am. Soc. Civil Engrs. 80:1-25.

Clapp, P.B. and Hornberger, G.M. 1978. Empirical equations for some soil hydraulic properties. Water Resour. Res. 14:601-604.

CSSC - Canada soil survey committee. 1978. The Canadian System of Soil Classification. Can. Dept. Agric. Publ. 1646. Supply and Services Canada, Ottawa.

Curry, R.B., Baker, H.C. and Streeter, G.J. 1975. SOYMODI: A dynamic simulator of soybean growth and development. Transactions of the ASAE 1975:963-968.

Dalal-Clayton, D.B. 1984. The development of soil survey in Zambia. Soil Survey and Land Evaluation 4(1):18-23.

Day, H.R. 1965. Probability distributions of field crop yields. J. Farm Econ. 47:713-741.

Day, W., Legg, J.B. French, K.B., Johnston, E.A., Lawlor, W.D. and Jeffers, C.W. 1978. Drought experiment using mobile shelters: the effect of drought on barley yield, water use and nutrient uptake. J. Agric. Sci. Camb. 91:599-623.

Denmead, O.T. and Shaw, R.H. 1962. Availability of soil water to plants as affected by soil moisture content and meteorological conditions. Agron. J. 45:385-390.

Dent, D. 1983. Editorial research development and survival. Soil Survey and Land Evaluation 3(3):57-58.

Dent, D. and Young, A. 1981. Soil Survey and Land Evaluation. George Allen & Unwin. London, Boston, Sydney.

Donald, C.M. and Hamblin, J. 1976. The biological yield and harvest index of cereals as agronomic and plant breeding criteria. Adv. Agron. 28:361-405.

Doraiswamy, C.P. and Thompson, D.R. 1982. A crop moisture stress index for large area and its application in the prediction of spring wheat phenology. Agric. Meteorol. 27:1-15.

Doorenbos, J. and Kassam, A.H. 1979. Yield response to water. Irrig. and Drainage Paper 33. FAO. Rome.

Duffy, J., Chung, C., Boast, C. and Franklin, M. 1975. A simulation model of biophysico-chemical transformations of nitrogen in tile-drained corn belt soil. J. Environ. Qual. 4:477-486.

Dumanski, J. and Stewart, R.B. 1981. Crop production potentials for land evaluation in Canada. LRRI, Agr. Canada. Ottawa, Ontario.

Dumanski, J. and Stewart, R.B. 1983. Crop production potentials for land evaluation in Canada. LRRI, Agr. Canada. Ottawa, Ontario.

Duncan, W.G. 1972. SIMCOT: a simulator for cotton growth and yield. In Proceedings Workshop on Tree Growth Dynamics and Modeling, Murphy, C. (ed.), Duke University, Durham, NC. p. 115-118.

Ellis, F.B. and Barnes, B.T. 1973. Estimation of the distribution of living roots of plants under field conditions. Plant Soil 39:81-91.

English, J.M. 1981. The uncertainty of crop models in irrigation optimization. Transactions of ASAE 79:917-928.

Evans, L.T. 1980. The natural history of crop yield. Am. Soc. 68:388-397.

FAO. 1976. A framework for land evaluation. Soils Bull. 32. Rome.

FAO. 1978. Report on the agro-ecological zones project. Vol. 1. Methodology and results for Africa. World Soil Resour. Rep. 48. Rome.

FAO. 1979. Land evaluation criteria for irrigation. Report of an expert consultation. Re. 5. Rome.

FAO. 1984. Guidelines: land evaluation for rainfed agriculture. Soils Bull. 52. Rome.

Feddes, R.A., Kowalik, P.J. and Zaradny, H. 1978. Simulation of field water use and crop yield. Simulation Monographs. Pudoc, Wageningen.

Fisher, R.A. 1979. Growth and water limitations to dryland wheat yield in Australia. A physiological framework. J. Aust. Inst. Agric. Sci. 45:83-94.

Forrester, J.W. 1978. Principles of Systems, Wright-Allen Press, Cambridge, Mass.

France, J. and Thornley, J.H.M. 1984. Mathematical Models in Agriculture. A Quantitative Approach to Problems in Agriculture and Related Sciences, Butterworth, London.

Franquin, P. 1983. Statistical models of the climatic growing period crop potentials. In Agroclimate Information for Development. Cusack, F.D. (ed.), Westview Press. Boulder, Colorado. p. 92-112.

Frissel, J.M. and van Veen, J.A. 1981. Simulation of Nitrogen Behaviour of Soil-Plant Systems. Pudoc, Wageningen.

Gallagher, N.J. and Biscoe, P.V. 1978. Physiological analysis of cereal yield: II partitioning of dry matter. Agric. Prog. 53:51-70.

Gallagher, N.J. 1979. Field studies of cereal leaf growth. J. Exp. Bot. 30:625-636.

Gold, J.H. 1977. Mathematical Modeling of Biological Systems. - An Introductory Guidebook. John Wiley and Sons, New York.

Gottman, M.J. 1981. Time-Series Analysis. A comprehensive introduction for social scientists. Cambridge University Press, Cambridge.

Goudriaan, J. 1982. Potential production processes. In Simulation of plant growth and crop production. Penning de Vries, F.W.T. and van Laar, H.H. (eds.), Pudoc, Wageningen. p. 98-113.

Goudriaan, J. and van Laar, H.H. 1978. Calculation of daily total of gross CO_2 assimilation of leaf canopies. Neth. J. Agric. Sci. 26:373-382.

Grant, E.W. and Matis, J.H. 1983. Stochastic compartment models of ecological succession: evaluation of their usefulness to natural resource managers. In Analysis of Ecological Systems: State-of-the-Art in Ecological Modelling. Lauenroth, K.W., Skogeboe, V.G. and Flug, M. (eds.), Elsevier Scientific Publishing Company, Amsterdam. p. 149-155.

Gupta, S.C. and Larson, W.E. 1979. Estimating soil water retention characteristics from particle size distribution, organic matter percent and bulk density. Water Resour. Res. 15:1633-1635.

Hald, A. 1952. Statistical Theory with Engineering Applications. Applied Statistics, John Wiley and Sons Inc.

Heen, A. 1980a. Methods for root studies of annual plants. Meldinger fra Norges Landbrukshogskole 59, 16:1-17.

Heen, A. 1980b. Root development and water use in some Norwegian barley, wheat and oat varieties. Meldinger Fra Norges Landbrukshogskole 59, 17:1-11.

Hesketh, J.D. and Jones, J.W. 1980. Predicting photosynthesis for ecosystem models, Volumes I and II. Florida, CRC Press.

Hiler, A.E. and Howell, T.A. 1983. Irrigation options to avoid critical stress: an overview. In Limitations to Efficient Water Use in Crop Production. Taylor, H., Jordan, W. and Sinclair, (eds.), p. 479-497. ASA-CSSA-SSSA Madison.

Hiler, E.A. and Clark, R.N. 1971. Stress day index to characterize effects of water stress on crop yield. Trans. ASAE 14:757-761.

Hobbs, E.H. and Krogman, K.K. 1968. Observed and estimated evapotranspiration in Southern Alberta. Trans. ASAE 11:502-503, 507.

Holt, D.A., Bula, J.R., Miles, E.G., Schreiber, E.G. and Peart, M.R. 1975. Environmental physiology, modeling and simulation. I. Conceptual development of SIMED. Research Bulletin No. 907, p. 26, Purdue University.

Hsiao, C.T. and Bradford, K.T. 1983. Physiological consequences of cellular water deficits. In Limitations to Efficient Water Use in Crop Production. Taylor, H., Jordan, W. and Sinclair, T. (eds.) p. 227-258, ASA-CSSA-SSSA Madison.

Ison, T.N., Feyerherm, M.A. and Bark, D.L. 1971. Wet period precipitation and the gamma distribution. J. App. Meteorol. 10:658-665.

Jones, H.G. 1980. Interaction and integration of adaptive responses to water stress: the implications of an unpredictable environment. In Adaptation of Plants to Water and High Temperature Stress. Turner, C.N. and Kramer, P.J., (eds.), John Wiley and Sons, New York. p. 353-365.

Jones, H.G. 1981. The use of stochastic modelling to study the influence of stomatal behaviour on yield-climate relationships. In Mathematics and Plant Physiology. Rose, A.D. and Charles-Edwards, D.A. (eds.), Academic Press, London. p. 231-244.

Jones, J.W. and Hesketh, J.D. 1980. Predicting leaf expansion. In Predicting photosynthesis for ecosystem models. Hesketh, J.D. and Jones, J.W., (eds.), CRC Press Inc., Boca Raton, Florida, Vol. 2:85-122.

de Jong, E. and Steppuhn, H. 1983. Water conservation: Canadian Prairies. In Dryland Agriculture, Dregne, H.E. and Willis, W.O., (eds.), Agronomy 23, ASA-CSSA-SSSA, Madison. p. 89-104.

de Jong, R. and Best, K.F. 1979. The effect of soil water potential, temperature and seeding depth on seedling emergence of wheat. Can. J. Soil Sci. 59:259-264.

de Jong, R. 1983. Assessment of empirical parameters that describe soil water characteristics. Can. Agric. Eng. 24:65-70

Jordan, R.W. 1983. Whole plant response to water deficits: an overview. In Limitations to Efficient Water Use in Crop Production, Taylor, H., Jordan, W and Sinclair, T. (eds.), ASA-CSSA-SSSA. Madison. p. 289-312.

Joseph, E.S. 1973. Spectral analysis of daily maximum and minimum temperature series on the east slope of the Colorado Front Range. Mon. Weather Rev. 101(6):505-509.

Kanemasu, T.E. 1983. Yield and water-use relationships: some problems of relating grain yield to transpiration. In Limitations to Efficient Water Use in Crop Production, Taylor, H., Jordan, W. and Sinclair, T. (eds.), ASA-CSSA-SSSA, Madison. p. 413-417.

Katz, W.R. 1979. Sensitivity analysis of statistical crop-weather models. Agric. Meteorol. 20:291-300.

van den Kevie, W. (ed.) 1976. Manual for land suitability classification for agriculture. Part II. Guidelines for soil survey party chiefs. Soil Survey Administration, Wad Medani. Min. of Agric., Food and Nat. Resources, Sudan, p. 106.

van Keulen, H. and van Beek, C.G.E.M. 1971. Water movement in layered soils; a simulation model. Neth. J. Agric. Sci. 19:138-153.

van Keulen, H. 1975. Simulation of water use and herbage growth in arid regions, Simulation monographs, Pudoc, Wageningen.

van Keulen, H. 1982. Crop production under semi-arid conditions, as determined by nitrogen and moisture availability. In Simulation of Plant Growth and Crop Production, Penning de Vries, F.W.T. and van Laar, H.H., (eds.), Pudoc, Wageningen. p. 234-249.

van Keulen, H., Penning de Vries, F.W.T. and Drees, M.E. 1982. A summary model for crop growth. In Simulation of Plant Growth and Crop Production, Penning de Vries, T.W.F. and van Laar, H.H. (eds.), Pudoc, Wageningen. p. 87-97.

Kiniry, L.N., Scrivner, L.C. and Keener, E.M. 1983. A soil productivity index based upon predicted water depletion and root growth. Research Bull. 1051. Univ. of Missouri-Columbia College of Agriculture.

Kirkham, B.M. and Ahring, R.M. 1978. Temperature and internal water status of wheat grown at different root temperature. Agron. J. 70:657-662.

Kirkham, B.M. and Kanemasu, E.G. 1983. Wheat. In Crop-Water Relations. Teare, D.I. and Peet, M.M. (eds.), John Wiley and Sons, New York. p. 481-520.

Klingbiel, A.A. and Montgomery, P.H. 1961. Land capability classification. U.S. Dept. of Agric. Soil Conserv. Service Agric. Handbook, Washington.

Kraft, F.D. and Senkiw, M. 1979. Production analysis of Canada land inventory classification. U. of M., Dept. of Agric. Economics, Winnipeg, Manitoba.

Kruh, G. and Segall, E. 1981. Nitrogen dynamics in soil. In Simulation of Nitrogen Behaviour of Soil-Plant Systems. Frissel, M.J. and van Veen, J.A. (eds.), Pudoc, Wageningen. p. 109-125.

Laliberte, G.E., Eilers, R.G. and Mustafa, G. 1982. Drought sensitivity analysis project. Estimating from drainage costs under irrigation. Department of Ag. Engineering, University of Manitoba, Winnipeg, Manitoba.

Law, M.A. and Kelton, W.D. 1982. Simulation Modeling and Analysis. McGraw-Hill Book Company, New York.

Leamy, M.L. 1974. An improved method of assessing the soil factor in land evaluation. Sci. Rep. N.Z. Soil Bur. No. 16.

Legg, B.J. 1981. Aerial environment and crop growth. In Mathematics and Plant Physiology. Rose, D.A. and Charles-Edwards, D.A. (eds.), Academic Press, London. p. 129-149.

Lehane, J.J. and Staple, J.W. 1965. Influence of soil texture, depth of soil moisture storage and rainfall distribution on wheat yields in Southwestern Saskatchewan. Can. J. Soil Sci. 45:207-219.

Luttrell, B.C. and Gilbert, A.R. 1976. Crop yields: random, cyclical or bunchy? Am. J. Agric. Econ. 58:521-531.

MacDowall, F.D.H. 1973. Grow kinetics of Marquis wheat. IV. Temperature dependence. Can. J. Bot. 51:729-736.

Magaldi, D. 1983. Progress in land evaluation in Italy. Soil Survey and Land Evaluation 3(1):18-21.

Mandelbrot, B.B. and Van Ness, J.W. 1968. Fractional Brownian motions, fractional noises and applications. SIAM Rev. 4(10):422-437.

McBride, R. 1984. Crop productivity estimates for a national land evaluation model. Working paper No. 8. Land Evaluation Group. University School of Rural Planning and Development, University of Guelph, Ontario.

McCormack, R.J. 1971. The Canadian land use inventory: a basic for land use planning. Journal of Soil and Water Conservation 26:141-146.

McCree, K.J. 1970. An equation for the rate of respiration of white clover plants grown under controlled conditions. In Prediction and Measurement of Photosynthetic Productivity. Sellik, I. (ed.), Pudoc, Wageningen. p. 22-219.

McKeague, A.J. 1981. Manual on soil sampling and methods of analysis. CSSC. ILRR. Ottawa, Ontario.

McKinon, J.M., Baker, N.D. and Hesketh, J.D. 1975. SIMCOTII: A simulation of cotton growth and yield. In Computer Simulation of Cotton Production System: User's Manual. USDA. ARS-S-52. p. 27-82.

McKinon, M.J. and Baker, D.N. 1983. Dynamic crop modelling: a synergism of computers, experimental research and the scientific method. In Analysis of Ecological Systems: State-of-the-Art in Ecological Modelling. Lauenroth, W.K., Skogerboe, G.V. and Flug, M. (eds.), Elsevier Scientific Publishing Company, Amsterdam. p. 503-516.

McPherson, H.G. and Boyer, J.S. 1977. Regulation of grain yield by photosynthesis in maize subjected to water deficiency. Agron. J. 59:714-718.

McRae, S.G. and Burnham, C.P. 1981. Land Evaluation. Clarendon Press, Oxford.

Meyer, E.G., Curry, B.R., Streeter, G.J. and Baker, H.C. 1981. Simulation of reproductive processes and senecence in intermediate soybeans. Transactions of the ASAE 24(2):421-435.

Meyer, E.G. 1985. Simulation of moisture stress effects on soybean yield components in Nebraska. Transactions of the ASAE 28, 1:118-128.

Meyer, W.S. and Ritchie, J.T. 1980. Resistance to water flow in the sorghum plant. Plant Physiol. 65:33-39.

Miller, J.G. 1978. Living Systems. McGraw-Hill, New York.

Milthorpe, F.L. and Moorby, J. 1974. An Introduction to Crop Physiology, Cambridge University Press, Cambridge.

Minhas, B.S., Parikh, S.K. and Srinivasan, N.T. 1974. Toward a structure of a production function for wheat yields with dated inputs of irrigation water. Water Resour. Res. 10:383-393.

Mishoe, J.W., Jones, W.J., Swany, P.D. and Wilkerson, G. 1982. Using crop models for management. I. Integration of weather data. ASAE Paper No. 82-4567 ASAE. St. Joseph, Michigan 49085.

Morgan, M.J. 1980. Differences in adaptation to water stress within crop species. In Adaptation of Plants to Water and High Temperature Stress. Turner, C.N. and Kramer, P.J. (eds.), John Wiley and Sons, New York. p. 360-382.

Moss, C.H. 1972. A revised approach to rating Saskatchewan Soils. Saskatchewan Institute of Pedology Publication M20.

Motha, R.J. 1979. Weather crop yield relationships in drought-prone countries of Sub-Saharan Africa. Final Report NOAA/CEAS. Models Branch and University of Missouri, Atmospheric Science Department, Columbia, Missouri.

Muchena, F.N. and van de Weg, R.F. 1982. Soil survey and land evaluation in Kenya. Soil Survey and Land Evaluation 2(2):42-47.

Mutsaers, H.J.W. 1979. An agricultural analysis of rainfall reliability for Cameroon. Neth. J. Agric. Sci. 27:67-78.

Nelson, L.A. 1963. Detailed land classification- Island of Oahu. Bull. Ld. Study Bur. Univ. Hawaii No. 3.

Niemann, Jr., J.B. and McCarthy, M.M. 1979. Spatial data analysis and information communication. In Planning the Use and Management of Land, ASA-CSSA-SSSA, Madison. p. 187-222.

Nix, H.A. 1968. The assessment of biological productivity. In Land Evaluation, Stewart, G.A. (ed.), Macmillan, London. p. 77-87.

Nix, A.H. 1981. Simplified simulation models based on specified minimum data sets: the CROPEVAL concept. In Application of Remote Sensing to Agricultural Production Forecasting. Berg. A. (ed.), A.A. Balkema/Rotterdam. p. 151-169.

Nyborg, M., Neufeld, A.J. and Bertrand, A.R. 1976. Measuring crop available nitrogen. In Nitrogen Symposium Proceedings. Calgary, Alberta. p. 102-128.

Odum, P.E. 1984. Properties of agroecosystems. In Agricultural Ecosystems. Lowrance, E., Stinner, B. and House, G. (eds.), John Wiley and Sons, New York. p. 5-11.

Olson, G.W. 1974. Interpretative land classification in English-speaking countries. In Approaches to Land Classification, Soils Bull. 22, Rome, FAO. p. 1-25.

Pant, M.M. 1979. Dependence of plant yield on density and planting pattern. Annals of Botany 44:513-516.

Patten, B.C. and Odum, E.P. 1981. The cybernetic nature of ecosystems. Am. Nat. 118:886-895.

Patterson, D.T. 1983. Phenotipic and physiological comparisons of field and phytroton grown plants. In Crop Reactions to Water and Temperature Stress in Humid Temperate Climates. Raper, Jr., C.D. and Kramer, P.J. (eds.), Westview Press, Boulder, Colorado. p. 299-314.

Patterson, T.G. and Mackintosh, E.E. 1976. Relationship between soil capability class and economic returns from grain corn production in Southwestern Ontario. Can. J. Soil. Sci. 56:167-174.

Penning de Vries, T.W.F. 1982. Phases of development of models. In Simulation of Plant Growth and Crop Production. Penning de Vries, T.W.F. and van Laar, H.H. (eds.), Pudoc, Wageningen. p. 20-25.

Penning de Vries, T.W.F. and van Laar, H.H. 1982. Simulation of growth processes and the model BACROS. In Simulation of Plant Growth and Crop Production. Penning de Vries, T.W.F. and van Laar, H.H. (eds.), Pudoc, Wageningen. p. 114-135.

Peters, W.T. 1977. Relationships of yield data to agroclimates, soil capability classification and soils of Alberta. Can. J. Soil Sci. 57:341-347.

Pierce, J.F., Larson, E.W., Dowdy, H.R. and Graham, P.A.W. 1984. Soil productivity in the Corn Belt: an assessment of erosion's long-term effects. J. Soil and Water Cons. 39:131-138.

Pitter, L.R. 1977. The effect of weather and technology on wheat yields in Oregon. Agric. meteorol. 18:115-131.

Philip, J.R. 1957. Evaporation and moisture and heat fields in the soil. J. Meteorol. 14:354-366.

Racz, J.G., Webber, M.D., Soper, J.R. and Hedlin, A.R. 1965. Phosphorus and nitrogen utilization by rape, flax and wheat. Agron. J. 57:335-337.

Rassmusen, V.P. and Hanks, R.J. 1978. Spring wheat yield model for limited moisture conditions. Agron. J. 70:940-944.

Ratliff, L.F., Ritchie, T.J. and Cassel, K.D. 1983. Field-measured limits of soil water availability as related to laboratory-measured properties. Soil Sci. Soc. Am. J. 47:770-775.

Reimer, A. 1978. Soil temperature estimation from meteorological measurements. Unpublished M.Sc. Thesis. Univ. of Manitoba, Winnipeg.

Richardson, W.C. 1981. Stochastic simulation of daily precipitation, temperature and solar radiation. Water Resources Research 17(1):182-190.

Rickman, W.R., Raming, E.R. and Allmaras, R.R. 1975. Modeling dry matter accumulation in dryland winter wheat. Agron. J. 67:283-289.

Riquier, J., Bramao, L.D. and Cornet, P.J. 1964. A new system of soil appraisal in terms of actual and potential productivity. Land and Water Development Division, FAO, Rome.

Riquier, J. 1974. A summary of parametric methods of soil and land evaluation. Approaches to Land Evaluation Soils Bull. 22, FAI, Rome.

Ritchie, T.J. 1983. Efficient water use in crop production: discussion on the generality of relations between biomass production and evapotranspiration. In Limitations to Efficient Water Use in Crop Production. Taylor, M.H., Jordan, R.W. and Sinclair, T.R. (eds.), ASA-CSSA-SSSA, Madison. pp. 29-44.

Ritchie, T.J. 1984. A user-oriented model of the soil water balance in wheat. In Wheat Growth and Modeling. Plenum Publishing Corp. NATO ASI Series, Day, W. and Atkin, K.R. (eds.).

Ritchie, T.J. and Otter, S. 1985. Description and performance of CERES-wheat: a user-oriented wheat yield model. USDA-ARR Series. In press.

Robertson, G.W. 1968. A biometeorological time scale for a cereal crop involving day and night temperatures and photo-period. Int. J. Biometeorol. 12:191-223.

Robertson, W.G. 1974. Wheat yields for 50 years at Swift Current, Saskatchewan in relation to weather. Can. J. Plant Sci. 54:625-650.

Ross, S.M. 1980. Introduction to Probability Models. Academic Press, New York.

Ryle, G.J.A., Cobby, M.J. and Powell, E.C. 1976. Synthetic and maintenance respiratiory losses of $14CO_2$ in uniculm barley and maize. Ann. Bot. 40:571-586.

Ryle, G.J.A. and Powell, E.C. 1976. Effect of rate of photosynthesis on the pattern of assimilate distribution in the Graminaceous plant. J. Exp Bot. 97:189-199.

Sakamoto, M.C. 1978. The Z-Index as a variable for crop yield estimation. Agric. Meteorol. 19:305-313.

Sakamoto, M.C. 1981a. Climate-crop regression yield model: an appraisal. In Application of Remote Sensing to Agricultural Production Forecasting. Berg, A. (ed.), A.A. Balkema, Rotterdam. p. 131-138.

Sakamoto, M.C. 1981b. Operational yield modeling and meteorological data flow. In Application of Remote Sensing to Agricultural Production Forecasting. Berg, A. (ed.), A.A. Balkema, Rotterdam. p. 139-149.

Salter, P.J. and Goode, E.J. 1967. Crop responses to water at different stages of growth. Commonwealth Agricultural Bureaux, London.

Sanchez, P.A., Couto, W. and Buol, W.S. 1982. The fertility capability soil classification system: interpretation, applicability and modification. Geoderma. 27(4):283-309.

SAS - Institute. 1982. Statistical Analysis System. SAS user's guide: statistics. Cary, North Carolina.

Seif, E. and Pederson, D.G. 1978. Effect of rainfall on the grain yield of spring wheat, with an application of the analysis of adaptation. Aust. J. Agric. Res. 29:1107-1115.

Seligman, N.G. and van Keulen, H. 1981. PAPRAN: A simulation model of annual pasture production limited by rainfall and nitrogen. In Simulation of Nitrogen Behaviour of Soil-Plant Systems. Frissel, M.J. and van Veen, J.A. (eds.). p. 192-221.

Selirio, S.I. and Brown, D.M. 1979. Soil moisture-based simulation of forage yield. Agric. Meteorol. 20:99-114.

Shankarnarayan, A.K., Kolarkar, S.A. and Singh, N. 1983. Application of the FAO framework for land evaluation to an arid area of Western Rajasthan, India. Soil Survey and Land Evaluation 393:59-68.

Shaw, H.R. 1963. Estimation of soil moisture under corn. Department of Agronomy, Iowa State University of Science and Technology. Res. Bull. 520.

Shaw, H.R. 1983. Estimates of yield reductions in corn caused by water and temperature stress. In Crop Reactions to Water and Temperature Stresses in Humid Temperate Climates. Raper, Jr. C.D. and Kramer, P.J. (eds.), Westview Press, Boulder, Colorado. p. 49-65.

Shaykewich, F.C. 1965. The relationship between soil components and soil physical constants of some Manitoba Soils. M.Sc. Thesis, University of Manitoba.

Shaykewich, C.F. and Zwarich, M.A. 1968. Relationships between soil physical constants and soil physical components of some Manitoba soils. Can. J. Soil Sci. 48:199-204.

Sims, P.L. and Coupland, R.T. 1979. Producers. In Grassland Ecosystems of the World. Coupland, R.T. (ed.), Cambridge, London. p. 49-72.

Snee, R.D. 1973. Some aspects of nonorthoganal data analysis. Part I. Developing prediction equations. J. Qual. Technol. 5:67-79.

Soil Survey Staff. 1975. Soil Taxonomy. A basic system of soil classification for making and interpreting soil surveys. Soil Conserv. Serv., U.S. Dept. Agric. Handbook. U.S. Govt. Printing Office, Washington, D.C.

Spedding, C.R.W. 1975. The Biology of Agricultural Systems. Academic Press, London.

Spedding, R.W.C. 1984. Agricultural systems and the role of modeling. In Agricultural Ecosystems, Lowrance, R., Stinner, R.B. and House, G.J. (eds.), John Wiley and Sons, New York. p. 179-185.

Spiertz, J.H.J. 1982. Grain formation and assimilate partitioning in wheat. Part I. Ear development, assimilate supply and grain growth of wheat. In Simulation of Plant Growth and Crop Production. Penning de Vries, F.W.T. and van Laar, H.H. (eds.), Pudoc, Wageningen. p. 136-144.

Staple, J.W. 1969. Comparison of computed and measured moisture redistribution following infiltration. Soil Sci. Amer. Proc. 33:841-847.

Stapper, M. and Arkin, G.F. 1980. A dynamic growth and development model for maize (Zea Mays, L.) Research Center Program and Model Documentation No. 80-2, Blackland Res. Center, Texas A&M University.

Stern, D.R. and Coe, R. 1982. The use of rainfall models in agricultural planning. Agric. Meteorol. 26:35-50.

Stewart, B.A. and Whitfield, C.J. 1965. Effects of crop residue, soil temperature and sulfur on the growth of winter wheat. Soil Sci. Soc. Amer. Proc. 29:752-755.

Stewart, R.B. 1981. Modeling methodology for assessing crop production potentials in Canada. Tech. Bull. 96 LRRI, Agrometeorology Section, Agr. Canada, Ottawa, Ontario.

Storie, R.E. 1933. An index for rating the agricultural value of soils (revised 1937). Bull. Calif. Agric. Exp. Stn. No. 556.

Storie, R.E. 1954. Land classification as used in California for appraisal of land for location purposes. Trans. 5th Int. Cong. Soil Sci. Vol. 3. p. 407-412.

Storie, R.E. 1976. Storie index soil rating (revised 1978). Spec. Publ. Div. Agric. Sci. Univ. Calif. No. 3202.

Stroosnijder, J. 1982. Simulation of the soil water balance. In Simulation of Plant Growth and Crop Production. Penning de Vries, T.W.F. and van Laar, H.H. (eds.). p. 175-193.

Swaney, P.D., Mishoe, W.J., Jones, W.J. and Boggess, G.W. 1983. Using crop models for management: impact of weather characteristics on irrigation decisions in soybeans. Transaction of the ASAE 2351:1808-1814.

Sweeney, D.G., Hand, W.D., Slack, G. and Thornley, M.H.J. 1981. Modelling the growth of winter lettuce. In Mathematics and Plant Physiology, Rose, D.A. and Charles-Edwards, D.A. (eds.), Academic Press, London. p. 217-229.

Tanji, K.K., Mehram, M. and Gupta, K.S. 1981. Water and nitrogen fluxes in the root zone of irrigated maize. In Simulation of Nitrogen Behaviour of Soil-Plant Systems, Frissel, J.M. and van Veen, J.A. (eds.) Pudoc, Wageningen. p. 51-66.

Tanner, B.C. and Sinclair, T.R. 1983. Efficient water use in crop production: research or re-search? In Limitation of Efficient Water Use in Crop Production. Taylor, M.H., Jordan, R.W. and Sinclair, T.R. (eds.) ASA-CSSA-SSSA, Madison. p. 1-27.

Teaci, D. 1970. Bonitarea Terenurilor Agricole. Editura Ceres, Bucuresti, Romania.

Teaci, D. and Burt, M. 1974. Land evaluation and classification in East European countries. Approaches to land classification. Soil Bull. 22. FAO, Rome. p. 35-46.

Thompson, M.L. 1969. Weather and technology in the production of corn in the U.S. corn belt. Agron. J. 61:453-456.

Thompson, M.L. 1970. Weather and technology in the production of soybeans in the Central United States. Agron. J. 62:232-236.

Thornley, J.H.M. 1978. Crop response to fertilizers. Ann. of Bot. 42:817-826.

Thornley, J.H.M. 1983. Crop yield and planting density. Ann. of Bot. 52:257-259.

Todorovic, P. and Woolhiser, D.A. 1975. A stochastic model of n-day precipitation. J. of App. Meteorol. 14:7-24.

Topp, G.C. and Miller, E.E. 1966. Hysteresis moisture characteristics and hydraulic conductivities for glass-bead media. Soil Sci. Soc. Amer. Proc. 30:156-162.

Tscheschke, D.P. and Gilley, J.R. 1979. Status and verification of Nebraska's corn growth model - CORNGRO. Transactions of the ASAE 1979: 1329-1337.

USBR. 1953. Bureau of Reclamation Manual, Vol. V. Irrigated Land Use, Part 2: Land Classification. Denver, Colorado.

Varade, S.B. Stolzy, H.L. and Letey, J. 1970. Influence of temperature, light intensity and aeration on growth and root porosity of wheat, Triticum aestivum. L. Agron. J. 62:505-507.

van Veen, J.A. 1977. The Behaviour of Nitrogen in Soil. A Computer Simulation Model. Ph.D. Thesis, Vrije Universiteit, Amsterdam.

van Veen, J.A. and Frissel, J.M. 1981. Simulation model of the behaviour of N in soil. In Simulation of Nitrogen Behaviour of Soil-Plant Systems. Frissel, J.M. and van Veen, J.A. (eds.), Pudoc, Wageningen. p. 126-154.

Vink, A.P.A. 1975. Land use in advancing agriculture. In Advanced Series in Agricultural Sciences 1, Springer Verlag, New York, Heidelberg, Berlin.

Vithayathil, F.J., Hirsch, A.H., Chung, C., Duffy, J., Franklin, M. and Boast, C. 1977. A program for simulation of nitrogen flow in a tile-drained corn belt agricultural field. CBNS-Washington, St. Louis.

Vos, J., Drees, M.E. and Penning de Vries, T.W.F. 1982. Part III. Modelling of post-floral growth of wheat. In Simulation of Plant Growth and Crop Production. Penning de Vries, T.W.F. and van Laar, H.H. (eds.), Pudoc, Wageningen. p. 144-151.

Waggoner, P.E. 1977. Overview of modeling. In Weather-climate modeling for real-time applications in agriculture and forest meteorology. Thirteenth Conference AMS, Purdue University, West Lafayette, Indiana. 47907.

Waggoner, E.P. 1979. Variability of annual wheat yields since 1909 among nations. Agric. Meteorol. 20:41-45.

Walker, K.G. 1977. Development of Wheat Model for Land Evaluation. Unpublished M.Sc. Thesis, Univ. of Saskatchewan.

Walker, L.O and Krenz, R.D. 1983. Economics. In Dryland Agriculture. ASA-CSSA-SSSA, Madison. p. 537-564.

Warrick, W.A. and Nielsen, D.R. 1980. Spatial variability of soil physical properties in the field. In Applications of Soil Physics. Hillel, D. (ed.), Academic Press, New York. p. 319-344.

Waymire, E. and Gupta, V.K. 1981. The mathematical structure of rainfall representations. 1. A review of the stochastic rainfall models. Water Resour. Res. 17(5):1261-1272.

Weiers, C.J. and Reid, I.G. 1974. Soil classification, land evaluation, and taxation, the German experience. Centre for European Agricultural Studies, Wye College, Ashford, Kent.

Weir, H.A., Bragg, L.P., Porter, R.J. and Rayner, H.J. 1984. A winter wheat crop simulation model without water or nutrient limitations. J. Agric. Sci. Camb. 102:317-382.

Welbank, P.J., Gibb, M.J., Taylor, J.P. and Williams, E.D. 1974. Rep. Rothamsted Experimental Station for 1973. Part 2. p. 26-66.

Wierenga, P.J., Hagan, J.P. and Nielsen, D.R. 1970. Soil temperature profiles during infiltration and redistribution of cool and warm irrigation water. Water Resour. Res. 6:230-238.

Williams, G.D.V., Joynt, I.M. and McCormick, A.P. 1975. Regression analyses of Canadian prairie crop-district cereal yields, 1961-1972, in relation to weather. Can. J. Soil Sci. 55:43-53.

Williams, R.J., Dyke, T.P. and Jones, A.C. 1983. EPIC - A model for assessing the effects of erosion on soil productivity. In Analysis of Ecological Systems: State-of-the-Art in Ecological Modelling. Lauenroth, K.W., Skogerboe, G.V. and Flug, M. (eds.), Elsevier Scientific Publishing Company, Amsterdam. p. 553-572.

de Wit, C.T. 1965. Photosynthesis of leaf canopies. Agricultural Research Report 663. Centre for Agricultural Publications and Documentation. Wageningen.

de Wit, C.T. and van Keulen, H. 1975. Simulation of transport processes in soils. Pudoc, Wageningen.

de Wit. C.T. et al. 1978. Simulation of assimilation, respiration and transpiration of crop. Simulation Monographs. Pudoc, Wageningen.

de Wit, C.T. 1982a. Simulation of living systems. In Simulation of Plant Growth and Crop Production. Penning de Vries, F.W.T. and van Laar, H.H. (eds.), Pudoc, Wageningen. P. 3-8.

de Wit, C.T. 1982b. Coordination of models. In Simulation of Plant Growth and Crop Production. Penning de Vries, F.W.T. and van Laar, H.H. (eds.), Pudoc, Wageningen. p. 26-31.

Woode, P.R. 1981. "We don't want soil maps. Just give us land capability". The Role of Land Capability Surveys in Zambia. Soil Survey and Land Evaluation 1(1):2-5.

Woolhiser, A.D. and Pegram, G.G.S. 1979. Maximum likelihood estimation of Fourier Coefficients to describe seasonal variation of parameters in stochastic daily precipitation models. J. Appl. Meteorol. 18:34-42.

Young, A. and Goldsmith, P.F. 1977. Soil survey and land evaluation in developing countries: a case study in Malawi. Geog. J. 153:407-438.

Zwarich, M.A. and Shaykewich, C.F. 1969. An evaluation of several methods of measuring bulk denisty of soils. Can. J. Soil. Sci. 49:241-245.

Appendix A

Symbols, Meanings and Units Used in Chapter 3

(Modeling Activity)

The main symbols used in Chapter 3 were listed below. The coefficients characteristic to the equations used throughout this chapter were defined in the sections where they have been introduced.

The units of the symbols used with the general meanings were presented in fundamental quantities within brackets; mass (M), length (L), and time (T).

Symbol	Meaning	Unit (dimension)
A	unit area	cm^2
A_0	amplitude of seasonal change of soil temperature	^0C
AFA	amount of nitrogen fertilizer applied	kh/ha
AMIN( )	FORTRAN IV logical function that selects the minimum value from arguments ( )	-
ANP	aboveground net production; assimilation, i.e., gross photosynthesis minus consumption, i.e., respiration and minus roots	kg/ha
anl	number of soil layers with roots	dimensionless
B	general term for biomass (either aboveground net production or net primary production)	$(M\ L^{-2})$
Bm	accumulated ANP from seeding up to a given time (rainfed agroecosystem)	kg/ha
Bma	accumulated ANP at the end of the growing season (rainfed agroecosystem)	kg/ha
Bmc	accumulated ANP at the end of the growing season (under specified growing conditions)	kg/ha
Bmgp	accumulated ANP at the end of the lifetime cycle of the crop, i.e., genetical potential	kg/plant
Bmp	accumulated ANP at the end of the growing season (agronomical optimum conditions)	kg/ha
Bp	cumulative ANP from seeding up to a given time during the growing season (agronomical optimum conditions)	kg/ha
b_T	auxiliary variable function of daily mean	

	air temperature used to compute the crop respiration rate	d^{-1}
$\dot{b}$	growth rate (unspecified conditions)	$(M\ L^{-2}\ T^{-1})$
$\dot{b}a$	growth rate (rainfed agroecosystem)	kg/ha-d
$\dot{b}gross$	standard maximum gross photosynthesis raate as function of the angular height of the sun and LAI=5	kg/ha-d
$\dot{b}gz$	adjusted standard maximum gross rate for mean daytime air temperature and LAI	kg/ha-d
$\dot{b}p$	growth rate (agronomical optimum conditions)	kg/ha-d
$\dot{b}pm$	maximum growth rate (agronomical optimum conditions)	kg/ha-d
$\dot{b}p(Pd)$	agronomical potential growth rate as function of phenological development of the crop	kg/ha-d
$\dot{b}p(Pd)$	potential growth rate expressed as relative frequency divided by the class length	dimensionless
C	nitrte nitrogen concentration in soil solution	$mg\text{-}N/cm^3$
CS_S	crop susceptibility index for water stress	dimensionless
Cx	concentration of mobile N species	$\mu g/cm^3$
$C(\psi)$	differential soil moisture capacity	$(L^3\ L^{-3}\ L^{-1})$
cPd	phenological development (accumulted Pd units)	dimensionless
cPdm	phenological development (Pd units) at which the root reaches the maximum depth (i.e., root growth ceases)	dimensionless
D	diffusivity coefficient	cm^2/d
D_A	apparent diffusivity coefficient	cm^2/d
D_O	diffusivity coefficient of NO -N in water	cm^2/d
D_S	dispersion factor	cm
$D(\theta)$	hydraulic diffusivity	cm /d
$\bar{D}(\theta)$	average hydraulis diffusivity for two adjacent soil layers	cm^2/d
$\dot{D}N$	denitrification rate	$mg\text{-}N/cm^2$ - d
DR	drainage (water flow out from the rooting zone)	(L)
d	time	day

dd	damping depth	cm
$\dot{ET}$	evapotranspiration rate	$(M\ L^{-2}\ T^{-1})$
$\dot{ET}$	potential evapotranspiration rate	$(M\ L^{-2}\ T^{-1})$
$\dot{Ev}$	"actual" evaporation rate	cm/cm^2 - d
$\dot{Evp}$	potential evaporation rate	$(M\ L^{-2}\ T^{-1})$
Ex	concentration of N species in the exchange phase	μg/g
$F^{-1}(Y)$	inverse normally distributed function that gives the fractiles of ln Pd which correspond to a given accumulated ANP	dimensionless
FC	field capacity	cm^3/cm^3
Fc(w)	field capacity, percentage by weight	%
FC(θ)	field capacity (general term)	$(L^3\ L^{-3})$
f(j)	total porosity within a soil layer	(cm^3/cm^3) x cm
f[bp(Pd)]	probability density function of potential growth rate as function of phenological development	dimensionless
f[bp(Pd)]xdPd	probability element	dimensionless
Hi	harvest index	dimensionless
h	maximum depth of water accumulated in small depressions	m
IL	imaginary layer	-
i	a given day during the growing season	dimensionless
i(ex)	absorption-desorption net result of the ion-exchange process	mg/cm^3 - d
j	soil layer number (downward direction); soil profile was divided into a number of layers of 15 cm thickness ($1 \leq j \leq 8$)	dimensionless
j*	soil layer number (downward direction); soil profile was divided into 6 layers of different thickness for heat simulation	dimensionless
K	hydraulic conductivity	$(L\ T^{-1})$
K_T	thermal conductivity	cal/cm s ^0C
K(θ)	hydraulic conductivity	cm/d
K(θ)	average hydraulic conductivity for two adjacent layers	cm/d
kys	crop suscetibility factor for water stress	dimensionless

L	photoperiod	h
Ll	lower boundary limit of the soil profile	(L)
Lu	upper boundary limit of the soil profile	(L)
LAI	leaf area index	dimensionless
LF	total stress effect ($0 \leq LF \leq 1$)	dimensionless
le	leaching efficiency factor	dimensionless
N	number of days within the growing season	dimensionless
Nl	nitrogen stress effect ($0 \leq Nl \leq 1$)	dimensionless
Nlf	nitrogen limiting factor	-
$\dot{N}M$	net mineralization rate	$mg\text{-}N/cm^2 - d$
NN	amount of nitrate nitrogen in soil	$mg\text{-}N/cm^2$
No(Pd)	optimum nitrogen fraction in the accumulated ANP	dimensionless
$(NO_3^- - N)m$	net mineralization over one growing season	kg/ha
$\dot{N}T$	nitrification rate	$mg\text{-}N/cm^2 - d$
Nu	total nitrogen uptake by the crop	kg/ha
nl	number of layers of 15 cm thickness within a given soil profile	dimensionless
n(m)	the last day within a given growing season	dimensionless
OM	organic matter in the soil profile	(%)
P	product, commercial yield, grain	kg/ha
Pd	phenological development (BMTS unitx100)	dimensionless
Pd*	transformed phenological development, Pd*=lnPd	dimensionless
PREC	daily precipitation (rate)	$(L^3\ L^{-2}\ T^{-1})$
Q	flow rate (amount of substance moving per unit of time; "flow")	$(M\ T^{-1})$
Q_0	solar radiation at the top of the atmosphere	ly/d
Qn	net flow (inflow - outflow) within a soil element with an area of 1 cm	$(M\ T^{-1})$
$\vec{q}$	specific discharge (flux density, "flux", flow per unit area in the direction normal to the area)	$(M\ L^{-2}\ T^{-1})$
$\vec{q}*$	flux at the centre of the first soil layer	$(M\ L^{-2}\ T^{-1})$

ROOF	runoff (rate)	$(L^3\ L^{-2}\ T^{-1})$
RZ	depth of the root system	cm
RZmax	maximum depth of the rooting zone	cm
r	the radius of circular area covered by water accumulated in small depression	m
S	sink term (water extraction function)	$(L^3\ L^{-3}\ T^{-1})$
S*	substrate concentration	$(M\ L^{-3})$
Sc.I	scenario I, simulation of the model with soil input data in situ measured	-
Sc.II	scenario II, simulation of the model with soil input data derived from the standard soil data measurements (soil survey data)	-
SDI	stress day index	dimensionless
SDs	stress day factor	dimensionless
SK	source-sink term (rate) used in the equation that described the changes in soil nitrogen content	µg/cm - d
Slm	uptake rate of less-mobile ion (NH4)	mg/cm - d
Sn	sink term (uptake rate) for mobile ion (NO_3^-)	mg/cm - d
Sv	state variable, general term	(M, L^3, etc.)
s	growth stage interval	-
T	soil temperature	^oC
$\bar{T}a$	daily mean air temperature	^oC
Tl	soil temperature stress effect ($0 \leq T \leq 1$)	dimensionless
Tlf	soil temperature limiting factor	-
Tmax	daily maximum air temperature	^oC
Tmin	daily minimum air temperature	^oC
$\dot{T}r$	"actual" transpiration rate	cm/cm^2 - d
$\dot{T}rp$	potential transpiration rate	$(M\ L^{-2}\ T^{-1})$
t	time	(T)
t_o	initial time	(T)
t_a	day in which the fertilizer was applied	Julian day
tm	time (the end of the biological cycle of the crop)	(T)
t_x	a given time during the growing season	(T)

V	a volume of water accumulated in one depression	m^3
v	NO_3^--N flow within a soil element with an area of 1 cm^2	mg/cm^2 - d
v_c	convective flow of NO_3^--N	mg/cm^2 - d
v_d	diffusion flow of NO_3^--N	mg/cm^2 - d
v_N	net flow (inflow-outflow) of NO_3^--N within a soil element with an area of 1 cm^2	mg/cm^2 - d
WA	percentage of land area from a quarter of a section on which the crop was lost due to water accumulation in small depressions	%
WC*	volumetric soil wetness at seeding time on imperfect or poorly drained soils	cm^3/cm^3
WE	water excess limiting factor	cm
Wl	water deficit stress effect ($0 \leq Wl \leq 1$)	dimensionless
Wl*	prolonged (severe) water deficit stress effect ($0 \leq Wl* \leq 1$)	dimensionless
Wlf	water deficit limiting factor	-
WP	wilting point	cm^3/cm^3
WP(w)	permanent wilting percentage by weight	%
WP(θ)	wilting point (general term)	(L^3 L^{-3})
Y	"actual" yield (general term)	(M L^{-2})
Y*	adjusted yield (ANP) for water excess limiting factor effect	kg/ha
Yp	potential yield (general term)	(M L^{-2})
Ys	simulated yield (ANP)	kg/ha
Zs	seeding depth	cm
z	depth	(L)
z_{j*}	depth of the centre of soil layer (soil profile divide for heat simulation)	cm
βs	crop susceptibility factor for water stress	dimensionless
Δj	distance between centres of two adjacent layers used to calculate the nitrogen movement ($\Delta j = \Delta z$)	cm
ΔPd	phenological development integration time integral (class length)	BMTS unitx100
ΔSMC	change in water content stored in the soil (general term)	(L^3 L^{-3} T^{-1})

Δt	integration time interval	(T)
Δz	thickness of soil layer	cm
Δz_c	distance between the centres of two adjacent soil layers	cm
Δzl_c	distance between the centre of the last layer within the rooting zone and the centre of imaginary layer	cm
$\Delta(\theta Cx)$	change in concentration of mobile N species over one time stage	$(M\ L^{-3}\ T^{-1})$
θ	soil volume wetness	$(L^3\ L^{-3})$
$\theta*$	relatived soil volumetric water content	$(L^3\ L^{-3})$
θ^1	the difference between soil volumetric wetness at seeding time, above FC, and WP	cm^3/cm^3
θ_{ar}	available soil water content in the active rooting zone	$(L^3\ L^{-3})$
θd	soil air-dry volumetric wetness	cm^3/cm^3
$\theta_{j,o}$	soil volumetric wetness (initial conditions)	cm^3/cm^3
θ_L	lower boundary conditions for the profile in terms of soil water content	cm^3/cm^3
θs	soil saturated volumetric wetness	cm^3/cm^3
θ_s	soil water content (undefined layer)	$(L^3\ L^{-3})$
θ_{ss}	available water content in the soil surface layer	$(L^3\ L^{-3})$
θ_U	upper boundary conditions for the profile in terms of soil water content	cm^3/cm^3
λ	root absorbtion coefficient	dimensionless
μ	50% fractiles of Pd normally distributed	dimensionless
$\mu*$	50% fractiles of transformed phenological development variable (Pd* = ln Pd), normally distributed	dimensionless
ξ	available energy for evapotranspiration (flux density)	W/m^2
ρb	bulk density	Mg/m^3
ρs	density of solids	g/cm^3
σ	standard deviation of normally distribution function of Pd	dimensionless
$\sigma*$	standard deviation of normally distribution function of transformed variable (Pd* = ln Pd)	dimensionless

τ	tortuosity factor	dimensionless
ϕ	phase of the periodic function used for heat flow	dimensionless
ψ	pressure head	(L)
ψm	matric suction	cm
ψp	pressure "potential"	bars
ω	angular frequency	radian month^{-1}

Appendix B

Symbols, Definitions, and Units

Used in PIXMOD Computer Program

Symbol	Definition	Unit
ANCX	Amount of nitrate within the profile	kg/ha
APPMR	Average NO3-N in rooting zone	ppm
APPMP	Average NO3-N within the profile	ppm
AOOM	Average organic matter content to 60 cm of the soil profile	%
AREA	Area occupied by the soil type within a region of interest (may be used for a weighting procedure when an aggregate value is required for a larger area), a default value	ha
ARAD	Actual radius of a watershed that may be formed on imperfectly and poorly drained soils when a high precipitation event occurs	m
AVBD	Average bulk density within the soil profile	g/cc
AZERO	Amplitude of seasonal soil heat wave	°C
AWCR	Average volumetric water content within the rooting zone	cc/cc
AWCP	Average volumetric water content within the soil profile	cc/cc
BYIELD	Grain yield (units that may be preferred by some users)	bu/ac
CDUT	Hydraulic conductivity (interpolated value)	cm/day
CLD	Clay content (particle size distribution)	%
CNORTX	Nitrate concentration (by layer)	mg N/cc (soil sol.)
CNPPM	Nitrate concentration (by layer)	ppm
CNORW	Average nitrate concentration below the profile considered in the model	mg N/cc
CPEV	Cumulative evaporation	cm
CPFC	Soil water content in % of FC	%
DC	Exponent value for diffusivity used for clayey soils	dimensionless
DDEPTH	Dampening depth	cm
DEPTH	Depth	cm
DENT	Rate of denitrification (ideal soil conditions)	mg N/cm^2-day

DHARVT	The day of harvest (if known)	Julian day
DISP	Dispersion coefficient (nitrate to water)	cm
DIF	Diffusion coefficient (nitrate to water)	cm^2/day
DL	Exponent value for diffusivity used for loamy soils	dimensionless
DMT	Day time mean temperature	°C
DNFMX	Rate of nitrification	mg N/cm^2-day
DNTUPX	Rate of nitrogen uptake (by layer)	mg N/cm^2-day
DPLANT	Planting date	Julian day
DRLF2	Drainage limiting factor (intermediate variable)	cm
DS	Exponent value for diffusivity used for sandy soils	dimensionless
EMEX	Emergence date	Julian day
ET	Actual transpiration rate	cm/day
ETLX	Actual evapotranspiration rate (by layer)	cm/day
EWSMR	Total amount evapotranspiration without soil moisture restriction (as effect of drainage and high water table)	cm
FAI	Initial phase of heat wave	dimensionless
FERTX	Fertilizer rate used	kg/ha
FERTMX	Date of application of fertilizer	Julian day
FGR	Ideal growth rate	kg/ha-day
FLRNX	Nitrate flux (by layer)	mg N/cm^2-day
FLRTX	Flow rate (by layer)	cm/day
FMBDD	Field measured bulk density	g/cc
FSD	Fine sand content (particle size distribution)	%
GR	Actual growth rate	kg/ha-day
GRA3L	Percent available moisture in the rooting zone (abscissa argument value for high stress)	%
GRAX	Percent available moisture in the rooting zone (abscissa argument value for low stress)	%
GYIELD	Grain yield	kg/ha

HINDEX	Harvest index for wheat	dimensionless

For implicit format all integer variable symbols start with letter "I".

IBLT	Boundry layer with the profile flag	dimensionless
IBMTSX	Biometeorological time scale	BMTS units
INCONST	Agronomical potential ceiling for a given management level	kg/ha*1000
ICLSLOP	Slope class	dimensionless
IDAY	Number of days per year for the model to be run (either full year or growing season)	dimensionless
IDRAIN	Drainage type flag	dimensionless
IDST55	Crop district number before 1977	dimensionless
IDST77	Crop district number from 1977 on	dimensionless
IESD	Estimated seeding date	Julian day
IFQOMD	Frequency of microdepressions (on a section bases)	dimensionless
IFX	Number of fertilizer applications	dimensionless
IG1	Number of variables to be printed	dimensionless
IG2	Number of variables to be plotted	dimensionless
IKX	Number of discrete layers within profile	dimensionless
ILL	Lowest layer affected by water table or poor drainage	dimensionless
INP	Number of data points to be plotted	dimensionless
INFR	Infiltration rate	cm/day
INLR	Number of layers within the soil profile (morphological description)	dimensionless
INT	Integration interval per day	dimensionless
IRFS	Flag for type of simulation (scenario code)	dimensionless
IROF	Outside runoff (code)	dimensionless
IUL	The uppermost layer affected by water table or poor drainage	dimensionless
IPREC	Precipitation	cm
IPSTON	Stoniness % by weight	%
IREGIO	Region number for drainage description (code)	dimensionless

ITEXT	Surface texture class (code)	dimensionless
ITCPD	Growth stage (Pd=BMTS*100)	Pd units
IWTABL	Water table depth	cm
IXZ1	Array of variables codes to be printed	dimensionless
IXZ2	Array of variables codes to be plotted	dimensionless
KC	Exponent value for hydraulic conductivity used for clay soils	dimensionless
KL	Exponent value for hydraulic conductivity used for loamy soils	dimensionless
KS	Exponent value for hydraulic conductivity used for sandy soils	dimensionless
LM	Minimum limiting factor	dimensionless
LMN	Nitrogen limiting factor	dimensionless
LMT	Temperature limiting factor	dimensionless
LMW	Water limiting factor	dimensionless
MATX	Maturity date	Julian day
MBD	Bulk density used (either measured or computed)	g /cc
MFC	Measured field capacity	cc/cc
MFL	Mass flow (for nitrate)	mg N/cm^2-day
MPDT	Middle point of soil profile master horizons	cm
MINR	Mineralization rate	mg N/cm^2-day
MWT	Measured wilting point	cc/cc
MOISTS	Stress excess water	dimensionless
NFLRN	Net flow of nitrate	mg N/cm^2-day
NITUP	Cumulative nitrogen uptake by plants	kg N/ha
NL	Time interval for printing	dimensionless
NORN	Nitrate concentration in rain	mg N/cc
NP	Time interval for plotting	dimensionless
NTRTX	Amount of nitrate (by layer)	mg N/cm^2
NTRATX	Total amount of nitrate formed from fertilizer	kg/ha
OCD	Organic carbon (by layer)	%
OC1	Organic carbon in first layer	%

OC2	Organic carbon in second layer	%
OC3	Organic carbon in third layer	%
OINX	Jointing date	Julian day
OMEGA	Angular frequency of heat wave	month-1
OPNIT	Optimal fraction of nitrogen	kg/ha
OPTXX	Growth stages (abscissa value of optimum nitrogen function)	BMTS units
OPTYX	Optimum % nitrogen (ordinate value of optimum nitrogen function)	%
OSM	Soil moisture on the previous day (by layer)	cm
PAO, PA1, PA2	Arrays which consist of regression coefficients used in BMTS that accounts for the photoperiod factor PAO - photoperiod threshold, PA1, PA2 - quadratic coefficients	dimensionless
PBO, PB1, PB2, PB3, PB4	Arrays which consist of regression coefficients used in BMTS that accounts for the temperature factor PBO - temperature threshold, PB1, PB2 - quadratic coefficients used for maximum temperature, PB3, PB4 - quadratic coefficents used for minimum temperature	dimensionless
PAMX, PAMCRZ	Available moisture content, within the rooting game	%
PAREAL	Area under watershed	%
PATN	Matrix water extraction pattern	%
PEV	Actual evaporation	cm/day
PET	Potential evapotranspiration	cm/day
PFFC	Available soil moisture as percent from F.C.	%
PHOTP	Photoperiod	hours
PGR	Potential growth rate	kg/ha day
PLANTX	Planting date	Julian day
PLGRX	Cumulative yield	kg/ha
PPMFC	Nitrate content (by layers discertized as in a field experiment)	ppm
PPM1	Nitrate content (by layer)	ppm
POACUM	Incoming water from a recharged neighboring area	%
PREC	Daily precipitation	cm/day

PTHD	Predicted thawing date	Julian day
PRECSH	Cumulative precipitation from seeding to harvest dates	cm
PSD	Predicted seeding date	Julian day
RATIO	Crop development ratio (actual/potenital transpiration)	dimensionless
RDAY	Current date	Julian day
RZONE	Cumulative root growth (depth)	cm
RUNOFF	Surface runoff to low lands	cm
SID	Silt content (particle size distribution)	%
SDOX	Seeding date	Julian day
SHC2	Array for plotting nitrate uptake	kg/ha
SOLD	Profile depth (if > 120 cm, SOLD = flag)	cm
SOILMX	Soil moisture (by layer)	cm
SOILTX	Soil temperature (by layer)	°C
STMN	Standard nitrate concentration (by layer)	mg N/cc (soil sol.)
STWC	Volumetric measured soil moisture content at seeding time	cc/cc
SR	Solar radiation at the top of the atmosphere (by parabola)	cal/cm -day
T	Time (counting method required to run the model)	Julian day
TANGT	Tangent of slope angle (tan( ))	degree
TCPD	Cumulative growth stages	Pd units 100* BMTS
TDENTX	Totoal denitrification	kg/ha
TEE	Months time value chosen in heat wave solution	dimensionless
TETL	Total evapotranspiration (by layer)	cm
TETWSM	Total evapotranspiration without soil moisture restriction	cm
TEVT	Total evaporation	cm
TEWSMR	Total transpiration without soil moisture restriction	cm
THIKNX	Layer thickness (used in heat transfer)	cm

TMAX	Daily air maximum temperature	°C
TMIN	Daily air minimum temperature	°C
TORT	Tortuosity	dimensionless
TOTPE	Cumulative potential evapotranspiration from seeding to maturity	cm
TOTALW	Soil water holding capacity within the profile	cm
TOTT	Cumulative evapotranspiration	cm
TPAMSE	Minimum limiting factor when plant stress occurs	dimensionless
TPEV	Total evaporation	cm
TPREC	Total precipitation from seeding to maturity dates	cm
TPORO	Total porosity by layer	%
TRESS 1, 2,3	Arrays containing stress factors as a function of % available water	dimensionless
TZERO	Average prairie soil temperature used in heat wave solution	°C
TWWPAS	Total water content within the soil profile at seeding time	cm
VFSD	Very fine sand content (particle size distribution)	%
VMAX	Maximum volume of water that can be stored in a microdepression (at { section scale)	m3
WACUM	Volume of water accumulated in microdepressions (at { section scale)	m3
WCC	Takes value on WCX	
WCX	Volumetric water content (by layer)	cm
WCAP	Water holding capacity (by layer)	cm
WCFC	Volumetric water content used in the model by layer (takes a value either on a measured or computed basis)	cc/cc
WCON	Actual available volumetric water content (by layer)	cc/cc
WCXFC	Volumetric water content (by layer as measured in the field for testing purposes)	cc/cc
WILT	Volumetric wilting point (by layer)	cc/cc
WTFC	Volumetric water content within the layer below the considered profile	cc/cc
YEAR	Year for which a simulation is performed	year (yyyy)

Appendix C

PIXMOD Program

```
C       PIXMOD  PROGRAM STRUCTYRE:
C
C
C
C         JCL
C         PROGRAM
C             MAIN,
C               BLOCKDATA,SSINP,SCINPW,SCPARA,
C               SETW,SSWTN,SNO3W,SPDW,SSTEPM,SCGRW,
C                 AFGAN,PLOT
C         JCL2,
C         DSMF
C
C
C JCL
//SOILCROP JOB '####,,,T=5,L=14,I=40,CO=1',C.ONOFREI
/*TSO  SOIL
//   EXEC FORTHCLG,OPT=2,LC=65,CSIZE=300K,S=NOSOURCE,MAP=NOMAP     F=JCL
//FORT.SYSIN DD *
C
C
C   PROGRAM:
C
C MAIN
C
      IMPLICIT REAL*4 (A-H,J-Z)
      COMMON /COMA/      ITEXT,YEAR,IESD,PHOTP,RDAY,IRFS,ICONST,ICNT,
     1 HEAD,IHEAD,T,WTFC,    F(10),WCFC(10),SR,TMAX,TMIN,TCPD,RZONE,
     2 PEV,TPEV,MSTF,TPAMSE
      COMMON /COMB/       AREA,CWHT,INLR,SOLD,IBLT,STWC(10),
     * MFC(10),MWT(10),HINDX,CNPPM(10),WCC(10),STMN(10)
      COMMON /COMC/      PREC,RUNOFF,
     * XX(10),DY(10),KY(10),OPTXX(7),OPTYX(7),WILT(10)
      COMMON /COMD/      CNORW,AOOM,MINR,OC1,OC2,OC3,
     * DENIT,DIF,DISP,NORN,TORT,WTSAT,WF(10)
      COMMON /COME/      IKX,CNORTX(10),FLRNX(11),FLRTX(11),AVBD
      COMMON /COMF/
     1 MBD(10),       FERTMX,FERTX,IBMTSX,DTX,
     2 HARVTX,NITUPX,NTRATX,PLANTX,PLGRX,PLGRMX,DNTUPX(10),
     3 NTRTX(10),SOILMX(10),WCX(10),          TDENTX,HIW
      COMMON /COMG/     TZERO,AZERO,DDEPTH,OMEGA,FAI,THIKNX(6),IX,
     * DEPTH(6),SOILTX(6)
      COMMON /COMI/      AA(8030),INP
      COMMON /COMK/      WCON(10),WCAP(10),PRFC(10)
      COMMON /COML/     ICDT,ICDS,PTHD,PSD,PFFC,EMEX,OINX,HADX,SDOX,
     1 MATX,GYIELD,GYIELM,BYIELD,PPMFC(5),WCXFC(5),PPM1(10),
     2 AWCR,AWCP,APPMR,APPMP,CPEV,PRECSH
      COMMON /COMN/  ILTCPD,ITCPDX,PA0(5),PA1(5),PA2(5),PB0(5),PB1(5),
     * PB2(5),PB3(5),PB4(5),DC(10),KC(10),DL(10),KL(10),DS(10),KS(10)
      COMMON /COMR/   IPSTON,IDRAIN,INFR,IWTABL,IROF,ICSLOP,IREGIO,
     * TPORO(10),TWWPAS
      COMMON /COMP/   TOTPE,TOTT,TEVT,TETL(10),LMNM,TEWSMR,
     * PET,ET,LMW,LMN,LMT,LM,PGR,GRM,GR,PAMCRZ,TPREC,EWSMR,LASTR
      COMMON /COMS/   IS5277(25,3),IS7780(4,3),IDST55,IDST77
      INTEGER*4 FG(9)/'(17X',',F2.','0,F4','.0,F','4.2,','2F4.',
     *              '0,F6','.1,F','4.1)'/
      INTEGER*4 FMT(3,2)/'(F9.','3)  ',',   ','(9X,','F7.4',')   '/,
     *FMTA(3)
      DIMENSION ETLX(10),FRTMX(3),FRTX(3),AWCC(10),AWIEL(10)
      DIMENSION CROP(1),FMBDD(10),IXZ1(2),IXZ2(2)
      DIMENSION MPDT(10),VFSD(10),FSD(10),SID(10),CLD(10),OCD(10)
      DATA CROP(1)/'CWHT'/,HEADA/'HEAD'/,SDPV/'SDPV'/,
     1 AREAA/'AREA'/,FMBD/'FMBD'/,MPLR/'MPLR'/,MADT/'MADT'/,
     2 DMAD/'DMAD'/,DADT/'DADT'/,LTHN/'LTHN'/,NPPM/'NPPM'/,
```

```
     3 WACT/'WACT'/,MFFC/'MFFC'/,MWLT/'MWLT'/,SMNC/'SMNC'/
      DIMENSION IMAGE(20)
      CALL SSINP
      CALL SCINPW
      II=0
      READ(5,200)A,(IMAGE(I),I=1,19)
  200 FORMAT(20A4)
      IF(A.NE.HEADA) GO TO 190
      WRITE(6,9878) (IMAGE(I),I=1,19)
 9878 FORMAT(1H1,2X,19A4//)
      WRITE(6,5030)
 5030 FORMAT(//' SPECIAL DRIVING PARAMETER VALUES')
      CALL REREAD
      READ(5,201)A,NP,NL,IDAY,YEAR,SOLD,HINDX,INTT,IFORM,IG1,IXZ1,IG2,
     1 IXZ2,INLR,ITEXT,IESD,IRFS,ICONST,IBLT,IPSTON,IDRAIN,INFR,
     2 IWTABL,IROF,ICSLOP,IREGIO,IDST55,IDST77
  201 FORMAT(A4,2F4.0,I4,2F4.0,F5.0,I2,I1,22I2)
      READ(99,9876) (IMAGE(I),I=1,20)
 9876 FORMAT(20A4)
      WRITE(6,9877) (IMAGE(I),I=1,20)
 9877 FORMAT(1H0,20A4/)
      IF(A.NE.SDPV) GO TO 190
      IF(NP.EQ.0.) NP=2.
      IF(NL.EQ.0.) NL=2.
      IF(INTT.EQ.0) INTT=1
      IF(INLR.NE.0.) INLSSR=INLR
      IKX=MIN1(10.,SOLD/15.)
      IF(ITEXT.GT.2) GO TO 460
      IF(ITEXT.GT.1) GO TO 450
      DO 440 I=1,IKX
      KY(I)=KC(I)
  440 DY(I)=DC(I)
      CDS=10**3.5
      DISP=4.
      TORT=0.4
      DO 462 I=1,5
  462 WF(I)=0.5
      DO 463 I=6,IKX
  463 WF(I)=0.9
      GO TO 470
  450 DO 451 I=1,IKX
      KY(I)=KL(I)
  451 DY(I)=DL(I)
      CDS=10**4.2
      DO 452 I=1,5
  452 WF(I)=0.6
      DO 453 I=6,IKX
  453 WF(I)=0.9
      DISP=2.
      TORT=0.4
      GO TO 470
  460 DO 461 I=1,IKX
      KY(I)=KS(I)
  461 DY(I)=DS(I)
      CDS=10**4
      DISP=0.7
      TORT=0.6
  470 CONTINUE
      IF(IFORM.EQ.0) GO TO 5
      CALL REREAD
      READ(5,202)FG
  202 FORMAT(31A1)
      READ(99,9876) (IMAGE(I),I=1,20)
      WRITE(6,9877) (IMAGE(I),I=1,20)
```

```
    5 CONTINUE
      CALL REREAD
      READ(5,793) A,CNPPM
  793 FORMAT(A4,10F5.0)
      READ(99,9876) (IMAGE(I),I=1,20)
      IF(A.NE.NPPM) GO TO 190
      CALL REREAD
      READ(5,206) A,FMBDD
  206 FORMAT(A4,10F5.0)
      READ(99,9876) (IMAGE(I),I=1,20)
      IF(A.NE.FMBD) GO TO 190
      DO 10 I=1,IKX
   10 MBD(I)=FMBDD(I)
      CALL REREAD
      READ(5,1000)A,MPDT
 1000 FORMAT(A4,10F5.0)
      READ(99,9876) (IMAGE(I),I=1,20)
      IF(A.NE.MPLR) GO TO 190
      CALL REREAD
      READ(5,1005)A,(VFSD(I),FSD(I),SID(I),CLD(I),I=1,5)
 1005 FORMAT(A4,20F2.0)
      READ(99,9876) (IMAGE(I),I=1,20)
      IF(A.NE.MADT) GO TO 190
      CALL REREAD
      READ(5,1001)A,(VFSD(I),FSD(I),SID(I),CLD(I),I=6,10)
 1001 FORMAT(A4,20F2.0)
      READ(99,9876) (IMAGE(I),I=1,20)
      IF(A.NE.DMAD) GO TO 190
      CALL REREAD
      READ(5,1008)A,(OCD(I),I=1,10)
 1008 FORMAT(A4,10F5.0)
      READ(99,9876) (IMAGE(I),I=1,20)
      IF (A.NE.DADT) GO TO 190
      OC1=OCD(1)
      OC2=OCD(2)
      OC3=OCD(3)
      IF(OC3.GT.1.) AOOM=(OC1+OC2)*1.724
      IF(OC3.LE.1.) AOOM=((OC1+OC2)/2)*1.724
      IF(OC2.LT.1.) AOOM=OC1/2*1.724
      IF(AOOM.GT.50.) AOOM=50.
      MINR=(12.9*EXP(0.15*AOOM))/18400
      CALL REREAD
      READ(5,800)A,(STWC(I),I=1,10)
  800 FORMAT(A4,10F5.0)
      READ(99,9876) (IMAGE(I),I=1,20)
      IF(A.NE.WACT) GO TO 190
      CALL REREAD
      READ(5,801)A,(MFC(I),I=1,10)
  801 FORMAT(A4,10F5.0)
      READ(99,9876) (IMAGE(I),I=1,20)
      IF(A.NE.MFFC) GO TO 190
      CALL REREAD
      READ(5,802)A,(MWT(I),I=1,10)
  802 FORMAT(A4,10F5.0)
      DO 2507 I=1,IKX
 2507 MWT(I)=MWT(I)*0.775+0.021
      READ(99,9876) (IMAGE(I),I=1,20)
      IF(A.NE.MWLT) GO TO 190
      CALL REREAD
      READ(5,803)A,(STMN(I),I=1,10)
  803 FORMAT(A4,10F7.0)
      READ(99,9876) (IMAGE(I),I=1,20)
      IF(A.NE.SMNC) GO TO 190
      IF(IRFS.GT.9) GO TO 780
```

```
      IF(IRFS.GT.8) GO TO 770
      IF(IRFS.GT.7) GO TO 760
      CALL SCPARA(MPDT,VFSD,FSD,SID,CLD,OCD,WCFC,WILT,
     * INLSSR,IKX,SOLD)
      DO 751 I=1,IKX
  751 WCX(I)=WCFC(I)
      GO TO 790
  760 DO 761 I=1,IKX
      WCFC(I)=MFC(I)
      WILT(I)=MWT(I)
  761 WCX(I)=WCFC(I)
      WCX(1)=WCX(1)*0.9
      GO TO 790
  770 CALL SCPARA(MPDT,VFSD,FSD,SID,CLD,OCD,WCFC,WILT,
     * INLSSR,IKX,SOLD)
      DO 771 I=1,IKX
  771 WCX(I)=STWC(I)
      GO TO 790
  780 DO 781 I=1,IKX
      WCX(I)=STWC(I)
      WCFC(I)=MFC(I)
  781 WILT(I)=MWT(I)
  790 CONTINUE
      TAWWP=0.
      DO 791 I=1,IKX
      AWCC(I)=WCFC(I)-WILT(I)
      AWIEL(I)=AWCC(I)*15.
      TAWWP=TAWWP+AWIEL(I)
      CNORTX(I)=(CNPPM(I)*MBD(I)*0.001)/WCX(I)
      SOILMX(I)=15.*WCX(I)
      DNTUPX(I)=0.
  791 NTRTX(I)=SOILMX(I)*CNORTX(I)
      READ(11,FG,END=180)YEAR,RDAY,PREC,TMAX,TMIN,SR,PHOTP
      YEAR=YEAR+1900.
      IF(YEAR.GT.1952.) GO TO 5080
      IF(IRFS.EQ.7) GO TO 5017
      WRITE(6,5018)
 5018 FORMAT(/' SIMULATION SCENARIO -I (SOIL PHYSICAL PARAMETERS ',
     1 'MEASURED,BOUNDARY AND INITIAL CONDITIONS KNOWN)')
      GO TO 5020
 5017 CONTINUE
      WRITE(6,5019)
 5019 FORMAT(/' SIMULATION SCENARIO - II (SOIL PHYSICAL PARAMETERS ',
     1 'CALCULATED,BOUNDARY AND INITIAL CONDITIONS APPROXIMATED)')
 5020 CONTINUE
      WRITE(6,5021)IDST55,WCFC,WILT,MBD,AWCC
 5021 FORMAT(//' GENERAL INFORMATION',//2X,'CROP DISTRICT:',2X,I3,
     1 ///2X,'SOIL PHYSICAL PARAMETERS  ',
     2 //3X,'FIELD CAPACITY (MC/MC) :',2X,10(F4.2,X),
     3 //3X,'WILTING POINT (MC/MC)  :',2X,10(F4.2,X),
     4 //3X,'BULK DENSITY (M G/MC)  :',2X,10(F4.2,X),
     5 //3X,'AVAILABEL WATER (MC/MC):',2X,10(F4.2,X))
      WRITE(6,5022)IWTABL,IBLT,IDRAIN
 5022 FORMAT(//' LOWER BOUNDARY CONDITIONS ',
     1 //2X,'WATER TABLE       :',3X,I2,
     2 //2X,'PHYSICAL BOUNDARY :',3X,I2,
     3 //2X,'DRAINAGE CLASS    :',3X,I2)
      WRITE(6,5023)
 5023 FORMAT(//5X,'LEGEND:',
     1 /6X,'WATER TABLE       : PRESENT=15, ABSENT   =99, UNKNOWN=98',
     2 /6X,'PHYSICAL BOUNDARY : PRESENT= 1, ABSENT   = 0',
     3 /6X,'DRINAGE CLASS     : WELL    = 3, IMPERFECT= 2, POORLY = 1')
 5080 CONTINUE
      DO 399 I=1,IKX
```

```
  399 TPORO(I)=0.
      IF(IWTABL.LT.16) GO TO 2565
      IF(IBLT:GT.0) GO TO 2565
      IF(IDRAIN.LT.3) GO TO 2565
      IF(IDRAIN.GT.2) GO TO 390
 2565 CONTINUE
      DO 2501 I=1,IKX
 2501 TPORO(I)=1-(MBD(I)/2.56)
      DWTFC=TPORO(IKX)-WCFC(IKX)
      IF(ITEXT.GT.2) GO TO 2502
      IN=IKX-2
      GO TO 2503
 2502 CONTINUE
      IN=IKX-1
 2503 CONTINUE
      TWWPAS=0
      DO 2555 I=IN,IKX
      IF(TPORO(I).LT.WCFC(I)) GO TO 2559
      TWWPAS=TWWPAS+(TPORO(I)-WILT(I))*15
      WCX(I)=TPORO(I)
      IF(IWTABL.LT.16) WCFC(I)=TPORO(I)
      IF(IWTABL.GT.15) WCFC(I)=WCFC(I)
      IF(IDRAIN.GT.2) GO TO 2555
      MULTF=TPORO(I)/WCX(I)
      CNORTX(I)=CNORTX(I)/MULTF
      GO TO 2555
 2559 CONTINUE
      IF(TPORO(I).LT.WCX(I)) GO TO 2504
      TWWPAS=TWWPAS+(WCFC(I)-WILT(I))*15
      WCX(I)=WCFC(I)
      IF(IDRAIN.GT.2) GO TO 2555
      MULTF=TPORO(I)/WCX(I)
      CNORTX(I)=CNORTX(I)/MULTF
      GO TO 2555
 2504 CONTINUE
      TWWPAS=TWWPAS+(WCX(I)-WILT(I))*15
 2555 CONTINUE
      IL=IN-1
      DO 2505 I=1,IL
 2505 TWWPAS=TWWPAS+(WCX(I)-WILT(I))*15
      DO 2556 I=1,IKX
      SOILMX(I)=WCX(I)*15
      NTRTX(I)=SOILMX(I)*CNORTX(I)
 2556 CONTINUE
      IF(IBLT.EQ.1.AND.IDRAIN.LT.3) GO TO 5512
      IF(IWTABL.LT.16.AND.IKX.LE.8) GO TO 5512
      GO TO 2560
 5512 IUB=IKX+1
      DO 5515 I=IUB,10
      TPORO(I)=TPORO(IKX)
      WILT(I)=WILT(IKX)
 5515 TWWPAS=TWWPAS+(TPORO(I)-WILT(I))*15
      WRITE(6,3002)TWWPAS
 3002 FORMAT('TWWPAS  ',F7.2)
 2560 CONTINUE
      WTFC=DWTFC+WCX(IKX)
  390 CONTINUE
      IF(YEAR.GT.1952.) GO TO 5081
      WRITE(6,5024)WCX,CNPPM
 5024 FORMAT(//' INITIAL CONDITIONS ',
     1 //2X,'WATER CONTENT (MC/MC)     :',2X,10(F4.2,X),
     2 //2X,'NO3-N CONCENTRATION (PPM):',2X,10(F4.1,X))
 5081 CONTINUE
      ICDT=0
```

```
      ICDS=0
      PTHD=0
      PSD=0
      TPEV=0.
      LASTR=0.
      IF(IESD.EQ.2) GO TO 65
      PFFC=WCX(1)*0.9
      PRFC(1)=PFFC
   65 CONTINUE
      CALL REREAD
      READ(5,207)A,(THIKNX(I),DEPTH(I),I=1,6)
  207 FORMAT(A4,12F3.0)
      READ(99,9876) (IMAGE(I),I=1,20)
      IF(A.NE.LTHN) GO TO 190
      DO 41 I=1,6
   41 SOILTX(I)=0.
      PEV=0.0
      CPEV=0.0
      IX=1
      TEWSMR=0.
      INEVTS=0
      POACUM=1.
      COMPE=0.
   35 DO 145 IJ=1,IDAY
      IF(T.GT.90..AND.T.LT.274.) GO TO 60
      CALL REREAD
      READ(5,204)A,DAREA,DCWHT,SDS,SDE,SDJ,SDH,SDD,SDM
  204 FORMAT(A4,2F4.0,6F6.0)
      READ(99,9876) (IMAGE(I),I=1,20)
      IF(A.NE.AREAA) GO TO 190
      IF(DAREA.NE.0.)AREA=DAREA
      IF(DCWHT.NE.0.)CWHT=DCWHT
      CALL REREAD
      READ(5,205)A,DPLANT,DHARVT,IFX,(FRTMX(I),FRTX(I),I=1,3)
  205 FORMAT(A4,2F4.0,I1,6F4.0)
      READ(99,9876) (IMAGE(I),I=1,20)
      IF(A.NE.CROP(1)) GO TO 190
      IF(DPLANT.NE.0.) PLANTX=DPLANT
      IF(DHARVT.NE.0.) HARVTX=DHARVT
      IF(YEAR.GT.1976.) GO TO 611
      I=YEAR-1951.
      J=IDST55
      IDISTR=IDST55
      PLANTX=IS5277(I,J)
      GO TO 612
  611 CONTINUE
      I=YEAR-1976.
      J=IDST77
      IDISTR=IDST77
      PLANTX=IS7780(I,J)
  612 CONTINUE
      IF(IDRAIN.EQ.1) PLANTX=PLANTX+8
      IF(IDRAIN.EQ.2) PLANTX=PLANTX
      IF(IDRAIN.EQ.3) PLANTX=PLANTX-8
      FRTMX(1)=PLANTX
      DO 40 I=1,IFX
   40 IF(FRTX(I).EQ.0.)FRTX(I)=28.
      ICX=0
   60 CONTINUE
      IF(TCPD.LT.5.) GO TO 600
C     HARVTX=MATX
  600 CONTINUE
      IF(T.GT.HARVTX) GO TO 145
      IF(IESD.EQ.2.OR.T.GT.90.) GO TO 61
```

```
      PLANTX=0.
      ICX=0
      FERTMX=0
      INT=2
   61 CHEKPD=PLANTX-1
      IF(T.LT.CHEKPD) GO TO 70
      IF(PLANTX.EQ.0..OR.T.GE.PLANTX) GO TO 70
      ICNT=0
      DTX=0.0
      IBMTSX=1
      EMEX=0.0
      OINX=0.0
      HADX=0.0
      SDOX=0.0
      MATX=0.0
      IF(PLANTX.GT.120) GO TO 601
      DV1=PLANTX-90
      DV2=1./30.*DV1
      TEE=3+DV2
      GO TO 602
  601 CONTINUE
      DV1=PLANTX-120
      DV2=1./31.*DV1
      TEE=4+DV2
  602 CONTINUE
      DO 211 I=1,6
      SOILTX(I)=TZERO+AZERO*EXP(-(DEPTH(I)/DDEPTH))*
     * SIN((OMEGA*TEE)-(DEPTH(I)/DDEPTH)+FAI)
  211 CONTINUE
      IF(YEAR.GT.1952.) GO TO 5082
      WRITE(6,5025)SOILTX(6)
 5025 FORMAT(/2X,'SOIL TEMPERATURE AT 0.20 M.(DEGREE CELSIUS):',2X,F5.2)
 5082 CONTINUE
      WRITE(6,5040)YEAR,PLANTX,FRTX(1)
 5040 FORMAT(///' MANAGEMENT DATA',
     1 //2X,'YEAR OF SIMULATION:',20X,F5.0,
     2 //2X,'SEEDING DATE (JULIAN DAY):',13X,F4.0,
     3 //2X,'NITROGEN FERTILIZER APPLIED (KG/HA):',3X,F4.0)
      WRITE(6,5027)
 5027 FORMAT(///' DAILY OUTPUTS'//)
      WRITE(6,398)
  398 FORMAT(' JDAY DPHD DAYP  CUMP  PETB CPEV ACET W- LA-1 LA-2 LA-3',
     1 ' LA-4 LA-5 N- LA-1 LA-2 LA-3 LA-4 LA-5 LMWF LMNF LMTF TLFT  CU',
     2 'MANP'//)
      IX=1
   70 T=T+1
      IF(ICX.GE.IFX.OR.T.NE.FRTMX(ICX+1)) GO TO 80
      ICX=ICX+1
      FERTX=FERTX+FRTX(ICX)
      FERTMX=FRTMX(ICX)
C  80 READ(11,FG,END=180)RDAY,PREC,TMAX,TMIN,SR,PHOTP
   80 READ(11,FG,END=180)YEAR,RDAY,PREC,TMAX,TMIN,SR,PHOTP
      YEAR=YEAR+1900.
      IF(PLANTX.GT.0.) GO TO 5000
      IF(TMIN.LT.0..OR.TMAX.LT.5.) GO TO 3500
      IF(PTHD.GT.0.) GO TO 3200
      ICDT=ICDT+1
      IF(ICDT.LE.5.) GO TO 145
      PTHD=T
      WRITE(6,4200)PTHD
 4200 FORMAT(' PTHD-',F4.0)
 3200 DMT=0.75*TMAX+0.25*TMIN
      WRITE(6,4201)DMT,T
 4201 FORMAT(' DMT-',F8.2,2X,' DAY-',F4.0)
```

```
      IF(DMT.LT.5.) GO TO 4000
      CALL SETW(ETLX,PAMX,HARVTX,PLANTX,IX,IKX,PRFC)
      DO 85 I=1,INT
      CALL SSWETN(WCX,FLRTX,SOILMX,ETLX,IKX,1,INT,PLANTX,CKS,CDS)
   85 CONTINUE
      IF (PREC.GT.1..OR.WCX(1).GT.PFFC) GO TO 4000
      ICDS=ICDS+1.
      WRITE(6,3300)ICDS
 3300 FORMAT(' ICDS-',2X,I2)
      IF(ICDS.LT.3.) GO TO 145
      PSD=T
      PLANTX=PSD
      FERTMX=PLANTX
      FRTMX(1)=FERTMX
      WRITE(6,3900)PTHD,PLANTX,FRTMX(1)
 3900 FORMAT(5X,' THAWING-',F4.0,/5X,' SEEDING-',F4.0,
     1 /5X,' FERT. DAY-',F4.0)
      GO TO 145
 3500 IF(PTHD.EQ.0.) GO TO 4901
 4000 ICDS=0
      GO TO 145
 4901 ICDT=0
      GO TO 145
 5000 CONTINUE
      IF(T.LT.PLANTX) GO TO 145
C     IF(TCPD.GT.2..AND.TMIN.LT.-1.) GO TO 2506
      INT=2
      IPREC=PREC
      IF(IPREC.LE.2) GO TO 1234
      INT=IPREC+1
 1234 CONTINUE
      IF(T.LT.PLANTX.OR.T.GT.HARVTX) GO TO 116
      IF(MATX.GT.0.) GO TO 2517
      TPREC=TPREC+PREC
      PRECSH=TPREC
      GO TO 116
 2517 PRECSH=PRECSH+PREC
  116 CONTINUE
      CALL SETW(ETLX,PAMX,HARVTX,PLANTX,IX,IKX,PRFC)
      DO 95 I=1,INT
      CALL SSWETN(WCX,FLRTX,SOILMX,ETLX,IKX,1,INT,PLANTX,CKS,CDS)
      CALL SNO3W(WCX,FLRTX,SOILMX,IKX,CNORTX,FLRNX,NTRTX,DNTUPX,FERTX,
     * PLANTX,HARVTX,FERTMX,DNFMX,NTRATX,INT,TDENTX,IBLT,SOLD)
   95 CONTINUE
      CALL SPDW(PLANTX,IBMTSX,DTX,EMEX,OINX,HADX,SDOX,MATX)
      CALL SSTEMP(THIKNX,SOILTX)
      IF(T.GE.PLANTX.AND.TCPD.LE.5.) CALL SCGRW(PLANTX,
     1 NITUPX,PLGRX,PLGRMX,SOILTX,PAMX,ETLX,IKX,
     2 DNTUPX,CNORTX,OPTXX,OPTYX,1,WCX,WILT,IX,AVBD,ILTCPD,ITCPDX,
     3 SOLD)
      IF(T.NE.HARVTX) GO TO 115
      DO 100 IZ=1,10
  100 DNTUPX(IZ)=0.
      RZONEX=0.
      NITUPX=0.
  115 CONTINUE
      IF(TCPD.GT.4.0) GO TO 8011
      IF(OINX.GT.0.) GO TO 8040
      IF(EMEX.GT.0.) GO TO 8020
      MSTF=1.
      GO TO 8011
 8020 CONTINUE
      MSTF=(1-(1-LASTR)**2)**1.5
      GO TO 8011
```

```
8040 MSTF=(1-(1-LASTR)**2)**5.0
8011 CONTINUE
     IF(IG1.EQ.0) GO TO 140
     IF(AMOD(T,NL).GT.0.) GO TO 140
     ANCX=0.0
     DO 2000 IK=1,IX
2000 ANCX=ANCX+NTRTX(IK)
     ANCX=ANCX/IX
     SHC2=NITUP*100.
     WRITE(6,360)T,PLGRX,ANCX
 360 FORMAT(1HO,F5.,6X,2F8.2)
     DO 136 I= 1,IG1
     IXZ=IXZ1(I)
     GO TO(130,131),IXZ
 130 WRITE(6,370)CNORTX
     GO TO 136
 131 WRITE(6,380)WCX
 136 CONTINUE
 370 FORMAT(' CNORT',3P10F7.2)
 380 FORMAT(' WCX',10F7.3)
 140 DO 4447 I=1,IKX
4447 PPM1(I)=(CNORTX(I)*WCX(I))/(MBD(I)*0.001)
     DO 4448 I=1,2
     PPMFC(I)=PPM1(I)
4448 WCXFC(I)=WCX(I)
     PPMFC(3)=(PPM1(3)+PPM1(4))/2
     WCXFC(3)=(WCX(3)+WCX(4))/2
     PPMFC(4)=(PPM1(5)+PPM1(6))/2
     WCXFC(4)=(WCX(5)+WCX(6))/2
     PPMFC(5)=(PPM1(7)+PPM1(8))/2
     WCXFC(5)=(WCX(7)+WCX(8))/2
     AWCR=0.0
     AWCP=0.0
     APPMR=0.0
     APPMP=0.0
     DO 4460 I=1,IX
     AWCR=AWCR+WCX(I)
4460 APPMR=APPMR+PPM1(I)
     DO 4461 I=1,IKX
     AWCP=AWCP+WCX(I)
4461 APPMP=APPMP+PPM1(I)
     AWCR=AWCR/IX
     APPMR=APPMR/IX
     APPMP=APPMP/IKX
     CPEV=CPEV+PEV
     AWCP=AWCP/IKX
     IF(IRFS.GT.7) GO TO 5041
     IF(TCPD.LT.4.90.OR.TCPD.GT.5.10) GO TO 603
5041 CONTINUE
     WRITE(6,4446)RDAY,TCPD,PREC,PRECSH,PET,CPEV,ET,WCXFC,PPMFC,
    1 LMW,LMN,LMT,LM,PLGRMX
4446 FORMAT(X,F4.0,X,F4.2,2(X,F5.2),3(X,F4.2),3X,5(X,F4.2),3X,5(X,F4.1,
    1 ),X,4(F4.2,X),F6.0)
 603 CONTINUE
     IF(IG2.EQ.0) GO TO 230
     IF(AMOD(T,NP).GT.0.) GO TO 230
     WRITE(12,400) PLGRX,NITUPX
 400 FORMAT(0PF9.3,2PF7.4)
     AA(II)=T
     II=II+1
 230 CONTINUE
     IF(PREC.LT.2..OR.IDRAIN.GT.2) GO TO 145
     INEVTS=INEVTS+1
     DIFPI=(PREC-2.)/100
```

```
      IF(COMPE.GT.DIFPI) GO TO 145
      COMPE=DIFPI
  145 CONTINUE
      WRITE(6,234)
  234 FORMAT(/////' S U M M A R Y   O U T P U T S',
     1 ///2X,'PREDICTED GROWTH STAGES (JULIAN DAY)')
      WRITE(6,235)PLANTX,EMEX,OINX,HADX,SDOX,MATX
  235 FORMAT(/5X,'SEEDING   EMERGENCE    JOINTING',
     1 '    HEADING    SOFT-DOUGH  MATURITY',/7X,F4.0,5X,
     2 F4.0,8X,F4.0,6X,F4.0,8X,F4.0,7X,F4.0)
      OTPREC=TPREC*10
      OPRECH=PRECSH*10
      OTOTPE=TOTPE*10
      WRITE(6,236)OTPREC
  236 FORMAT(//5X,' PRECIPITATION DURING THE GROWING',
     1 ' SEASON: ',F6.2,X,'MM')
      WRITE(6,2516)OPRECH
 2516 FORMAT(/5X,' PRECIPITATION FROM SEEDING TO',
     1 ' HARVEST  : ',F6.2,X,'MM')
      WRITE(6,237)OTOTPE
  237 FORMAT(/5X,' POTENTIAL EVAPOTRANSPIRATION              :',X,
     1 F6.2,X,'MM')
      TOTALW=0.
      TETWSM=TEWSMR+CPEV
      OTEVT=TEVT*10
      WRITE(6,238)OTEVT
  238 FORMAT(/5X,' ACTUAL TRANSPIRATION                      :',X,
     1 F6.2,X,'MM')
      IF(IRFS.LT.7) GO TO 2222
      HIW=HINDX
 2222 CONTINUE
      IF(COMPE.EQ.0.) GO TO 670
      IF(IREGIO.GT.1) GO TO 610
      ISLOPE=80
      IFQOMD=7
      VMAX=58946
      GO TO 620
  610 ISLOPE=100
      IFQOMD=4
      VMAX=26315
  620 IF(ICSLOP.EQ.1) TETAS=0.005235988
      IF(ICSLOP.EQ.2) TETAS=0.010471975
      IF(ICSLOP.EQ.3) TETAS=0.017453292
      TANGT=TAN(TETAS)
      WACUM=(320000*COMPE)/IFQOMD
      IF(INFR.GT.3) GO TO 630
      POACUM=POACUM+0.25
  640 IF(IROF.GT.1) GO TO 641
      POACUM=POACUM+0.50
  641 CONTINUE
      IF(IWTABL.GT.15) GO TO 650
      POACUM=POACUM+0.25
      GO TO 650
  630 IF(IWTABL.GT.15) GO TO 660
      POACUM=POACUM+0.50
  660 IF(IROF.GT.1) GO TO 650
      POACUM=POACUM+0.25
  650 CONTINUE
      POACUM=POACUM-1
      WACUM=WACUM*POACUM
      ARAD=((WACUM/TANGT)/1.5708)**0.3333
      PAREAL=1-(((3.14159*ARAD**2)*IFQOMD)/640000)
      PLGRX=PLGRX*PAREAL
      PLGRM=PLGRMX*PAREAL
```

```
      WRITE(6,638)PLGRX
  638 FORMAT(3X,'PLGRXBWEXC=',F9.3)
  670 CONTINUE
      IF(IDRAIN.EQ.3) GO TO 2508
      IF(IDRAIN.EQ.2) GO TO 2509
      IF(TPREC.LT.5.) GO TO 2510
      IF(TPREC.LT.15.) GO TO 4462
      GO TO 2511
 2509 IF(TPREC.LT.10.) GO TO 2510
      IF(TPREC.LT.20..AND.IWTABL.GT.15) GO TO 4462
      GO TO 2511
 2508 IF(TPREC.GT.15.) GO TO 4462
 2510 PLGRX=PLGRMX
      GO TO 4462
 2511 CONTINUE
      TOTALW=TWWPAS
      DRLF2=TOTALW+TPREC-(TEWSMR+CPEV)
      IF(DRLF2.LE.15.) GO TO 2515
      MOISTS=1-(1.15*(DRLF2-15)/35)
      PLGRX=PLGRX*MOISTS
 2515 CONTINUE
      WRITE(6,605)TEWSMR,CPEV,TETWSM,TOTALW,DRLF2,MOISTS,
     * INEVTS,DIFPI,COMPE,PAREAL,TANGT,WACUM,ARAD
  605 FORMAT(/5X,'TET',X,F5.2,X,'SEV',X,F5.2,X,'TTRWR',X,F5.2,
     1 'TWA',X,F5.2,X,'DRLF2',X,F5.2,X,'MSF',X,F5.2,X,
     2 'INE',I3,X,'DIF',X,F5.2,X,'C',F4.2,X,'P',F4.2,X,
     3 'T',F5.3,'W',F5.0,'A',F3.0)
 4462 CONTINUE
      GYIELD=PLGRX*HIW
      BYIELD=GYIELD*0.0149
      WRITE(6,240)YEAR,OTPREC,PLGRX,GYIELD
  240 FORMAT(////4X,' Y I E L D (KG/HA) ',//6X,
     1 'ABOVEGROUND NET PRODUCTION',5X,'GRAIN'/16X,
     2 3F6.0,15X,F5.0)
      IF(IG2.EQ.0) GO TO 999
      INP=IDAY/NP
      DO 5031 IX=1,IG2
      REWIND 12
      DO 5032 IZ=1,3
 5032 FMTA(IZ)=FMT(IZ,IXZ2(IX))
      DO 5033 II=1,INP
 5033 READ(12,FMTA,END=156) AA(INP+II)
      GO TO 5034
  156 INP=II
 5031 CALL PLOT(IXZ2(IX),2)
 5034 CONTINUE
      GO TO 999
  180 WRITE(6,500)
  500 FORMAT(' INSUFFICIENT WEATHER DATA')
  190 WRITE(6,550)
  550 FORMAT(' CONTROL CARD ERROR')
C2506 WRITE(6,2507)YEAR,RDAY,TCPD,TMIN
C2507 FORMAT(//'      ************* ',F5.0,'- FROST *************',
C    1 / 'JULINA DAY = ',F4.0,2X,'BMTS = ',F4.2,2X,
C    2 'MINIMUM TEMPERATURE = ',F4.0,2X,'YIELD = 0.0')
  999 STOP
      END
```

```
C INITIALIZATION SUBROUTINS
C
C
C  SUBROUTINE BLOCKDATA - BLOCK DATA.
C
C
      BLOCK DATA
      IMPLICIT REAL*4 (A-H,J-Z)
      COMMON /COMA/      ITEXT,YEAR,IESD,PHOTP,RDAY,IRFS,ICONST,ICNT,
     1 HEAD,IHEAD,T,WTFC,    F(10),WCFC(10),SR,TMAX,TMIN,TCPD,RZONE,
     2 PEV,TPEV,MSTF,TPAMSE
      COMMON /COMC/       PREC,RUNOFF,
     * XX(10),DY(10),KY(10),OPTXX(7),OPTYX(7),WILT(10)
      COMMON /COMH/
     1 GRA1X(10),GRA1Y(10),GRAX(11),GRA3L(11),STRES1(11),STRES2(11),
     2 STRES3(11),TRESS1(11),TRESS2(11),TRESS3(11),PATN(10,10),DATES(10)
      COMMON /COMN/  ILTCPD,ITCPDX,PA0(5),PA1(5),PA2(5),PB0(5),PB1(5),
     * PB2(5),PB3(5),PB4(5),DC(10),KC(10),DL(10),KL(10),DS(10),KS(10)
      COMMON /COMS/   IS5277(25,3),IS7780(4,3),IDST55,IDST77
      DATA XX/  0.1,0.3,0.5,0.7,0.9,1.,1.,1.,1.,1./,
     1 KC/  -4.65,-4.0,-3.6,-2.8,-1.85,-1.6,-1.6,-1.6,-1.6,-1.6/,
     2 DC/  -0.2,0.10,0.35,1.02,1.45,2.05,2.05,2.05,2.05,2.05/,
     3 KL/  -6.0,-4.7,-3.75,-2.8,-2.4,-2.0,-2.0,-2.0,-2.0,-2.0/,
     4 DL/  0.0,0.08,0.20,0.95,1.3,1.5,1.5,1.5,1.5,1.5/,
     5 KS/  -5.3,-5.0,-4.5,-3.5,-2.6,-2.4,-2.4,-2.4,-2.4,-2.4/,
     6 DS/  0.35,0.25,0.33,0.45,0.8,1.0,1.0,1.0,1.0,1.0/
      DATA GRA1X/1.,1.24,1.5,2.13,2.5,3.03,3.3,3.6,4.3,5.0/,
     5 GRA1Y/0.3,0.51,0.6,0.86,0.96,1.05,1.,0.95,0.66,0.32/,
     7 GRAX/0.,0.1,0.2,0.3,0.4,0.5,0.6,0.7,0.8,0.9,1./,
     8 GRA3L/0.,0.1,0.15,0.2,0.25,0.3,0.4,0.5,0.6,0.7,1./,
     9 STRES1/0.05,0.15,0.25,0.4,0.57,0.72,0.85,0.95,0.98,1.,1./
      DATA STRES2/0.13,0.23,0.4,0.65,0.84,0.94,0.97,0.98,1.,1.,1./,
     1 STRES3/0.35,0.65,0.77,0.88,0.93,0.95,0.97,0.98,0.99,1.,1./,
     2 TRESS1/0.01,0.05,0.12,0.21,0.32,0.47,0.62,0.76,0.89,0.98,1./,
     3 TRESS2/0.05,0.12,0.25,0.4,0.56,0.74,0.85,0.94,0.97,1.,1./,
     4 TRESS3/0.15,0.28,0.42,0.6,0.76,0.86,0.94,0.96,0.98,1.,1./,
     5 DATES/1.,2.,3.,4.,5.,6.,7.,8.,9.,10./,
     6 PATN/1.,9*0.,2*0.5,8*0.,2*0.4,0.2,7*0.,2*0.35,0.2,0.1,6*0.,
     7 0.35,0.3,0.2,0.1,0.05,5*0.,0.35,0.3,0.15,0.1,2*0.05,4*0.,
     8 0.35,0.3,2*0.1,3*0.05,3*0.,2*0.3,2*0.1,4*0.05,2*0.,
     9 2*0.3,0.1,6*0.05,0.,2*0.3,0.1,5*0.05,2*0.025/
      DATA OPTXX/0.,1.9,2.7,3.2,3.7,4.5,5./,
     1 OPTYX/0.030,0.052,0.039,0.025,0.021,0.018,0.017/
      DATA PA0/0.,8.413,10.93,10.94,24.38/,
     1 PA1/0.,1.005,0.9256,1.389,-1.14/,
     2 PA2/0.,0.,-0.06025,-0.08191,0./,
     3 PB0/44.37,23.64,42.65,42.18,37.67/,
     4 PB1/0.01086,-0.003512,2.958E-4,2.458E-4,6.733E-5/,
     5 PB2/-0.000223,5.026E-5,0.,0.,0./,
     6 PB3/0.009732,3.666E-4,3.943E-4,3.109E-5,3.442E-4/,
     7 PB4/-2.267E-4,-4.282E-6,0.,0.,0./
      DATA IS5277/111,117,122,127,134,126,118,121,134,133,131,
     1 133,137,133,140,136,131,135,147,136,139,134,152,143,135,
     2 112,117,132,130,141,132,116,141,142,139,148,140,137,138,
     3 145,143,138,137,152,135,136,132,152,134,132,114,124,126,
     4 130,140,131,120,132,142,140,142,135,137,133,139,138,137,
     5 139,149,139,141,135,152,141,132/,
     6 IS7780/123,135,144,122,123,135,148,122,124,135,148,122/
      END
```

```
C  SUBROUTINE SOIL INITIALIZATION PARAMETERS - SSINP.
C
C
      SUBROUTINE SSINP
      IMPLICIT REAL*4 (A-H,J-Z)
      COMMON /COMA/      ITEXT,YEAR,IESD,PHOTP,RDAY,IRFS,ICONST,ICNT,
     1 HEAD,IHEAD,T,WTFC,    F(10),WCFC(10),SR,TMAX,TMIN,TCPD,RZONE,
     2 PEV,TPEV,MSTF,TPAMSE
      COMMON /COMB/       AREA,CWHT,INLR,SOLD,IBLT,STWC(10),
     * MFC(10),MWT(10),HINDX,CNPPM(10),WCC(10),STMN(10)
      COMMON /COMD/       CNORW,AOOM,MINR,OC1,OC2,OC3,
     * DENIT,DIF,DISP,NORN,TORT,WTSAT,WF(10)
      COMMON /COMG/      TZERO,AZERO,DDEPTH,OMEGA,FAI,THIKNX(6),IX,
     * DEPTH(6),SOILTX(6)
      T=90.
      TZERO=5.5
      AZERO=12.5
      DDEPTH=140.7
      OMEGA=0.5236
      FAI=-1.964
      NORN=0.001
      DENIT=0.00136
      CNORW=0.004
      HEAD=0.
      IHEAD=1
      CWHT=1.
      DO 10 I=1,3
   10 WF(I)=0.7
      DO 40 I=4,10
   40 WF(I)=1.
      DO 20 I=1,2
   20 F(I)=0.5
      DO 30 I=3,10
   30 F(I)=1.
      RETURN
      END
C
C
C  SUBROUTIN CROP INITIALIZATION PARAMETERS (WHEAT) - SCINPW.
C
C
C
      SUBROUTINE SCINPW
      IMPLICIT REAL*4 (A-H,J-Z)
      COMMON /COMA/      ITEXT,YEAR,IESD,PHOTP,RDAY,IRFS,ICONST,ICNT,
     1 HEAD,IHEAD,T,WTFC,    F(10),WCFC(10),SR,TMAX,TMIN,TCPD,RZONE,
     2 PEV,TPEV,MSTF,TPAMSE
      COMMON /COME/      IKX,CNORTX(10),FLRNX(11),FLRTX(11),AVBD
      COMMON /COMF/
     1 MBD(10),       FERTMX,FERTX,IBMTSX,DTX,
     2 HARVTX,NITUPX,NTRATX,PLANTX,PLGRX,PLGRMX,DNTUPX(10),
     3 NTRTX(10),SOILMX(10),WCX(10),          TDENTX,HIW
      COMMON /COMP/   TOTPE,TOTT,TEVT,TETL(10),LMNM,TEWSMR,
     * PET,ET,LMW,LMN,LMT,LM,PGR,GRM,GR,PAMCRZ,TPREC,EWSMR,LASTR
      PLGRX=200.
      PLGRMX=200.
      TOTPE=0.
      TOTT=0.
      TEVT=0.
      EWSMR=0.
      DO 50 I=1,10
      TETL(I)=0.
   50 CONTINUE
      NTRATX=0.
```

```
      NITUPX=0.
      TPREC=0.
      FERTX=0.0
      TDENTX=0.
      HIW=0.38
      TPAMSE=1.
      RETURN
      END
C
C
C  SUBROUTINE COMPUTATION PARAMETERS - SCPARA.
C
C
C
      SUBROUTINE SCPARA(MPL,VFS,FS,SI,CL,OC,WCFCV,WILTV,
     * INLSS,IK,SOLDX)
      IMPLICIT REAL*4 (A-H,J-Z)
      COMMON /COMA/      ITEXT,YEAR,IESD,PHOTP,RDAY,IRFS,ICONST,ICNT,
     1 HEAD,IHEAD,T,WTFC,    F(10),WCFC(10),SR,TMAX,TMIN,TCPD,RZONE,
     2 PEV,TPEV,MSTF,TPAMSE
      COMMON /COMC/      PREC,RUNOFF,
     * XX(10),DY(10),KY(10),OPTXX(7),OPTYX(7),WILT(10)
      COMMON /COME/      IKX,CNORTX(10),FLRNX(11),FLRTX(11),AVBD
      COMMON /COMF/
     1 MBD(10),       FERTMX,FERTX,IBMTSX,DTX,
     2 HARVTX,NITUPX,NTRATX,PLANTX,PLGRX,PLGRMX,DNTUPX(10),
     3 NTRTX(10),SOILMX(10),WCX(10),          TDENTX,HIW
      COMMON /COMR/   IPSTON,IDRAIN,INFR,IWTABL,IROF,ICSLOP,IREGIO,
     * TPORO(10),TWWPAS
      DIMENSION MPL(10),VFS(10),FS(10),SI(10),CL(10),OC(10),WC(10),
     1 BDC(10),FCC(10),WPC(10),BD(10),FC(10),WP(10),WCFCV(10),WILTV(10),
     2 SOILM(10),NTRT(10),CNORT(10)
      DO 8 I=1,INLSS
      BDC(I)=1.7756-0.0016*VFS(I)-0.0017*SI(I)-0.0047*CL(I)-0.1216*OC(I)
     1 +0.0008*(CL(I)*(1.72*OC(I)))
      FCC(I)=9.8708+0.1182*SI(I)+0.2741*CL(I)+2.1767*OC(I)
      WPC(I)=3.796-0.0375*FS(I)-0.0334*VFS(I)+0.2202*CL(I)+1.1431*OC(I)
    8 CONTINUE
      PDI=7.5
      DO 9 I=1,IK
      BD(I)=AFGEN(MPL,BDC,INLSS,PDI)
      FC(I)=AFGEN(MPL,FCC,INLSS,PDI)
      WP(I)=AFGEN(MPL,WPC,INLSS,PDI)
      WCFCV(I)=FC(I)*0.01*BD(I)
      WILTV(I)=WP(I)*0.01*BD(I)
      MBD(I)=BD(I)
      IF(I.GT.2) GO TO 5
      MBD(I)=MBD(I)*0.75
      WCFCV(I)=WCFCV(I)*MBD(I)
    5 CONTINUE
      PDI=PDI+15.
    9 CONTINUE
      AVBD=0
      DO 500 I=1,IK
  500 AVBD=AVBD+BD(I)
      AVBD=AVBD/IK
      IF(IPSTON.EQ.0) GO TO 600
      AFSPAR=1-((100*IPSTON*AVBD)/(270+IPSTON*(AVBD-2.7)))/100
      DO 15 I=1,IK
      WCFCV(I)=WCFCV(I)*AFSPAR
   15 WILTV(I)=WILTV(I)*AFSPAR
  600 CONTINUE
      RETURN
      END
```

```
C  FUNCTIONAL SUBROUTINES:
C
C
C  SUBROUTINE EVAPOTRANSPIRATION (WHEAT) - SETW.
C
C
C
      SUBROUTINE SETW(ETL,PAM,HARVT,PLANT,IXR,IK,PRFCX)
      IMPLICIT REAL*4 (A-H,J-Z)
      COMMON /COMA/      ITEXT,YEAR,IESD,PHOTP,RDAY,IRFS,ICONST,ICNT,
     1 HEAD,IHEAD,T,WTFC,    F(10),WCFC(10),SR,TMAX,TMIN,TCPD,RZONE,
     2 PEV,TPEV,MSTF,TPAMSE
      COMMON /COMH/
     1 GRA1X(10),GRA1Y(10),GRAX(11),GRA3L(11),STRES1(11),STRES2(11),
     2 STRES3(11),TRESS1(11),TRESS2(11),TRESS3(11),PATN(10,10),DATES(10)
      COMMON /COMP/   TOTPE,TOTT,TEVT,TETL(10),LMNM,TEWSMR,
     * PET,ET,LMW,LMN,LMT,LM,PGR,GRM,GR,PAMCRZ,TPREC,EWSMR,LASTR
      COMMON /COMR/   IPSTON,IDRAIN,INFR,IWTABL,IROF,ICSLOP,IREGIO,
     * TPORO(10),TWWPAS
      DIMENSION ETL(10),PRFCX(10)
      CTMAX=TMAX*1.8+32.
      CTMIN=TMIN*1.8+32.
      LET=-87.03+(0.928*CTMAX)+(0.933*(CTMAX-CTMIN))+(0.0486*SR)
      IF(LET.GT.0.) GO TO 500
      LET=0.
  500 CONTINUE
      PET=LET*0.0094
      TOTPE=TOTPE+PET
      IF(PLANT.EQ.0..OR.TCPD.LT.1.) GO TO 70
      RATIO=AFGEN(GRA1X,GRA1Y,10,TCPD)
      EWSMR=PET*RATIO
      TEWSMR=TEWSMR+EWSMR
      IF(TCPD.GT.3..AND.TCPD.LT.4.5) GO TO 20
      IF(PET.LE..4) ET=PET*RATIO*AFGEN(GRA3L,STRES3,11,PAM)
      IF(PET.GT..4.AND.PET.LE..56)ET=PET*RATIO*AFGEN(GRAX,STRES2,11,PAM)
      IF(PET.GT..56)ET=PET*RATIO*AFGEN(GRAX,STRES1,11,PAM)
      GO TO 40
   20 IF(PET.LE..41) ET=PET*RATIO*AFGEN(GRA3L,TRESS3,11,PAM)
      IF(ET.GT..41)ET=PET*RATIO*AFGEN(GRAX,TRESS2,11,PAM)
   40 CONTINUE
      IF(EWSMR.EQ.0.) GO TO 501
      LASTR=ET/EWSMR
  501 CONTINUE
      TOTT=TOTT+ET
      DO 45 IJ=1,IK
      IF(DATES(IJ).GE.IXR) GO TO 55
   45 CONTINUE
   55 DO 50 I=1,IK
   50 ETL(I)=PATN(I,IJ)*ET
      DUAR=1-RATIO
      IF(DUAR.LT.0.) GO TO 59
      DPET=PET*DUAR
      IF(TCPD.GT.1.) GO TO 71
   70 CONTINUE
      DO 72 I=1,IK
   72 ETL(I)=0.
      DPET=PET
   71 CVAR=PRFCX(1)
      IF(ITEXT.GT.2) GO TO 450
      IF(ITEXT.GT.1) GO TO 430
      IF(CVAR.GT.0.66) GO TO 480
      PEV=DPET*(0.010258*EXP(6.877143*CVAR))
      GO TO 60
  430 IF(CVAR.GT.0.71) GO TO 480
```

```
      PEV=DPET*(0.003333+1.397619*CVAR)
      GO TO 60
  450 IF(CVAR.GT.0.505) GO TO 480
      PEV=DPET*(0.00381+1.968571*CVAR)
      GO TO 60
   59 PEV=0
      GO TO 60
  480 PEV=DPET
   60 CONTINUE
      IF(TCPD.GT.1.1) GO TO 80
      PEV=PEV/3
   80 TETL(1)=TETL(1)+ETL(1)+PEV
      TPEV=TPEV+PEV
      IF(TCPD.LT.1.) GO TO 1002
      DO 1001 I=2,IK
 1001 TETL(I)=TETL(I)+ETL(I)
 1002 CONTINUE
      DO 1003 I=1,IK
      TEVT=TEVT+ETL(I)
 1003 CONTINUE
      RETURN
      END
C
C
C  SUBROUTINE SOIL WETNESS - SSWETN.
C
C
C
      SUBROUTINE SSWETN(WC,FLRT,SOILM,ETL,IK,IWH,INT,PLANT,KSIL,DSIL)
      IMPLICIT REAL*4 (A-H,J-Z)
      COMMON /COMA/      ITEXT,YEAR,IESD,PHOTP,RDAY,IRFS,ICONST,ICNT,
     1 HEAD,IHEAD,T,WTFC,    F(10),WCFC(10),SR,TMAX,TMIN,TCPD,RZONE,
     2 PEV,TPEV,MSTF,TPAMSE
      COMMON /COMB/       AREA,CWHT,INLR,SOLD,IBLT,STWC(10),
     * MFC(10),MWT(10),HINDX,CNPPM(10),WCC(10),STMN(10)
      COMMON /COMC/       PREC,RUNOFF,
     * XX(10),DY(10),KY(10),OPTXX(7),OPTYX(7),WILT(10)
      COMMON /COMK/       WCON(10),WCAP(10),PRFC(10)
      COMMON /COMR/   IPSTON,IDRAIN,INFR,IWTABL,IROF,ICSLOP,IREGIO,
     * TPORO(10),TWWPAS
      DIMENSION WC(10),FLRT(11),SOILM(10),ETL(10),OSM(10),DPFC(10),
     * CPFC(10)
      DIFN(X)=10.**AFGEN(XX,DY,10,X)
      CDUT(X)=10.**AFGEN(XX,KY,10,X)
      IK=MIN1(10.,SOLD/15.)
      DO 10 I=1,IK
      OSM(I)=SOILM(I)
      WCON(I)=WC(I)-WILT(I)
      WCAP(I)=WCFC(I)-WILT(I)
   10 PRFC(I)=WCON(I)/WCAP(I)
      IF(PRFC(I).LT.1.) GO TO 950
      PRFC(I)=1.
  950 CONTINUE
      IF(PLANT.EQ.0..OR.TCPD.LT.1.) GO TO 101
      IL=IK+1
      IF(IBLT.EQ.0..AND.IWTABL.GT.15) GO TO 880
      IF(IBLT.EQ.1) GO TO 870
      FLRT(IL)=(DSIL*(WC(IK)-WTFC)/57.5)/INT
      GO TO 991
  870 CONTINUE
      FLRT(IL)=0.
      GO TO 20
  880 CONTINUE
      WTFC=0.9*WC(IK)
```

```
 890 CONTINUE
     PWTFC=(WTFC-WILT(IK))/WCAP(IK)
     AVD=(DIFN(PRFC(IK))+DIFN(PWTFC))/2.
     AVC=(CDUT(PRFC(IK))+CDUT(PWTFC))/2.
     FLRT(IL)=(AVD*(WC(IK)-WTFC)/57.5+AVC)/INT
 991 CONTINUE
  20 DO 30 I=2,IK
     AVD=(DIFN(PRFC(I-1))+DIFN(PRFC(I)))/2.
     AVC=(CDUT(PRFC(I-1))+CDUT(PRFC(I)))/2.
  30 FLRT(I)=(AVD*(WC(I-1)-WC(I))/15.+AVC)/INT
     IF(IWH.NE.1) GO TO 70
     IF ((PREC+HEAD/IHEAD).GT.3.) GO TO 60
     RUNOFF=0.
     GO TO 70
  60 RUNOFF=0.344*(PREC+HEAD/IHEAD)-0.344
  70 FLRT(1)=(PREC-RUNOFF+HEAD/IHEAD*INT) /INT
     ETL(1)=ETL(1)+PEV
     DO 400 I=1,IK
     SOILM(I)=OSM(I)+FLRT(I)-FLRT(I+1)-ETL(I)/INT
     WC(I)=SOILM(I)/15.
     IF(WC(I).LE.WCFC(I)) GO TO 90
     FLRT (I+1)=FLRT(I+1)+(WC(I)-WCFC(I))*15.
     WC(I)=WCFC(I)
     SOILM(I)=15.*WC(I)
  90 IF(WC(I).GE.WILT(I)) GO TO 400
     SOILM(I)=SOILM(I)+ETL(I)/INT
     IF(I.LT.IK) ETL(I+1)=ETL(I+1)+ETL(I)
     ETL(I)=0.
     WC(I)=SOILM(I)/15.
     IF(WC(I).GE.WILT(I)) GO TO 400
     FLRT(I+1)=FLRT(I+1)-(WILT(I)-WC(I))*15.
     WC(I)=WILT(I)
     SOILM(I)=15*WC(I)
 400 CONTINUE
     ETL(1)=ETL(1)-PEV
     GO TO 500
 101 OSM(1)=SOILM(1)
     SOILM(1)=OSM(1)+((PREC-PEV)/INT)
     WC(1)=SOILM(1)/15.
     IF(WC(1).LE.WCFC(1)) GO TO 700
     WC(1)=WCFC(1)
     SOILM(1)=15*WC(1)
 700 IF(WC(1).GE.WILT(1)) GO TO 500
     WC(1)=WILT(1)
     SOILM(1)=15*WC(1)
 500 CONTINUE
 300 RETURN
     END
C
C
C  SUBROUTINE SOIL NITRATE NITROGEN (WHEAT) - SNO3W.
C
C
C
      SUBROUTINE SNO3W(WC,FLRT,SOILM,IK,CNORT,FLRN,NTRT,DNTUP,FERT,
     * PLANT,HARVT,FERTIM,DNFM,NTRAT,INT,TDENIT,IBLT,SOLD)
      IMPLICIT REAL*4 (A-H,J-Z)
      COMMON /COMA/       ITEXT,YEAR,IESD,PHOTP,RDAY,IRFS,ICONST,ICNT,
     1 HEAD,IHEAD,T,WTFC,    F(10),WCFC(10),SR,TMAX,TMIN,TCPD,RZONE,
     2 PEV,TPEV,MSTF,TPAMSE
      COMMON /COMD/       CNORW,AOOM,MINR,OC1,OC2,OC3,
     * DENIT,DIF,DISP,NORN,TORT,WTSAT,WF(10)
      COMMON /COMK/       WCON(10),WCAP(10),PRFC(10)
      COMMON /COMR/   IPSTON,IDRAIN,INFR,IWTABL,IROF,ICSLOP,IREGIO,
```

```
     * TPORO(10),TWWPAS
      DIMENSION DNTUP(10),WC(10),FLRT(11),SOILM(10),CNORT(10),FLRN(11),
     * NTRT(10),DFL(11),MFL(11),NFLRN(10)
      IK=MIN1(10.,SOLD/15.)
      IF(TCPD.LT.1.) GO TO 700
      FLRN(1)=FLRT(1)*NORN
      DO 20 I=2,IK
      DFL(I)=(DISP*ABS(FLRT(I))+DIF*TORT*0.5*(WC(I-1)+WC(I))/INT)
     *    *(CNORT(I-1)-CNORT(I))/15.
      IF(FLRT(I).LE.0.) MFL(I)=FLRT(I)*CNORT(I)*WF(I)
      IF(FLRT(I).GT.0.) MFL(I)=FLRT(I)*CNORT(I-1)*WF(I)
   20 FLRN(I)=MFL(I)+DFL(I)
      IL=IK+1
      IF(IBLT.EQ.0..AND.IWTABL.GT.15.) GO TO 880
      IF(IBLT.EQ.1.) GO TO 870
      GO TO 887
  870 CONTINUE
      FLRN(IL)=0.
      GO TO 888
  880 CONTINUE
      CNORW=CNORT(IK)/4
  887 CONTINUE
      DFL(IL)=(DISP*ABS(FLRT(IL))+DIF*TORT*0.5*(WC(IK)+WTFC)/INT)
     *    *(CNORT(IK)-CNORW)/57.5
      IF(FLRT(IL).LE.0.) MFL(IL)=0.
      IF(FLRT(IL).GT.0.) MFL(IL)=FLRT(IL)*CNORT(IK)
      FLRN(IL)=MFL(IL)+DFL(IL)
  888 CONTINUE
      DO 80 I=1,IK
      NFLRN(I)=FLRN(I)-FLRN(I+1)
      NTRT(I)=NTRT(I)+NFLRN(I)-DNTUP(I)/INT
      IF(NTRT(I).GE.0.) GO TO 80
      FLRN(I+1)=FLRN(I+1)+NTRT(I)
      NTRT(I)=0.
   80 CONTINUE
  700 CONTINUE
      IF(NTRAT.GE.FERT) GO TO 90
      DNFM=0.005
      IF(T.LT.(FERTIM+45)) DNFM=FERT*0.0002
      NTRAT=NTRAT+DNFM*100/INT
      NTRT(1)=NTRT(1)+DNFM/INT
      IF(TCPD.LT.1.1) GO TO 101
   90 DO 100 I=1,2
      IF(WC(I).LT.WCFC(I)) GO TO 100
      DENT=AMIN1(DENIT,NTRT(I))
      NTRT(I)=NTRT(I)-DENT/INT
      TDENIT=TDENIT+DENT/INT
  100 CONTINUE
  101 IF(TCPD.GT.5.) GO TO 120
  122 CONTINUE
      NTRT(1)=NTRT(1)+MINR/INT
      NTRT(2)=NTRT(2)+MINR/INT
      GO TO 130
  120 NTRT(1)=NTRT(1)+0.0008/INT
      NTRT(2)=NTRT(2)+0.0008/INT
  130 DO 140 I=1,IK
  140 CNORT(I)=NTRT(I)/SOILM(I)
      RETURN
      END
C
C
C   SUBROUTINE PHENOLOGICAL DEVELOPMENT (WHEAT) - SPDW.
C
C
```

```
C
      SUBROUTINE SPDW(PLANT,IBMTS,DT,EME,OIN,HAD,SDO,MAT)
      IMPLICIT REAL*4 (A-H,J-Z)
      COMMON /COMA/       ITEXT,YEAR,IESD,PHOTP,RDAY,IRFS,ICONST,ICNT,
     1 HEAD,IHEAD,T,WTFC,    F(10),WCFC(10),SR,TMAX,TMIN,TCPD,RZONE,
     2 PEV,TPEV,MSTF,TPAMSE
      COMMON /COMC/       PREC,RUNOFF,
     * XX(10),DY(10),KY(10),OPTXX(7),OPTYX(7),WILT(10)
      COMMON /COMN/  ILTCPD,ITCPDX,PA0(5),PA1(5),PA2(5),PB0(5),PB1(5),
     * PB2(5),PB3(5),PB4(5),DC(10),KC(10),DL(10),KL(10),DS(10),KS(10)
      ILTCPD=TCPD*100
      FTMAX=TMAX*1.8+32
      FTMIN=TMIN*1.8+32
      IF(IBMTS.GT.1) GO TO 100
      FUN1=1.
      GO TO 200
  100 FUN1=(PA1(IBMTS)*(PHOTP-PA0(IBMTS)))+
     * (PA2(IBMTS)*((PHOTP-PA0(IBMTS))**2))
      IF(FUN1.LT.0.) FUN1=0.
  200 FUN2=(PB1(IBMTS)*(FTMAX-PB0(IBMTS)))+
     * (PB2(IBMTS)*((FTMAX-PB0(IBMTS))**2))
      IF(FUN2.LT.0.) FUN2=0.
      FUN3=(PB3(IBMTS)*(FTMIN-PB0(IBMTS)))+
     * (PB4(IBMTS)*((FTMIN-PB0(IBMTS))**2))
      IF (FUN3.LT.0.) FUN3=0.
      CDT=FUN1*(FUN2+FUN3)
      DT=DT+CDT
      TCPD=IBMTS+DT-1
      IF(DT.LT.1.) GO TO 1000
      DT=0.0
      IBMTS=IBMTS+1
      IF(IBMTS.EQ.6) GO TO 900
      IF(IBMTS.EQ.5) GO TO 800
      IF(IBMTS.EQ.4) GO TO 700
      IF(IBMTS.EQ.3) GO TO 600
      IF(EME.GT.0.) GO TO 1000
      EME=RDAY
      GO TO 1000
  600 IF(OIN.GT.0.) GO TO 1000
      OIN=RDAY
      GO TO 1000
  700 IF (HAD.GT.0.) GO TO 1000
      HAD=RDAY
      GO TO 1000
  800 IF(SDO.GT.0.) GO TO 1000
      SDO=RDAY
      GO TO 1000
  900 IF(MAT.GT.0.) GO TO 1000
      MAT=RDAY
 1000 CONTINUE
      RETURN
      END
C
C
C  SUBROUTINE SOIL TEMPERATURE - SSTEMP.
C
C
C
      SUBROUTINE SSTEMP(THIKN,SOILT)
      IMPLICIT REAL*4 (A-H,J-Z)
      COMMON /COMA/       ITEXT,YEAR,IESD,PHOTP,RDAY,IRFS,ICONST,ICNT,
     1 HEAD,IHEAD,T,WTFC,    F(10),WCFC(10),SR,TMAX,TMIN,TCPD,RZONE,
     2 PEV,TPEV,MSTF,TPAMSE
      DIMENSION THIKN(6),SOILT(6)
```

```
      CTMEAN=(TMAX+TMIN)/2
      TDEPTH=0
      DO 50 I=1,6
      MTDEPT=TDEPTH+(THIKN(I)/2)
      EMPQ=(MTDEPT/6)-.25
      IF(EMPQ.GT.0.) GO TO 20
      IF((I-1).GE.1) GO TO 10
      SOILT(1)=CTMEAN
      GO TO 40
   10 SOILT(I)=SOILT(I-1)
      GO TO 40
   20 IF((I-1).GE.1) GO TO 30
      SOILT(I)=((EMPQ*SOILT(I))+CTMEAN)/(EMPQ+1.)
      GO TO 40
   30 SOILT(I)=((EMPQ*SOILT(I))+SOILT(I-1))/(EMPQ+1.)
   40 TDEPTH=TDEPTH+THIKN(I)
   50 CONTINUE
      RETURN
      END
C
C
C  SUBROUTINE CROP GROWTH (WHEAT) - SCGRW.
C
C
C
      SUBROUTINE SCGRW(PLANT,NITUP,PLGR,PLGRM,SOILT,
     1 PAM,ETL,IK,DNTUP,CNORT,OPTX,OPTY,IWH,WC,WILT,IXR,AVBD,
     2 ILTCPD,ITCPDX,SOLDX)
      IMPLICIT REAL*4 (A-H,J-Z)
      INTEGER MAX1
      COMMON /COMA/       ITEXT,YEAR,IESD,PHOTP,RDAY,IRFS,ICONST,ICNT,
     1 HEAD,IHEAD,T,WTFC,    F(10),WCFC(10),SR,TMAX,TMIN,TCPD,RZONE,
     2 PEV,TPEV,MSTF,TPAMSE
      COMMON /COMP/    TOTPE,TOTT,TEVT,TETL(10),LMNM,TEWSMR,
     * PET,ET,LMW,LMN,LMT,LM,PGR,GRM,GR,PAMCRZ,TPREC,EWSMR,LASTR
      COMMON /COMR/    IPSTON,IDRAIN,INFR,IWTABL,IROF,ICSLOP,IREGIO,
     * TPORO(10),TWWPAS
      DIMENSION WC(10),ETL(10),DNTUP(10),CNORT(10),OPTX(7),OPTY(7),
     * WILT(10),SOILT(6)
      IF(TCPD.LE.1.) GO TO 100
      RZONE=3.0+(147./(1.0+EXP(5.-(8.*(TCPD/3.5)))))
      RZONE=RZONE+7.5
      IXR=AMIN0(MAX1(RZONE,15.)/15,10,IK)
      W=0.
      WX=0.
      IXRW=MIN0(IXR,IK)
      DO 10 I=1,IXRW
      WX=WX+WCFC(I)-WILT(I)
   10 W=W+WC(I)-WILT(I)
      PAM=W/WX
      PAMCRZ=PAM
      LMW=1-EXP(-3.*PAM)
      DO 20 I=1,IK
      DNTUP(I)=ETL(I)*CNORT(I)
   20 NITUP=NITUP+DNTUP(I)
      OPNIT=AFGEN(OPTX,OPTY, 7,TCPD)
      R=AMIN1(100.*NITUP/PLGR,OPNIT)
      LMN=EXP(-(OPNIT-R)**2/(0.75*OPNIT)**2)
      RM=AMIN1(100.*NITUP/PLGRM,OPNIT)
      LMNM=EXP(-(OPNIT-RM)**2/(0.75*OPNIT)**2)
      SOILK=SOILT(6)+273
      LMT=EXP(-((1.02721**SOILK)*((288-SOILK)/SOILK)**2))
      IF(SOILK.LE.291.) GO TO 951
      LMT=0.74
```

```
951 CONTINUE
    LM=AMIN1(LMT,LMW,LMN)
    TPAMSE=AMIN1(LMT,LMW,LMNM,MSTF)
    CRFTX=1.058504834
    ITCPDX=TCPD*100
    MDMP=1000*ICONST
    ILTCPD=ILTCPD+1
    PGR=0.
    IF(ITCPDX.GT.ILTCPD) GO TO 900
    ILTCPD=ITCPDX-3
900 CONTINUE
    DO 950 I=ILTCPD,ITCPDX
    FGR=(CRFTX*((1/((SQRT(2*3.14159265))*106.0132422))*
   * EXP(-((I-273.1949148)**2)/(2*106.0132422**2))))*MDMP
950 PGR=PGR+FGR
    GR=LM*PGR
    GRM=TPAMSE*PGR
    PLGR=PLGR+GR
    PLGRM=PLGRM+GRM
100 CONTINUE
    RETURN
    END
```

```
C SUPPORTING SUBROUTINS:
C
C
C INTERPOLATION SUBROUTINE - AFGEN.
C
C
C
      FUNCTION AFGEN(ARG,FUNC,IDIM,X)
      IMPLICIT REAL*4 (A-H,J-Z)
      DIMENSION ARG(IDIM),FUNC(IDIM)
      DO 10 I=1,IDIM
      IF(ARG(I).GE.X) GO TO 20
   10 CONTINUE
   35 AFGEN=FUNC(IDIM)
      RETURN
   20 IF(I.EQ.1.) GO TO 45
      J=I-1
      AFGEN=FUNC(J)+(FUNC(I)-FUNC(J))/(ARG(I)-ARG(J))*(X-ARG(J))
      RETURN
   45 AFGEN=FUNC(1)
      RETURN
      END
C
C
C PLOTTING SUBROUTINE - PLOT.
C
C
C
      SUBROUTINE PLOT(NO,M)
      COMMON /COMI/      A(8030),N
      DIMENSION YM(2),YPR(11),JP(10)
      DATA YM/10000.,150./
      INTEGER*4 ANG(9)/'*123','4567','89  ','/,BL','ANK/','    ',
     *                 '/,OV','ER/ ','+   '/
      LOGICAL*1 OUT(101)/ 101 * ' ' /
      INTEGER*4 HEAD(5,2)/'WHEA','T GR','OWTH','(KG/','HA) ','N-UP',
     *                    'TAKE',' (KG','/HA)','    '/
      WRITE(6,200)NO
  200 FORMAT(1H1,60X,7H CHART ,I3,//)
      WRITE(6,300)(HEAD(I,NO),I=1,20)
  300 FORMAT(57X,20A1,/)
      YMIN=0.0
      YMAX=YM(NO)
      YSCAL=(YMAX-YMIN)/100.0
      YPR(1)=YMIN
      DO 20 I=1,9
   20 YPR(I+1)=YPR(I)+YSCAL*10.0
      YPR(11)=YMAX
      WRITE(6,400)(YPR(I),I=1,11)
  400 FORMAT(9X,11F10.2)
      WRITE(6,500)
  500 FORMAT(16X,10('.',9X),'.')
      MY=M-1
      DO 50 L=1,N
      DO 30 I=1,MY
      LL=L+I*N
      IF(A(LL).GT.YMAX) GO TO 25
      JP(I)=((A(LL)-YMIN)/YSCAL)+1.0
      OUT(JP(I))=ANG(I)
      GO TO 30
   25 JP(I)=101.
      OUT(101)=OVER
   30 CONTINUE
      LL=A(L)
```

```
      WRITE(6,600) (OUT(I),I=1,101)
  600 FORMAT(16X,101A1)
      DO 40 I=1,MY
   40 OUT(JP(I))=BLANK
   50 CONTINUE
      WRITE(6,500)
      WRITE(6,400)(YPR(I),I=1,11)
      RETURN
      END
C
C
C
C JCL2
C
//GO.FT11F001 DD DSN=ONOFREI.WEATHER.DATA,DISP=SHR               F=JCL2
//GO.FT12F001 DD SPACE=(TRK,(6,6)),UNIT=SYSDA,
//   DCB=(RECFM=FB,LRECL=103,BLKSIZE=1030)
//GO.SYSIN DD *
```

Appendix D

Example of Driving, Soil, Management Input Data,

- DSMF for Winnipeg Site, 1982

```
C  DRIVING PARAMETERS, SOIL AND MANAGEMENT DATA ; FILE - DSMF.
C
C
HEAD SITE/YEAR OF SIMULATION - WINNIPEG(U. OF M.) / 1982
SDPV   2    2 1831952 1200.351 20 0 1 2 0 1 2 8 1 21018 0 0 39999 2 2 1 1 1
NPPM 48.6 49.6 46.0 36.0 30.6 30.6 28.2 28.2 27.5 27.5
FMBD 0.85 0.89 0.99 0.99 1.10 1.10 1.16 1.16 1.16 1.16
MPLR  7.5 22.5 37.5 52.5 67.5 82.5 97.5112.5
MADT 2 23858 1 13959 1 13958 1 13958 1 14058
DMAD 1 14058 1 14553 1 14553 0 0 0 0 0 0 0 0
DADT  4.6  2.0  1.3  1.3  0.9  0.9  0.7  0.7  0.0  0.0
WACT 0.32 0.35 0.38 0.38 0.40 0.40 0.37 0.37 0.37 0.37
MFFC 0.35 0.37 0.41 0.41 0.38 0.38 0.38 0.38 0.38 0.38
MWLT 0.26 0.23 0.24 0.24 0.27 0.27 0.23 0.23 0.23 0.23
SMNC 0.3996 0.5026 0.5461 0.5461 0.4968 0.4968 0.4978 0.4978 0.4855 0.4855
LTHN  1  1  2  3  2  5  5 10  5 15  5 20
AREA  64 1.0 132.0 146.0 166.0 189.0 222.0 236.0
CWHT 132 2361 132  32
C
C
```

The first line "HEAD" contains general information for the trail test site and the year of simulation. When the simulation is run for practical application the site location is substituted with the appropriate soil type or soil series name and the year or range of years for which the simulation is performed. The user can develop any desired heading (RECL = 80, A4) suited to his purpose.

The second line "SDPV", a special line required by the model, contains 29 hetrerogenous variables.They are presented in detail below:

1. Plotting time interval, F 4.0. It may take any value > 1. Because the particular value of a variable for a given day is plotted and not the average over the interval, the value = 1 or 2 is suggested.
2. Printing time interval, F 4.0. The comment made for first variable holds true here.
3. Number of days the program is required to be run, I4. The model was run over the growing season employing a 183 day growing period from March 31 to October 1. This assumes that within the prairie region that the growing season for wheat will always fall within this period. Potential users can chose any desired length including a full year. In tis case new appropriate sub-routines must be added to the model.
4. The year of simulation or the 1st year of simulation, if more than 1 year is run. This variable is not mandatory if the weather file contains this variable, in which case the variable becomes a dummy variable.
5. Depth of the profile in cm, F 4.0. A limiting layer or boundary such as bed rock, water table,Bnt horizon may be present within a particular soil profile If no such limiting layer is present or information is not available a dummy variable, 120,is used.
6. Harvest index, F 4.0. For model testing with respect to the impact of soil an actual value is used. For practical simulation pruposes Hi was assumed to be standard, 0.350. For our purpose of land evaluation we assume that only a variety of wheat is used, therefore the Hi which is mainly genetically controlled can be considered constant. However, the user can chose any value, standard, or nonstandard, whichever best fits his particular data set.
7. Integration interval, I2. Some of the functional subroutines, especially those related with water balance, i.e. water flow, require several iterations per day in order to avoid instability of solution. Default value is 2.
8. Weather information format, I2. The weather file is structured in a special format and will be described later. The user can keep the same structure of the weather file in which case this

variable must be declared 0 or he can change it to any suitable format, in which case, this variable must be declared 1. Obviously, if the weather format is changed, the main program must be slightly changed to accommodate this.

9. Number of variables required to be printed, I2. The maximum value is 14 variables. Use of this capability of the program is convenient for a relatively small number of variables. For testing purposes a larger set of variables were carefully monitored. By setting this variable to 0 and using a WRITE statement within the main program any desired variable value can be printed.
10. First variable number that will be stored in an array and latter printed, I2.
11. Second variable number that will be stored in an array for latter printing, I2.
12. The number of variables to be plotted, I2. A maximum of 14 variables. Default 0.
13. First variable number to be plotted, I2.
14. Second variable number to be plotted, I2. The number of variables to be printed and plotted is given as an example. In our test runs we did not use the main frame capability for plotting, therefore, its value was set to 0.
15. Number of layers for which soil physical properties are given in the datacards that follow. Usually the description of soil profiles is made either by employing standard incremental layers or by natural horizons. Soil parameter prediction (SCPARA) and the interpolation subroutines convert input data into the format required by the model.
16. Surface textural class, I2. A code for surface texture in order to select an appropriate set of hydraulic properties. The codes are as follows:
    1 - clay
    2 - loam
    3 - sand
17. Dummy variables for estimating seeding date, I2. Both for testing the model as well as for real simulation purposes for crops, the seeding date is usually known. In this circumstance this variable takes a value of 1. However, if the model is to be applied for simulation of crop productivity in regions that at the present time are not cultivated but which may have some potential for agriculture the seeding date must be predicted. For such applications this variable is declared to be 0 and the program will estimate seeding date.
18. Simulation type, I2. This variable takes values based on the assumptions used in simulation. More details relative to this are given in chapter III.
    However the variable takes the value of 10 when soil parameters are known (Sc.I) and 7 when such parameters must by predicted from available, standard Soil Survey data from fundamental soil properties (Sc.II).
19. Agronomical ceiling for aboveground net production, I2.
20. The presence or absence of a boundary or limiting layer, I2. It takes the value of 1 present, 0 for absent boundary.
21. Gravimetric percent stones within the profile, I2. It takes the values:
    - for value between 1 and 99 - the approximated value
    - absent or unknown - 0
22. Drainage class, I2. Three major classes are recognized:
    poor - 1,
    imperfect - 2,
    well - 3.
23. Infiltration rate (cm/day), I2.
    for value < 3 cm/day - the approximate value,
    for value > 3 cm/day - 99,

unknown - 98.

24. The water table depth (cm), I2. The following values are employed:
    < 150 cm - the approximated value,
    > 150 cm - 99,
    unknown - 98.
25. Incoming runoff, I2. This variable identifys if the area of interest can be regarded as partial discharging area. This variable takes the following values:
    yes - 1
    no - 2
    unknown - 3
26. Slope class of microdepressions, I2. This variable approximates class slope for a large region so that more than one soil type can be identified within such a region. At the present time the program uses the value 1 for slope class 0.5 < 2.5,the value of 2 for slope class 2.5 to < 5.0.
27. A code number to indicate 2 parameters regarding the shape and frequency of microdepressions within a section, characteristic to a region, I2. This variable takes the following value:
    for slope lengths between 60-80 m and frequency = 7 the value is 1.
    for slope lengths between 81-100 and frequency = 4 the value is 2.

    Variables 26 and 27 were established for simulation in regions where microdepressions were a significant feature of the landscape.
28. Crop district number up to 1976.
29. Crop district number after 1976.

    These two variables permit the reading of appropriate seeding dates for the past years which are given in matrix format in BLOCKDATA by year and crop district. Obviously, users must provide their own data for seeding date arranged by crop district or other criteria.

- The third line "NPPM" contains nitrate concentration data by layer (ppm), F 5.0. These values may be either measured or approximated by soil series, soil type, or region.
- The fourth line "FMBD" contains field measured bulk density by layer, F 5.0.
- The fifth line "MPLR" contains the middle point layer data for which particle size distribution is provided, F 5.0. The number of midlayers must match variable 15 from SDPV.
- The sixth line "MADT" contains particle size distribution data for the first five in percent, F 2.0, by soil (very fine sand, fine sand, silt ,loam) and by layer.
- The seventh line "DMAD" contains particle size distribution data for the last layers, F 2.0, and has a similar structure with preceding lines.
- The eighth line "DADT" contains organic carbon content data in percent by layer, F 5.0.
- The ninth line "NACT" contains volumetric water data at seeding time, F 5.0.
- The tenth line "MFFC" contains volumetric field measured FC by layer , F 5.0.
- The eleventh line "MWLT" contains volumetric wilting point data by layer, F 5.0.
- The twelfth line "SMNC" contains a computed standard value for nitrate concentration by layer (mg N/cc soil solution) that is weighted by using observed soil moisture content at seeding time, F 5.0.
- The thirteenth line "LTHN" contains a standard matrix (6,2) for soli layer (number,depth) used to simulate soil temperature. F3.0.
- The fourteenth line "AREA" contains two dummy variables (area in ha, and % from area of interest), 2 F 4.0. These two variables are not

used in the model at the present time but they become useful if a weighting method is required to accommodate simulation for small scale map (1/125.000 or 1/500.00) applications.

- The fifth line "CWHT" contains five management elements as follow:
  1 - seeding date (Julian day)
  2 - harvest date
  3 - number of fertilization
  4 - day of applying the fertilizer
  5 - amount of fertilizer used.

All the variables are in F 4.0 format. The amount of nitrogen fertilizer used is in kg/ha.

Not all the data-lines are required for a specific run (scenario). For example if the variable data-lines 4, 9, 10, and 11 are known then variable 18 within SDPV is set to 10 and the variables of data-lines 5,6 and 7 are not required. The reverse situation holds true, in which case variable 18 within SDPV must be set to 7. However, the structure of the soil management data-lines file must be kept complete.

Appendix E

Example of Daily Weather Input Data File

- WEATHER for Winnipeg Site, 1982

```
C DAILY WEATHER VARIABLES ;FILE - WEATHER.
C
C
WINNIPE 5023222 -82  91        -1 -10   6694 128
WINNIPE 5023222 -82  92        -2 -13   6766 129
WINNIPE 5023222 -82  93       -10 -16   6837 130
WINNIPE 5023222 -82  94        -7 -19   6909 131
WINNIPE 5023222 -82  95        -6 -15   6980 132
WINNIPE 5023222 -82  96        -3 -14   7051 132
WINNIPE 5023222 -82  97         2  -9   7121 133
WINNIPE 5023222 -82  98         3  -4   7191 133
WINNIPE 5023222 -82  99         4  -5   7261 134
WINNIPE 5023222 -82 100         0  -7   7330 135
WINNIPE 5023222 -82 101         8  -5   7399 135
WINNIPE 5023222 -82 102    2   12   0   7467 136
WINNIPE 5023222 -82 103         7  -3   7535 136
WINNIPE 5023222 -82 104        18   2   7602 137
WINNIPE 5023222 -82 105   26   17   6   7669 138
WINNIPE 5023222 -82 106         8  -2   7735 138
WINNIPE 5023222 -82 107    4    9  -5   7801 139
WINNIPE 5023222 -82 108    4   11  -1   7867 139
WINNIPE 5023222 -82 109         7  -4   7931 140
WINNIPE 5023222 -82 110        11  -6   7996 141
WINNIPE 5023222 -82 111        12  -2   8059 141
WINNIPE 5023222 -82 112        23   3   8122 142
WINNIPE 5023222 -82 113        26   7   8184 142
WINNIPE 5023222 -82 114        29   7   8235 143
WINNIPE 5023222 -82 115         9  -3   8296 144
WINNIPE 5023222 -82 116        13  -4   8356 144
WINNIPE 5023222 -82 117        19   0   8415 145
WINNIPE 5023222 -82 118        20   3   8474 145
WINNIPE 5023222 -82 119    8   15   5   8532 146
WINNIPE 5023222 -82 120        19   3   8589 146
WINNIPE 5023222 -82 121        23   3   8646 147
WINNIPE 5023222 -82 122        28  11   8701 147
WINNIPE 5023222 -82 123        28  15   8756 147
WINNIPE 5023222 -82 124        22   9   8810 148
WINNIPE 5023222 -82 125        19   4   8864 148
WINNIPE 5023222 -82 126        13  -1   8916 149
WINNIPE 5023222 -82 127         8  -3   8967 150
WINNIPE 5023222 -82 128         9  -5   9018 150
WINNIPE 5023222 -82 129        12   3   9068 151
WINNIPE 5023222 -82 130        10   7   9117 151
WINNIPE 5023222 -82 131        18   5   9165 152
WINNIPE 5023222 -82 132        20   5   9212 152
WINNIPE 5023222 -82 133        20   9   9258 153
WINNIPE 5023222 -82 134        20   8   9303 153
WINNIPE 5023222 -82 135   38   14   9   9347 154
WINNIPE 5023222 -82 136   20   15  11   9390 154
WINNIPE 5023222 -82 137   15   18  11   9432 155
WINNIPE 5023222 -82 138        16  11   9473 155
WINNIPE 5023222 -82 139        17   7   9513 155
WINNIPE 5023222 -82 140        20   4   9552 156
WINNIPE 5023222 -82 141        22   5   9590 156
WINNIPE 5023222 -82 142        24   5   9627 157
WINNIPE 5023222 -82 143        26  10   9663 157
WINNIPE 5023222 -82 144        23  13   9698 158
WINNIPE 5023222 -82 145        28   9   9731 158
WINNIPE 5023222 -82 146        27  13   9764 158
WINNIPE 5023222 -82 147        29  12   9765 159
WINNIPE 5023222 -82 148        31  13   9825 159
WINNIPE 5023222 -82 149        22  10   9855 159
WINNIPE 5023222 -82 150        15   6   9882 160
WINNIPE 5023222 -82 151   18   12   5   9902 160
```

WINNIPE	5023222	-82	152		14	2	9935	160
WINNIPE	5023222	-82	153		18	-1	9959	161
WINNIPE	5023222	-82	154		26	4	9982	161
WINNIPE	5023222	-82	155		25	10	10004	161
WINNIPE	5023222	-82	156		23	14	10025	161
WINNIPE	5023222	-82	157	147	16	11	10045	162
WINNIPE	5023222	-82	158	254	14	3	10063	162
WINNIPE	5023222	-82	159		11	1	10070	162
WINNIPE	5023222	-82	160	20	16	7	10085	162
WINNIPE	5023222	-82	161		24	4	10100	163
WINNIPE	5023222	-82	162		18	7	10113	163
WINNIPE	5023222	-82	163		24	4	10125	163
WINNIPE	5023222	-82	164		24	8	10136	163
WINNIPE	5023222	-82	165		21	8	10145	163
WINNIPE	5023222	-82	166		20	4	10154	163
WINNIPE	5023222	-82	167	36	24	10	10161	163
WINNIPE	5023222	-82	168		16	4	10166	163
WINNIPE	5023222	-82	169		18	9	10171	164
WINNIPE	5023222	-82	170	71	15	9	10174	164
WINNIPE	5023222	-82	171		22	9	10176	164
WINNIPE	5023222	-82	172		21	6	10177	164
WINNIPE	5023222	-82	173		23	5	10176	164
WINNIPE	5023222	-82	174		27	13	10174	164
WINNIPE	5023222	-82	175		20	6	10171	164
WINNIPE	5023222	-82	176		23	4	10167	164
WINNIPE	5023222	-82	177		26	11	10161	164
WINNIPE	5023222	-82	178		25	9	10154	163
WINNIPE	5023222	-82	179		22	8	10146	163
WINNIPE	5023222	-82	180		20	5	10136	163
WINNIPE	5023222	-82	181		24	4	10126	163
WINNIPE	5023222	-82	182		27	10	10114	163
WINNIPE	5023222	-82	183	254	23	17	10101	163
WINNIPE	5023222	-82	184		25	17	10086	163
WINNIPE	5023222	-82	185		31	17	10071	163
WINNIPE	5023222	-82	186	234	27	17	10054	162
WINNIPE	5023222	-82	187		25	14	10036	162
WINNIPE	5023222	-82	188		21	11	10027	162
WINNIPE	5023222	-82	189		24	11	10007	162
WINNIPE	5023222	-82	190		26	14	9985	162
WINNIPE	5023222	-82	191		27	14	9962	161
WINNIPE	5023222	-82	192		28	13	9938	161
WINNIPE	5023222	-82	193		30	14	9913	161
WINNIPE	5023222	-82	194	94	21	13	9887	160
WINNIPE	5023222	-82	195		26	8	9859	160
WINNIPE	5023222	-82	196		29	20	9831	160
WINNIPE	5023222	-82	197		29	16	9801	159
WINNIPE	5023222	-82	198	231	22	12	9770	159
WINNIPE	5023222	-82	199		22	10	9738	159
WINNIPE	5023222	-82	200		25	15	9705	158
WINNIPE	5023222	-82	201		28	16	9671	158
WINNIPE	5023222	-82	202		24	13	9636	158
WINNIPE	5023222	-82	203		23	12	9600	157
WINNIPE	5023222	-82	204		26	18	9563	157
WINNIPE	5023222	-82	205		26	19	9525	156
WINNIPE	5023222	-82	206		25	14	9486	156
WINNIPE	5023222	-82	207		28	11	9445	156
WINNIPE	5023222	-82	208	38	27	15	9404	155
WINNIPE	5023222	-82	209		28	14	9362	155
WINNIPE	5023222	-82	210	196	24	13	9319	154
WINNIPE	5023222	-82	211		26	14	9275	154
WINNIPE	5023222	-82	212		31	16	9231	153
WINNIPE	5023222	-82	213		22	10	9185	153
WINNIPE	5023222	-82	214	53	25	16	9138	152
WINNIPE	5023222	-82	215		29	16	9091	152

WINNIPE	5023222	-82	216		27	16	9042	151
WINNIPE	5023222	-82	217		28	11	8993	151
WINNIPE	5023222	-82	218		27	18	8943	150
WINNIPE	5023222	-82	219		26	15	8892	150
WINNIPE	5023222	-82	220	107	20	9	8841	149
WINNIPE	5023222	-82	221		19	7	8788	149
WINNIPE	5023222	-82	222		21	4	8735	148
WINNIPE	5023222	-82	223		24	8	8681	148
WINNIPE	5023222	-82	224		21	15	8626	147
WINNIPE	5023222	-82	225		27	14	8571	147
WINNIPE	5023222	-82	226	48	30	16	8515	146
WINNIPE	5023222	-82	227		24	14	8458	145
WINNIPE	5023222	-82	228		27	11	8400	145
WINNIPE	5023222	-82	229	353	29	12	8342	144
WINNIPE	5023222	-82	230		29	16	8283	144
WINNIPE	5023222	-82	231		26	13	8223	143
WINNIPE	5023222	-82	232		26	13	8163	143
WINNIPE	5023222	-82	233		24	13	8102	142
WINNIPE	5023222	-82	234		23	11	8052	142
WINNIPE	5023222	-82	235	46	22	8	7990	141
WINNIPE	5023222	-82	236		18	11	7927	140
WINNIPE	5023222	-82	237	5	14	4	7864	140
WINNIPE	5023222	-82	238		16	3	7800	139
WINNIPE	5023222	-82	239		14	1	7736	139
WINNIPE	5023222	-82	240		19	3	7672	138
WINNIPE	5023222	-82	241		19	6	7602	137
WINNIPE	5023222	-82	242		17	4	7541	137
WINNIPE	5023222	-82	243		23	11	7475	136
WINNIPE	5023222	-82	244	51	14	7	7408	136
WINNIPE	5023222	-82	245		20	9	7341	135
WINNIPE	5023222	-82	246		26	5	7274	134
WINNIPE	5023222	-82	247		24	9	7206	134
WINNIPE	5023222	-82	248		17	5	7138	133
WINNIPE	5023222	-82	249	89	13	4	7070	133
WINNIPE	5023222	-82	250		24	10	7001	132
WINNIPE	5023222	-82	251		30	17	6937	131
WINNIPE	5023222	-82	252		35	17	6863	131
WINNIPE	5023222	-82	253		31	17	6793	130
WINNIPE	5023222	-82	254		23	9	6723	130
WINNIPE	5023222	-82	255		19	7	6653	129
WINNIPE	5023222	-82	256		17	7	6583	128
WINNIPE	5023222	-82	257		11	-1	6512	128
WINNIPE	5023222	-82	258		14	-3	6442	127
WINNIPE	5023222	-82	259		20	2	6371	126
WINNIPE	5023222	-82	260		13	5	6300	126
WINNIPE	5023222	-82	261		23	7	6229	125
WINNIPE	5023222	-82	262		13	1	6157	125
WINNIPE	5023222	-82	263		16	0	6086	124
WINNIPE	5023222	-82	264		23	3	6014	123
WINNIPE	5023222	-82	265		25	7	5943	123
WINNIPE	5023222	-82	266		16	7	5871	122
WINNIPE	5023222	-82	267		15	0	5811	122
WINNIPE	5023222	-82	268		17	2	5740	121
WINNIPE	5023222	-82	269		16	8	5668	120
WINNIPE	5023222	-82	270	318	8	5	5597	120
WINNIPE	5023222	-82	271	119	15	5	5525	119
WINNIPE	5023222	-82	272		12	5	5454	118
WINNIPE	5023222	-82	273		8	0	5383	118

C
C
C

The file contains the following daily weather information:

1 - The AES station name (or plot location), 2A4, optional.
2 - The weather station number, I7, optional.

3 - Year (last two digits), F 2.0.
4 - Date (Julian day), F 4.0.
5 - Precipitation (tenths of millimeters), F 4.2.
6 - Maximum temperature (C), F 4.0.
7 - Minimum temperature (C), F 4.0.
8 - Solar readiation at the top of the atmosphere (cal/cm -day), F 6.4.
9 - Photoperiod (hr), F 4.1.

Appendix F

Statistical Analysis of Bulk Denisty

VARIABLE	N	MEAN	STANDARD DEVIATION	MINIMUM VALUE	MAXIMUM VALUE	STD ERROR OF MEAN	SUM	VARIANCE	C.V.
LOCATION=BAGOT LAYER=1									
BD	6	1.10	0.02	1.07	1.13	0.01	6.61	0.00	2.10
LOCATION=BAGOT LAYER=2									
BD	6	1.25	0.02	1.23	1.27	0.01	7.50	0.00	1.52
LOCATION=BAGOT LAYER=3									
BD	6	1.35	0.04	1.30	1.40	0.02	8.10	0.00	3.11
LOCATION=BAGOT LAYER=4									
BD	6	1.44	0.03	1.40	1.48	0.01	8.64	0.00	1.81
LOCATION=BAGOT LAYER=5									
BD	6	1.51	0.03	1.46	1.54	0.01	9.06	0.00	2.01
LOCATION=BEAUSEJOUR LAYER=1									
BD	6	0.84	0.08	0.75	0.97	0.03	5.07	0.01	9.64
LOCATION=BEAUSEJOUR LAYER=2									
BD	6	1.28	0.11	1.17	1.48	0.04	7.70	0.01	8.20
LOCATION=BEAUSEJOUR LAYER=3									
BD	6	1.45	0.12	1.30	1.61	0.05	8.73	0.01	7.94
LOCATION=BEAUSEJOUR LAYER=4									
BD	6	1.55	0.13	1.35	1.74	0.05	9.30	0.02	8.58
LOCATION=BEAUSEJOUR LAYER=5									
BD	6	1.39	0.22	1.10	1.69	0.09	8.34	0.05	16.02
LOCATION=DAUPHIN LAYER=1									
BD	6	0.60	0.05	0.55	0.66	0.02	3.61	0.00	7.54

VARIABLE	N	MEAN	STANDARD DEVIATION	MINIMUM VALUE	MAXIMUM VALUE	STD ERROR OF MEAN	SUM	VARIANCE	C.V.
LOCATION=DAUPHIN LAYER=2									
BD	6	0.88	0.05	0.82	0.93	0.02	5.26	0.00	5.29
LOCATION=DAUPHIN LAYER=3									
BD	6	0.70	0.03	0.66	0.74	0.01	4.22	0.00	4.47
LOCATION=DAUPHIN LAYER=4									
BD	6	0.84	0.08	0.74	0.92	0.03	5.03	0.01	9.19
LOCATION=DAUPHIN LAYER=5									
BD	6	1.11	0.08	1.01	1.20	0.03	6.65	0.01	7.16
LOCATION=DURBAN LAYER=1									
BD	6	0.96	0.04	0.91	1.02	0.02	5.76	0.00	4.22
LOCATION=DURBAN LAYER=2									
BD	6	1.34	0.07	1.29	1.47	0.03	8.06	0.00	4.84
LOCATION=DURBAN LAYER=3									
BD	6	1.47	0.04	1.41	1.52	0.02	8.84	0.00	2.93
LOCATION=DURBAN LAYER=4									
BD	6	1.45	0.06	1.35	1.50	0.02	8.72	0.00	3.86
LOCATION=DURBAN LAYER=5									
BD	6	1.39	0.06	1.31	1.48	0.02	8.37	0.00	4.12
LOCATION=MARIAPOLIS LAYER=1									
BD	6	0.91	0.04	0.88	0.98	0.01	5.46	0.00	3.93
LOCATION=MARIAPOLIS LAYER=2									
BD	6	1.15	0.05	1.08	1.21	0.02	6.92	0.00	4.44
LOCATION=MARIAPOLIS LAYER=3									
BD	6	1.17	0.11	1.02	1.31	0.04	7.05	0.01	9.27

VARIABLE	N	MEAN	STANDARD DEVIATION	MINIMUM VALUE	MAXIMUM VALUE	STD ERROR OF MEAN	SUM	VARIANCE	C.V.
LOCATION=MARIAPOLIS LAYER=4									
BD	6	1.17	0.13	0.92	1.30	0.05	7.04	0.02	11.43
LOCATION=MARIAPOLIS LAYER=5									
BD	6	1.12	0.07	1.00	1.21	0.03	6.73	0.01	6.36
LOCATION=ROBLIN LAYER=1									
BD	6	0.73	0.14	0.58	0.90	0.06	4.39	0.02	18.47
LOCATION=ROBLIN LAYER=2									
BD	6	1.21	0.06	1.12	1.29	0.02	7.26	0.00	4.93
LOCATION=ROBLIN LAYER=3									
BD	6	1.29	0.07	1.20	1.37	0.03	7.76	0.00	5.14
LOCATION=ROBLIN LAYER=4									
BD	6	1.36	0.05	1.28	1.43	0.02	8.18	0.00	3.82
LOCATION=ROBLIN LAYER=5									
BD	6	1.54	0.04	1.49	1.60	0.02	9.25	0.00	2.58
LOCATION=SHOAL LAKE LAYER=1									
BD	6	0.94	0.13	0.71	1.05	0.05	5.66	0.02	13.34
LOCATION=SHOAL LAKE LAYER=2									
BD	6	1.43	0.09	1.31	1.54	0.04	8.56	0.01	6.09
LOCATION=SHOAL LAKE LAYER=3									
BD	6	1.56	0.06	1.50	1.66	0.03	9.39	0.00	4.12
LOCATION=SHOAL LAKE LAYER=4									
BD	6	1.66	0.16	1.51	1.91	0.06	9.98	0.02	9.39
LOCATION=SHOAL LAKE LAYER=5									
BD	6	1.80	0.19	1.61	2.12	0.08	10.80	0.04	10.69
LOCATION=SOURIS LAYER=1									

VARIABLE	N	MEAN	STANDARD DEVIATION	MINIMUM VALUE	MAXIMUM VALUE	STD ERROR OF MEAN	SUM	VARIANCE	C.V.
LOCATION=SOURIS LAYER=1									
BD	6	0.75	0.09	0.67	0.90	0.04	4.49	0.01	11.93
LOCATION=SOURIS LAYER=2									
BD	6	1.05	0.03	1.01	1.08	0.01	6.30	0.00	2.63
LOCATION=SOURIS LAYER=3									
BD	6	1.38	0.03	1.35	1.43	0.01	8.27	0.00	2.31
LOCATION=SOURIS LAYER=4									
BD	6	1.40	0.06	1.31	1.46	0.02	8.41	0.00	4.31
LOCATION=SOURIS LAYER=5									
BD	6	1.38	0.08	1.27	1.50	0.03	8.28	0.01	6.15
LOCATION=SWAN RIVER LAYER=1									
BD	6	0.78	0.07	0.69	0.91	0.03	4.66	0.01	9.41
LOCATION=SWAN RIVER LAYER=2									
BD	6	1.15	0.04	1.11	1.20	0.02	6.93	0.00	3.23
LOCATION=SWAN RIVER LAYER=3									
BD	6	1.21	0.06	1.10	1.27	0.03	7.29	0.00	5.22
LOCATION=SWAN RIVER LAYER=4									
BD	6	1.23	0.08	1.10	1.33	0.03	7.41	0.01	6.81
LOCATION=SWAN RIVER LAYER=5									
BD	6	1.26	0.06	1.19	1.34	0.02	7.59	0.00	4.71
LOCATION=TEULON LAYER=1									
BD	6	0.88	0.08	0.78	1.01	0.03	5.27	0.01	8.92

VARIABLE	N	MEAN	STANDARD DEVIATION	MINIMUM VALUE	MAXIMUM VALUE	STD ERROR OF MEAN	SUM	VARIANCE	C.V.
LOCATION=TEULON LAYER=2									
BD	6	1.32	0.04	1.25	1.36	0.02	7.93	0.00	3.36
LOCATION=TEULON LAYER=3									
BD	6	1.31	0.04	1.25	1.36	0.02	7.84	0.00	2.85
LOCATION=TEULON LAYER=4									
BD	6	1.36	0.02	1.33	1.38	0.01	8.14	0.00	1.20
LOCATION=TEULON LAYER=5									
BD	6	1.46	0.05	1.40	1.55	0.02	8.77	0.00	3.36
LOCATION=WINNIPEG LAYER=1									
BD	6	0.85	0.07	0.76	0.95	0.03	5.11	0.00	8.05
LOCATION=WINNIPEG LAYER=2									
BD	6	0.89	0.02	0.86	0.92	0.01	5.34	0.00	2.46
LOCATION=WINNIPEG LAYER=3									
BD	6	0.99	0.06	0.94	1.11	0.03	5.94	0.00	6.36
LOCATION=WINNIPEG LAYER=4									
BD	6	1.10	0.04	1.04	1.15	0.02	6.60	0.00	3.35
LOCATION=WINNIPEG LAYER=5									
BD	6	1.16	0.05	1.09	1.21	0.02	6.96	0.00	3.93
LOCATION=WOODMORE LAYER=1									
BD	6	1.28	0.04	1.21	1.35	0.02	7.69	0.00	3.47
LOCATION=WOODMORE LAYER=2									
BD	6	1.61	0.04	1.56	1.67	0.02	9.65	0.00	2.37

VARIABLE	N	MEAN	STANDARD DEVIATION	MINIMUM VALUE	MAXIMUM VALUE	STD ERROR OF MEAN	SUM	VARIANCE	C.V.
LOCATION=WOODMORE LAYER=3									
BD	6	1.59	0.06	1.52	1.67	0.02	9.55	0.00	3.50
LOCATION=WOODMORE LAYER=4									
BD	6	1.71	0.09	1.56	1.83	0.04	10.25	0.01	5.05
LOCATION=WOODMORE LAYER=5									
BD	6	1.69	0.08	1.62	1.85	0.03	10.14	0.01	5.01

Appendix G

Statistical Analysis of Gravimetric Field Capacity

C

VARIABLE	N	MEAN	STANDARD DEVIATION	MINIMUM VALUE	MAXIMUM VALUE	STD ERROR OF MEAN	SUM	VARIANCE	C.V.
LOCATION=BAGOT LAYER=1									
FC	6	0.18	0.01	0.16	0.20	0.01	1.10	0.00	7.35
LOCATION=BAGOT LAYER=2									
FC	6	0.17	0.01	0.15	0.19	0.01	0.91	0.00	9.38
LOCATION=BAGOT LAYER=3									
FC	6	0.17	0.01	0.15	0.18	0.01	0.79	0.00	11.32
LOCATION=BAGOT LAYER=4									
FC	6	0.24	0.01	0.21	0.25	0.00	0.82	0.00	8.15
LOCATION=BAGOT LAYER=5									
FC	6	0.26	0.01	0.21	0.27	0.00	0.73	0.00	8.22
LOCATION=BEAUSEJOUR LAYER=1									
FC	6	0.38	0.03	0.34	0.40	0.01	2.29	0.00	6.88
LOCATION=BEAUSEJOUR LAYER=2									
FC	6	0.29	0.01	0.28	0.31	0.01	1.74	0.00	4.44
LOCATION=BEAUSEJOUR LAYER=3									
FC	6	0.23	0.01	0.22	0.24	0.00	1.39	0.00	3.45
LOCATION=BEAUSEJOUR LAYER=4									
FC	6	0.26	0.01	0.24	0.28	0.01	1.54	0.00	5.67
LOCATION=BEAUSEJOUR LAYER=5									
FC	6	0.33	0.02	0.31	0.37	0.01	1.99	0.00	7.16
LOCATION=DAUPHIN LAYER=1									
FC	6	0.53	0.03	0.49	0.56	0.01	3.17	0.00	4.73

VARIABLE	N	MEAN	STANDARD DEVIATION	MINIMUM VALUE	MAXIMUM VALUE	STD ERROR OF MEAN	SUM	VARIANCE	C.V.
LOCATION=DAUPHIN LAYER=2									
FC	6	0.45	0.01	0.44	0.46	0.00	2.70	0.00	1.78
LOCATION=DAUPHIN LAYER=3									
FC	6	0.52	0.01	0.51	0.54	0.01	3.12	0.00	2.59
LOCATION=DAUPHIN LAYER=4									
FC	6	0.47	0.02	0.44	0.51	0.01	2.82	0.00	5.23
LOCATION=DAUPHIN LAYER=5									
FC	6	0.36	0.03	0.33	0.40	0.01	2.15	0.00	7.22
LOCATION=DURBAN LAYER=1									
FC	6	0.28	0.01	0.27	0.30	0.00	1.69	0.00	4.14
LOCATION=DURBAN LAYER=2									
FC	6	0.22	0.01	0.20	0.23	0.00	1.32	0.00	4.70
LOCATION=DURBAN LAYER=3									
FC	6	0.18	0.00	0.18	0.19	0.00	1.11	0.00	2.58
LOCATION=DURBAN LAYER=4									
FC	6	0.20	0.01	0.18	0.22	0.01	1.20	0.00	6.53
LOCATION=DURBAN LAYER=5									
FC	6	0.23	0.01	0.20	0.24	0.01	1.36	0.00	6.49
LOCATION=MARIAPOLIS LAYER=1									
FC	6	0.37	0.01	0.36	0.38	0.00	2.24	0.00	1.85
LOCATION=MARIAPOLIS LAYER=2									
FC	6	0.34	0.01	0.32	0.35	0.00	2.02	0.00	2.31

VARIABLE	N	MEAN	STANDARD DEVIATION	MINIMUM VALUE	MAXIMUM VALUE	STD ERROR OF MEAN	SUM	VARIANCE	C.V.
LOCATION=MARIAPOLIS LAYER=3									
FC	6	0.31	0.01	0.30	0.32	0.00	1.84	0.00	2.25
LOCATION=MARIAPOLIS LAYER=4									
FC	6	0.30	0.03	0.25	0.33	0.01	1.78	0.00	8.71
LOCATION=MARIAPOLIS LAYER=5									
FC	6	0.30	0.04	0.26	0.35	0.02	1.82	0.00	13.52
LOCATION=ROBLIN LAYER=1									
FC	6	0.36	0.03	0.33	0.39	0.01	2.18	0.00	8.09
LOCATION=ROBLIN LAYER=2									
FC	6	0.28	0.02	0.25	0.32	0.01	1.70	0.00	8.35
LOCATION=ROBLIN LAYER=3									
FC	6	0.24	0.01	0.23	0.25	0.00	1.45	0.00	2.44
LOCATION=ROBLIN LAYER=4									
FC	6	0.23	0.01	0.22	0.25	0.00	1.40	0.00	2.98
LOCATION=ROBLIN LAYER=5									
FC	6	0.22	0.01	0.20	0.22	0.00	1.29	0.00	3.31
LOCATION=SHOAL LAKE LAYER=1									
FC	6	0.32	0.01	0.30	0.33	0.00	1.89	0.00	3.51
LOCATION=SHOAL LAKE LAYER=2									
FC	6	0.24	0.02	0.21	0.27	0.01	1.43	0.00	10.11
LOCATION=SHOAL LAKE LAYER=3									
FC	6	0.19	0.03	0.15	0.21	0.01	1.14	0.00	13.25

VARIABLE	N	MEAN	STANDARD DEVIATION	MINIMUM VALUE	MAXIMUM VALUE	STD ERROR OF MEAN	SUM	VARIANCE	C.V.
LOCATION=SHOAL LAKE LAYER=4									
FC	6	0.21	0.01	0.18	0.22	0.01	1.25	0.00	7.16
LOCATION=SHOAL LAKE LAYER=5									
FC	6	0.19	0.01	0.19	0.20	0.00	1.16	0.00	3.76
LOCATION=SOURIS LAYER=1									
FC	6	0.36	0.01	0.35	0.37	0.00	2.15	0.00	2.89
LOCATION=SOURIS LAYER=2									
FC	6	0.23	0.01	0.21	0.33	0.00	1.92	0.00	2.31
LOCATION=SOURIS LAYER=3									
FC	6	0.20	0.02	0.18	0.30	0.01	1.61	0.00	6.96
LOCATION=SOURIS LAYER=4									
FC	6	0.20	0.02	0.17	0.22	0.01	1.60	0.00	8.17
LOCATION=SOURIS LAYER=5									
FC	6	0.22	0.01	0.21	0.24	0.01	1.80	0.00	4.15
LOCATION=SWAN RIVER LAYER=1									
FC	6	0.35	0.03	0.31	0.38	0.01	2.08	0.00	8.38
LOCATION=SWAN RIVER LAYER=2									
FC	6	0.26	0.01	0.25	0.26	0.00	1.54	0.00	2.20
LOCATION=SWAN RIVER LAYER=3									
FC	6	0.23	0.02	0.21	0.25	0.01	1.37	0.00	7.21
LOCATION=SWAN RIVER LAYER=4									
FC	6	0.21	0.02	0.19	0.23	0.01	1.27	0.00	10.23

VARIABLE	N	MEAN	STANDARD DEVIATION	MINIMUM VALUE	MAXIMUM VALUE	STD ERROR OF MEAN	SUM	VARIANCE	C.V.
LOCATION=SWAN RIVER LAYER=5									
FC	6	0.24	0.01	0.23	0.25	0.00	1.45	0.00	3.73
LOCATION=TEULON LAYER=1									
FC	6	0.33	0.01	0.32	0.34	0.00	2.00	0.00	3.36
LOCATION=TEULON LAYER=2									
FC	6	0.26	0.01	0.25	0.27	0.00	1.58	0.00	4.55
LOCATION=TEULON LAYER=3									
FC	6	0.24	0.01	0.23	0.25	0.00	1.44	0.00	2.37
LOCATION=TEULON LAYER=4									
FC	6	0.24	0.00	0.23	0.24	0.00	1.43	0.00	1.73
LOCATION=TEULON LAYER=5									
FC	6	0.24	0.01	0.23	0.25	0.01	1.46	0.00	5.24
LOCATION=WINNIPEG LAYER=1									
FC	6	0.41	0.01	0.40	0.43	0.00	2.49	0.00	2.32
LOCATION=WINNIPEG LAYER=2									
FC	6	0.41	0.02	0.40	0.45	0.01	2.48	0.00	4.98
LOCATION=WINNIPEG LAYER=3									
FC	6	0.38	0.01	0.37	0.39	0.00	2.28	0.00	1.57
LOCATION=WINNIPEG LAYER=4									
FC	6	0.35	0.01	0.33	0.36	0.00	2.08	0.00	3.09
LOCATION=WINNIPEG LAYER=5									
FC	6	0.33	0.01	0.32	0.34	0.00	1.97	0.00	2.28

VARIABLE	N	MEAN	STANDARD DEVIATION	MINIMUM VALUE	MAXIMUM VALUE	STD ERROR OF MEAN	SUM	VARIANCE	C.V.
LOCATION=WOODMORE LAYER=1									
FC	6	0.18	0.02	0.15	0.21	0.01	1.07	0.00	13.42
LOCATION=WOODMORE LAYER=2									
FC	6	0.13	0.00	0.13	0.14	0.00	0.81	0.00	3.23
LOCATION=WOODMORE LAYER=3									
FC	6	0.11	0.03	0.08	0.15	0.01	0.67	0.00	28.21
LOCATION=WOODMORE LAYER=4									
FC	6	0.14	0.04	0.11	0.19	0.02	0.86	0.00	26.76
LOCATION=WOODMORE LAYER=5									
FC	6	0.17	0.03	0.12	0.20	0.01	0.99	0.00	20.63

Appendix H

Statistical Analysis of Grain

C

VARIABLE	N	MEAN	STANDARD DEVIATION	MINIMUM VALUE	MAXIMUM VALUE	STD ERROR OF MEAN	SUM	VARIANCE	C.V.
LOCATION=BAGA HARV.DATE=01SEP82 GROWTH STAGE=MATU									
GRAIN	3	3404.533	482.579	2851.200	3738.200	278.617	10213.600	232882.333	14.175
C									
LOCATION=BEAU HARV.DATE=01SET82 GROWTH STAGE=MATU									
GRAIN	3	4324.267	684.533	3833.200	5106.200	395.215	12972.800	468584.813	15.830
C									
LOCATION=DAUP HARV.DATE=14SEP82 GROWTH STAGE=MATU									
GRAIN	3	4760.333	866.908	3841.000	5563.000	500.510	14281.000	751529.333	18.211
C									
LOCATION=MARI HARV.DATE=01SEP82 GROWTH STAGE=MATU									
GRAIN	3	4127.200	452.176	3856.200	4649.200	261.064	12381.600	204463.000	10.956
C									
LOCATION=ROBL HARV.DATE=13SEP82 GROWTH STAGE=MATU									
GRAIN	3	2199.533	143.820	2036.200	2307.200	83.035	6598.600	20684.333	6.539
C									
LOCATION=SWRI HARV.DATE=13SEP82 GROWTH STAGE=MATU									
GRAIN	3	3834.667	517.897	3488.000	4430.000	299.008	11504.000	268217.333	13.506
C									
LOCATION=TEUL HARV.DATE=08SEP82 GROWTH STAGE=MATU									
GRAIN	3	3844.533	215.296	3673.200	4086.200	124.301	11533.600	46352.333	5.600
C									
LOCATION=WASK HARV.DATE=24AUG82 GROWTH STAGE=MATU									
GRAIN	3	4175.667	80.002	4127.000	4268.000	46.189	12527.000	6400.333	1.916
C									
LOCATION=WINN HARV.DATE=24AUG82 GROWTH STAGE=MATU									
GRAIN	3	4628.533	720.045	3827.200	5221.200	415.718	13885.600	518465.333	15.557
C									
LOCATION=WOOD HARV.DATE=08SEP82 GROWTH STAGE=MATU									
GRAIN	3	3473.200	105.228	3372.200	3582.200	60.754	10419.600	11073.000	3.030
C									
LOC=BAGA DAY=18AUG83 GS=MATU									
C									
GRAIN	6	3269.433	521.185	2585.800	3965.800	212.773	19616.600	271634.023	15.941
C									

VARIABLE	N	MEAN	STANDARD DEVIATION	MINIMUM VALUE	MAXIMUM VALUE	STD ERROR OF MEAN	SUM	VARIANCE	C.V.
LOC=BEAU DAY=15AUG83 GS=MATU									
C									
GRAIN	6	3234.000	614.505	2534.200	4126.400	250.871	19404.000	377616.768	19.001
C									
LOC=DAUP DAY=11SEP83 GS=MATU									
C									
GRAIN	6	3922.800	697.476	2964.200	4946.600	284.743	23536.800	486473.152	17.780
C									
LOC=MARI DAY=17AUG83 GS=MATU									
C									
GRAIN	6	1640.533	413.714	1106.000	2121.200	168.898	9843.200	171159.323	25.218
C									
LOC=ROBL DAY=11SEP83 GS=MATU									
C									
GRAIN	6	2960.767	359.070	2395.800	3295.200	146.590	17764.600	128931.415	12.128
C									
LOC=SHOL DAY=30AUG83 GS=MATU									
C									
GRAIN	6	2909.133	335.637	2603.200	3355.400	137.023	17454.800	112652.155	11.537
C									
LOC=SOUR DAY=02SEP83 GS=MATU									
C									
GRAIN	6	3528.233	440.361	2839.600	4132.600	179.776	21169.400	193917.495	12.481
C									
LOC=SWRI DAY=11SEP83 GS=MATU									
C									
GRAIN	6	3279.767	501.883	2732.600	3894.200	204.893	19678.600	251886.295	15.302
C									
LOC=TEUL DAY=15SEP83 GS=MATU									
C									
GRAIN	6	3680.000	396.776	3175.600	4153.800	161.983	22080.000	157431.296	10.782
C									
LOC=WASK DAY=17AUG83 GS=MATU									
C									
GRAIN	6	3414.033	592.640	2575.000	4314.600	241.944	20484.200	351222.071	17.359
C									
LOC=WINN DAY=11AUG83 GS=MATU									
C									
GRAIN	6	4018.267	780.064	2600.600	4629.000	318.460	24109.600	608499.355	19.413
C									
LOC=WOOD DAY=16AUG83 GS=MATU									
C									
GRAIN	6	2736.233	397.513	2199.800	3391.200	162.284	16417.400	158016.663	14.528
C									

Appendix I

Statistical Analysis of Aboveground Net Production

C

VARIABLE	N	MEAN	STANDARD DEVIATION	MINIMUM VALUE	MAXIMUM VALUE	STD ERROR OF MEAN	SUM	VARIANCE	C.V.
LOCATION=BAGO SAMPLING DATE=24JUN82 GROWTH STAGE=JOIN									
ANP	6	734.333	176.138	524.000	980.000	71.908	4406.000	31024.667	23.986
LOCATION=BAGO SAMPLING DATE=16JUL82 GROWTH STAGE=HEAD									
ANP	6	5593.333	988.467	4320.000	6680.000	403.540	33560.000	977066.667	17.672
LOCATION=BAGO SAMPLING DATE=17AUG82 GROWTH STAGE=SOFT									
ANP	6	11183.333	2292.681	8240.000	14560.000	935.983	67100.000	5256386.667	20.501
LOCATION=BAGO SAMPLING DATE=01SEP82 GROWTH STAGE=MATU									
ANP	6	12126.667	1183.920	10910.000	13610.000	483.333	72760.000	1401666.667	9.763
LOCATION=BEAU SAMPLING DATE=22JUN82 GROWTH STAGE=JOIN									
ANP	6	596.000	77.604	470.000	698.000	31.682	3576.000	6022.400	13.021
LOCATION=BEAU SAMPLING DATE=15JUL82 GROWTH STAGE=HEAD									
ANP	6	5336.667	767.272	4560.000	6240.000	313.238	32020.000	588706.667	14.377
LOCATION=BEAU SAMPLING DATE=16AUG82 GROWTH STAGE=SOFT									
ANP	6	11073.333	1442.701	10080.000	13800.000	588.980	66440.000	2081386.667	13.029
LOCATION=BEAU SAMPLING DATE=01SEP82 GROWTH STAGE=MATU									
ANP	6	11486.667	1627.153	9860.000	14080.000	664.282	68920.000	2647626.667	14.166
LOCATION=DAUP SAMPLING DATE=21JUL82 GROWTH STAGE=HEAD									
ANP	6	6610.000	764.068	5860.000	7760.000	311.929	39660.000	583800.000	11.559
LOCATION=DAUP SAMPLING DATE=14SEP82 GROWTH STAGE=MATU									
ANP	6	12980.000	2477.967	8300.000	15100.000	1011.626	77880.000	6140320.000	19.091
LOCATION=MARI SAMPLING DATE=24JUN82 GROWTH STAGE=JOIN									
ANP	6	596.667	109.037	432.000	712.000	44.514	3580.000	11889.067	18.274

VARIABLE	N	MEAN	STANDARD DEVIATION	MINIMUM VALUE	MAXIMUM VALUE	STD ERROR OF MEAN	SUM	VARIANCE	C.V.
LOCATION=MARI SAMPLING DATE=16JUL82 GROWTH STAGE=HEAD									
ANP	6	5910.000	1328.864	4860.000	8360.000	542.507	35460.000	1765880.000	22.485
LOCATION=MARI SAMPLING DATE=17AUG82 GROWTH STAGE=SOFT									
ANP	6	9526.667	2541.170	7040.000	12900.000	1037.428	57160.000	6457546.667	20.286
LOCATION=MARI SAMPLING DATE=01SEP82 GROWTH STAGE=MATU									
ANP	6	10103.333	266.358	9900.000	10620.000	108.740	60620.000	70946.667	2.636
LOCATION=ROBL SAMPLING DATE=21JUL82 GROWTH STAGE=HEAD									
ANP	6	3863.333	176.824	3600.000	4100.000	72.188	23180.000	31266.667	4.577
LOCATION=ROBL SAMPLING DATE=13SEP82 GROWTH STAGE=MATU									
ANP	6	8416.667	510.594	7840.000	9200.000	208.449	50500.000	260706.667	6.066
LOCATION=SHOL SAMPLING DATE=23JUL82 GROWTH STAGE=HEAD									
ANP	6	8480.000	801.099	7040.000	9340.000	327.047	50880.000	641760.000	9.447
LOCATION=SWRI SAMPLING DATE=21JUL82 GROWTH STAGE=HEAD									
ANP	6	5850.000	478.289	5040.000	6340.000	195.261	35100.000	228760.000	8.176
LOCATION=SWRI SAMPLING DATE=13SEP82 GROWTH STAGE=MATU									
ANP	6	11100.000	1192.510	9960.000	12800.000	486.840	66600.000	1422080.000	10.743
LOCATION=TEUL SAMPLING DATE=22JUN82 GROWTH STAGE=JOIN									
ANP	6	830.667	133.989	588.000	972.000	54.701	4984.000	17953.067	16.130
LOCATION=TEUL SAMPLING DATE=15JUL82 GROWTH STAGE=HEAD									
ANP	6	5836.667	907.869	4640.000	7160.000	370.636	35020.000	824226.667	15.555
LOCATION=TEUL SAMPLING DATE=13AUG82 GROWTH STAGE=SOFT									
ANP	6	9973.333	951.266	8380.000	10720.000	388.353	59840.000	904906.667	9.538

VARIABLE	N	MEAN	STANDARD DEVIATION	MINIMUM VALUE	MAXIMUM VALUE	STD ERROR OF MEAN	SUM	VARIANCE	C.V.
----- LOCATION=TEUL SAMPLING DATE=08SEP82 GROWTH STAGE=MATU -----									
ANP	6	10293.333	1108.994	9120.000	11880.000	452.745	61760.000	1229866.667	10.774
----- LOCATION=WASK SAMPLING DATE=14JUL82 GROWTH STAGE=HEAD -----									
ANP	6	3046.667	324.879	2640.000	3460.000	132.631	18280.000	105546.667	10.663
----- LOCATION=WASK SAMPLING DATE=24AUG82 GROWTH STAGE=MATU -----									
ANP	6	9667.333	1396.663	7734.000	10734.000	570.185	58004.000	1950666.667	14.447
----- LOCATION=WINN SAMPLING DATE=15JUN82 GROWTH STAGE=JOIN -----									
ANP	6	1305.000	355.374	1000.000	1872.000	145.081	7830.000	126290.800	27.232
----- LOCATION=WINN SAMPLING DATE=08JUL82 GROWTH STAGE=HEAD -----									
ANP	6	7290.000	915.096	6220.000	8900.000	373.586	43740.000	837400.000	12.553
----- LOCATION=WINN SAMPLING DATE=10AUG82 GROWTH STAGE=SOFT -----									
ANP	6	12776.667	1134.930	11500.000	14800.000	463.333	76660.000	1288066.667	7.194
----- LOCATION=WINN SAMPLING DATE=24AUG82 GROWTH STAGE=MATU -----									
ANP	6	13206.667	1891.525	10800.000	16400.000	772.212	79240.000	3577866.667	14.323
----- LOCATION=WOOD SAMPLING DATE=28JUN82 GROWTH STAGE=JOIN -----									
ANP	6	765.000	107.657	690.000	980.000	43.951	4590.000	11590.000	14.073
----- LOCATION=WOOD SAMPLING DATE=19JUL82 GROWTH STAGE=HEAD -----									
ANP	6	5273.333	880.969	4020.000	6320.000	359.654	31640.000	776106.667	16.706
----- LOCATION=WOOD SAMPLING DATE=23AUG82 GROWTH STAGE=SOFT -----									
ANP	6	9916.667	1471.620	8100.000	11200.000	600.787	59500.000	2165666.667	14.840
----- LOCATION=WOOD SAMPLING DATE=08SEP82 GROWTH STAGE=MATU -----									

VARIABLE	N	MEAN	STANDARD DEVIATION	MINIMUM VALUE	MAXIMUM VALUE	STD ERROR OF MEAN	SUM	VARIANCE	C.V.
LOC=BAGA DAY=24JUN83 GS=JOIN									
ANP	6	1026.433	296.734	792.000	1597.600	121.141	6158.600	88051.271	28.909
LOC=BAGA DAY=13JUL83 GS=HEAD									
ANP	6	4874.033	762.955	3808.000	5771.800	311.475	29244.200	582101.047	15.653
LOC=BAGA DAY=03AUG83 GS=SOFT									
ANP	6	7657.000	1334.049	5700.000	9572.000	544.623	45942.000	1779686.000	17.423
LOC=BAGA DAY=18AUG83 GS=MATU									
ANP	6	8134.333	1162.778	6748.000	9964.000	474.702	48806.000	1352053.467	14.295
LOC=BEAU DAY=28JUN83 GS=JOIN									
ANP	6	1158.733	163.523	929.400	1370.600	66.758	6952.400	26739.643	14.112
LOC=BEAU DAY=12JUL83 GS=HEAD									
ANP	6	3714.200	460.359	2961.200	4246.400	187.941	22285.200	211930.624	12.395
LOC=BEAU DAY=04AUG83 GS=SOFT									
ANP	6	8209.000	580.202	7282.000	8950.000	236.867	49254.000	336634.800	7.068
LOC=BEAU DAY=15AUG83 GS=MATU									
ANP	6	8500.000	1456.683	6849.200	10845.200	594.688	51000.000	2121924.704	17.137
LOC=DAUP DAY=06JUL83 GS=JOIN									
ANP	6	1336.133	213.749	1060.000	1702.600	87.263	8016.800	45688.523	15.998
LOC=DAUP DAY=26JUL83 GS=HEAD									
ANP	6	6237.200	590.907	5108.600	6836.600	241.237	37423.200	349171.056	9.474
LOC=DAUP DAY=10AUG83 GS=SOFT									
ANP	6	10420.200	705.324	9642.000	11390.400	287.947	62521.200	497482.032	6.769

VARIABLE	N	MEAN	STANDARD DEVIATION	MINIMUM VALUE	MAXIMUM VALUE	STD ERROR OF MEAN	SUM	VARIANCE	C.V.
LOC=DAUP DAY=11SEP83 GS=MATU									
ANP	6	11092.667	1618.489	8958.000	13714.000	660.745	66556.000	2619505.067	14.591
LOC=MARI DAY=27JUN83 GS=JOIN									
ANP	6	1265.933	331.443	906.600	1754.600	135.311	7595.600	109854.331	26.182
LOC=MARI DAY=13JUL83 GS=HEAD									
ANP	6	4926.933	759.178	4066.200	6146.600	309.933	29561.600	576350.955	15.409
LOC=MARI DAY=03AUG83 GS=SOFT									
ANP	6	6198.667	959.763	5166.000	7442.000	391.822	37192.000	921145.067	15.483
LOC=MARI DAY=17AUG83 GS=MATU									
ANP	6	8335.000	563.753	7583.600	9093.600	230.151	50010.000	317817.024	6.764
LOC=ROBL DAY=07JUL83 GS=JOIN									
ANP	6	889.033	275.962	497.400	1120.000	112.661	5334.200	76154.999	31.041
LOC=ROBL DAY=26JUL83 GS=HEAD									
ANP	6	4259.867	792.294	3074.000	5091.400	323.453	25559.200	627729.675	18.599
LOC=ROBL DAY=10AUG83 GS=SOFT									
ANP	6	7058.900	1568.533	4910.400	8533.000	640.351	42353.400	2460294.780	22.221
LOC=ROBL DAY=11SEP83 GS=MATU									
ANP	6	8166.667	838.752	7356.000	9362.000	342.419	49000.000	703505.067	10.270
LOC=SHOL DAY=06JUL83 GS=JOIN									
ANP	6	1121.700	247.644	849.000	1427.600	101.100	6730.200	61327.372	22.078
LOC=SHOL DAY=23JUL83 GS=HEAD									
ANP	6	4380.100	468.251	3933.800	5067.800	191.163	26280.600	219258.892	10.690

VARIABLE	N	MEAN	STANDARD DEVIATION	MINIMUM VALUE	MAXIMUM VALUE	STD ERROR OF MEAN	SUM	VARIANCE	C.V.
LOC=SHOL DAY=09AUG83 GS=SOFT									
ANP	6	6454.000	652.764	5750.000	7410.000	266.490	38724.000	426100.800	10.114
LOC=SHOL DAY=30AUG83 GS=MATU									
ANP	6	7699.867	854.018	6658.400	8648.200	348.651	46199.200	729346.923	11.091
LOC=SOUR DAY=27JUN83 GS=JOIN									
ANP	6	536.600	79.989	424.000	665.800	32.655	3219.600	6398.288	14.907
LOC=SOUR DAY=25JUL83 GS=HEAD									
ANP	6	5962.667	889.074	4911.000	7349.000	362.963	35776.000	790452.875	14.911
LOC=SOUR DAY=09AUG83 GS=SOFT									
ANP	6	7630.333	761.955	6172.000	8246.000	311.067	45782.000	580575.067	9.986
LOC=SOUR DAY=02SEP83 GS=MATU									
ANP	6	8741.000	1089.607	7086.000	9838.000	444.830	52446.000	1187244.400	12.465
LOC=SWRI DAY=07JUL83 GS=JOIN									
ANP	6	599.300	119.086	398.200	714.000	48.617	3595.800	14181.548	19.871
LOC=SWRI DAY=26JUL83 GS=HEAD									
ANP	6	4019.467	379.712	3716.800	4740.000	155.017	24116.800	144181.531	9.447
LOC=SWRI DAY=10AUG83 GS=SOFT									
ANP	6	6568.333	529.711	5732.000	7206.000	216.254	39410.000	280594.267	8.065
LOC=SWRI DAY=11SEP83 GS=MATU									
ANP	6	9102.667	1012.184	7646.000	10024.000	413.222	54616.000	1024516.267	11.120
LOC=TEUL DAY=29JUN83 GS=JOIN									
ANP	6	1920.700	197.961	1696.400	2279.600	80.817	11524.200	39188.380	10.307

VARIABLE	N	MEAN	STANDARD DEVIATION	MINIMUM VALUE	MAXIMUM VALUE	STD ERROR OF MEAN	SUM	VARIANCE	C.V.
LOC=TEUL DAY=12JUL83 GS=HEAD									
ANP	6	5498.733	542.945	4808.400	6231.600	221.656	32992.400	294788.907	9.874
LOC=TEUL DAY=02AUG83 GS=SOFT									
ANP	6	9850.333	467.647	9146.000	10512.000	190.916	59102.000	218693.467	4.748
LOC=TEUL DAY=15SEP83 GS=MATU									
ANP	6	11057.000	594.940	10422.000	11814.000	242.883	66342.000	353953.200	5.381
LOC=WASK DAY=27JUN83 GS=JOIN									
ANP	6	1573.033	162.258	1425.000	1884.000	66.241	9438.200	26327.607	10.315
LOC=WASK DAY=13JUL83 GS=HEAD									
ANP	6	5516.433	720.768	4700.000	6793.200	294.252	33098.600	519506.471	13.066
LOC=WASK DAY=03AUG83 GS=SOFT									
ANP	6	9507.333	1754.858	6482.000	11626.000	716.418	57044.000	3079527.467	18.458
LOC=WASK DAY=17AUG83 GS=MATU									
ANP	6	9152.667	1395.337	7106.000	11112.000	569.644	54916.000	1946965.867	15.245
LOC=WINN DAY=23JUN83 GS=JOIN									
ANP	6	1766.367	519.379	1078.200	2636.000	212.036	10598.200	269754.679	29.404
LOC=WINN DAY=08JUL83 GS=HEAD									
ANP	6	6337.133	457.210	5816.200	7072.600	186.655	38022.800	209040.923	7.215
LOC=WINN DAY=27JUL83 GS=SOFT									
ANP	6	11088.833	463.273	10252.000	11488.000	189.130	66533.000	214621.767	4.178
LOC=WINN DAY=11AUG83 GS=MATU									
ANP	6	11343.667	938.647	9840.000	12398.000	383.201	68062.000	881058.267	8.275

VARIABLE	N	MEAN	STANDARD DEVIATION	MINIMUM VALUE	MAXIMUM VALUE	STD ERROR OF MEAN	SUM	VARIANCE	C.V.
LOC=WOOD DAY=24JUN83 GS=JOIN									
ANP	6	1215.000	281.874	885.400	1629.200	115.075	7290.000	79453.120	23.200
LOC=WOOD DAY=15JUL83 GS=HEAD									
ANP	6	5788.000	590.396	5072.800	6484.000	241.028	34728.000	348567.232	10.200
LOC=WOOD DAY=04AUG83 GS=SOFT									
ANP	6	8263.000	511.050	7862.000	9132.000	208.635	49578.000	261172.400	6.185
LOC=WOOD DAY=16AUG83 GS=MATU									
ANP	6	8668.667	1034.615	7184.000	10016.000	422.380	52012.000	1070428.267	11.935

Appendix J

Example of Simulation Outputs for Bagot,

Mariapolis and Winnipeg Sites

Simulation Sc. I and Sc. II in 1982

1 SITE/YEAR OF SIMULATION - BAGOT / 1982

SPECIAL DRIVING PARAMETER VALUES
0SDPV 2 2 1831952 1200.280 20 0 1 2 0 1 2 6 3 21018 0 0 39999 2 2 1 1 1

SIMULATION SCENARIO -I (SOIL PHYSICAL PARAMETERS MEASURED,BOUNDARY AND INITIAL CONDITIONS KNOWN)

GENERAL INFORMATION

CROP DISTRICT: 1

SOIL PHYSICAL PARAMETERS

FIELD CAPACITY (mc/mc)	:	0.20	0.21	0.23	0.23	0.34	0.34	0.39	0.39	0.0	0.0
WILTING POINT (mc/mc)	:	0.06	0.08	0.11	0.11	0.11	0.11	0.14	0.14	0.0	0.0
BULK DENSITY (Mg/mc)	:	1.10	1.25	1.35	1.35	1.44	1.44	1.51	1.51	0.0	0.0
AVAILABEL WATER (mc/mc)	:	0.14	0.13	0.12	0.12	0.23	0.23	0.25	0.25	0.0	0.0

LOWER BOUNDARY CONDITIONS

WATER TABLE : 99

PHYSICAL BOUNDARY : 0

DRAINAGE CLASS : 3

LEGEND:
WATER TABLE : PRESENT=15, ABSENT =99, UNKNOWN=98
PHYSICAL BOUNDARY : PRESENT= 1, ABSENT = 0
DRINAGE CLASS : WELL = 3, IMPERFECT= 2, POORLY = 1

INITIAL CONDITIONS

WATER CONTENT (mc/mc)	:	0.16	0.19	0.23	0.23	0.31	0.31	0.39	0.39	0.0	0.0
NO3-N CONCENTRATION (ppm)	:	20.7	10.8	10.3	10.3	12.0	12.0	8.8	8.8	8.4	8.4

SOIL TEMPERATURE AT 0.20 M.(DEGREE CELSIUS): 9.32

MANAGEMENT DATA

SEEDING DATE (JULIAN DAY): 142.

NITROGEN FERTILIZER APPLIED (kg/ha): 32.

DAILY OUTPUTS

JDAY	DPHO	DAYP	CUMP	PETB	CPEV	ACET	W- LA-1	LA-2	LA-3	LA-4	LA-5	N- LA-1	LA-2	LA-3	LA-4	LA-5	LMWF	LMNF	LMTF	TLFT	CUMANP
142.	0.13	0.0	0.0	0.47	0.00	0.0	0.16	0.19	0.23	0.31	0.39	21.1	10.8	10.3	12.0	8.8	0.0	0.0	0.0	0.0	200.
143.	0.27	0.0	0.0	0.53	0.18	0.0	0.15	0.19	0.23	0.31	0.39	21.6	10.9	10.3	12.0	8.8	0.0	0.0	0.0	0.0	200.
144.	0.39	0.08	0.08	0.60	0.38	0.0	0.14	0.19	0.23	0.31	0.39	22.0	10.9	10.3	12.0	8.8	0.0	0.0	0.0	0.0	200.
145.	0.50	0.0	0.08	0.63	0.59	0.0	0.13	0.19	0.23	0.31	0.39	22.5	11.0	10.3	12.0	8.8	0.0	0.0	0.0	0.0	200.
146.	0.67	0.0	0.08	0.57	0.78	0.0	0.11	0.19	0.23	0.31	0.39	22.9	11.0	10.3	12.0	8.8	0.0	0.0	0.0	0.0	200.
147.	0.84	0.0	0.08	0.58	0.94	0.0	0.10	0.19	0.23	0.31	0.39	23.4	11.1	10.3	12.0	8.8	0.0	0.0	0.0	0.0	200.
148.	1.02	0.0	0.08	0.44	1.04	0.0	0.10	0.19	0.23	0.31	0.39	23.8	11.1	10.3	12.0	8.8	0.54	0.17	0.98	0.17	249.
149.	1.05	0.09	0.17	0.41	1.09	0.07	0.09	0.19	0.23	0.31	0.39	24.3	11.2	10.3	12.0	8.8	0.53	0.31	1.00	0.31	267.
150.	1.08	0.0	0.17	0.37	1.14	0.12	0.09	0.19	0.23	0.31	0.39	23.6	11.2	10.3	12.1	8.7	0.43	0.63	1.00	0.43	294.
151.	1.11	0.0	0.17	0.34	1.17	0.11	0.08	0.19	0.23	0.31	0.39	21.9	11.2	10.2	12.1	8.7	0.33	0.85	1.00	0.33	322.
152.	1.14	0.0	0.17	0.34	1.23	0.10	0.07	0.19	0.23	0.31	0.38	20.5	11.3	10.2	12.1	8.7	0.18	0.97	0.99	0.18	335.
153.	1.18	0.0	0.17	0.36	1.27	0.08	0.06	0.19	0.23	0.32	0.38	19.0	11.3	10.2	12.1	8.7	0.06	1.00	0.95	0.06	339.
154.	1.22	0.0	0.17	0.47	1.30	0.03	0.06	0.19	0.23	0.32	0.38	17.9	11.3	10.2	12.2	8.6	0.02	1.00	0.91	0.02	342.
155.	1.27	0.0	0.17	0.58	1.31	0.02	0.06	0.19	0.23	0.32	0.38	17.7	11.3	10.2	12.2	8.6	0.02	1.00	0.88	0.02	345.
156.	1.33	0.0	0.17	0.49	1.31	0.03	0.06	0.18	0.23	0.32	0.38	17.9	11.3	10.2	12.2	8.6	0.01	1.00	0.90	0.01	346.
157.	1.39	1.87	2.04	0.23	1.31	0.05	0.18	0.18	0.23	0.32	0.38	17.8	11.4	10.2	12.2	8.6	0.92	1.00	0.94	0.92	516.
158.	1.43	0.59	2.63	0.30	1.43	0.17	0.20	0.19	0.23	0.32	0.38	17.4	12.0	10.1	12.2	8.6	0.94	0.94	0.96	0.94	639.
159.	1.45	0.0	2.63	0.41	1.60	0.24	0.18	0.18	0.22	0.32	0.38	17.3	11.7	10.1	12.2	8.5	0.91	0.87	0.95	0.87	728.
160.	1.49	0.0	2.63	0.44	1.78	0.26	0.16	0.17	0.22	0.32	0.38	17.0	11.3	10.1	12.2	8.5	0.88	0.86	0.93	0.86	819.
161.	1.53	0.0	2.63	0.61	2.03	0.35	0.13	0.16	0.22	0.32	0.38	16.6	10.8	10.1	12.3	8.5	0.82	0.87	0.91	0.82	970.
162.	1.58	0.0	2.63	0.38	2.18	0.23	0.11	0.16	0.22	0.32	0.38	15.5	10.1	10.1	12.3	8.5	0.76	0.81	0.91	0.76	1117.
163.	1.61	0.08	2.71	0.71	2.41	0.31	0.09	0.15	0.22	0.32	0.37	15.0	9.6	10.1	12.3	8.5	0.67	0.79	0.91	0.67	1199.
164.	1.66	0.0	2.71	0.54	2.53	0.27	0.08	0.14	0.22	0.32	0.37	13.8	9.0	10.1	12.3	8.5	0.56	0.80	0.92	0.56	1317.
165.	1.71	0.0	2.71	0.48	2.59	0.18	0.07	0.13	0.22	0.32	0.37	12.7	8.5	10.1	12.3	8.4	0.72	0.78	0.94	0.72	1444.
166.	1.75	0.0	2.71	0.48	2.62	0.28	0.06	0.12	0.22	0.32	0.37	12.0	8.2	10.1	12.3	8.4	0.67	0.74	0.95	0.67	1567.
167.	1.80	0.0	2.71	0.49	2.63	0.27	0.06	0.11	0.22	0.32	0.37	12.8	7.1	10.0	12.3	8.4	0.63	0.71	0.96	0.63	1746.
168.	1.84	0.0	2.71	0.29	2.63	0.20	0.06	0.10	0.22	0.32	0.37	13.4	6.2	9.9	12.3	8.4	0.59	0.66	0.97	0.59	1862.
169.	1.89	0.0	2.71	0.43	2.63	0.20	0.06	0.09	0.21	0.32	0.37	13.9	5.6	9.8	12.3	8.4	0.54	0.64	0.96	0.54	1974.
170.	1.93	0.54	3.25	0.43	2.63	0.18	0.09	0.09	0.21	0.32	0.37	14.4	5.0	9.7	12.3	8.4	0.77	0.63	0.95	0.63	2141.
171.	1.98	0.33	3.58	0.46	2.66	0.33	0.11	0.08	0.21	0.32	0.37	14.1	4.9	9.7	12.2	8.4	0.77	0.63	0.94	0.63	2279.
172.	2.03	0.0	3.58	0.43	2.71	0.32	0.09	0.09	0.20	0.32	0.37	13.5	5.0	9.4	12.2	8.3	0.74	0.63	0.93	0.63	2457.
173.	2.02	0.0	3.58	0.35	2.74	0.28	0.09	0.09	0.20	0.32	0.37	12.9	5.0	9.1	12.2	8.3	0.71	0.62	0.93	0.62	2597.
174.	2.07	0.0	3.58	0.62	2.79	0.29	0.08	0.08	0.19	0.32	0.37	12.3	5.1	8.8	12.1	8.3	0.67	0.62	0.94	0.62	2779.
175.	2.11	0.0	3.58	0.38	2.81	0.31	0.07	0.08	0.19	0.32	0.37	11.7	5.2	8.6	12.1	8.3	0.77	0.62	0.96	0.62	2928.
176.	2.15	0.0	3.58	0.67	2.83	0.40	0.06	0.08	0.18	0.32	0.37	10.9	5.2	8.3	12.0	8.3	0.74	0.62	0.97	0.62	3041.
177.	2.19	0.0	3.58	0.54	2.83	0.41	0.06	0.09	0.17	0.32	0.37	11.5	5.3	7.7	12.0	8.3	0.71	0.63	0.99	0.63	3237.
178.	2.23	0.0	3.58	0.55	2.83	0.41	0.06	0.09	0.15	0.31	0.37	12.0	5.3	7.1	11.9	8.3	0.68	0.62	1.00	0.62	3396.
179.	2.27	0.0	3.58	0.36	2.83	0.31	0.06	0.09	0.14	0.31	0.37	12.5	5.4	6.4	11.9	8.3	0.77	0.62	1.00	0.62	3556.
180.	2.30	0.0	3.58	0.52	2.84	0.44	0.06	0.09	0.13	0.31	0.37	12.9	5.4	6.0	11.8	8.3	0.75	0.62	0.99	0.62	3638.
181.	2.33	0.0	3.58	0.63	2.84	0.38	0.06	0.09	0.12	0.31	0.36	13.4	5.5	5.4	11.8	8.2	0.73	0.63	0.99	0.63	3763.
182.	2.37	0.0	3.58	0.66	2.84	0.38	0.06	0.09	0.11	0.31	0.36	13.9	5.5	4.8	11.7	8.2	0.71	0.64	0.99	0.64	3934.
183.	2.43	0.33	3.91	0.47	2.84	0.37	0.08	0.09	0.11	0.30	0.36	14.4	5.6	4.3	11.6	8.2	0.71	0.65	0.99	0.65	4200.
184.	2.49	0.0	3.91	0.65	2.85	0.36	0.07	0.09	0.11	0.29	0.36	13.2	5.6	4.3	11.2	8.2	0.77	0.65	0.96	0.65	4518.
185.	2.56	0.08	3.99	0.64	2.85	0.43	0.06	0.09	0.11	0.28	0.36	12.1	5.7	4.4	10.9	8.2	0.75	0.66	0.90	0.66	4842.
186.	2.62	0.0	3.99	0.50	2.85	0.44	0.06	0.09	0.11	0.27	0.36	10.6	5.7	4.4	10.5	8.2	0.74	0.65	0.80	0.65	5118.
187.	2.67	1.87	5.86	0.45	2.86	0.39	0.18	0.09	0.11	0.26	0.36	11.1	5.8	4.4	9.9	8.1	0.83	0.64	0.74	0.64	5346.
188.	2.70	0.0	5.86	0.49	2.86	0.46	0.17	0.09	0.11	0.25	0.36	10.8	5.9	4.4	9.6	8.1	0.82	0.64	0.74	0.64	5484.
189.	2.73	0.0	5.86	0.45	2.86	0.43	0.16	0.08	0.11	0.25	0.36	10.5	6.0	4.4	9.2	8.1	0.81	0.65	0.74	0.65	5623.
190.	2.78	0.0	5.86	0.55	2.86	0.52	0.15	0.09	0.11	0.24	0.35	10.3	6.1	4.4	8.9	8.0	0.79	0.67	0.74	0.67	5816.
191.	2.83	1.01	6.87	0.56	2.86	0.43	0.20	0.09	0.11	0.23	0.35	9.7	6.3	4.5	8.5	8.0	0.81	0.69	0.74	0.69	6061.
192.	2.88	0.0	6.87	0.64	2.86	0.51	0.19	0.08	0.11	0.23	0.35	9.5	6.5	4.5	8.2	7.9	0.80	0.71	0.74	0.71	6363.
193.	2.93	0.0	6.87	0.59	2.86	0.46	0.18	0.09	0.11	0.22	0.35	9.2	5.8	4.5	8.0	7.9	0.78	0.72	0.74	0.72	6616.
194.	2.98	1.20	8.07	0.48	2.86	0.47	0.20	0.12	0.11	0.21	0.35	7.3	7.1	4.5	7.7	7.8	0.80	0.73	0.74	0.73	6820.
195.	3.02	0.0	8.07	0.49	2.86	0.49	0.19	0.12	0.11	0.21	0.34	7.0	6.6	4.5	7.5	7.8	0.79	0.75	0.74	0.74	7026.
196.	3.05	0.0	8.07	0.67	2.86	0.53	0.18	0.11	0.11	0.20	0.34	6.6	6.1	4.5	7.4	7.7	0.77	0.76	0.74	0.74	7229.
197.	3.10	3.57	11.64	0.46	2.86	0.35	0.20	0.21	0.13	0.20	0.34	3.7	7.0	4.9	7.2	7.7	0.83	0.78	0.74	0.74	7431.
198.	3.13	0.0	11.64	0.38	2.86	0.39	0.19	0.20	0.12	0.20	0.34	3.6	6.7	4.9	7.1	7.7	0.83	0.79	0.74	0.74	7630.
199.	3.18	0.0	11.64	0.49	2.86	0.39	0.18	0.19	0.12	0.20	0.34	3.5	6.5	4.9	7.0	7.6	0.82	0.81	0.74	0.74	7826.
200.	3.22	0.0	11.64	0.52	2.86	0.39	0.18	0.18	0.12	0.19	0.33	3.4	6.3	4.9	6.9	7.6	0.81	0.82	0.74	0.74	8019.

201.	3.26	0.0	11.64	0.50	2.86	0.39	0.17	0.17	0.12	0.19	0.33	3.3	6.0	4.8	6.8	7.5	0.80	0.82	0.74	0.74	8255.
202.	3.30	0.0	11.64	0.48	2.86	0.39	0.16	0.17	0.12	0.19	0.33	3.2	5.8	4.8	6.7	7.5	0.79	0.82	0.74	0.74	8440.
203.	3.34	0.37	12.01	0.47	2.86	0.39	0.18	0.16	0.12	0.19	0.33	3.2	5.6	4.7	6.6	7.5	0.78	0.82	0.74	0.74	8577.
204.	3.39	0.0	12.01	0.54	2.87	0.39	0.17	0.15	0.12	0.19	0.33	3.1	5.4	4.7	6.5	7.4	0.77	0.83	0.74	0.74	8799.
205.	3.44	0.0	12.01	0.49	2.87	0.39	0.16	0.14	0.12	0.18	0.33	3.0	5.1	4.7	6.5	7.4	0.76	0.83	0.74	0.74	9058.
206.	3.49	0.0	12.01	0.56	2.89	0.39	0.15	0.14	0.12	0.18	0.32	2.9	4.9	4.6	6.4	7.3	0.75	0.83	0.74	0.74	9225.
207.	3.54	0.62	12.63	0.62	2.91	0.39	0.19	0.13	0.11	0.18	0.32	2.8	4.7	4.6	6.3	7.3	0.75	0.84	0.74	0.74	9428.
208.	3.58	1.12	13.75	0.38	2.92	0.35	0.20	0.17	0.11	0.18	0.32	2.3	4.8	4.5	6.2	7.3	0.78	0.84	0.74	0.74	9585.
209.	3.63	1.29	15.04	0.49	2.94	0.35	0.20	0.21	0.13	0.18	0.32	1.8	4.6	4.7	6.1	7.2	0.80	0.84	0.74	0.74	9774.
210.	3.67	0.0	15.04	0.47	2.97	0.35	0.19	0.20	0.13	0.17	0.32	1.8	4.4	4.7	6.1	7.2	0.79	0.84	0.74	0.74	9921.
211.	3.71	0.0	15.04	0.45	3.01	0.35	0.18	0.19	0.13	0.17	0.32	1.8	4.3	4.7	6.0	7.2	0.78	0.85	0.74	0.74	10097.
212.	3.76	0.0	15.04	0.59	3.06	0.35	0.17	0.19	0.13	0.17	0.31	1.7	4.2	4.7	5.9	7.1	0.77	0.85	0.74	0.74	10266.
213.	3.79	0.0	15.04	0.32	3.10	0.27	0.16	0.18	0.13	0.17	0.31	1.7	4.1	4.6	5.9	7.1	0.76	0.84	0.74	0.74	10364.
214.	3.83	0.0	15.04	0.27	3.14	0.23	0.16	0.17	0.12	0.17	0.31	1.7	4.0	4.6	5.8	7.1	0.75	0.85	0.74	0.74	10459.
215.	3.88	0.0	15.04	0.63	3.23	0.23	0.15	0.17	0.12	0.17	0.31	1.7	3.9	4.6	5.8	7.0	0.74	0.85	0.74	0.74	10611.
216.	3.92	0.0	15.04	0.52	3.31	0.23	0.14	0.16	0.12	0.17	0.31	1.7	3.9	4.6	5.7	7.0	0.73	0.85	0.74	0.73	10725.
217.	3.96	0.0	15.04	0.56	3.42	0.23	0.13	0.16	0.12	0.17	0.31	1.8	3.8	4.5	5.7	7.0	0.72	0.85	0.74	0.72	10860.
218.	4.01	0.09	15.13	0.53	3.52	0.23	0.12	0.15	0.12	0.17	0.31	1.8	3.7	4.5	5.6	6.9	0.71	0.85	0.74	0.71	10961.
219.	4.12	0.12	15.25	0.42	3.60	0.23	0.12	0.15	0.12	0.16	0.31	1.8	3.7	4.5	5.6	6.9	0.70	0.86	0.74	0.70	11234.
220.	4.22	0.34	15.59	0.31	3.67	0.21	0.13	0.14	0.12	0.16	0.30	1.8	3.6	4.5	5.5	6.9	0.70	0.86	0.74	0.70	11415.
221.	4.28	0.0	15.59	0.29	3.75	0.19	0.12	0.14	0.12	0.16	0.30	1.8	3.5	4.5	5.5	6.9	0.69	0.86	0.74	0.69	11523.
222.	4.31	0.0	15.59	0.46	3.90	0.19	0.11	0.14	0.12	0.16	0.30	1.8	3.5	4.4	5.5	6.8	0.68	0.86	0.74	0.68	11572.
223.	4.37	0.0	15.59	0.52	4.04	0.19	0.10	0.13	0.12	0.16	0.30	1.8	3.4	4.4	5.4	6.8	0.66	0.87	0.74	0.66	11663.
224.	4.47	0.0	15.59	0.28	4.11	0.16	0.09	0.13	0.12	0.16	0.30	1.8	3.4	4.4	5.4	6.8	0.65	0.88	0.74	0.65	11808.
225.	4.57	0.0	15.59	0.54	4.22	0.16	0.08	0.13	0.12	0.16	0.30	1.8	3.3	4.4	5.4	6.8	0.64	0.88	0.78	0.64	11907.
226.	4.67	0.56	16.15	0.62	4.33	0.15	0.11	0.12	0.12	0.16	0.30	1.8	3.3	4.4	5.3	6.7	0.65	0.88	0.78	0.65	12013.
227.	4.79	0.0	16.15	0.43	4.43	0.15	0.10	0.12	0.12	0.16	0.30	1.8	3.2	4.4	5.3	6.7	0.64	0.89	0.74	0.64	12098.
228.	4.86	0.0	16.15	0.51	4.61	0.16	0.08	0.12	0.11	0.16	0.30	1.8	3.2	4.3	5.3	6.7	0.62	0.89	0.74	0.62	12149.
229.	4.96	0.0	16.15	0.58	4.76	0.10	0.07	0.11	0.11	0.16	0.30	1.8	3.2	4.3	5.3	6.7	0.61	0.90	0.74	0.61	12197.
230.	5.08	0.0	16.15	0.53	4.85	0.12	0.06	0.11	0.11	0.16	0.29	1.8	3.1	4.3	5.3	6.7	0.61	0.90	0.74	0.61	12197.
231.	****	0.47	16.62	0.51	4.88	0.11	0.09	0.11	0.11	0.16	0.29	1.8	3.1	4.3	5.3	6.6	0.61	0.90	0.74	0.61	12197.
232.	****	0.0	16.62	0.54	4.97	0.12	0.08	0.11	0.11	0.16	0.29	1.8	3.1	4.3	5.2	6.6	0.61	0.90	0.74	0.61	12197.
233.	****	0.31	16.93	0.37	5.07	0.11	0.09	0.10	0.11	0.16	0.29	1.9	3.1	4.2	5.2	6.6	0.61	0.90	0.74	0.61	12197.
234.	****	1.48	18.41	0.41	5.18	0.09	0.18	0.10	0.11	0.16	0.29	1.9	3.1	4.2	5.2	6.6	0.61	0.90	0.74	0.61	12197.
235.	****	0.0	18.41	0.41	5.46	0.09	0.16	0.10	0.11	0.16	0.29	1.9	3.1	4.2	5.2	6.6	0.61	0.90	0.74	0.61	12197.
236.	****	0.0	18.41	0.26	5.64	0.08	0.15	0.10	0.11	0.16	0.29	1.9	3.1	4.2	5.2	6.6	0.61	0.90	0.74	0.61	12197.
237.	****	0.16	18.57	0.17	5.75	0.05	0.15	0.10	0.11	0.16	0.29	1.9	3.1	4.1	5.2	6.5	0.61	0.90	0.74	0.61	12197.
238.	****	0.0	18.57	0.27	5.94	0.08	0.13	0.10	0.11	0.16	0.29	1.9	3.1	4.1	5.2	6.5	0.61	0.90	0.74	0.61	12197.
239.	****	0.0	18.57	0.30	6.14	0.09	0.12	0.10	0.11	0.16	0.29	1.9	3.1	4.1	5.2	6.5	0.61	0.90	0.74	0.61	12197.
240.	****	0.0	18.57	0.41	6.41	0.09	0.10	0.10	0.11	0.16	0.29	1.9	3.1	4.1	5.2	6.5	0.61	0.90	0.74	0.61	12197.
241.	****	0.0	18.57	0.34	6.57	0.10	0.09	0.09	0.11	0.16	0.29	1.9	3.0	4.0	5.2	6.5	0.61	0.90	0.74	0.61	12197.
242.	****	0.0	18.57	0.32	6.67	0.10	0.08	0.09	0.11	0.16	0.29	1.9	3.0	4.0	5.2	6.5	0.61	0.90	0.74	0.61	12197.
243.	****	0.0	18.57	0.46	6.77	0.10	0.07	0.09	0.11	0.16	0.29	1.9	3.0	4.0	5.2	6.4	0.61	0.90	0.74	0.61	12197.
244.	****	0.15	18.72	0.29	6.81	0.09	0.08	0.09	0.11	0.16	0.28	1.9	3.0	4.0	5.2	6.4	0.61	0.90	0.74	0.61	12197.
245.	****	0.0	18.72	0.36	6.86	0.11	0.07	0.09	0.11	0.15	0.28	2.0	3.1	3.9	5.2	6.4	0.61	0.90	0.74	0.61	12197.

S U M M A R Y   O U T P U T S

PREDICTED GROWTH STAGES (JULIAN DAY)

SEEDING	EMERGENCE	JOINTING	HEADING	SOFT-DOUGH	MATURITY
142.	148.	172.	195.	218.	230.

PRECIPITATION DURING THE GROWING SEASON: 161.50 mm

PRECIPITATION FROM SEEDING TO HARVEST : 187.20 mm

POTENTIAL EVAPOTRANSPIRATION : 488.33 mm

ACTUAL EVAPORATION : 250.73 mm

Y I E L D (kg/ha)

ABOVEGROUND NET PRODUCTION	GRAIN
12197.	3415.

1 SITE/YEAR OF SIMULATION - BAGOT / 1982

SPECIAL DRIVING PARAMETER VALUES

0SDPV 2 2 1831952 1200.280 20 0 1 2 0 1 2 6 3 2 718 0 0 39999 2 2 1 1 1

SIMULATION SCENARIO - II (SOIL PHYSICAL PARAMETERS CALCULATED,BOUNDARY AND INITIAL CONDITIONS APPROXIMATED)

GENERAL INFORMATION

CROP DISTRICT: 1

SOIL PHYSICAL PARAMETERS

FIELD CAPACITY (mc/mc) :	0.28	0.29	0.22	0.20	0.20	0.18	0.23	0.34	0.0	0.0
WILTING POINT (mc/mc) :	0.07	0.06	0.04	0.03	0.02	0.01	0.05	0.12	0.0	0.0
BULK DENSITY (Mg/mc) :	1.10	1.18	1.64	1.67	1.69	1.70	1.66	1.55	0.0	0.0
AVAILABEL WATER (mc/mc):	0.21	0.23	0.18	0.17	0.17	0.17	0.19	0.22	0.0	0.0

LOWER BOUNDARY CONDITIONS

WATER TABLE : 99

PHYSICAL BOUNDARY : 0

DRAINAGE CLASS : 3

LEGEND:
WATER TABLE : PRESENT=15, ABSENT =99, UNKNOWN=98
PHYSICAL BOUNDARY : PRESENT= 1, ABSENT = 0
DRINAGE CLASS : WELL = 3, IMPERFECT= 2, POORLY = 1

INITIAL CONDITIONS

WATER CONTENT (mc/mc) :	0.28	0.29	0.22	0.20	0.20	0.18	0.23	0.34	0.0	0.0
NO3-N CONCENTRATION (ppm):	20.7	10.8	10.3	10.3	12.0	12.0	8.8	8.8	8.4	8.4

SOIL TEMPERATURE AT 0.20 M.(DEGREE CELSIUS): 9.32

MANAGEMENT DATA

SEEDING DATE (JULIAN DAY): 142.

NITROGEN FERTILIZER APPLIED (kg/ha): 32.

DAILY OUTPUTS

JDAY	DPHD	DAYP	CUMP	PETB	CPEV	ACET	W-	LA-1	LA-2	LA-3	LA-4	LA-5	N-	LA-1	LA-2	LA-3	LA-4	LA-5	LMWF	LMNF	LMTF	TLFT	CUMANP
229.	4.96	0.0	16.15	0.58	6.13	0.10		0.11	0.11	0.03	0.08	0.21		2.9	3.2	1.1	4.5	6.7	0.60	0.97	0.74	0.60	12357.
230.	5.08	0.0	16.15	0.53	6.28	0.12		0.09	0.11	0.03	0.08	0.21		2.9	3.2	1.1	4.5	6.7	0.60	0.97	0.74	0.60	12357.

S U M M A R Y   O U T P U T S

PREDICTED GROWTH STAGES (JULIAN DAY)

SEEDING	EMERGENCE	JOINTING	HEADING	SOFT-DOUGH	MATURITY
142.	148.	172.	195.	218.	230.

PRECIPITATION DURING THE GROWING SEASON: 161.50 mm

PRECIPITATION FROM SEEDING TO HARVEST : 187.20 mm

POTENTIAL EVAPOTRANSPIRATION : 488.33 mm

ACTUAL TRANSPIRATION : 260.04 mm

Y I E L D (kg/ha)

ABOVEGROUND NET PRODUCTION	GRAIN
12357.	3460.

```
1    SITE/YEAR OF SIMULATION - MARIAPOLIS / 1982


 SPECIAL DRIVING PARAMETER VALUES
0SDPV    2    2 1831952 1200.410 20  0  1  2  0  1  2  8  2  21018  0  0  39999  2  2  1  1  1

 SIMULATION SCENARIO -I (SOIL PHYSICAL PARAMETERS MEASURED,BOUNDARY AND INITIAL CONDITIONS KNOWN)

 GENERAL INFORMATION
  CROP DISTRICT:     1

  SOIL PHYSICAL PARAMETERS
   FIELD CAPACITY (mc/mc) :  0.34 0.39 0.36 0.36 0.35 0.35 0.34 0.34 0.0  0.0
   WILTING POINT (mc/mc)  :  0.14 0.16 0.17 0.17 0.17 0.17 0.14 0.14 0.0  0.0
   BULK DENSITY ( Mg/mc)  :  0.91 1.15 1.17 1.17 1.17 1.17 1.12 1.12 0.0  0.0
   AVAILABEL WATER (mc/mc):  0.20 0.23 0.19 0.19 0.18 0.18 0.20 0.20 0.0  0.0

 LOWER BOUNDARY CONDITIONS
  WATER TABLE         :   99
  PHYSICAL BOUNDARY :      0
  DRAINAGE CLASS      :    3

     LEGEND:
      WATER TABLE         : PRESENT=15, ABSENT    =99, UNKNOWN=98
      PHYSICAL BOUNDARY : PRESENT= 1, ABSENT    = 0
      DRINAGE CLASS       : WELL    = 3, IMPERFECT= 2, POORLY = 1

 INITIAL CONDITIONS
  WATER CONTENT (mc/mc)     :  0.28 0.34 0.34 0.34 0.35 0.35 0.34 0.34 0.0  0.0
  NO3-N CONCENTRATION (ppm):  30.5 21.2 13.6 13.6 23.0 23.0 29.0 29.0 28.4 28.4
  SOIL TEMPERATURE AT 0.20 M.(DEGREE CELSIUS):   9.15


 MANAGEMENT DATA
  SEEDING DATE (JULIAN DAY):                141.
  NITROGEN FERTILIZER APPLIED (kg/ha):      32.
```

DAILY OUTPUTS

JDAY	DPHD	DAYP	CUMP	PETB	CPEV	ACET	W- LA-1	LA-2	LA-3	LA-4	LA-5	N- LA-1	LA-2	LA-3	LA-4	LA-5	LMWF	LMNF	LMTF	TLFT	CUMANP
141.	0.13	0.0	0.0	0.50	0.00	0.0	0.28	0.34	0.34	0.35	0.34	31.1	21.3	13.6	23.0	29.0	0.0	0.0	0.0	0.0	200.
142.	0.26	0.0	0.0	0.55	0.18	0.0	0.27	0.34	0.34	0.35	0.34	31.6	21.4	13.6	23.0	29.0	0.0	0.0	0.0	0.0	200.
143.	0.38	0.0	0.0	0.63	0.38	0.0	0.25	0.34	0.34	0.35	0.34	32.2	21.4	13.6	23.0	29.0	0.0	0.0	0.0	0.0	200.
144.	0.57	0.10	0.10	0.36	0.48	0.0	0.25	0.34	0.34	0.35	0.34	32.8	21.5	13.6	23.0	29.0	0.0	0.0	0.0	0.0	200.
145.	0.69	0.0	0.10	0.60	0.64	0.0	0.24	0.34	0.34	0.35	0.34	33.3	21.6	13.6	23.0	29.0	0.0	0.0	0.0	0.0	200.
146.	0.84	0.0	0.10	0.60	0.80	0.0	0.23	0.34	0.34	0.35	0.34	33.9	21.7	13.6	23.0	29.0	0.0	0.0	0.0	0.0	200.
147.	1.00	0.0	0.10	0.59	0.94	0.0	0.22	0.34	0.34	0.35	0.34	34.5	21.7	13.6	23.0	29.0	0.0	0.0	0.0	0.0	200.
148.	1.15	0.0	0.10	0.57	1.06	0.0	0.22	0.34	0.34	0.35	0.34	35.0	21.8	13.6	23.0	29.0	0.69	0.17	0.99	0.17	257.
149.	1.05	0.70	0.80	0.38	1.18	0.16	0.25	0.34	0.34	0.35	0.34	35.8	21.8	13.6	22.9	29.0	0.80	0.32	1.00	0.32	257.
150.	1.08	0.0	0.80	0.31	1.23	0.10	0.24	0.33	0.34	0.35	0.34	34.9	21.8	13.6	22.9	28.9	0.78	0.41	1.00	0.41	294.
151.	1.12	0.20	1.00	0.24	1.26	0.09	0.25	0.33	0.34	0.35	0.34	34.6	21.8	13.6	22.8	28.9	0.80	0.46	1.00	0.46	326.
152.	1.15	0.0	1.00	0.34	1.41	0.13	0.23	0.33	0.34	0.35	0.34	34.4	21.8	13.6	22.8	28.9	0.75	0.56	0.99	0.56	367.
153.	1.18	0.0	1.00	0.36	1.56	0.15	0.21	0.33	0.34	0.35	0.34	33.7	21.8	13.6	22.7	28.9	0.68	0.65	0.95	0.65	432.
154.	1.22	0.0	1.00	0.56	1.74	0.14	0.20	0.33	0.34	0.34	0.34	32.9	21.8	13.6	22.7	28.9	0.58	0.69	0.90	0.58	491.
155.	1.27	0.0	1.00	0.52	1.86	0.16	0.18	0.32	0.34	0.34	0.34	32.0	21.8	13.6	22.7	28.9	0.47	0.74	0.88	0.47	541.
156.	1.33	0.0	1.00	0.45	1.93	0.10	0.17	0.32	0.34	0.34	0.34	30.8	21.8	13.6	22.6	28.8	0.40	0.74	0.89	0.40	609.
157.	1.38	0.28	1.28	0.23	1.96	0.10	0.18	0.32	0.34	0.34	0.34	30.3	21.8	13.6	22.6	28.8	0.76	0.72	0.91	0.72	711.
158.	1.42	0.39	1.67	0.20	1.99	0.11	0.21	0.31	0.34	0.34	0.34	29.9	21.8	13.6	22.6	28.8	0.79	0.64	0.92	0.64	800.
159.	1.45	0.60	2.27	0.22	2.03	0.12	0.24	0.31	0.34	0.34	0.34	30.0	21.6	13.6	22.6	28.8	0.83	0.62	0.90	0.62	844.
160.	1.49	0.50	2.77	0.32	2.11	0.18	0.27	0.30	0.34	0.34	0.34	30.2	21.3	13.6	22.5	28.7	0.85	0.63	0.86	0.63	936.
161.	1.52	0.0	2.77	0.57	2.29	0.30	0.24	0.29	0.34	0.34	0.34	30.1	21.0	13.5	22.5	28.7	0.81	0.65	0.82	0.65	1034.
162.	1.57	0.0	2.77	0.35	2.40	0.21	0.23	0.29	0.34	0.34	0.34	29.4	20.4	13.5	22.5	28.7	0.78	0.64	0.78	0.64	1134.
163.	1.60	0.0	2.77	0.62	2.56	0.28	0.21	0.28	0.33	0.34	0.34	29.1	20.0	13.5	22.5	28.7	0.74	0.64	0.77	0.64	1240.
164.	1.66	0.0	2.77	0.55	2.67	0.31	0.19	0.27	0.33	0.34	0.34	28.4	19.4	13.5	22.5	28.6	0.68	0.65	0.79	0.65	1379.
165.	1.71	0.0	2.77	0.41	2.74	0.22	0.18	0.26	0.33	0.34	0.34	27.5	18.7	13.5	22.4	28.6	0.77	0.63	0.83	0.63	1519.
166.	1.75	0.0	2.77	0.48	2.79	0.30	0.17	0.26	0.33	0.34	0.34	26.9	18.3	13.4	22.4	28.6	0.74	0.62	0.87	0.62	1663.
167.	1.81	0.20	2.97	0.48	2.83	0.30	0.17	0.25	0.33	0.34	0.34	26.2	17.9	13.3	22.4	28.6	0.73	0.61	0.91	0.61	1810.
168.	1.84	0.0	2.97	0.27	2.84	0.19	0.17	0.25	0.32	0.34	0.34	25.6	17.4	13.2	22.4	28.5	0.72	0.58	0.93	0.58	1927.
169.	1.88	0.0	2.97	0.40	2.87	0.29	0.16	0.24	0.32	0.34	0.34	25.4	17.1	13.2	22.4	28.5	0.69	0.58	0.92	0.58	2047.
170.	1.93	0.70	3.67	0.32	2.88	0.23	0.20	0.24	0.32	0.34	0.34	24.8	16.7	13.1	22.3	28.5	0.80	0.57	0.91	0.57	2169.
171.	1.97	0.0	3.67	0.41	2.91	0.31	0.19	0.23	0.32	0.34	0.34	24.6	16.3	13.0	22.3	28.5	0.78	0.58	0.89	0.58	2296.
172.	2.01	0.0	3.67	0.45	2.95	0.33	0.18	0.22	0.31	0.34	0.34	24.3	15.9	12.9	22.3	28.4	0.76	0.59	0.86	0.59	2428.
173.	2.02	0.20	3.87	0.46	2.98	0.34	0.18	0.22	0.31	0.34	0.34	23.8	15.5	12.7	22.3	28.4	0.75	0.59	0.85	0.59	2495.
174.	2.07	0.0	3.87	0.59	3.01	0.32	0.17	0.21	0.30	0.34	0.34	23.4	15.0	12.6	22.2	28.4	0.73	0.61	0.86	0.61	2674.
175.	2.10	0.0	3.87	0.33	3.02	0.27	0.17	0.20	0.30	0.34	0.34	22.9	14.6	12.5	22.2	28.3	0.78	0.60	0.88	0.60	2741.
176.	2.13	0.0	3.87	0.54	3.04	0.43	0.16	0.20	0.30	0.33	0.34	22.6	14.2	12.4	22.2	28.3	0.76	0.62	0.91	0.62	2854.
177.	2.18	0.0	3.87	0.51	3.06	0.40	0.15	0.19	0.29	0.33	0.34	21.7	13.7	12.2	22.1	28.3	0.74	0.64	0.94	0.64	3053.
178.	2.22	0.0	3.87	0.52	3.06	0.41	0.14	0.18	0.29	0.33	0.34	20.9	13.2	12.0	22.0	28.2	0.72	0.63	0.97	0.63	3213.
179.	2.26	0.60	4.47	0.48	3.06	0.36	0.17	0.17	0.29	0.33	0.34	21.6	11.9	11.9	21.9	28.2	0.73	0.64	0.99	0.64	3378.
180.	2.28	0.0	4.47	0.43	3.07	0.34	0.16	0.16	0.28	0.33	0.33	21.1	11.5	11.8	21.9	28.2	0.77	0.63	1.00	0.63	3460.
181.	2.31	0.0	4.47	0.54	3.08	0.45	0.15	0.16	0.27	0.33	0.33	20.7	11.1	11.6	21.8	28.1	0.75	0.65	1.00	0.65	3589.
182.	2.35	0.0	4.47	0.55	3.09	0.46	0.14	0.16	0.27	0.33	0.33	19.8	11.2	11.3	21.7	28.1	0.73	0.67	1.00	0.67	3767.
183.	2.41	0.80	5.27	0.47	3.09	0.38	0.19	0.16	0.26	0.32	0.33	19.0	11.3	10.9	21.6	28.1	0.75	0.67	1.00	0.67	4040.
184.	2.47	0.0	5.27	0.66	3.10	0.41	0.18	0.16	0.25	0.32	0.33	18.6	11.4	10.7	21.5	28.0	0.79	0.66	0.98	0.66	4313.
185.	2.53	0.0	5.27	0.68	3.11	0.48	0.16	0.16	0.25	0.32	0.33	18.1	11.4	10.4	21.4	28.0	0.77	0.66	0.94	0.66	4545.
186.	2.58	0.22	5.49	0.49	3.11	0.44	0.17	0.16	0.24	0.32	0.33	17.4	11.5	10.1	21.2	27.8	0.77	0.65	0.87	0.65	4825.
187.	2.63	0.0	5.49	0.46	3.12	0.41	0.16	0.16	0.23	0.32	0.33	16.8	11.6	9.8	21.1	27.7	0.75	0.65	0.79	0.65	5010.
188.	2.67	0.0	5.49	0.44	3.12	0.39	0.15	0.16	0.23	0.31	0.33	16.2	11.7	9.5	21.0	27.6	0.78	0.65	0.74	0.65	5198.
189.	2.70	0.0	5.49	0.47	3.12	0.44	0.14	0.16	0.22	0.31	0.33	15.7	11.8	9.3	20.9	27.5	0.77	0.65	0.74	0.65	5340.
190.	2.74	0.60	6.09	0.44	3.12	0.40	0.17	0.16	0.21	0.31	0.32	15.3	11.8	9.0	20.8	27.4	0.78	0.67	0.74	0.67	5583.
191.	2.79	0.0	6.09	0.48	3.12	0.45	0.16	0.16	0.21	0.31	0.32	15.0	11.9	8.7	20.7	27.2	0.76	0.69	0.74	0.69	5830.
192.	2.84	0.0	6.09	0.56	3.12	0.39	0.16	0.16	0.20	0.31	0.32	14.5	12.0	8.4	20.6	27.0	0.75	0.70	0.74	0.70	6031.
193.	2.89	0.0	6.09	0.59	3.12	0.40	0.15	0.16	0.20	0.30	0.32	13.8	12.1	8.2	20.5	26.9	0.74	0.72	0.74	0.72	6286.
194.	2.94	0.20	6.29	0.37	3.12	0.37	0.15	0.16	0.19	0.30	0.32	13.2	12.1	7.9	20.3	26.8	0.73	0.72	0.74	0.72	6440.
195.	2.98	0.0	6.29	0.54	3.12	0.49	0.14	0.16	0.18	0.30	0.31	12.7	12.2	7.7	20.2	26.6	0.71	0.74	0.74	0.71	6639.
196.	3.04	0.0	6.29	0.56	3.12	0.49	0.14	0.16	0.17	0.30	0.31	11.9	12.3	7.4	20.1	26.4	0.69	0.78	0.74	0.69	6976.
197.	3.05	0.13	6.42	0.46	3.12	0.27	0.14	0.16	0.17	0.30	0.31	12.0	12.4	6.8	19.9	26.3	0.69	0.76	0.74	0.69	7166.
198.	3.08	0.0	6.42	0.36	3.12	0.35	0.14	0.16	0.17	0.29	0.31	11.7	12.4	6.7	19.8	26.2	0.67	0.78	0.74	0.67	7232.
199.	3.12	0.0	6.42	0.43	3.12	0.35	0.14	0.16	0.17	0.28	0.31	11.8	12.5	6.7	19.1	26.0	0.66	0.80	0.74	0.66	7410.

200.	3.16	0.0	6.42	0.52	3.12	0.35	0.14	0.16	0.17	0.27	0.31	11.9	12.6	6.7	18.3	25.9	0.64	0.83	0.74	0.64	7624.
201.	3.20	0.0	6.42	0.42	3.12	0.35	0.14	0.16	0.17	0.25	0.31	12.0	12.6	6.7	17.6	25.8	0.63	0.86	0.74	0.63	7766.
202.	3.24	0.0	6.42	0.44	3.12	0.35	0.14	0.16	0.17	0.24	0.30	12.1	12.7	6.7	16.8	25.6	0.61	0.87	0.74	0.61	7884.
203.	3.28	0.0	6.42	0.45	3.12	0.35	0.14	0.16	0.17	0.23	0.30	12.2	12.8	6.7	16.0	25.5	0.59	0.88	0.74	0.59	8034.
204.	3.33	0.14	6.56	0.46	3.12	0.35	0.14	0.16	0.17	0.23	0.30	12.3	12.9	6.7	15.3	25.4	0.58	0.89	0.74	0.58	8213.
205.	3.37	0.0	6.56	0.48	3.12	0.35	0.14	0.16	0.17	0.22	0.30	11.8	12.9	6.7	14.8	25.2	0.56	0.89	0.74	0.56	8382.
206.	3.41	0.0	6.56	0.48	3.12	0.35	0.14	0.16	0.17	0.21	0.30	11.9	13.0	6.6	14.4	25.1	0.54	0.90	0.74	0.54	8478.
207.	3.45	0.0	6.56	0.59	3.12	0.35	0.14	0.16	0.17	0.20	0.29	12.0	13.1	6.6	13.7	24.9	0.52	0.92	0.74	0.52	8627.
208.	3.49	0.0	6.56	0.43	3.12	0.35	0.14	0.16	0.17	0.19	0.29	12.1	13.2	6.6	13.0	24.7	0.49	0.92	0.74	0.49	8728.
209.	3.54	0.30	6.86	0.57	3.12	0.35	0.15	0.16	0.17	0.18	0.29	12.2	13.2	6.6	12.3	24.5	0.49	0.94	0.74	0.49	8835.
210.	3.58	0.0	6.86	0.47	3.12	0.35	0.14	0.16	0.17	0.18	0.29	11.8	13.3	6.6	11.9	24.3	0.47	0.95	0.74	0.47	8934.
211.	3.62	0.0	6.86	0.45	3.12	0.35	0.14	0.16	0.17	0.17	0.28	11.3	13.4	6.6	11.5	24.1	0.44	0.96	0.74	0.44	9025.
212.	3.67	0.0	6.86	0.70	3.12	0.35	0.14	0.16	0.17	0.17	0.27	10.8	13.4	6.6	11.1	23.9	0.42	0.97	0.74	0.42	9148.
213.	3.70	0.30	7.16	0.37	3.12	0.18	0.15	0.16	0.17	0.17	0.27	10.9	13.5	6.6	11.2	22.8	0.42	0.97	0.74	0.42	9191.
214.	3.74	0.0	7.16	0.32	3.13	0.16	0.15	0.16	0.17	0.17	0.27	10.8	13.6	6.6	11.0	22.7	0.41	0.97	0.74	0.41	9230.
215.	3.79	0.0	7.16	0.63	3.13	0.16	0.15	0.16	0.17	0.17	0.26	10.7	13.7	6.6	11.0	22.3	0.40	0.98	0.74	0.40	9299.
216.	3.83	0.0	7.16	0.52	3.14	0.16	0.14	0.16	0.17	0.17	0.26	10.5	13.7	6.6	11.0	22.0	0.39	0.98	0.74	0.39	9303.
217.	3.87	0.0	7.16	0.53	3.14	0.16	0.14	0.16	0.17	0.17	0.26	10.4	13.8	6.6	11.0	21.7	0.37	0.98	0.74	0.37	9313.
218.	3.91	2.40	9.56	0.48	3.15	0.16	0.30	0.16	0.17	0.17	0.25	10.4	13.9	6.6	11.0	21.3	0.53	0.99	0.74	0.53	9323.
219.	3.94	0.0	9.56	0.39	3.19	0.24	0.29	0.16	0.17	0.17	0.25	10.4	14.0	6.6	11.0	21.0	0.51	0.99	0.74	0.51	9337.
220.	3.97	0.0	9.56	0.29	3.24	0.17	0.28	0.16	0.17	0.17	0.25	10.3	14.1	6.6	11.0	20.5	0.50	0.99	0.74	0.50	9392.
221.	4.00	0.0	9.56	0.41	3.33	0.17	0.26	0.16	0.17	0.17	0.24	10.2	13.9	6.6	11.1	20.3	0.48	0.99	0.74	0.48	9443.
222.	4.04	0.0	9.56	0.36	3.40	0.19	0.25	0.16	0.17	0.17	0.24	10.2	13.7	6.6	11.1	20.1	0.46	0.99	0.74	0.46	9506.
223.	4.09	0.0	9.56	0.52	3.50	0.19	0.24	0.16	0.17	0.17	0.24	10.1	13.8	6.6	11.1	19.7	0.44	0.99	0.79	0.44	9563.
224.	4.16	0.20	9.76	0.33	3.56	0.14	0.25	0.16	0.17	0.17	0.23	10.0	13.9	6.6	11.1	19.4	0.44	1.00	0.86	0.44	9657.
225.	4.25	0.0	9.76	0.61	3.69	0.14	0.24	0.16	0.17	0.17	0.23	10.0	14.0	6.6	11.1	19.1	0.42	1.00	0.89	0.42	9772.
226.	4.38	0.0	9.76	0.45	3.80	0.14	0.23	0.16	0.17	0.17	0.23	10.0	14.0	6.6	11.1	18.8	0.40	1.00	0.89	0.40	9886.
227.	4.50	0.70	10.46	0.48	3.92	0.14	0.26	0.16	0.17	0.17	0.22	10.0	14.1	6.6	11.1	18.5	0.44	1.00	0.86	0.44	9989.
228.	4.59	0.0	10.46	0.48	4.07	0.14	0.25	0.16	0.17	0.17	0.22	10.0	14.2	6.6	11.1	18.2	0.41	1.00	0.81	0.41	10058.
229.	4.67	0.0	10.46	0.54	4.28	0.10	0.23	0.16	0.17	0.17	0.22	9.9	14.3	6.6	11.1	18.0	0.39	1.00	0.74	0.39	10103.
230.	4.81	0.0	10.46	0.45	4.45	0.07	0.22	0.16	0.17	0.17	0.22	10.0	14.4	6.6	11.1	17.8	0.37	1.00	0.74	0.37	10160.
231.	4.89	0.0	10.46	0.48	4.62	0.06	0.21	0.16	0.17	0.17	0.22	10.0	14.5	6.6	11.1	17.6	0.35	1.00	0.74	0.35	10191.
232.	4.98	0.0	10.46	0.53	4.79	0.06	0.19	0.16	0.17	0.17	0.22	10.0	14.5	6.6	11.1	17.5	0.33	1.00	0.74	0.33	10213.
233.	5.04	0.70	11.16	0.35	4.90	0.09	0.23	0.16	0.17	0.17	0.21	10.1	14.6	6.6	11.1	17.4	0.33	1.00	0.74	0.33	10213.
234.	****	0.0	11.16	0.37	5.02	0.09	0.22	0.16	0.17	0.17	0.21	10.1	14.7	6.6	11.1	17.3	0.33	1.00	0.74	0.33	10213.
235.	****	0.0	11.16	0.39	5.19	0.09	0.21	0.16	0.17	0.17	0.21	10.1	14.7	6.6	11.1	17.2	0.33	1.00	0.74	0.33	10213.
236.	****	0.0	11.16	0.31	5.30	0.07	0.20	0.16	0.17	0.17	0.21	10.1	14.8	6.6	11.1	17.1	0.33	1.00	0.74	0.33	10213.
237.	****	0.0	11.16	0.15	5.35	0.04	0.19	0.16	0.17	0.17	0.21	10.1	14.8	6.6	11.1	17.0	0.33	1.00	0.74	0.33	10213.
238.	****	0.0	11.16	0.31	5.43	0.07	0.19	0.16	0.17	0.17	0.21	10.0	14.9	6.6	11.1	16.9	0.33	1.00	0.74	0.33	10213.
239.	****	0.0	11.16	0.30	5.51	0.07	0.18	0.16	0.17	0.17	0.20	10.0	14.9	6.6	11.1	16.8	0.33	1.00	0.74	0.33	10213.
240.	****	0.0	11.16	0.36	5.59	0.09	0.17	0.16	0.17	0.17	0.20	10.0	15.0	6.6	11.1	16.6	0.33	1.00	0.74	0.33	10213.
241.	****	0.0	11.16	0.39	5.66	0.09	0.17	0.16	0.17	0.17	0.20	10.0	15.0	6.6	11.1	16.5	0.33	1.00	0.74	0.33	10213.
242.	****	0.0	11.16	0.17	5.68	0.04	0.16	0.16	0.17	0.17	0.20	10.0	15.1	6.6	11.1	16.4	0.33	1.00	0.74	0.33	10213.
243.	****	0.0	11.16	0.45	5.74	0.04	0.16	0.16	0.17	0.17	0.20	10.0	15.1	6.6	11.1	16.3	0.33	1.00	0.74	0.33	10213.
244.	****	0.0	11.16	0.32	5.78	0.08	0.15	0.16	0.17	0.17	0.20	10.0	15.2	6.6	11.1	16.2	0.33	1.00	0.74	0.33	10213.
245.	****	0.0	11.16	0.38	5.82	0.09	0.15	0.16	0.17	0.17	0.19	10.1	15.2	6.6	11.1	16.2	0.33	1.00	0.74	0.33	10213.

S U M M A R Y O U T P U T S

PREDICTED GROWTH STAGES (JULIAN DAY)

SEEDING	EMERGENCE	JOINTING	HEADING	SOFT-DOUGH	MATURITY
141.	148.	172.	196.	221.	233.

PRECIPITATION DURING THE GROWING SEASON: 111.60 mm

PRECIPITATION FROM SEEDING TO HARVEST : 111.60 mm

POTENTIAL EVAPOTRANSPIRATION : 471.19 mm

ACTUAL TRANSPIRATION : 240.20 mm

Y I E L D (kg/ha)

ABOVEGROUND NET PRODUCTION	GRAIN
10213.	4187.

1 SITE/YEAR OF SIMULATION - MARIAPOLIS / 1982

SPECIAL DRIVING PARAMETER VALUES
0SDPV 2 2 1831952 1200.410 20 0 1 2 0 1 2 8 2 2 718 0 0 39999 2 2 1 1 1

SIMULATION SCENARIO - II (SOIL PHYSICAL PARAMETERS CALCULATED,BOUNDARY AND INITIAL CONDITIONS APPROXIMATED)

GENERAL INFORMATION

CROP DISTRICT: 1

SOIL PHYSICAL PARAMETERS

FIELD CAPACITY (mc/mc)	:	0.38	0.37	0.36	0.36	0.36	0.36	0.34	0.35	0.0	0.0
WILTING POINT (mc/mc)	:	0.16	0.15	0.15	0.15	0.15	0.15	0.14	0.13	0.0	0.0
BULK DENSITY (Mg/mc)	:	1.01	1.03	1.45	1.49	1.49	1.50	1.51	1.54	0.0	0.0
AVAILABEL WATER (mc/mc)	:	0.22	0.22	0.21	0.21	0.21	0.21	0.21	0.22	0.0	0.0

LOWER BOUNDARY CONDITIONS

WATER TABLE : 99

PHYSICAL BOUNDARY : 0

DRAINAGE CLASS : 3

LEGEND:
WATER TABLE : PRESENT=15, ABSENT =99, UNKNOWN=98
PHYSICAL BOUNDARY : PRESENT= 1, ABSENT = 0
DRINAGE CLASS : WELL = 3, IMPERFECT= 2, POORLY = 1

INITIAL CONDITIONS

WATER CONTENT (mc/mc)	:	0.38	0.37	0.36	0.36	0.36	0.36	0.34	0.35	0.0	0.0
NO3-N CONCENTRATION (ppm)	:	30.5	21.2	13.6	13.6	23.0	23.0	29.0	29.0	28.4	28.4

SOIL TEMPERATURE AT 0.20 M.(DEGREE CELSIUS): 9.15

MANAGEMENT DATA

SEEDING DATE (JULIAN DAY): 141.

NITROGEN FERTILIZER APPLIED (kg/ha): 32.

DAILY OUTPUTS

JDAY	DPHD	DAYP	CUMP	PETB	CPEV	ACET	W-	LA-1	LA-2	LA-3	LA-4	LA-5	N-	LA-1	LA-2	LA-3	LA-4	LA-5	LMWF	LMNF	LMTF	TLFT	CUMANP
232.	4.98	0.0	10.46	0.53	5.47	0.07		0.22	0.15	0.15	0.15	0.26		10.5	13.9	5.8	9.0	20.9	0.41	1.00	0.74	0.41	11059.
233.	5.04	0.70	11.16	0.35	5.56	0.10		0.25	0.15	0.15	0.15	0.25		10.6	13.9	5.8	9.1	20.7	0.41	1.00	0.74	0.41	11059.

S U M M A R Y   O U T P U T S

PREDICTED GROWTH STAGES (JULIAN DAY)

SEEDING	EMERGENCE	JOINTING	HEADING	SOFT-DOUGH	MATURITY
141.	148.	172.	196.	221.	233.

PRECIPITATION DURING THE GROWING SEASON: 111.60 mm

PRECIPITATION FROM SEEDING TO HARVEST : 111.60 mm

POTENTIAL EVAPOTRANSPIRATION : 471.19 mm

ACTUAL EVAPORATION : 260.28 mm

Y I E L D (kg/ha)

ABOVEGROUND NET PRODUCTION	GRAIN
11059.	4534.

1 SITE/YEAR OF SIMULATION - WINNIPEG(U. OF M.) / 1982

SPECIAL DRIVING PARAMETER VALUES
0SDPV 2 2 1831952 1200.351 20 0 1 2 0 1 2 8 1 21018 0 0 39999 2 2 1 1 1

SIMULATION SCENARIO -I (SOIL PHYSICAL PARAMETERS MEASURED,BOUNDARY AND INITIAL CONDITIONS KNOWN)

GENERAL INFORMATION

CROP DISTRICT: 1

SOIL PHYSICAL PARAMETERS

FIELD CAPACITY (mc/mc) :	0.35	0.37	0.41	0.41	0.38	0.38	0.38	0.38	0.0	0.0
WILTING POINT (mc/mc) :	0.22	0.20	0.21	0.21	0.23	0.23	0.20	0.20	0.0	0.0
BULK DENSITY (Mg/mc) :	0.85	0.89	0.99	0.99	1.10	1.10	1.16	1.16	0.0	0.0
AVAILABEL WATER (mc/mc):	0.13	0.17	0.20	0.20	0.15	0.15	0.18	0.18	0.0	0.0

LOWER BOUNDARY CONDITIONS

WATER TABLE : 99

PHYSICAL BOUNDARY : 0

DRAINAGE CLASS : 3

LEGEND:
WATER TABLE : PRESENT=15, ABSENT =99, UNKNOWN=98
PHYSICAL BOUNDARY : PRESENT= 1, ABSENT = 0
DRINAGE CLASS : WELL = 3, IMPERFECT= 2, POORLY = 1

INITIAL CONDITIONS

WATER CONTENT (mc/mc) :	0.32	0.35	0.38	0.38	0.40	0.40	0.37	0.37	0.0	0.0
NO3-N CONCENTRATION (ppm):	48.6	49.6	46.0	36.0	30.6	30.6	28.2	28.2	27.5	27.5

SOIL TEMPERATURE AT 0.20 M.(DEGREE CELSIUS): 7.56

MANAGEMENT DATA

SEEDING DATE (JULIAN DAY): 132.

NITROGEN FERTILIZER APPLIED (kg/ha): 32.

DAILY OUTPUTS

JDAY	DPHD	DAYP	CUMP	PETB	CPEV	ACET	W-	LA-1	LA-2	LA-3	LA-4	LA-5	N-	LA-1	LA-2	LA-3	LA-4	LA-5	LMWF	LMNF	LMTF	TLFT	CUMANP
132.	0.13	0.0	0.0	0.43	0.00	0.0		0.32	0.35	0.38	0.40	0.37		49.4	49.9	41.0	30.6	28.2	0.0	0.0	0.0	0.0	200.
133.	0.30	0.0	0.0	0.37	0.13	0.0		0.31	0.35	0.38	0.40	0.37		50.2	50.2	41.0	30.6	28.2	0.0	0.0	0.0	0.0	200.
134.	0.45	0.0	0.0	0.39	0.26	0.0		0.30	0.35	0.38	0.40	0.37		51.0	50.5	41.0	30.6	28.2	0.0	0.0	0.0	0.0	200.
135.	0.59	0.38	0.38	0.19	0.32	0.0		0.32	0.35	0.38	0.40	0.37		51.8	50.8	41.0	30.6	28.2	0.0	0.0	0.0	0.0	200.
136.	0.76	0.20	0.58	0.19	0.38	0.0		0.33	0.35	0.38	0.40	0.37		52.6	51.0	41.0	30.6	28.2	0.0	0.0	0.0	0.0	200.
137.	0.94	0.15	0.73	0.29	0.48	0.0		0.34	0.35	0.38	0.40	0.37		53.4	51.3	41.0	30.6	28.2	0.0	0.0	0.0	0.0	200.
138.	1.12	0.0	0.73	0.22	0.55	0.0		0.33	0.35	0.38	0.40	0.37		54.2	51.6	41.0	30.6	28.2	0.92	0.17	0.71	0.17	261.
139.	1.04	0.0	0.73	0.32	0.74	0.13		0.31	0.35	0.37	0.38	0.38		55.2	51.9	40.6	29.0	28.5	0.88	0.30	0.76	0.30	284.
140.	1.08	0.0	0.73	0.46	0.84	0.15		0.30	0.35	0.37	0.38	0.38		54.6	52.2	40.5	28.9	28.4	0.83	0.48	0.80	0.48	314.
141.	1.11	0.0	0.73	0.51	0.94	0.18		0.28	0.35	0.37	0.38	0.38		53.8	52.4	40.5	28.9	28.4	0.76	0.69	0.82	0.69	374.
142.	1.15	0.0	0.73	0.58	1.08	0.16		0.27	0.35	0.37	0.38	0.38		52.6	52.5	40.4	28.8	28.3	0.65	0.76	0.84	0.65	419.
143.	1.20	0.0	0.73	0.56	1.13	0.12		0.26	0.34	0.37	0.38	0.38		51.6	52.6	40.4	28.8	28.2	0.58	0.80	0.88	0.58	489.
144.	1.25	0.0	0.73	0.42	1.15	0.12		0.25	0.34	0.37	0.37	0.38		51.1	52.8	40.3	28.7	28.2	0.52	0.80	0.93	0.52	570.
145.	1.30	0.0	0.73	0.65	1.17	0.11		0.25	0.34	0.37	0.37	0.37		50.5	52.9	40.3	28.7	28.1	0.47	0.77	0.97	0.47	622.
146.	1.35	0.0	0.73	0.55	1.19	0.12		0.24	0.34	0.37	0.37	0.37		50.2	53.0	40.2	28.7	28.0	0.39	0.79	1.00	0.39	693.
147.	1.41	0.0	0.73	0.63	1.20	0.08		0.24	0.33	0.37	0.37	0.37		49.5	53.2	40.2	28.6	28.0	0.79	0.75	1.00	0.75	813.
148.	1.46	0.0	0.73	0.68	1.21	0.29		0.23	0.32	0.36	0.37	0.37		49.5	53.3	40.1	28.6	27.9	0.75	0.78	0.96	0.75	965.
149.	1.51	0.0	0.73	0.45	1.21	0.24		0.23	0.32	0.36	0.37	0.37		48.5	52.0	40.1	28.6	27.9	0.71	0.76	0.90	0.71	1093.
150.	1.55	0.0	0.73	0.29	1.21	0.17		0.22	0.31	0.36	0.37	0.37		47.8	51.0	40.0	28.5	27.9	0.68	0.74	0.88	0.68	1196.
151.	1.59	0.18	0.91	0.21	1.21	0.13		0.23	0.31	0.36	0.37	0.37		47.5	50.4	39.9	28.5	27.8	0.70	0.71	0.91	0.70	1306.
152.	1.62	0.0	0.91	0.32	1.21	0.20		0.23	0.30	0.36	0.37	0.37		47.5	50.0	39.9	28.4	27.8	0.66	0.71	0.96	0.66	1387.
153.	1.64	0.0	0.91	0.50	1.22	0.25		0.22	0.29	0.36	0.37	0.37		47.0	49.2	39.8	28.4	27.7	0.60	0.73	1.00	0.60	1486.
154.	1.68	0.0	0.91	0.67	1.22	0.18		0.22	0.28	0.36	0.37	0.37		47.9	46.8	39.8	28.4	27.7	0.74	0.73	0.99	0.73	1611.
155.	1.73	0.0	0.91	0.55	1.22	0.33		0.23	0.26	0.35	0.37	0.37		48.7	45.1	39.7	28.3	27.7	0.71	0.74	0.97	0.71	1769.
156.	1.79	0.0	0.91	0.42	1.22	0.25		0.23	0.25	0.35	0.37	0.37		49.6	42.5	39.4	28.3	27.6	0.68	0.72	0.96	0.68	1959.
157.	1.84	1.47	2.38	0.25	1.22	0.17		0.32	0.25	0.35	0.37	0.37		50.5	40.6	39.1	28.3	27.6	0.81	0.67	0.97	0.67	2125.
158.	1.87	2.54	4.92	0.31	1.24	0.23		0.35	0.37	0.35	0.37	0.37		41.9	48.2	39.1	28.2	27.5	0.92	0.65	0.97	0.65	2257.
159.	1.90	0.0	4.92	0.25	1.30	0.19		0.35	0.35	0.35	0.37	0.37		42.4	47.0	39.0	28.2	27.5	0.91	0.63	0.94	0.63	2324.
160.	1.94	0.20	5.12	0.32	1.37	0.24		0.35	0.35	0.35	0.37	0.37		42.6	46.5	38.9	28.2	27.5	0.91	0.65	0.90	0.65	2498.
161.	1.98	0.0	5.12	0.62	1.51	0.47		0.33	0.34	0.35	0.37	0.37		42.7	46.0	38.7	28.1	27.4	0.89	0.67	0.87	0.67	2645.
162.	2.03	0.0	5.12	0.38	1.58	0.30		0.32	0.33	0.34	0.37	0.37		42.1	44.8	38.1	28.1	27.4	0.88	0.67	0.84	0.67	2797.
163.	2.03	0.0	5.12	0.62	1.70	0.48		0.30	0.32	0.34	0.36	0.37		42.0	44.1	37.8	28.0	27.4	0.86	0.69	0.83	0.69	2954.
164.	2.07	0.0	5.12	0.55	1.80	0.44		0.28	0.31	0.33	0.36	0.37		41.2	42.8	37.2	28.0	27.3	0.83	0.70	0.84	0.70	3077.
165.	2.10	0.0	5.12	0.46	1.83	0.37		0.27	0.30	0.33	0.36	0.37		40.6	41.6	36.7	28.0	27.3	0.84	0.72	0.87	0.72	3205.
166.	2.12	0.0	5.12	0.49	1.84	0.40		0.26	0.29	0.33	0.36	0.37		40.1	40.7	36.3	27.9	27.3	0.83	0.73	0.89	0.73	3338.
167.	2.16	0.36	5.48	0.52	1.85	0.43		0.27	0.28	0.32	0.36	0.37		39.5	39.9	35.8	27.8	27.2	0.82	0.75	0.91	0.75	3522.
168.	2.18	0.0	5.48	0.37	1.85	0.31		0.27	0.28	0.32	0.36	0.37		38.9	39.0	35.3	27.7	27.2	0.81	0.75	0.93	0.75	3707.
169.	2.21	0.0	5.48	0.35	1.86	0.30		0.26	0.27	0.32	0.36	0.36		38.6	38.4	35.0	27.7	27.2	0.79	0.74	0.93	0.74	3847.
170.	2.23	0.71	6.19	0.26	1.86	0.22		0.30	0.27	0.32	0.36	0.36		38.4	37.8	34.6	27.6	27.1	0.82	0.74	0.93	0.74	3988.
171.	2.27	0.0	6.19	0.48	1.88	0.41		0.29	0.26	0.31	0.36	0.36		38.5	37.5	34.4	27.5	27.1	0.83	0.75	0.93	0.75	4134.
172.	2.29	0.0	6.19	0.49	1.90	0.43		0.28	0.25	0.31	0.35	0.36		38.1	36.7	33.9	27.4	27.0	0.81	0.76	0.93	0.76	4284.
173.	2.32	0.0	6.19	0.57	1.92	0.41		0.27	0.24	0.30	0.35	0.36		37.5	35.7	33.5	27.3	27.0	0.79	0.77	0.93	0.77	4438.
174.	2.37	0.0	6.19	0.57	1.93	0.39		0.26	0.23	0.30	0.35	0.36		37.0	34.8	33.2	27.2	27.0	0.78	0.79	0.95	0.78	4698.
175.	2.40	0.0	6.19	0.46	1.93	0.40		0.25	0.23	0.30	0.35	0.36		36.4	34.0	32.8	27.1	26.9	0.76	0.78	0.97	0.76	4801.
176.	2.43	0.0	6.19	0.59	1.93	0.37		0.24	0.22	0.30	0.35	0.36		35.9	33.1	32.4	27.0	26.8	0.74	0.80	0.98	0.74	4953.
177.	2.48	0.0	6.19	0.57	1.93	0.34		0.23	0.21	0.29	0.35	0.36		35.3	32.3	32.1	26.9	26.8	0.77	0.81	0.99	0.77	5220.
178.	2.52	0.0	6.19	0.57	1.93	0.39		0.23	0.20	0.29	0.34	0.36		34.7	31.6	31.8	26.8	26.7	0.76	0.81	1.00	0.76	5432.
179.	2.55	0.0	6.19	0.49	1.93	0.43		0.23	0.20	0.28	0.34	0.36		35.4	29.2	31.5	26.7	26.6	0.74	0.81	1.00	0.74	5588.
180.	2.57	0.0	6.19	0.47	1.93	0.41		0.23	0.20	0.27	0.34	0.36		36.1	29.5	29.9	26.6	26.5	0.72	0.82	1.00	0.72	5741.
181.	2.60	0.0	6.19	0.62	1.93	0.36		0.23	0.20	0.26	0.34	0.35		36.8	29.8	28.5	26.5	26.4	0.70	0.83	1.00	0.70	5891.
182.	2.65	0.0	6.19	0.62	1.94	0.35		0.22	0.20	0.25	0.34	0.35		37.5	30.1	27.2	26.4	26.3	0.68	0.84	1.00	0.68	6086.
183.	2.70	2.54	8.73	0.38	1.94	0.36		0.35	0.24	0.24	0.34	0.35		36.3	32.2	26.2	26.3	26.2	0.81	0.85	1.00	0.81	6434.
184.	2.76	0.0	8.73	0.44	1.94	0.42		0.32	0.24	0.24	0.33	0.35		35.1	33.1	25.6	26.2	26.2	0.80	0.85	0.98	0.80	6777.
185.	2.83	0.0	8.73	0.63	1.94	0.48		0.31	0.24	0.24	0.33	0.35		34.3	32.4	25.4	26.0	26.0	0.78	0.87	0.94	0.78	7169.
186.	2.89	2.34	11.07	0.50	1.94	0.48		0.35	0.34	0.24	0.33	0.35		29.4	35.4	25.1	25.9	25.9	0.83	0.88	0.86	0.83	7525.
187.	2.94	0.0	11.07	0.49	1.94	0.48		0.34	0.33	0.24	0.33	0.34		28.7	34.6	24.9	25.8	25.7	0.82	0.89	0.74	0.74	7786.
188.	2.98	0.0	11.07	0.41	1.94	0.41		0.33	0.32	0.24	0.33	0.34		28.2	33.8	24.6	25.6	25.5	0.81	0.91	0.74	0.74	7994.
189.	3.02	0.0	11.07	0.50	1.94	0.50		0.32	0.30	0.23	0.32	0.34		27.7	33.1	24.4	25.5	25.4	0.80	0.93	0.74	0.74	8199.
190.	3.05	0.0	11.07	0.51	1.94	0.42		0.31	0.30	0.23	0.32	0.34		27.2	32.3	24.1	25.4	25.3	0.78	0.94	0.74	0.74	830[illegible].

191.	3.10	0.0	11.07	0.55	1.94	0.43	0.30	0.29	0.23	0.32	0.34	26.7	31.6	23.8	25.3	25.1	0.77	0.96	0.74	0.74	8553.
192.	3.15	0.0	11.07	0.59	1.94	0.44	0.29	0.28	0.23	0.32	0.33	26.2	31.0	23.6	25.2	25.0	0.75	0.98	0.74	0.74	8801.
193.	3.20	0.0	11.07	0.64	1.94	0.45	0.28	0.27	0.23	0.32	0.33	25.7	30.2	23.3	25.0	24.9	0.74	0.99	0.74	0.74	9091.
194.	3.24	0.94	12.01	0.37	1.94	0.36	0.34	0.26	0.22	0.32	0.33	25.3	29.5	23.1	24.9	24.7	0.76	0.99	0.74	0.74	9282.
195.	3.29	0.0	12.01	0.60	1.94	0.36	0.32	0.26	0.22	0.32	0.33	24.9	29.1	22.9	24.8	24.6	0.74	0.99	0.74	0.74	9469.
196.	3.34	0.0	12.01	0.51	1.94	0.36	0.31	0.25	0.22	0.31	0.33	24.6	28.7	22.7	24.7	24.5	0.73	1.00	0.74	0.73	9694.
197.	3.39	0.0	12.01	0.57	1.94	0.36	0.31	0.25	0.22	0.31	0.33	24.3	28.2	22.4	24.6	24.4	0.72	1.00	0.74	0.72	9952.
198.	3.43	2.31	14.32	0.41	1.95	0.36	0.35	0.34	0.22	0.31	0.33	21.7	30.0	22.2	24.5	24.3	0.79	1.00	0.74	0.74	10124.
199.	3.47	0.0	14.32	0.44	1.96	0.36	0.34	0.33	0.22	0.31	0.32	21.5	29.5	22.1	24.4	24.2	0.77	1.00	0.74	0.74	10251.
200.	3.51	0.0	14.32	0.45	1.97	0.36	0.33	0.32	0.22	0.31	0.32	21.3	29.0	21.9	24.3	24.1	0.76	1.00	0.74	0.74	10456.
201.	3.56	0.0	14.32	0.53	1.99	0.36	0.32	0.31	0.22	0.31	0.32	21.1	28.6	21.8	24.2	24.0	0.75	1.00	0.74	0.74	10655.
202.	3.60	0.0	14.32	0.45	2.01	0.36	0.31	0.30	0.21	0.31	0.32	21.0	28.2	21.6	24.1	23.9	0.73	1.00	0.74	0.73	10807.
203.	3.64	0.0	14.32	0.43	2.03	0.36	0.30	0.30	0.21	0.30	0.32	20.8	27.8	21.4	24.0	23.8	0.72	1.00	0.74	0.72	10916.
204.	3.69	0.0	14.32	0.43	2.06	0.36	0.29	0.29	0.21	0.30	0.32	20.6	27.4	21.1	23.9	23.7	0.70	1.00	0.74	0.70	11087.
205.	3.73	0.0	14.32	0.41	2.08	0.36	0.29	0.28	0.21	0.30	0.32	20.4	27.0	20.9	23.8	23.6	0.68	1.00	0.74	0.68	11248.
206.	3.77	0.0	14.32	0.46	2.10	0.36	0.28	0.27	0.21	0.30	0.32	20.2	26.6	20.7	23.7	23.5	0.67	1.00	0.74	0.67	11368.
207.	3.82	0.0	14.32	0.60	2.12	0.36	0.27	0.27	0.21	0.30	0.31	20.0	26.1	20.7	23.4	23.4	0.65	1.00	0.74	0.65	11508.
208.	3.87	0.38	14.70	0.50	2.13	0.36	0.29	0.26	0.21	0.29	0.31	19.8	25.7	20.7	23.1	23.3	0.65	1.00	0.74	0.65	11615.
209.	3.92	0.0	14.70	0.55	2.14	0.36	0.28	0.25	0.21	0.29	0.31	19.6	25.3	20.7	22.9	23.2	0.63	1.00	0.74	0.63	11739.
210.	3.95	1.96	16.66	0.44	2.16	0.36	0.35	0.29	0.21	0.29	0.31	18.7	25.6	20.7	22.6	23.1	0.71	1.00	0.74	0.71	11845.
211.	4.00	0.0	16.66	0.48	2.26	0.36	0.33	0.30	0.21	0.28	0.31	18.4	25.4	20.8	22.3	23.0	0.69	1.00	0.74	0.69	11944.
212.	4.05	0.0	16.66	0.61	2.39	0.36	0.31	0.29	0.21	0.28	0.31	18.3	25.1	20.8	22.0	22.9	0.66	1.00	0.74	0.66	12079.
213.	4.07	0.0	16.66	0.42	2.49	0.36	0.30	0.28	0.21	0.28	0.31	18.2	24.7	20.8	21.7	22.8	0.64	1.00	0.74	0.64	12164.
214.	4.18	0.53	17.19	0.41	2.57	0.36	0.32	0.27	0.21	0.27	0.30	18.1	24.4	20.8	21.4	22.7	0.64	1.00	0.74	0.64	12380.
215.	4.29	0.0	17.19	0.54	2.72	0.36	0.30	0.27	0.21	0.27	0.30	18.0	24.1	20.8	21.2	22.6	0.62	1.00	0.74	0.62	12573.
216.	4.41	0.0	17.19	0.47	2.88	0.36	0.28	0.26	0.21	0.27	0.30	17.8	23.7	20.8	20.9	22.5	0.59	1.00	0.74	0.59	12717.
217.	4.49	0.0	17.19	0.58	2.97	0.36	0.27	0.25	0.21	0.26	0.30	17.7	23.4	20.8	20.6	22.4	0.56	1.00	0.74	0.56	12814.
218.	4.62	0.0	17.19	0.44	3.01	0.36	0.26	0.25	0.21	0.26	0.30	17.5	23.0	20.8	20.3	22.3	0.53	1.00	0.74	0.53	12926.
219.	4.73	0.0	17.19	0.45	3.03	0.12	0.25	0.24	0.21	0.26	0.30	17.3	22.6	20.8	20.0	22.3	0.52	1.00	0.74	0.52	13002.
220.	4.79	1.07	18.26	0.35	3.04	0.15	0.32	0.24	0.21	0.26	0.30	17.5	22.7	20.8	19.9	22.2	0.58	1.00	0.74	0.58	13042.
221.	4.84	0.0	18.26	0.35	3.11	0.14	0.31	0.24	0.21	0.26	0.30	17.6	22.7	20.8	19.8	22.2	0.57	1.00	0.74	0.57	13066.
222.	4.87	0.0	18.26	0.46	3.39	0.11	0.29	0.24	0.21	0.26	0.30	17.8	22.8	20.8	19.7	22.1	0.54	1.00	0.74	0.54	13081.
223.	4.93	0.0	18.26	0.49	3.60	0.10	0.27	0.24	0.21	0.25	0.30	17.9	22.8	20.8	19.6	22.1	0.52	1.00	0.74	0.52	13109.
224.	5.03	0.0	18.26	0.28	3.64	0.09	0.27	0.24	0.21	0.25	0.30	18.1	22.9	20.8	19.6	22.1	0.52	1.00	0.74	0.52	13109.
225.	****	0.0	18.26	0.48	3.69	0.08	0.26	0.24	0.21	0.25	0.30	18.0	22.8	20.8	19.6	22.0	0.52	1.00	0.74	0.52	13109.
226.	****	0.48	18.74	0.54	3.73	0.09	0.29	0.23	0.21	0.25	0.30	18.0	22.7	20.8	19.5	22.0	0.52	1.00	0.74	0.52	13109.
227.	****	0.0	18.74	0.38	3.78	0.11	0.28	0.23	0.21	0.25	0.30	17.9	22.5	20.7	19.5	22.0	0.52	1.00	0.74	0.52	13109.
228.	****	0.0	18.74	0.52	3.90	0.09	0.27	0.23	0.21	0.25	0.29	17.8	22.4	20.7	19.4	21.9	0.52	1.00	0.74	0.52	13109.
229.	****	3.53	22.27	0.57	3.99	0.06	0.35	0.32	0.21	0.25	0.29	16.5	23.5	20.7	19.4	21.9	0.52	1.00	0.74	0.52	13109.
230.	****	0.0	22.27	0.50	4.33	0.08	0.32	0.32	0.21	0.25	0.29	16.4	23.4	20.7	19.3	21.8	0.52	1.00	0.74	0.52	13109.
231.	****	0.0	22.27	0.45	4.64	0.07	0.30	0.32	0.21	0.25	0.29	16.3	23.2	20.7	19.3	21.8	0.52	1.00	0.74	0.52	13109.
232.	****	0.0	22.27	0.45	4.94	0.07	0.28	0.31	0.21	0.25	0.29	16.3	22.9	20.7	19.2	21.8	0.52	1.00	0.74	0.52	13109.
233.	****	0.0	22.27	0.38	5.04	0.11	0.27	0.31	0.21	0.25	0.29	16.2	22.7	20.7	19.2	21.7	0.52	1.00	0.74	0.52	13109.
234.	****	0.0	22.27	0.38	5.08	0.11	0.27	0.30	0.21	0.25	0.29	16.2	22.5	20.7	19.1	21.7	0.52	1.00	0.74	0.52	13109.
235.	****	0.46	22.73	0.39	5.11	0.12	0.29	0.30	0.21	0.25	0.29	16.2	22.3	20.6	19.1	21.7	0.52	1.00	0.74	0.52	13109.
236.	****	0.0	22.73	0.22	5.14	0.06	0.29	0.30	0.21	0.25	0.29	16.1	22.2	20.6	19.0	21.6	0.52	1.00	0.74	0.52	13109.
237.	****	0.05	22.73	0.20	5.20	0.06	0.29	0.30	0.21	0.25	0.29	16.1	22.2	20.6	19.0	21.6	0.52	1.00	0.74	0.52	13109.

S U M M A R Y   O U T P U T S

PREDICTED GROWTH STAGES (JULIAN DAY)

SEEDING	EMERGENCE	JOINTING	HEADING	SOFT-DOUGH	MATURITY
132.	138.	162.	189.	212.	224.

PRECIPITATION DURING THE GROWING SEASON: 182.60 mm

PRECIPITATION FROM SEEDING TO HARVEST : 227.30 mm

POTENTIAL EVAPOTRANSPIRATION : 486.84 mm

ACTUAL TRANSPIRATION : 280.41 mm

Y I E L D (kg/ha)

ABOVEGROUND NET PRODUCTION	GRAIN
13109.	4601.

1 SITE/YEAR OF SIMULATION - WINNIPEG(U. OF M.) / 1982

SPECIAL DRIVING PARAMETER VALUES
0SDPV 2 2 1831952 1200.351 20 0 1 2 0 1 2 8 1 2 718 0 0 39999 2 2 1 1 1

SIMULATION SCENARIO - II (SOIL PHYSICAL PARAMETERS CALCULATED,BOUNDARY AND INITIAL CONDITIONS APPROXIMATED)

GENERAL INFORMATION

CROP DISTRICT: 1

SOIL PHYSICAL PARAMETERS

FIELD CAPACITY (mc/mc) :	0.47	0.48	0.46	0.46	0.45	0.45	0.44	0.44	0.0	0.0
WILTING POINT (mc/mc) :	0.27	0.26	0.25	0.25	0.24	0.24	0.23	0.23	0.0	0.0
BULK DENSITY (Mg/mc) :	0.93	1.01	1.38	1.38	1.40	1.40	1.41	1.41	0.0	0.0
AVAILABEL WATER (mc/mc):	0.20	0.22	0.21	0.21	0.21	0.21	0.21	0.21	0.0	0.0

LOWER BOUNDARY CONDITIONS

WATER TABLE : 99

PHYSICAL BOUNDARY : 0

DRAINAGE CLASS : 3

LEGEND:
WATER TABLE : PRESENT=15, ABSENT =99, UNKNOWN=98
PHYSICAL BOUNDARY : PRESENT= 1, ABSENT = 0
DRINAGE CLASS : WELL = 3, IMPERFECT= 2, POORLY = 1

INITIAL CONDITIONS

WATER CONTENT (mc/mc) :	0.47	0.48	0.46	0.46	0.45	0.45	0.44	0.44	0.0	0.0
NO3-N CONCENTRATION (ppm):	48.6	49.6	46.0	36.0	30.6	30.6	28.2	28.2	27.5	27.5

SOIL TEMPERATURE AT 0.20 M.(DEGREE CELSIUS): 7.56

MANAGEMENT DATA

SEEDING DATE (JULIAN DAY): 132.

NITROGEN FERTILIZER APPLIED (kg/ha): 32.

DAILY OUTPUTS

JDAY	DPHD	DAYP	CUMP	PETB	CPEV	ACET	W-	LA-1	LA-2	LA-3	LA-4	LA-5	N-	LA-1	LA-2	LA-3	LA-4	LA-5	LMWF	LMNF	LMTF	TLFT	CUMANP
223.	4.93	0.0	18.26	0.49	4.33	0.14		0.36	0.27	0.25	0.34	0.36		21.8	23.6	20.8	23.6	22.5	0.63	1.00	0.74	0.63	13554.
224.	5.03	0.0	18.26	0.28	4.38	0.09		0.35	0.27	0.25	0.34	0.36		21.9	23.6	20.8	23.6	22.5	0.63	1.00	0.74	0.63	13554.

S U M M A R Y   O U T P U T S

PREDICTED GROWTH STAGES (JULIAN DAY)

SEEDING	EMERGENCE	JOINTING	HEADING	SOFT-DOUGH	MATURITY
132.	138.	162.	189.	212.	224.

PRECIPITATION DURING THE GROWING SEASON: 182.60 mm

PRECIPITATION FROM SEEDING TO HARVEST : 227.30 mm

POTENTIAL EVAPOTRANSPIRATION : 486.84 mm

ACTUAL EVAPORATION : 297.95 mm

Y I E L D (kg/ha)

ABOVEGROUND NET PRODUCTION	GRAIN
13554.	4757.