LAND EVALUATION MODEL

by

CONSTANTIN ONOFREI

A thesis
presented to the University of Manitoba
in partial fulfillment of the
requirements for the degree of
MASTER OF SCIENCE
in
DEPARTMENT OF SOIL SCIENCE

Winnipeg, Manitoba, 1981

LAND EVALUATION MODEL

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

MASTER OF SCIENCE

ACKNOWLEDGEMENTS

I wish to thank Dr. R. A. Hedlin and Mr. R. E. Smith for their assistance and guidance during the research program and preparation of the thesis. I would like to thank Dr. C. F. Shaykewich for his help and comments as well as Mr. G. J. Mills for his help with job computer program.

A special thanks to my wife, Maria, for her support and encouragement.

ABSTRACT

In recent years, as more information has become available through research, attempts have been made to extend simulation techniques to more complex areas. The idea of using computer simulation for evaluation of land is very new. Use of models for such purposes has been developed as part of an extensive program recently initiated by the Land Resource Research Institute of Canada.

The goal of the present study was not only to present a technique for a quantitatve description of certain processes within the system of interest, but also to study the possibilities of simulation itself. The model was based on a program for simulation of nitrogen flow under field conditions developed by Vithayathil et al. (1977). The model might be defined as a limiting factors type. The major limiting factors considered were water, nitrogen and temperature.

The prediction of yield, as a result of the combined effect of climate, soil and management factor, was expressed in terms of above ground dry matter. For validation purposes, as a first approximation, dry matter production was converted to grain yield using the harvest index approach.

A partial validation and verification of the model was realized using data from a farming system and from a field program carried out during 1979 on two farms (on clayey Chernozemic soil and a clayey Gleysolic soil). Under these circumstances the overall output of the model in terms of both grain and above ground dry matter was considered reasonably good. The deviation of model prediction in terms of grain, as compared with actual farming system output, fell in a range of +66 to -272 kg/ha. In terms of above ground dry matter, as compared with field program data, the final yield deviation was in a range of +48 to -1154 kg/ha. The model seems to underpredict dry matter production especially at the beginning of the growing season.

Some compromises and modifications must be accepted in order to make a model simple enough for a problem to be solved within a reasonable

time. With some improvement in prediction of soil water content, the present model can be used for simulation purposes at a pilot plant scale, i.e. land areas of about two townships.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter I
INTRODUCTION

Many concepts of Land Evaluation as well as methods for rating land have been proposed in the past. As a result several rating systems currently are employed.

Some of them are based on inherent characterstics of the soil and require the competence of soil scientists in order to be interpreted. Others are based on the empirical evaluation of soil survey information and require, to some extent, special soil surveys.

Indeed, Land Evaluation may be expressed in socio-economic terms but this approach is exceedingly complex. At the present time there is concensus in Canada that development of reliable productivity indices to homogenous land units are a necessary first step in developing a rational quantitative land evaluation program.

Two terms (productivity and capability) are very often employed to describe, in a general way, the relation between soil characteristics and yield. The productivity is defined as the initial soil capability to produce a certain amount of crop per unit area during a year. For virgin land the productivity may be related to natural fertility whereas for cultivated land it is related mostly with present and past management. The second term, capability, is employed in the sense of productivity of soil when all possible improvements, regardless of cost and difficulty, have been made. Neither of the above concepts, alone, can be used to evaluate various land units. In the real system there will always be some characteristics which can not be modified even by present day technology. On the other hand the Productivity can be increased by practices such as fertilizer use.

In recent years several attempts have been made to approach land evaluation from a quantitative view point and to extend simulation techniques to this area, considered until now too complex and difficult for such an approach. Basically, the aim of modeling is to predict quantitative estimates from some of the physical, chemical and biological processes.

The objective of the present study was to examine the possibility of using computer simulation techniques to evaluate different land units in Manitoba by means of crop yield. Therefore, the system of interest was crop-soil within which the mutual organization of smaller structural parts determined the characteristics of the whole.

Since a particular organization of the system will occur with each crop or group of crops and because cereals constitute the main group of crops in Manitoba, wheat was considered as the basis for development of the model.

Chapter II
LITERATURE REVIEW

2.1 SYSTEMS - SYSTEM ANALYSIS

The evaluation of land by means of simulation technique is very new and there is a need for improvement in this area.

As Naylor et al. (1966) pointed out, simulation is a technique which involves building a model of a real system and then performing experiments on the model. It is obvious that the simulation studies can not progress beyond the modeling phase before the model is proven to be satisfactory.

The starting point in this activity is defining the system to be studied. Forrester (1976) considered the system as a grouping of parts which operate together for a common purpose. Baker and Curry (1976) defined a system, in general terms, as a collection of identifiable parts capable of interacting in such a way that the entire collection functions together to satisfy a set of specific requirements. From those view points a system may be any socio-economic activity or any physical, chemical or biological process as well as interactions between them. However, it is not possible to build a model without knowing the structure of the system and how its parts are related.

Most of the information in this area comes from research work which employed either analysis or a synthesis method in studying the systems. The analysis, which has been extensively used, has tended to be concentrated on small parts of the system in isolation from the whole. During the last century knowledge of systems at the micro-level has increased substantially but few attempts have been successful in synthesizing this knowledge into the context of the whole system. As Ashby (1970) pointed out, that is to be expected since the method of analysis, sometimes presented as obligatory, is in fact a strategy. By dividing the whole into parts the amount of information with which one has to deal decreases substantially. By contrast, the combination of parts to form a whole is much more difficult since frequently the amount of information necessary to comprehend the whole does not increase proportionally to the number of the parts, but exponentially. It is obvious that in modeling there is difficulty in using existing research data. Since this activity has to deal especially with the process of synthesis it is often necessary to modify existing data or even to synthesize relationships from only a few or no data.

The fundamental assumption of system analysis is that the system is organized in a hierarchy of complexity and the final behaviour of the whole is a consequence of the actions and interactions of simple activities and processes. Since, within the system of interest, man is attempting to control a biological entity in an uncertain environment to achieve a desirable goal, the system may be confounded with the farming system. From the Land Evaluation view point it is more appropriate to focus only short-term management decisions (i.e. that set of decisions which are taken by the farmer in order to operate the plant-soil system). The second type of policy or planning with which the farmer must deal, namely long-term goals, was not considered. Such decisions are under socio-economic environmental control and to account for them the system of interest becomes extremely complex.

2.1.1 Boundary of the System

No system is isolated. Every system interacts with other systems on its own level of organization as well as at lower and higher levels. Although to some extent system boundaries are arbitrary and a matter of convenience, they must exist. Otherwise the problem under study will be continuously moved from a lower level of organization to a higher one and never solved. However, the boundary of the system does not necessarily mean a complete isolation of the system from its surrounding environment. The interactions with neighbouring systems constitute the overall input and output of the system being considered. Always between the system and its environment as well as within the system, between the system components (sub-systems), exchanges of matter, energy and information will occur.

2.1.2 The Biological System and some of its Characteristics

Regardless of the boundaries which are chosen, any agricultural system must include in its structure the biological sub-system (i.e. the crop of interest). For convenience this sub-system will be treated in this chapter as a system.

The most convenient way to treat the quantitative aspects of any system is to treat them in a mathematical manner. This is not easy when we are dealing with a biological system. It is generally agreed that such systems are very complex and that they are hierarchically organized with particular relationships between levels. In addition the basic characteristic of a living system is its self-regulation mechanism (control) and this aspect is difficult, if not impossible, to account for in a model.

Although biology and mathematics evolved simultaneously, specific terminology and laws govern each of them. In the past many attempts have been made to use these two sciences for a mutual benefit. The subject is very complex and has been reviewed elsewhere (Smith, 1968; Rubinow, 1975; Pielow, 1969;Rosen, 1973).

A brief discussion of the terminology customarily used as well as of several aspects of the mathematical treatment of biological systems might be helpful in developing the idea of a model. Usually, any object of interest within a system has been termed "entity" and its property, "attribute". The status of a system at one point in time (i.e. instantaneous condition) which includes a description of entities, attributes, as well as the processes that cause changes, has been called the state of the system. Since any biological system is dynamic in nature, it is obvious that its state is changing with time. The term employed to describe such a process has been the rate of change with respect to time. Gold (1977) emphasized two important consequences of treating a biological system in a dynamic manner.

1. The state of the system at any given time carries within it the memory of certain aspects of what it has been and the condition which prevailed previous to that time.
2. The influence of any new input does not affect the state at that instant in time but affects the direction and rate of change in the time immediately following.

In a dynamic condition, the state variables of a biological system as well as the status of the entire system considered will change with time. Consequently, all entities, attributes and processes will change. Pritsker (1974) termed those "statuses" as state variables. These state variables and their rates of change are the most important aspects within a system and their quantification is of great interest.

Two basic mathematical methods have been employed in describing the evolution of a dynamic system; Stochastic and Deterministic. The decision as to which description is valid is determined by the characteristics of the system itself and/or by the assumptions made in analyzing the system.

The Stochastic method has been applied to describe a system, subject to a variety of uncertainties, which presents a distribution of probabilites of state at any given time. The set of possible behaviours of the system has been based on probability. As Baier (1979) pointed out, stochastic models are more adaptable to relating climatological data to yield in a geographical region. Such a method becomes extremely complex when the model must consider the variation of soil characteristics in more detail.

The second method, Deterministic, might be applied to a system which is, or at least may be considered, completely determined by its state and by specified conditions. In this case the rate change can be described by a derivative. One of the requirements for a derivative to exist is that the curve which represents the pathway of the system through space must be continuous and smooth. Unfortunately most biological systems exist under unpredictable environmental conditions and their changes occur in rather small steps. Therefore, a stochastic description is a much more correct representation. However, due to the mathematical simplicity of deterministic description, it is often used to describe a biological system when the uncertainty is relatively small compared with the need for accuracy in representing the system. In this case an average expected behaviour of the system is considered. This can be done satisfactorily if the scale on which the system is observed is rather broad relative to the individual steps of change which occur.

2.2 MODEL - A GENERAL CONCEPT

A variety of definitions of the idea of the model have been discussed in the literature. One of the simplest, but perhaps the most meaningful definition, was given by Gold (1977).

"We may say that some object (call it object M) is a model of another object (call it object S) if the following conditions hold:

1. There is some collection of components of M each of which corresponds to a component of S;
2. For at least some relationships, the relation between the components of M is analogous to that between the corresponding components of S."

The word "model" has very much the same meaning as its every day meaning. At the same time, Gold's definition overcomes the frequent confusion which is made between system and model. It is obvious that two objects M (model) and S (system) do not correspond to each other in every detail, unless they are identical objects. But in this case the concept of model loses its usefulness.

As Ashby (1970) pointed out, we have to realize that every model is inferior to a real system. Nothing can equal the truth and accuracy of the real system itself.

If that is the case, a pertinent question might arise: Why do we develop the models? Basically, we develop models for their convenience in saving money and time and to gain some insight about what might happen to a real system under extreme conditions.

2.2.1 Mathematical Modeling of Processes

The highest logical and abstract way to describe a system is the mathematical approach. This particular description of a real world system is generally termed a mathematical model.

Usually, in analyses of a system the whole is broken down into a convenient number of parts and then one searches for relationships between the parts of interest. A similar procedure is employed through synthesis, only in the opposite direction. In model building both methods are used; analysis is concerned mostly with the system of interest whereas synthesis is related to model building itself.

If the input/output activities are treated as relationships between system parts, any simple equation is a model. Some of its symbols stand for parts and other symbols stand for relationships. However, such a description is to some extent an oversimplification since biological systems operate on the basis of process relationships rather than on relationships of parts of the system.

"Biological model" is another term often used in the literature. Smith (1975) defined such a model as a laboratory ecosystem composed of an actual organism.

In dealing with a large system such as crop growth both model types must be considered since mathematical and biological models complement one another. A unilateral mathematical treatment leads to models that will be difficult, if not impossible, to apply due to their higher degree of abstraction and generality. On the other hand, in the absence of a mathematical treatment, the general relevance of a particular biological model is lost and the technological strength of a computer is helpless.

A large number of model types as well as schemes for their classification are discussed in the literature. From a philosophical point of view, Harré (1972) categorized models into homeomorph (model form) and paromorph (model function). In the first category he included models related to the art whereas the second category included models of systems characterized by physical, chemical and biological processes.

Beckner (1959) described models as being nonexplanatory and explanatory. Gold (1977) followed up Beckner's idea and made a comparison between the two model types. He names nonexplanatory models as correlative types. A schematic representation of those model types and some of the relationships between them is presented in Figure 1. Basically, a correlative model only describes and summarises observed relationships between variables within processes. An explanatory model, in addition, reflects some concept of the causal mechanism that underlies the relationship.

de Wit and Arnold (1976) pointed out that explanatory model types have gained wide acceptance in describing research as well as management ecosystems. The basic assumption within such a model type is that the

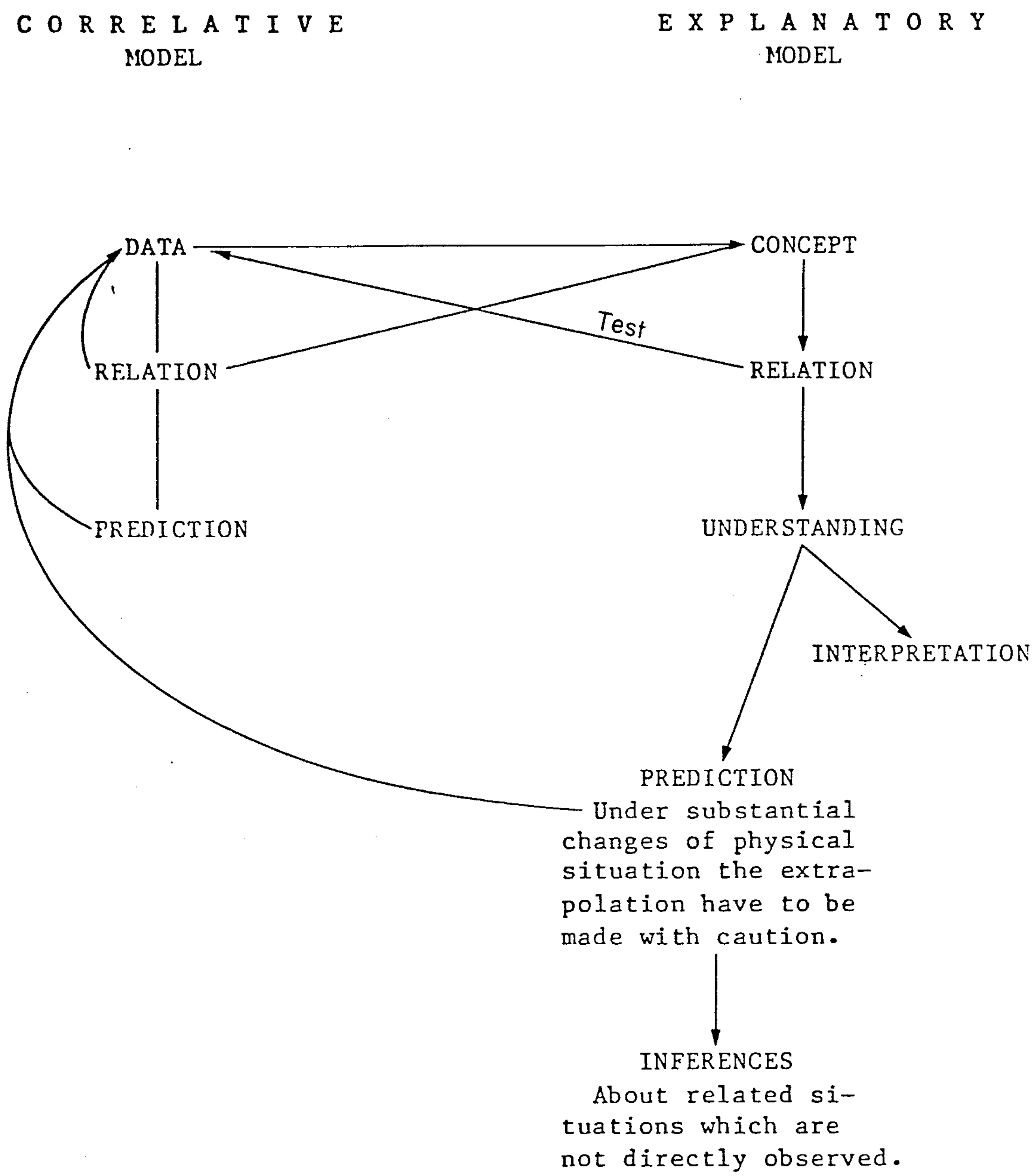


FIG. 1 : RELATIONSHIPS BETWEEN CORRELATIVE AND EXPLANATORY MODEL. (After Gold,1977)

state of systems or subsystems, at any point in time, can be quantitatively characterized and the change in the state can be mathematically described.

2.2.2 Modeling Activities in Agriculture

In the past two decades there has been a good deal of interest in agricultural sciences, in the use of computer techniques to describe various physiological processes. Relatively complex reviews on this subject have been given by Hesketh and Jones (1975) and Nye and Tinker (1977). Some of the existing models of processes are presented in Table 1.

It might appear paradoxical, but models which describe a similar physiological process are not necessarily the same. There are several reasons for this. First, the difference among models is due to the difference in the objectives. Second, even when objectives are identical a difference may occur due to the selection of system characteristics which are represented in the model. Finally, the difference between models may occur even if both the objective and selected characteristics of the system under consideration are similar. Such a difference may occur due to different theories chosen to describe a particular process. Although, it is true that the biological system can be described more realistically in terms of processes, some inconveniences occur due to the incomplete understanding of most of the biological processes. For example, even an Evapotranspiration model, considered the most successful, is to some extent empirical indicating an incomplete description of how the system works. As Visser (1974) pointed out such models assume that the yield (or yield increase) is directly proportional to the opening of the stomata and the uptake of CO_2. The entry of CO_2 is considered to occur at the same moment as water vapour flows from stomata to the atmosphere. Consequently, such models assumed a direct relationship between evapotranspiration and growth. According to Meidner (1975), the major path for water vapor diffusion is from inner epidermal and guard cell walls to stomata pores whereas the paths for CO_2 lead from stomata via substomatal cavities to mesophyll cell walls in the interior of the leaf and, therefore, are considerably longer. If Meidner's findings are true, the stomatal opening, essential for photosynthesis, can be initi-

TABLE 1: MODELS OF PROCESSES

I PHOTOSYNTHESIS (de Wit,1970;Hall and Bjorkman,1975 ;Nobel et al.,1975;Sestak et al., 1971;Rosenburg,1974)
- Leaf models;
- Canopy models.

II RESPIRATION(Peenning de Vries,1972)
- Gas exchange and growth models;
- Maintenance and growth models.

III TRANSPORT-TRANSLOCATION(de Wit and van Keulen,1972 ;Canny,1973;Peel,1974)
- The most used hypotheses: Mass-flow; Diffusion; Active transport.

IV EVAPOTRANSPIRATION(Monteith,1972;Baier,1971,1973; De Vries and Afgan, 1975)

V SOIL-PLANT WATER TRANSPORT(Taylor and Klepper,1975 ;Fiscus,1975;Hiler and Hawell,1974; van Keulen,1975;Morgan et al.1980)
- Root models;
- Whole plant models.

VI PHYSIOLOGICAL DEVELOPMENT(Robertson,1968;Williams 1974;McArthur et al.,1975)
- Degree-day phenological models;
- Degree-day-photoperiod models.

VII STRESS PHYSIOLOGY(Jensen,1971;Minhas et al.,1974; Hiler and Clark,1971)
- Water stress models;
- Nutrients stress models.

VIII SOIL CHEMISTRY,ROOT UPTAKE,PLANT NUTRITION(Olsen and Kemper,1968;Beek and Frissel, 1973;Baldwin and Nye,1974;Tanji-Gupta,1977;Frissel and van Veen 1977)
- Nitrogen transformations models;
- Soil chemistry-water flow-ions uptake models.

ated and maintained over a wide range of overall leaf water potentials since the epidermis contains its own water supply route and provides a major evaporation site within the leaf air space system. Therefore, the theory behind evapotranspiration models must be considered with caution.

However, a second step has been taken in agricultural modeling in order to explore the possibilities of studying whole plant behavior by integrating information describing various physiological processes. de Wit et al. (1970), after developing a model for photosynthetic processes, constructed a comprehensive Plant Growth model. Others followed, and several six-letter computer program abbreviations denoting large models appeared: SIMCOT (cotton), SIMAIZ (corn), SIMSOY (soybeans), etc.

The technique frequently employed in constructing a large model is based on subprograms (subroutines) already in existence which describe one or a group of physical, chemical and biological processes. Since natural systems are capable of providing a great variety of models with no one of them having absolute priority, when a submodel is needed a pertinent question arises: Which one shall we choose?

Unfortunately, the selection is to some extent arbitrary. Baker and Curry (1976) suggested some of the most important factors that might be considered in selecting the model structure as follows:

1. the purpose of the model (objective);
2. the availability of data;
3. the accuracy and precision of output which is required.

The objective of the study and availability of data were the main reference points in selecting the structure and subroutines used in the present model.

2.2.3 Plant Growth - Process

The most concise and powerful parameter used to describe an agricultural system is yield. Yield makes possible a practical interpretation of scientific data and basically closes the gap in understanding and communication between soil scientist, plant scientist, climatologist, agronomist, economist and farmer. Factors determining yield are complex so that it is not possible to produce a definition broad enough and explicit enough to cover the entire spectrum of processes and their interactions which, in fact, this parameter represents. However, it is unanimously recognized that the yield of a plant depends upon climatic conditions, physical and chemical properties of the soil and the presence and absence of adjacent plants. Within the agricultural system, the yield is strongly dependent on human activities. Without a farmer's activities the crop yield is virtually zero.

In its everyday meaning growth is a progressive development of something in time. Vegetative growth is perhaps the most convenient overall term that describes all activities concerning formation and expansion of any particular part as well as of a whole plant. One of the most frequent measurements used to express vegetative changes is weight of above ground dry matter per unit area.

Since the beginning of the present century two theories have been proposed to describe plant growth. T.B. Robertson advanced the so called "autocatalytic theory" which described plant growth as:

$$dw/dt=GW(c - w) \qquad (1)$$

Where: G-a constant;

W-initial plant weight;

c-plant final dry weight;

w-plant dry weight at time t.

A particular interest was shown in V.M. Blackman's plant growth equation:

$$dw/dt=GW \qquad (2)$$

All terms have the same meaning as for equation (1), except that Blackman treated G as a parameter and termed it relative growth rate.

In order to relate soil properties to yield it has been common to use mathematical and graphical representations of relationships between essential soil nutrients and plant growth known as "yield curve". One of the most extensive reviews on this subject was published by Steenbjerg and Jakobson (1963). They concluded that by smoothing the experimental results, some of the suggested yield curves might be successfully used for practical purposes. In order to improve the reliability of such curves, they have to be designated on the basis of working hypotheses concerning a knowledge of transformations and movement of nutrients in the soil and root growth as well as a knowledge of metabolic processes that occur within the plant.

2.2.4 Rate of Change and Some of the Hypotheses Considered in Computing Growth Rate

In a dynamic biological system all of its state variables change with time. Using digital-computer models, which are based on finite-difference techniques, the new value of any state variable of interest can be determined by calculating the rate of change. In order to determine the final value, the process is repeated at chosen time intervals for the entire given time. Basically, this approach is similar to the method used in models to represent the industrial system.

As Forrester (1976) pointed out, since in the system energy and matter are characterized by accumulation, storing or dissipating, the new value of the entity that describes the state variable will change by adding and/or substracting to or from the previous value a certain amount formed and/or dissipated during the intervening time interval. This statement is expressed in differential form as follows:

$$L=Lo + \int_0^t (Ra - Rd)dt \qquad (3)$$

Where: L-level at any time (t);

Lo-level at previous time (t-1);

(Ra - Rd) -rate of change over small time intv.;

Ra-rate of accumulation,

Rd-rate of dissipation.

$\int_0^t$ -operator (ac./dis. from initial to final time)

Equation (3) is the so called level-equation and is frequently used in industrial models. "Level" might be defined in more general terms as the value of the attribute of a state variable.

Concerning plant growth, the rate of change, i.e. the rate of growth, very often is computed based on the Blackman's equation. A general form of computing growth might be considered as follows:

$$dB/dt=RGR * B \qquad (4)$$

Where: dB/dt-change in biomass/unit time;

RGR -relative growth rate;

B -biomass.

For small differences in time (Δt), the so called time interval or time step interval, equation (4) is expressed:

$$dB/dt \sim \Delta B/\Delta t=(B_2 - B_1)/(t_2 - t_1) \qquad (5)$$

By substitution of equation (5) in equation (4)

$$(B_2 - B_1)/\Delta t=RGR * B_1$$

$$B_2 = B_1 + RGR * B_1 * \Delta t \qquad (6)$$

Two further assumptions are made in order to compute accumulation of growth:

1. The relative growth rate (RGR) is constant only during a small interval of time (t) and is controlled by the environment and by the physiological status of the crop.
2. The value of RGR can be calculated for each time interval.

Finally, the amount of biomass (dry matter) at any given time (t) is computed by summation of quantities accumulated during each time step.

$$Bn = Bo + \sum_{i=1}^{n} RGR_i * B_{i-1} * \Delta t \qquad (7)$$

This method, stepping time and summating rate, is known as the rectangular integration type or the Euler method.

In a large model, plant growth is one of the most dynamic processes and the rate of growth constitutes the central core of any plant growth model. The rate of plant growth appears to be the most important common element among plant growth models developed, regardless of the objective. Since the growth rate may be based on different existing theories each model structure and its development is to a large extent a reflection of the working hypothesis adopted by each individual modeler. Some of the most frequent working hypotheses used to express plant growth and associated model types are described briefly.

2.2.4.1 Precursor Pools Hypothesis

This type of model focussed on the major soil nutrients. Consequently, plant-soil parts of the system were represented in the model in more detail than other parts. Basically, such a model starts with two premises:

1. First, the plant is assumed to consist of two pools:
   a) Structural material produced by metabolism and
   b) Precursors to structural material:
      i) Fixed carbon (simple carbohydrates);
      ii) Absorbed nitrogen (free nitrate).
2. The second premise is that the structural material is produced by reaction between precursors at a given rate.

In accordance with the above mentioned premises and assuming other nutrients are in adequate supply, the precursors are the driving force in computing the rate of growth.

$$dW/dt=f(NAR * LA) \qquad (8)$$

Where: dW/dt-plant growth rate;

NAR -net assimilation rate;

LA -leaf area.

Net assimilation rate is assumed to be proportional to the increment in carbon (dC) and the relation between this and the increment in nitrogen (dU) is controlled by the C/N ratio in the structural tissue.

$$dU=(C/N) * dC \qquad (9)$$

In this model type it is necessary to assess influx of C and N into the pool of precursors. This was represented in different degrees of complexity and detail.

Several models have been based on this working hypothesis: Baldwin and Nye, 1974;Nye et al.,1975;Baldwin, 1976; Brewster et al.,1976.

Baldwin (1976) ran a sensitivity analysis for several factors (plant and soil) considering a whole plant model. From the value of sensitivity coefficients, i.e. an overall measurement of change for a change in a given factor, he concluded that the net assimilation rate, root extension and nitrogen concentration in the soil were the most important characteristics affecting the magnitude of crop yield.

2.2.4.2 Element Assimilation and Cell Biochemistry Hypothesis

Based on the assumption that the plant growth rate is controlled by concentration of labile constituents stored by the plant and used later in assimilation, Smith (1976) developed a comprehensive, theoretically oriented model:

$$Cl=\mathcal{M}l/\mathcal{M}t \qquad (10)$$

Where: Cl-labile element concentration in plant (g/g);

$\mathcal{M}l$-total labile element in plant (g);

$\mathcal{M}_t$-total biomass (g dry weight).

By differentiating equation(10) with respect to time and applying other mathematical manipulations the total biomass was expressed as:

$$dMt/dt=\sum(GM - HM) \qquad (11)$$

Where: dMt/dt-change in total biomass;

GM -accounts for new growth;

HM -accounts for all loss processes.

Since G (i.e. the growth rate) is itself a function of the labile element concentration (C_l), Smith developed a global cell synthesis picture based on cell chemistry reaction equations.

The cell chemistry is too complex to be fully described mathematically. Therefore, the submodel of cell chemistry was simplified. Even with such simplification, the model was extremely complex and considerable speculation was needed in order to compute the rate of growth as a function of substrate concentration. Finally, the growth function was related to the rate of production of new biomass which was assumed to be proportional to reaction rates from cell chemistry at quasi-equilibrium given by the following equation:

$$G=a_8 E Cl_N Cl_P Cl_K Cl_S \left[a_8/a_1 Cl_N Cl_P Cl_K + a_8/a_2 Cl_N Cl_K Cl_S + a_8/a_5 Cl_N Cl_P Cl_S + a_8/a_6 Cl_P Cl_K Cl_S + a_8/a_3 Cl_N Cl_P Cl_S (1 + a_4/a_{-4} Cl_P) + Cl_N Cl_P Cl_S (1 + a_9/a_{-9} Cl_K + a_{10}/a_{-10} Cl_N) \right]^{-1} \qquad (12)$$

Where: E -substrate concentration;

Cl -labile element concentration in the plant;

N,P,K,S -macronutrients;

$a_1, a_2, \ldots, a_{10}$ -reaction rate constants.

Although such a model is very elaborate, based on true premises and is logically valid, its value is theoretical rather than practical. This model type as well as the one presented earlier (2.2.4.1) can not be used for practical purposes on a large scale. There is always a danger in modeling of trying to be too fundamental; theoretical complexity must be commensurate with detail and consistency of available data.

2.2.4.3 Evapotranspiration - Plant Growth Hypothesis

More practically oriented models frequently use an equation developed by de Wit (1958). Basically, the working hypothesis considered by such models assumes a certain relationship between the amount of water transpired by a particular crop during the growing season and magnitude of yield. This hypothesis was employed mostly in the so called hydrological models which focussed on water balance in soil.

Using data published in 1913 and 1914 by J. Briggs and H. Shantz, de Wit (1958) concluded that dry matter yield in the semi-arid Great-Plains areas was related to the amount of water transpired divided by the amount of water evaporated from an open pan.

Assuming constant fertility, the amount of dry matter produced was expressed as :

$$Y=k'(Tr/Ee) \quad (13)$$

Where: Y -dry matter yield;

Tr -water transpired during the growing season;

Ee -water evaporated from evaporation pan;

k' -crop specific constant.

Many regression-type models have been developed on the basis of equation (13). An extensive review of relationships between plant growth and transpiration has been published by Arkley (1963). It is perhaps worthwhile to refer to some of the comments emphasized by Arkley as virtues and weaknesses of this approach. By applying equation (13) to more humid climates some conflicting results occurred. In order to overcome the inaccuracy of the equation under different climatic conditions a correction, in the term for relative humidity, was proposed as follows:

$$Y=k'\{Tr/(100 - H)\} \quad (14)$$

Where H stands for mean relative atmospheric humidity (in percentage).

Further modifications have been proposed in order to account for variations in soil fertility since it was found that in a soil of 50% of the optimum fertility level the plant produces only about 70% as much dry matter per unit of water transpired as in soils of optimum fertility. With these improvements, and assuming that de Wit's equation holds also at daily time step levels, this approach has been used in developing several field models. For example: Visser (1974); van Keulen (1975); Walker (1977).

It seems that when the prediction of transpiration and evapotranspiration during the growing season is based on relatively precise measurement of weather and crop variables (as was, for example, done in van Keulen's model) de Wit's finding can be applied successfully. Accurate measurements of climatic input variables can be made only for relatively small areas (let us say a particular irrigated area).

2.2.4.4 Limiting Factors Hypothesis

Some other practically oriented models are based on the so-called limiting factors hypothesis.

The starting point for this hypothesis is the general assumption that plant growth is affected by its genetic constitution and its own environment. In an ideal environment there will be an ideal growth rate which is genetically controlled. In a real world system, i.e. under field conditions, the actual growth rate is never equal to the ideal rate. Its magnitude is diminished by a number of factors. In a simple form this may be expressed:

$$GR=IGR * LF \qquad (15)$$

Where: GR-actual growth rate;

IGR-ideal growth rate;

LF-effect of limiting factor.

The selection of environmental factors which are to be considered as limiting is not easy and it is much more difficult to obtain data on their separate effects. Usually, the simultaneous effects of environmental factors are lacking. Therefore, their mutual action can not be programmed very precisely.

The second problem concerns the manner in which the factors being considered are combined in order to obtain a measure of their total effect on the growth process. Two approaches were customarily employed.

One approach considered only the minimum value among the factors (the most limiting factor):

$$LF=AMIN1(f_1,f_2,\ldots,f_n) \qquad (16)$$

The second approach considered the final effect to be a product of all limiting factors:

$$LF=f_1* f_2*\ldots* f_n \qquad (17)$$

Where $f_1,f_2\ldots f_n$ are the percentage adequacy of the considered factors affecting plant growth.

Basically, these two extreme view points follow the idea behind two well-known nutrient plant growth theories: Liebig's Minimum Law and Baule's Product Law. The corollary of Liebig's theory is that plant growth can be improved only by increasing nutrient concentration of the nutrient in minimum supply. The corollary of Baule's theory is that increasing the supply of any one of the deficient elements alone will improve growth in proportion to the degree of deficiency of that element.

It seems that the second theory fails to account for the so called negative feedback interaction. If two nutrients are simultaneously deficient and only one is increased, assuming the growth increased,the other element becomes even more deficient; therefore, it will tend to limit growth to a larger extent. Some of the experimental work reported in the literature indicates that plant growth is much lower than the result expected according to Baule's Product Law (Wood et al., 1972; Smith, 1976)

Much less is known about the effect of environmental factors (other than nutrients). Frissel and van Veen (1977) suggested that a more balanced view might be obtained by grouping the environmental factors and considering the effect of each group and both theories rather than the effect of each individual factor and only one theory. This problem has not yet been resolved.

However, several models have been developed on the basis of the limiting factors hypothesis. A few examples are: Greenwood et al. (1974); Barnes et al. (1976); Vithayathil et al. (1977); Selirio and Brown (1977, 1979); Morgan et al. (1980).

2.2.5 Verificiation and Validation of the Model

The first requirement of a model is that it be useful. Before simulation, some test of the model relative to the real system which it represents must be undertaken since the model results are obtained from mathematical rather than from physical, chemical or biological experiments. Therefore, no model is complete until tested.

Either in every day meaning or in a literal context to verify means "to establish the truth, accuracy or reality of ...". In order to "verify" a model relative to the real system which it is intended to describe, two procedures termed "verification" and "validation" are customarily used. The use of these two terms interchangeably and sometimes synonymously leads to confusion about the stage reached by the intended simulation study.

A useful distinction between these two activities has been suggested by Baker and Curry (1976). Basically, both verification and validation are tests made for the same reason: to find out if the model is a correct representation of the reality. The main difference between them consists in the fact that they test the model at two different levels.

Verification might be considered as a test relating to performance of a hypothesis on which the model was developed. The verification can be made for any hypothesis considered. The information from such verifications is very useful in interpretation of model logic and assessing the accuracy of parameter values. In practice this testing phase was often avoided because of the lack of observed data and difficulties of a statistical interpretation.

Validation is concerned with testing the performance of the model, as a whole, against real data. The typical approach is the comparison of ouput data from the model (run with input data recorded for the real system) with real system output.

2.3 SUMMARY

Natural systems are very complex and are capable of being represented by a great variety of models. Any model is " a second rate - representation" of the real system and can not equal the true behaviour of a real system.

Although highly theoretcal and sophisticated plant growth models represent more correctly the natural systems, they can not be used to solve practical problems such as the one with which this study is concerned. This is mostly due to difficulties in measuring or estimating the required input variables over a large land area.

A less complex model is a more suitable approach for practical purposes. Such models represent a high degree of simplification of the real system. Therefore, under such circumstances testing for both validation (which is concerned with the usefulness of the model) and verification (which is concerned with the truthfulness of the model) must be considered before simulation is possible.

Chapter III

MODELING AND DESCRIPTION OF THE MODEL

3.1 OBJECTIVE

As Cooper (1976) pointed out, in constructing a model one of the first jobs is to decide which characteristics of the system of interest are going to be represented in the model. This in turn requires that the purpose of making the model be defined as clearly as possible. Others went further and considered it to be necessary to decide what questions the model has to answer and also who is going to use it.

The purpose of the present study was to examine the possibilities of using simulation techniques for evaluation of productivity of various land units in Manitoba by biological means using wheat as the test crop. In a general sense, the model had to predict the behaviour of the system of interest as a consequence of different conditions. More precisely the model was developed to predict the wheat yield that might be obtained from different land units.

Although simulation must consist of two phases: modeling and experimentation (application), it is obvious that no simulation study can progress beyond model building until the model proves satisfactory.

Recently two attempts were made to use simulation techniques for land evaluation in Canada: SIMFOY and SIMCOY developed by Selirio and Brown (1976,1977) in Ontario and WHTMOD developed by Walker (1977) in Saskatchewan.

The models mentioned above have many virtues. Therefore, without minimizing the significance of what has been done, the following comments will point up some of the limitations of these models.

SYMFOY and SIMCOY were based in essence on the limiting factors hypothesis. The central axis of the models might be considered the idealized growth curve developed on the basis of the Corn Heat Units concept (i.e. energetic in nature) with available soil moisture as the limiting factor.

WHTMOD was based on de Wit's finding. Therefore, it was based on relationships between the amount of water transpired by wheat during the growing season and the magnitude of plant yield.

From the validation point of view SIMCOY, a corn yield model, and more particularly SIMFOY, which predicts forage dry matter yield,provided good predictions of yield. This was to be expected since the computed limiting factor, expressed as available moisture, affected daily growth rate only to a limited extent. Daily growth rate was balanced in a dynamic manner by the ideal growth rate which was, in essence, dependent on genetic characteristic of the crop. By contrast, in WHTMOD the crop characteristic was treated as a static factor ('m'), which was constant over the entire season, and the dynamic adjustment was made based on intermediate variables such as transpiration and potential evapotranspiration. Consequently, the correctness of daily growth rate depended largely on the precision of predicting intermediate variables (i.e. transpiration and actual evapotranspiration).

In the last three years more work has been done in order to validate and to verify the above mentioned models. Some of the more significant conclusions were:

Concerning SIMFOY and SIMCOY- "Although considerable progress has been made in model development and testing, major problems remain to be solved before the models can be used for this purpose (Land Evaluation). Some of these problems are in the models themselves, some are related to data availability and some are related to the applications of the models to land evaluation ... Three aspects which have yet to be included in the models are excess moisture, fertility and management"(Miller et al., 1979).

Regarding WHTMOD- "The results show that the model does require some improvement, but at the same time some cautious optimism is justified regarding the basic approach" (Ward, 1979).

In light of the above comments, development of the present model named PIXMOD was undertaken. The model was based on the limiting factors hypothesis. It accounted for climate and management factors and focussed on soil characteristics. The study dealt mostly with the first phase of simulation-model building and partial validation and verification.

3.2 SYSTEM OF INTEREST AND ITS BOUNDARY

Within physiological models, the plant as a natural unit constitutes the whole system. Due to our goal of evaluating land, the system of interest was expanded to include soil, in particular soil properties within the rooting zone of wheat. Although the system of interest was represented as simply as possible in the model, it was still very complex. Consequently, it was separated into several natural parts (sub-systems). The parts interact with one another and only for the sake of expressing their quantitative contributions do we consider them as independent constituents. This separation is, of course, somewhat arbitrary.

Since all ecosystems are open systems, there is always some exchange of matter, energy and information between them and the exterior environment. The environment of the system as it was defined is probably best considered in three distinct parts: weather, management and soil (that part of the soil beyond the root zone). A simplified diagramatic representation of the system of interest and its neighbouring systems is presented in Figure 2.

Although important and always present within the system, the energy and information exchanges were further neglected. Our effort was focussed on the matter exchanges and flow within the system. All incoming/outgoing entities were treated as overall INPUT/OUTPUT. Within the system the entities considered were treated as state variables.

3.3 CONCEPTUAL FRAMEWORK

If Productivity is defined as the maximum yield that can be obtained from a certain land unit,then some of the environmental variation from year to year must be neglected. Otherwise, productivity will be different from one year to another within the same land unit. In order to have an objective comparison between different land units, our attention was focussed on spatial variations of the system characteristics and environmental input/output. The dynamics of the processes considered was restricted to one growing season. If this assumption is not too critical for soil and management characteristics some problems arise relative to weather. It varies in both space and greatly in time in the long run (from year to year).

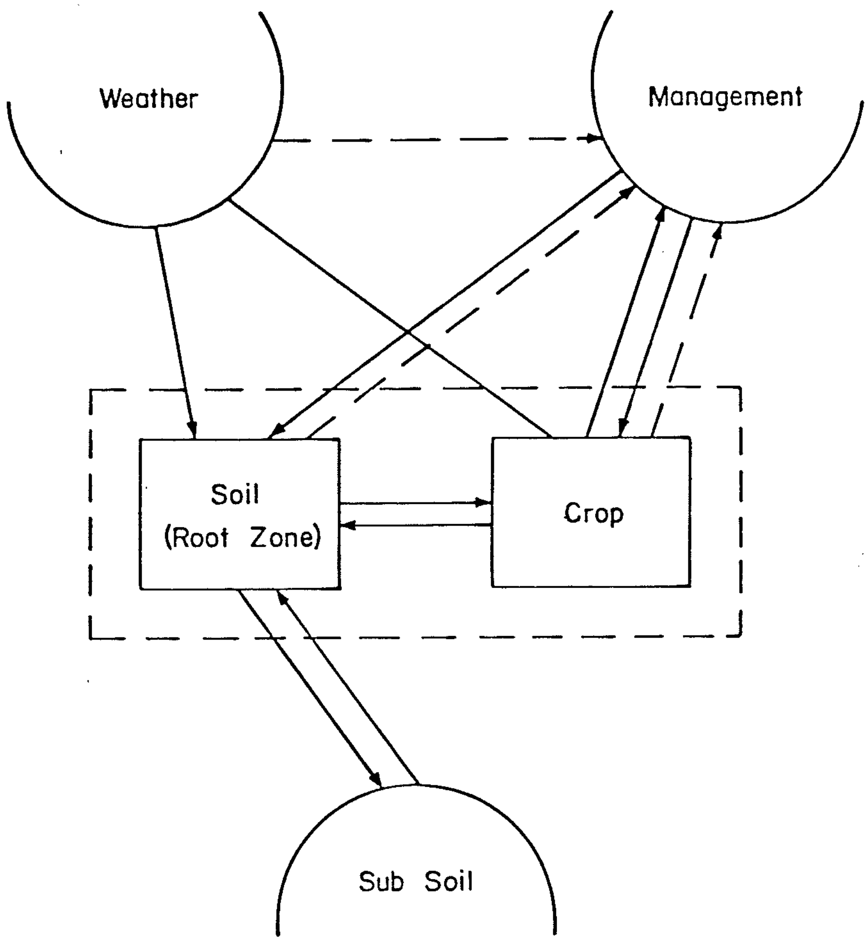


FIG. 2 SYSTEM OF INTEREST AND ITS ENVIRONMENT.

System of interest ⌐ ⌐ ⌐ ; Main subsystems within the system ▭ ; Neighboring systems) ; Flow: Matter/Energy ⟶; Information — →.

In order to overcome this difficulty, for simulation purposes, the climatic factor has to be treated as a history of weather over a large number of years and weather elements of interest as averages and frequencies of occurrence.

Some of the aspects within the management factor have to be considered in a similar manner. For example, seeding time is one of the most critical parameters in the system since it establishes the initial position of the biological sub-system (crop) in time. Although it is well known that in Manitoba as well as in all the Prairie Provinces the seeding date may vary widely due to climatic conditions and to some extent farmer decisions, an average seeding date must be considered, at least at the level of each climatic region, such as Black,Dark Grey and Luvisolic soil zones.

A second important decision that must be made, before model building proceeds is the land unit upon which a soil productivity index is to be applied. This is perhaps one of the most critical aspects in developing a model for land evaluation. Such a decision must consider: the heterogenity of the soil, which has to be described; the accuracy desired of the model output; and the objective of the model,i.e. it has to evaluate a large land area.

Many of the strong theoretically oriented type of models were based on a rigid, but otherwise correct, statement that natural heterogeneity does not permit accurate soil physical measurements on a large scale. The applicability of these models is reduced to laboratory experiments or small land areas such as one square meter. By contrast, the so called "crop-weather" type of models, which were concerned mostly with variation of crop yield from year to year due to weather factors paid less attention to soil heterogeneity.

A more realistic view point was adopted in the SIMFOY, SIMCOY and WHTMOD models where soil series was considered as the unit basis. The assumption of homogeneity within a soil series holds as long as a nutrient factor is not considered in the model. The present model was intended to take into account the effect of soil nitrogen on yield. The quarter section was considered an appropriate land unit on which to assess the effect of past management on soil fertility in the Prairie region. Reliable data describing nitrate-nitrogen content in soil are stored in various provincial soil testing laboratory data banks on the basis of the quarter of section. In addition, many farm field units are frequently of this size or multiples of this size. Therefore, the assumption that the effect of past management on soil fertility might be considered uniform on this size of field unit seems to be reasonably sound. It provides a homogenous land unit of very useful and practical size to which productivity indices can be applied.

Finally, the possibilites of using the model for predicting the yield of crops other than wheat is very important. Since different crop species may behave in different ways under the same soil, climatic and basic management conditions, it is not realistic to compute a land productivity index based entirely on the yield prediction of a single crop. One solution suggested was to build several models for different crops or crop groups. It was considered a more appropriate approach to use only one basic model for all crop species of major interest. Indeed, for a crop other than wheat some parameters and functions must be changed , but input/output variables as well as the main processes within the system should be the same. This represents a gain not only in the time required to build a model but it seems to be a realistic assumption that most of the processes involved in the system will be affected by the same soil characteristics in the same manner regardless of what crop is grown. These considerations lead to a separation of the system into sub-systems in a natural way. Any desirable changes required for a different crop species can be readily achieved.

In developing the present model, the necessity of expanding the model to include special problems that exist within Manitoba was considered,e.g. excess moisture and water balance for the entire year. In subsequent chapters some consideration was given to these even though they lie beyond the scope of the model presented.

3.4 STATE VARIABLES AND PROCESSES CONSIDERED

The number of variables within the system is very large. Only a few state variables that could be roughly quantified in time were monitored in the system.

Since a desirable characteristic of the model was that plant-water and plant-nutrient be represented as dynamic processes rather than as static relationships to plant demand and soil supply, the following state variables were considered in the model:

1. biomass (above ground dry matter production);
2. water content of the soil;
3. amount of nitrogen in the soil.

Soil was considered to be only that part included in the system (the root zone).

The number of activites/processes (physical, chemical and biological in nature) that affect the magnitude of selected state variables is so large that for a model to account for all of them is not realistic. Therefore, only the following processes were considered in some detail:

1. plant growth;
2. root extension (in a vertical direction only);
3. evapotranspiration;
4. water movement in the soil;
5. NO_3-N transformations and movement.

An overall view of the system represented by the model is shown in Figure 3. The focus of interest was the soil profile from the soil surface to the maximum possible depth of rooting. Any exchanges across the boundaries (top of the canopy and bottom of the root zone) were considered as either an overall INPUT or OUTPUT.

Having defined the main state variables and processes, a time step (Δt) was chosen. Most existing models designed for a practical purpose employed a time step of one day, one week or even longer whereas more theoretical models used one hour or minute as the time step. From a theoretical point of view, a shorter time step is better choice since a smaller error is introduced by assuming that derivative of an equation which describes a process which remains constant throughout each time step. From a practical point of view, even a day is considered a short

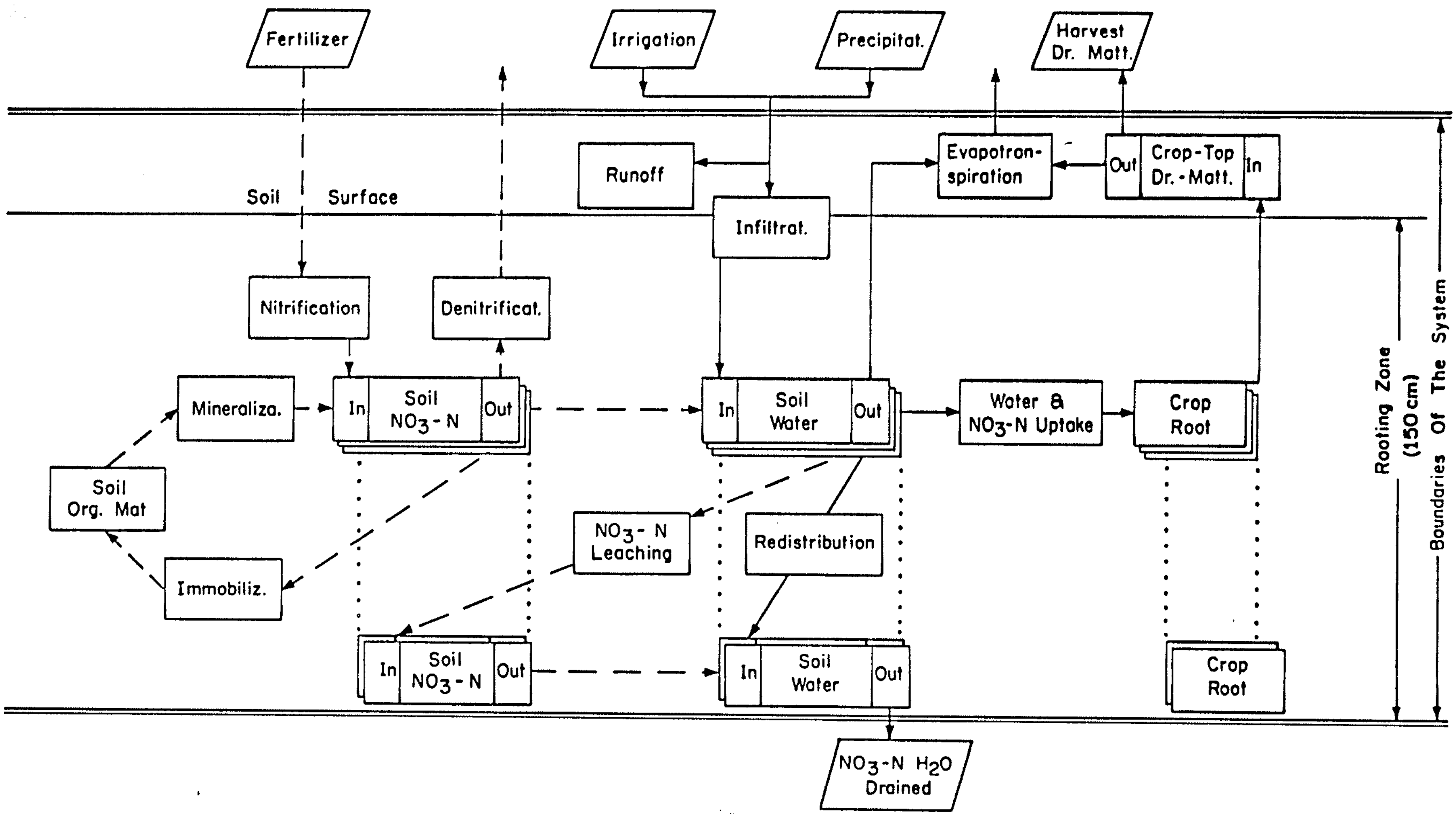


FIG. 3 SCHEMATIC REPRESENTATION OF THE SYSTEM CONSIDERED IN THE MODEL.

Overall INPUT/OUTPUT ▱ ; Process ▭ ; State Variable ▭ ;
Flow: Water ⟶ , NO_3-N – – → .

time step and presents some inconvenience since the state variables are not currently testable. Consequently, verification of the model becomes difficult. Since the present model included several empirical equations, increasing the accuracy of prediction was of primary concern. Consequently, one-half day time step was employed in the model.

3.5 MODEL STRUCTURE

de Wit and Arnold (1976) considered a modular type of model more manageable than a single model. Consequently, the system of interest was broken down into components separated in natural way. As a result the model consists of several structural parts, some of them material and some of them conceptual. This structure led to a program with subroutines which has several advantages of which the most important are:

1. The model/program can be relatively easily assembled and disassembled;
2. The error produced by some particular part as well as its impact on other parts can be detected and more accurately estimated;
3. Any desirable changes can be more easily achieved.

Basically, the model was physically oriented. It focussed on water and nitrogen, two entites vital for crop development and closely related to soil properties. Consequently, three major processes were considered in the model:

1. water movement through the soil;
2. nitrogen transformations and transport;
3. plant growth.

Each of the above processes constituted a separate sub-model (module) and they were treated in the program as individual subroutines named MOIST, NITRO and PLGRTH, respectively.

Other processes such as evapotranspiration, root extension, runoff, etc. were included in the model but these were described in less detail.

A logical sequence of processes was considered in order to define the model at work. The primary cause of disequilibrium in the system/model, or the driving variable, was considered to be loss of water by evaporation and by evapotranspiration. Although the photosynthetic process was not represented in the model, it existed within the system and the real driving force in plant growth was energetic in nature.

As the plant starts to grow, roots proliferate. For convenience, only the vertical extension of the root was considered. In order to keep the model simple and because of lack of better information, the extension of the root was assumed to follow an empirical pattern based on a model described by Gerwitz and Page (1974). Water and nutrient uptake was assumed to be a consequence of plant growth and evapotranspiration. Finally, the levels (state variables) were considered to be a result of the simultaneous effect of plant uptake of water and nutrients, water movement in the soil profile as well as due to the overall input/output variables such as precipitation and drainage or leaching. The main program flow chart, which represents a general view of the model structure and how its parts are connected, is given in Figure 4. Beside the processes mentioned, three other subroutines were incorporated within the structure of the model. They are as follows:

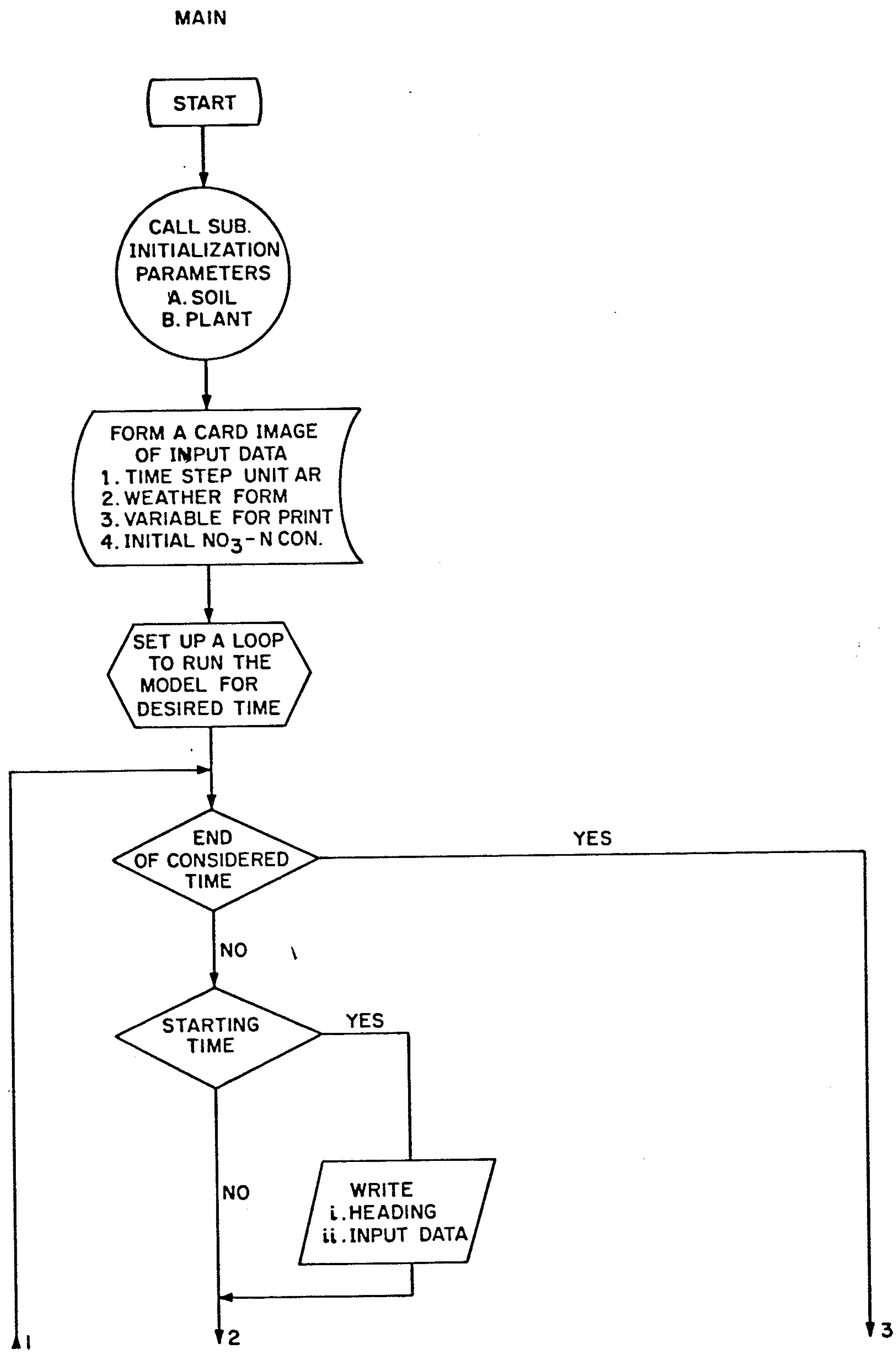
1. Initialization of the parameters;
2. Plot;
3. Afgen.

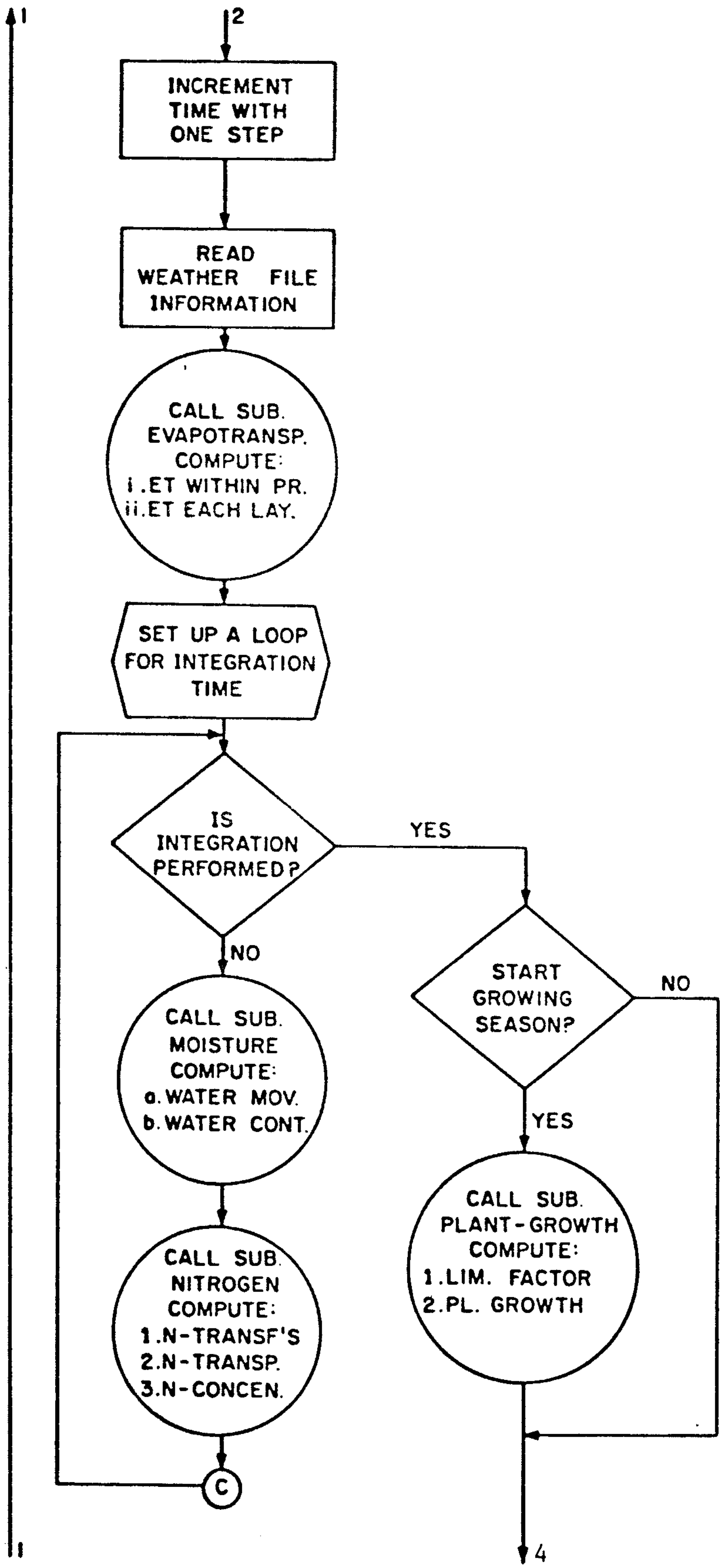
The first subroutine was related to parameters involved in the model. This was further split into two distinct parts: soil parameters and plant parameters. It is obvious that when the model is needed for a crop other than wheat, the main change will be the plant parameters whereas the soil parameters will be constant. The latter two subroutines were formal. The Plot subroutine graphed the value of the dry matter variable with respect to time. Afgen,a computer library subroutine, was basically an interpolation function which was used in model subroutines when a value had to be drawn from a graphical representation.

The model was based on a program developed by Vithayathil et al.(1977) for simulation of nitrogen flow in field conditions.

3.5.1 Some Important Soil Parameters and their Computation

There are many aspects of interest within soil water-plant relationships. Some of the factors that control water balance are better expressed in terms of energy. Other factors, biological in nature, are treated mostly by physiological models developed on micro-scales.


MAIN
START
CALL SUB.
INITIALIZATION
PARAMETERS
A. SOIL
B. PLANT
FORM A CARD IMAGE
OF INPUT DATA
1. TIME STEP UNIT AR
2. WEATHER FORM
3. VARIABLE FOR PRINT
4. INITIAL NO3 - N CON.
SET UP A LOOP
TO RUN THE
MODEL FOR
DESIRED TIME
END
OF CONSIDERED
TIME
YES
NO
STARTING
TIME
YES
NO
WRITE
i. HEADING
ii. INPUT DATA
1
2
3


1
2
3
INCREMENT TIME WITH ONE STEP
READ WEATHER FILE INFORMATION
CALL SUB. EVAPOTRANSP. COMPUTE:
i.ET WITHIN PR.
ii.ET EACH LAY.
SET UP A LOOP FOR INTEGRATION TIME
IS INTEGRATION PERFORMED?
YES
NO
START GROWING SEASON?
NO
YES
CALL SUB. MOISTURE COMPUTE:
a. WATER MOV.
b. WATER CONT.
CALL SUB. PLANT-GROWTH COMPUTE:
1.LIM. FACTOR
2.PL. GROWTH
CALL SUB. NITROGEN COMPUTE:
1.N-TRANSF'S
2.N-TRANSP.
3.N-CONCEN.
C
1
4
3

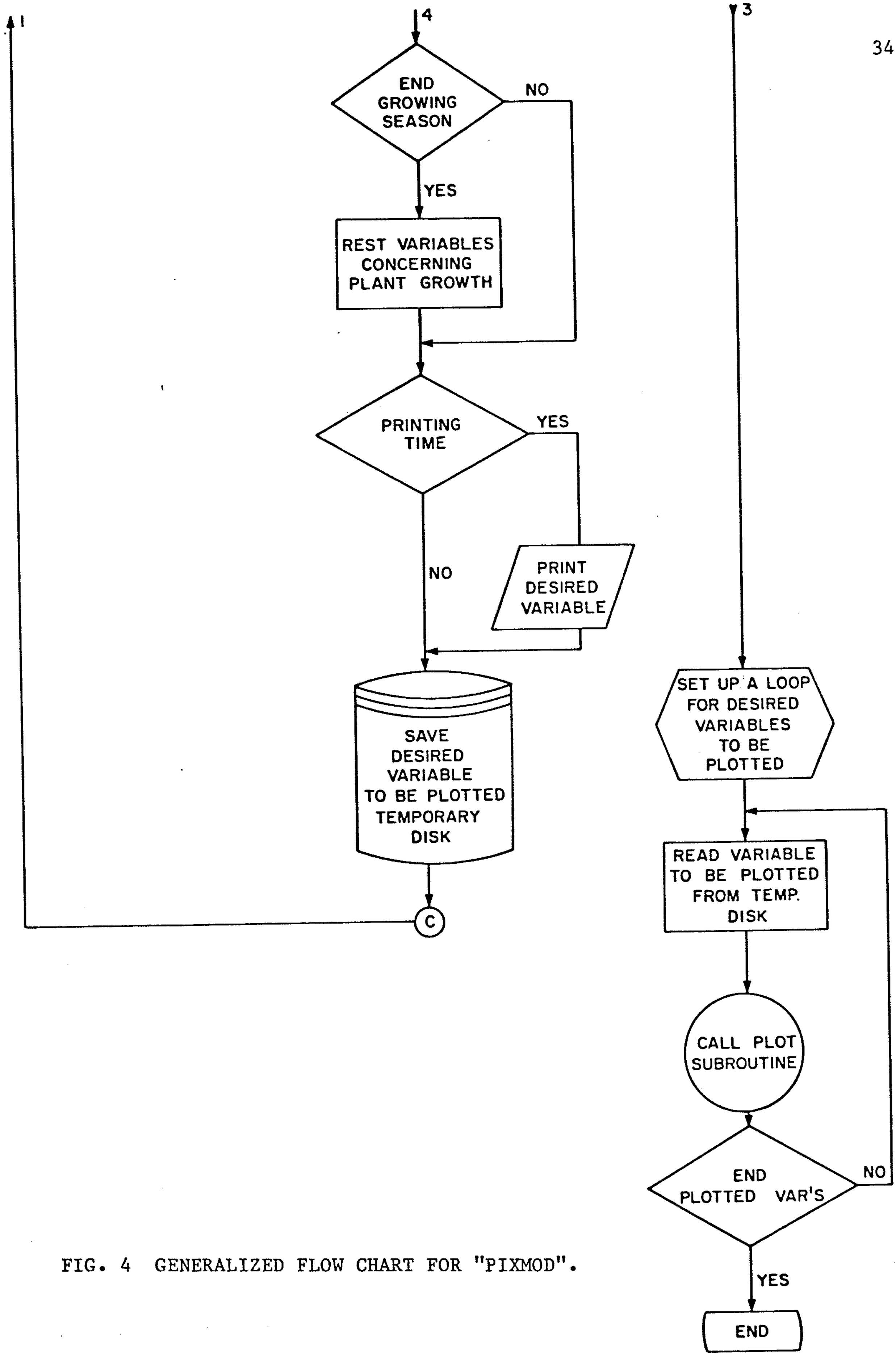


FIG. 4 GENERALIZED FLOW CHART FOR "PIXMOD".

Nevertheless, physical soil properties play a major role in soil water-plant relationships. In models which account continuously for the amount of water in the root zone, soil properties must be carefully considered.

In a general way it was emphasized that the soil root zone was considered as part of the system. A more precise definition of that part of the soil included in the system of interest and that part of the soil which was treated as a neighbouring system was required. The depth of the profile considered differs among existing models. A few examples of depths which have been used are: Musick et al. (1976)- 120 cm; van Keulen (1975)- 150 cm; Jackson et al. (1977)- 110 cm.: Morgan et al. (1980)- 100 cm. These values which represent the maximum depth of rooting were treated as constants and were related to crop species characteristics. Although Nye and Tinker (1977) showed that root distribution depends more upon soil properties than genetic composition of the plant, no model successfully treated root distribution from a full knowledge of soil and plant characteristics. For several reasons it was considered better approach to treat the maximum depth of soil as a parameter rather than a constant. In Manitoba, as well as in the other Prairie Provinces, there are at least three soil characteristics (relatively easily identified) which may restrict root penetration:

1. a shallow profile (bedrock near the surface);
2. a high water table;
3. the existence of a "Bnt" horizon.

Many environmental factors as well as genetic plant characteristics affect the root pattern. Among soil characteristics, temperature, oxygen concentration, nutrient level, bulk density and soil water potential have been considered. Mirreh and Ketcheson (1973) and Miller et al. (1979) attempted to relate the root penetration pattern with soil bulk density; Hurd (1967) emphasized some effects of soil temperature and soil moisture levels on the root pattern; Newman (1966) and Lawlor (1972) related root growth to soil water potential. The main problem in developing a mathematical model that accounts for such effects is that "relevant variables" are often difficult to measure or control and sometimes it is hard to identify them explicitly.

In deciding the maximum rooting depth, crop species characteristics were considered. Usually, for wheat, 110 - 120 cm was considered to be the maximum depth. van Bavel and Ahmed (1975) concluded that about 30% of the water used by a crop during a dry period comes from below the root zone. Hurd (1968) showed that Marquis wheat roots reached to depths of 120 to 150 cm. Consequently, since none of the earlier mentioned restrictions occured the maximum rooting depth considered was 150 cm.

However, as Taylor et al. (1970) pointed out, for any crop species there will be a general increase in rooting depth with time. Therefore the active soil layer from which plants can extract water and nutrients will vary during the growing season. Since the soil properties vary with depth, the soil profile was divided into distinct individual layers. Indeed, the number of layers into which the soil profile is split is a function of the maximum rooting depth considered and the layer thickness chosen. In developed models the layer thickness chosen varied from one to 30 cm. The selection of layer thickness is to some extent a subjective decision. Theoretically, dividing the profile into thin layers is not wrong. From a practical view point it is hardly possible to distinguish soil layers less than 5 - 10 cm in thickness. The second extreme ,using very thick layers following the natural horizons, might appear appropriate. However, such an approach might bring about some problems regarding the transport process. For instance Frissel et al. (1970) pointed out that the use of too thick layers creates "pseudo-dispersion effects" which may lead to an underestimate of actual diffusion.

In the present model the rooting zone was divided into 10 equal layers, each of 15 cm thick.

Two concepts, "Field capacity" and "Permanent wilting percent", sometimes termed "soil physical constants", are very helpful in describing soil water availability to plants. These traditional concepts have frequently been criticized since they describe soil moisture status with ambiguous terms such as "negligible" or "practically zero" and because the redistribution process of water within soil is, in fact, continuous and does not exhibit a static level (Richards, 1960). All these comments are true but no better concepts have been suggested to replace them. Consequently, both concepts are frequently employed in modeling in order to compute water availability to plants as well as to determine water balance in soil.

In addition to overall INPUT/OUTPUT of water into the system/model (i.e. precipitation/drainage) the amount of water available to the crop is affected by several processes among which the most important might be considered as follows:

1. water storage capacity of the soil;
2. evaporation/evapotranspiration;
3. redistribution of water within the soil profile.

These processes interact with one another and their presentation as independent constituents is to some extent arbitrary. However, each of the processes mentioned is more or less affected by soil characteristics.

In order to define the quantity of water that might be stored in the soil in the available form for the plant, the concepts field capacity and permanent wilting percent are usually used. For any particular soil these values are usually determined in the laboratory using either equilibration of the soil samples in a centrifuge or in a suction apparatus. The methods have some weaknesses. First, the methods are static whereas the redistribution process is essentially dynamic (Hillel, 1971). Second, as Slatyer (1957) pointed out, there is experimental evidence that permanent wilting percent does not correspond to a unique suction of 15 atmospheres.

Several investigators attempted to predict field capacity and permanent wilting percent from more basic soil components. Shaykewich and Zwarich (1968) investigated 112 samples of soil varying widely in physical composition. The results of their study showed that there is a highly significant relationship between soil components and each soil physical constant. They found that where values for the components - sand, silt, clay and organic matter - are known it is possible to predict field capacity, permanent wilting percentage and bulk density fairly accurately.

The following equations, developed by Shaykewich and Zwarich have been used in the model to compute some of the most important soil parameters:

$$FC=9.8708 + 0.1182(Si) + 0.2741(C) + 1.2655(O.M.) \quad [R=0.878] \quad (18)$$

PWP=3.7960 - 0.0375(FS) - 0.0334(VFS) + 0.2202(C) +
0.6646(O.M.) [R=0.943] (19)

Where: FC -Field Capacity (percent by weight);
PWP-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);
O.M-organic matter.

All the above components are expressed on a percent by weight basis.

For modeling purposes the water content is more appropriately expressed in terms of volumetric water content (θ). This permits an easier computation of the quantity of water added and/or subtracted from each soil layer.

The conversion from water content on a weight basis (w) to water content on volume basis (θ) was realized using the equations:

FC(v/v)=FC(w/w) * B.D.

(20)

PWP(v/v)=PWP(w/w) * B.D.

Where B.D. is bulk density. Values for bulk density were computed using the following equation:

B.D.=1.7756 - 0.0016(VFS) - 0.0017(Si) - 0.0047(C) -
0.0707(O.M.) + 0.0008(C)*(O.M.) [R=0.805] (21)

The terms have the same meaning as for equations 18 and 19.

3.5.2 Evapotranspiration (Evaporation and Transpiration)

All models concerned with water transport within the soil-plant-atmosphere system have treated the evapotranspiration process in a more or less detalied way. Two terms, conceptually justified, are frequently employed to describe this process: Evaporation and Transpiration. Basically, Evaporation refers to the process that occurs at or near the soil surface or from the exterior of plant surfaces whereas Transpiration refers to the process that occurs in sub-stomatal cavities and is controlled by stomatal guard cells. From the point of view of the phase change of water from liquid to gas, the process is physically identical ot where it takes place (i.e. soil or external or internal plant surfaces).

The physical requirements for evaporation to occur are:

1. energy (latent heat of vaporization);
2. existence of a vapor/pressure gradient;
3. availability of water.

Consequently, evaporation was treated either as a component of the energy balance or as a part of the transport process. A summary of methods available for estimating evaporation by means of "Energy balance", "Aerodynamic method" or by a "Combined method" have been given by Rose (1966).

3.5.2.1 Evapotranspiration - The Driving Force of the System

The great importance of the evapotranspiration process in modeling is that, very often, it is considered to be the primary process determining the disequilibrium of the system; that is, it is the driving force within the system.

Most of the information on this subject has come from models developed to determine water use efficiency under irrigation. Two major model types can be considered in this group: Hydrological and Agro-hydrological.

The first type is based on the law of conservation of matter which leads to water balance models. The main goal of such models is to determine water use efficiency, generally described by an equqtion as:

$$WUE=Y/ET... \quad (22)$$

Where: WUE-water use efficiency (Kg/Ha/mm.);

Y -yield,often as grain (Kg/Ha);

ET -seasonal evapotranspiration (mm.).

Since under field conditions plant evapotranspiration is difficult to measure, water use has been associated with total evapotranspiration. As Howell and Hiler (1975) pointed out,in most of the models,evapotranspiration is determined by balancing input, storage and output of water in the root zone using an equation of the general form:

$$TWU=ET=ISWC - FSWC + PREC + IRR - RUNOFF + DRAIN \quad (23)$$

Where: TWU -total water used;

ET -evapotranspiration;

ISWC-initial water content in soil;

FSWC-final water content in soil;

PREC- precipitation;

IRR -irrigation;

RUNOFF-field runoff;

DRAIN -flow of water IN(+) and/or OUT(-).

The agro-hydrological type of models are based on a diffusion equation and this often leads to the limiting factors growth law. A general mathematical equation has been given by Visser (1974) as follows:

$$\underbrace{\left[1 - (T - T_o)/a\Delta T * \Delta q/Q + (1/q + 1/(Q - q)\right]}_{ps} *$$
$$\underbrace{\underbrace{(1 - \Delta q/\Delta q)^n}_{oy} \underbrace{\Delta q}_{go} \underbrace{(1 - \Delta q/C_3\Psi^{C_2})}_{a} * \underbrace{(1 - \Delta q/fEr)}_{e}}_{gf} =$$
$$\underbrace{-\underbrace{F}_{i}\underbrace{(1 - \underbrace{2}_{Si}\, q/\, q)}_{mf}} \qquad (24)$$

Where: gf-growth factor;

ps-plant size;

oy-optimum yield;

go-zero growth of ripened plant;

a -aeration;

e -evaporation;

mf-mathematical factor;

i -integration constant;

Si-sign of integration constant.

Equation 24 is relatively complex and only two terms ("a" and "e") are of interest.

Term "a" states that yield increase (Δq) depends on moisture stress (Ψ) which determines the air content. Diffusivity is considered to be linearly related to air content. Therefore, the equation for plant growth was reduced to:

$$\Delta q = C_3 \Psi^{C_2} \qquad (25)$$

Term "e" states that the yield increase (Δq) depends upon CO_2 uptake which in turn depends upon opening of the stomata. Based on the assumption that CO_2 and water follow the same pathway, plant growth as a function of evapotranspiration becomes:

$$\Delta q = fEr \qquad (26)$$

Two possible situations were considered further:

1. Evaporation was limited by climate in which case it depended on potential evaporation.

$$Er = gPE \qquad (27)$$

2. In the second situation evaporation depended upon the moisture content of the soil and was calculated from the soil moisture stress.

$$Er = K_1 \Psi^{K_2} \qquad (28)$$

The decision as to which situation was valid was determined by solving a system of equations that described capillary rise and moisture stress. Such a model, in fact, relates soil water supply to atmospheric demand.

However, the evapotranspiration process is much more complex and a plant under a water-stressed condition may affect the magnitude of evapotranspiration. The water deficit within a plant depends upon several soil and plant characteristics:

1. the water deficit in the soil (root zone);
2. soil hydraulic properties;
3. water distribution pattern within the soil profile;
4. plant characteristics among which the most important is perhaps the susceptibility of the crop to a certain water deficit level at various stages of growth.

All models account for the soil characteristics in some detail. In order to account for plant characteristics (4) a factor has been computed and integrated within a complex daily evapotranspiration equation. This factor was computed and named in different ways. Jensen et al. (1971) termed it "water deficits"; Minhas et al. (1974) called it "sensitivity factor to water". Hiler and Clark (1971) developed their model based on "Stress Day Index". Basically, stress factor was a measure of degree and duration (for certain crop species and stage of development) of plant water deficit. One of the problems encountered in using such an approach is that "stress day factor" must be determined in a preliminary experiment where the soil water variable can be at least partially controlled.

3.5.2.2 Estimation of Evapotranspiration

Essentially, each model attempts to include in the general equation some soil and plant factors which affect evapotranspiration as well as to calculate the variables of the equation from a small amount of input data. In the present study the last criterion was extremely important since most input data were not readily available.

Baier and Robertson (1965) and Baier (1971), using data from several locations over Canada and based on a multiple regression analysis method, proposed a set of equations which predict Latent Evapotranspiration.

$$LE = -53.39 + 0.337\ TMAX + 0.531\ RANGE + 0.0107\ Qo + 0.0512\ Qs + 0.0977\ WIND + 1.77\ VPD \qquad (29)$$

Where: LE -latent evaporation (cc/day);

TMAX-maximum temperature (F°);

RANGE-(TMAX-TMIN) in (F°);

Qo -total solar radiation on a horizontal surface at the top of the atmosphere (cal/cm^2);

Qs -total energy received (cal/cm^2-day);

WIND-wind run at 5 feet (miles/day);

VPD -vapor pressure deficit ($e_w - e_s$) in (mb).

The above equation is complex and requires input data that is not recorded at many weather stations. A simpler equation is frequently used in order to predict Latent Evaporation:

$$LE = -87.03 + 0.928 TMAX + 0.933 RANGE + 0.0486 Qo \qquad (30)$$

Although equation 30 predicts latent evaporation with less accuracy than equation 29, it has the advantage that the input variables required are available. Therefore equation 30 was used to predict further Potential Evapotranspiration in cm/day.

$$PE = 0.0086 * LE \qquad (31)$$

In a real system, over the growing season, the actual evapotranspiration is usually a function of crop species as well as a function of its development stage. In order to account for the effect of stage of development the potential evapotranspiration was multiplied with the ratio of Actual Evapotranspiration/Potential Evapotranspiration as a function of time during the growing season.

ET=PE * RATIO (31a)

The value of the RATIO (ET/PE) was derived from a time function developed by Hobbs and Krogman (1968), Figure 5.

As the growing season progresses and the plant develops, the RATIO increases up to a point and therefore Evapotranspiration (ET) as calculated from equation 31a increases. In a dry land crop production system, the plant frequently undergoes a water stress and this reduces Evapotranspiration. To account for that a "Stress Day Index" is perhaps the best approach. Since an experimental index to describe this does not exist for wheat, following the approach suggested by Shaw (1963) and used by Vithayathil et al. (1977), a stress factor was considered as follows:

ET=PE * RATIO * fSTRESS (32)

The value of the stress factor was derived from Figures 6 and 7 using the AFGEN interpolation function. Since the stress factor was expressed as a function of the water content in the root zone, the actual percent of available moisture (PAM) was computed as follows:

$$PAM = \sum_{1}^{rb} WC / \sum_{1}^{rb} WCFC \quad (33)$$

Where: $\sum_{1}^{rb} WC$ -sum of the water content in the root zone from soil surface to the bottom of the root zone;

$\sum_{1}^{rb} WCFC$-sum of the water in the same zone when the soil is at Field Capacity.

3.5.3 Transport Processes

Wilson (1972) pointed out that the processes that occur within a growing crop can be described in terms of two basic activities:

1. physical transport;
2. chemical conversion.

In general, the first activity leads to changes in structure while the second leads to changes in composition. Two components were further distinguished within physical transport:

1. movement within the plant (translocation)
2. exchanges between the plant and its own immediate environment (i.e. water and salts)

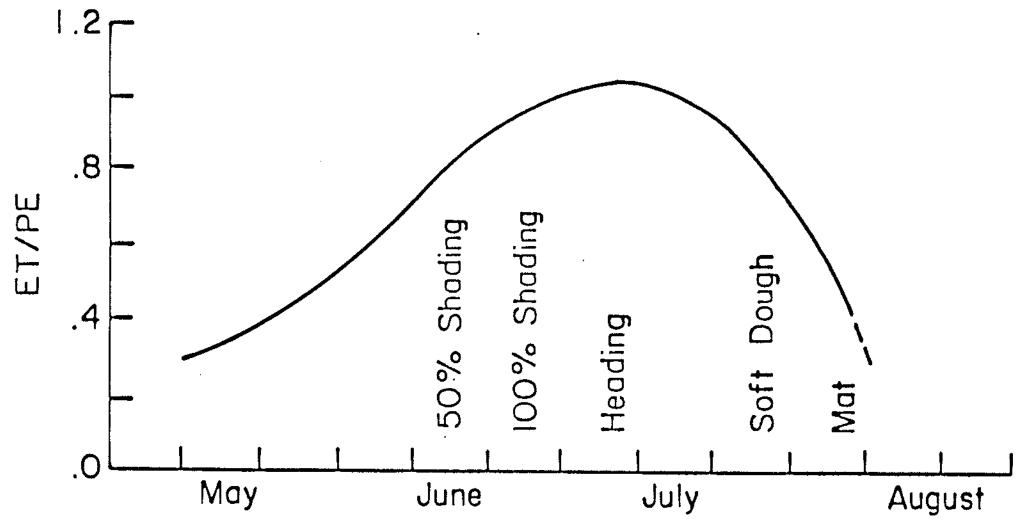


FIG. 5 RATIO OF ACTUAL TO POTENTIAL EVAPOTRANSPIRATION.
(After Hobbs and Krogman, 1968).

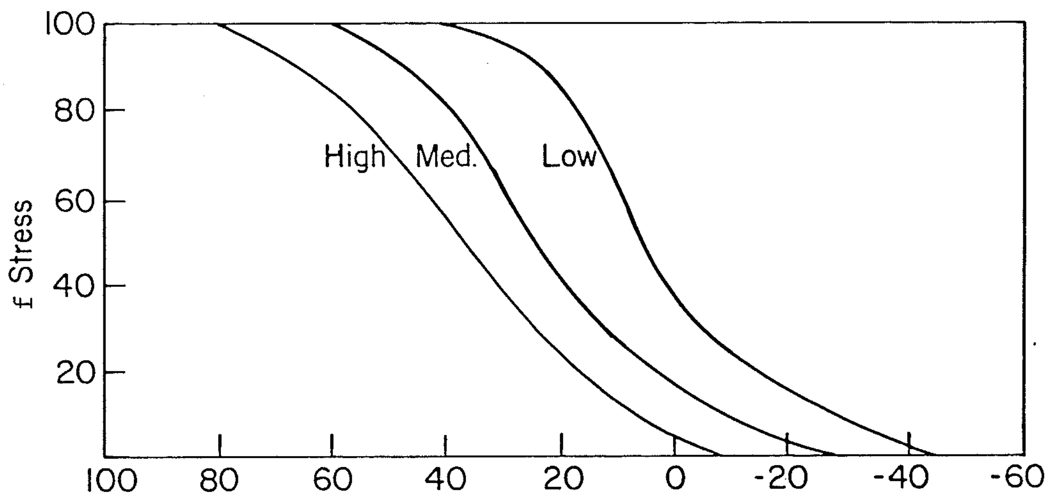


FIG. 6. RELATION BETWEEN EVAPOTRANSPIRATION STRESS AND % AVAILABLE MOISTURE (before August, 1).

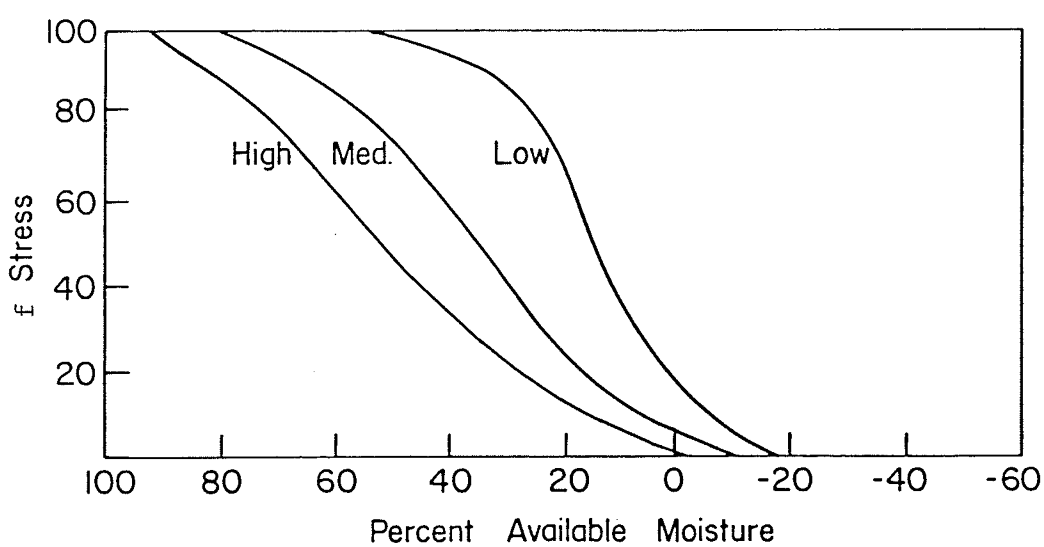


FIG. 7. RELATION BETWEEN EVAPOTRANSPIRATION STRESS AND % AVAILABLE MOISTURE (after August, 1) (After Vithayathil et al., 1977).

Since we are interested especially in those changes that affect the total plant weight, the last group of components are the most important. At the same time, due to the fact that the soil profile to the depth of root penetration has been considered as part of the system, physical transport processes within the soil must be represented in the model.

The transport of heat and water and the transport of solutes in the water are considered to be the most important transport processes in soil. There are several comprehensive reviews which treat different aspects of these processes from a modeling point of view (de Wit and van Keulen, 1972, described transport processes in soil; Makkink and Heemst, 1975, referred to simulation of the water balance and Nye and Tinker, 1977, focussed on water transport in the soil-root system).

As de Wit and van Keulen pointed out, the main assumption in treating transport processes in soil is that the frictional forces during movement of a substance are proportional to the velocity of flow and compensate the driving force in full. Therefore, uniform motion results with a velocity in the same direction as, and proportional to, the driving force. Based on this assumption the rate of flow was described in a very simple way by the following general equation:

FLOW = TRANSPORT COEFFICIENT * DRIVING FORCE

Although there is a similarity between transport of heat, water and solute within the soil there are some differences. For example, it is generally agreed that for diffusion of heat or solutes the transport coefficients (conductivity and diffusion coefficient) do not depend, to a great extent, upon concentration of the diffusing agent. For water, under unsaturated condition the diffusivity will decrease as the volumetric water content in the soil decreases due to increasing frictional forces per unit volume of water since the pores that remain filled with water have smaller radii.

3.5.3.1 Water Movement

In order to account for different possible combinations of soil, climate and plant conditions at an instant in time, the movement of water within the system seems to be one of the most pertinent physical processes that have to be considered in a model.

There are many conceptual models on this subject described in the literature. The Vithayathil et al. (1977) program and earlier mentioned review constituted the basis for representation of water movement within the soil profile, as described in the model by the subroutine program MOIST.

The first decision made was concerning the type of water flow. Since the model described a dry land crop production system during the growing season, only unsaturated water flow was considered, assuming that in the field the soil is unsaturated most of the time.

In the first place, de Wit and van Keulen (1972) considered horizontal flow as a function of diffusivity. This assumption holds if the force of gravity is neglected. In order to account for that, by combining the law, of conservation of matter with Darcy's law they expressed the water flow in the soil profile in a vertical direction as follows:

$$\vartheta = D d\theta/dx + K \quad (34)$$

Where: ϑ -flow rate (cm/day);

D-diffusivity (cm/day);

θ-water content (cc/cc);

x-distance (cm);

K-conductivity (cm/day).

Equation 34 was used to describe water transport. However, equation 34 holds only within a uniform soil profile and with an initial water content which is uniform throughout. This is not the case with the real system. Consequently, the movement of water was calculated in steps from one layer to another, assuming that within each layer the soil was uniform and that the expression of diffusivity and conductivity over two adjacent layers was correctly represented by an average for the layers.

For layers with similar boundary conditions, that is from the second to the tenth layer, equation 34 was written as a difference equation as follows:

AVD={DIFN(I - 1) + DIFN(I)}/2

AVC={CDUT(I - 1) + CDUT(I)}/2

FLRT(I)=AVD * {WC(I -1) - WC(I)}/15 + AVC (35)

Where: I -number of layers from 2 to 10 ;

AVD -average diffusivity (cm^2/day);

DIFN-diffusivity (cm^2/day);

AVC -average conductivity (cm./day);

CDUT-conductivity (cm./day);

WC -water content (cc/cc).

All layers had the same thickness.Therefore, the distance between the centre of two adjacent layers was constant (i.e. dx = 15).

Flow rate for the first and last layer were computed differently because of their particular boundary conditions. For the first layer, the flow rate was computed as a function of the overall input (i.e. precipitation) less the loss by runoff.

Hiler and Howell (1974), using a set of curves (Figure 8) developed by Mockus (1972), expressed runoff as a function of rainfall and water content in the soil.

$$Q=(R - IA)^2/(R - IA + SP) \qquad (36)$$

WHERE: Q -runoff (mm.);

R -rainfall (mm.);

IA-initial abstraction :

$$IA=116 - 0.41SW \qquad (37)$$

SW-soil water content (mm.)

PS-max.pot.difference (rainfall-runoff);

$$PS=(25400/CN) -254 \qquad (38)$$

CN-curve number

$$CN=50 + 0.15SW \qquad (39)$$

This can be an appropriate method if precipitation is intense or if soil water content is high.

Duffy et al. (1975) proposed a simpler manner of computing runoff of precipitation using an empirical equation.

$$RUNOFF=0.344 * PREC - 0.344 \qquad (40)$$

Equation 40 was used in the model for the dry land cropping system. A similar approach to that of Hiler and Howell can easily be incorporated into the model if excess moisture is to be considered.

The first layer inflow rate was expressed as:

$$FLRT(1)=PREC - RUNOFF \qquad (41)$$

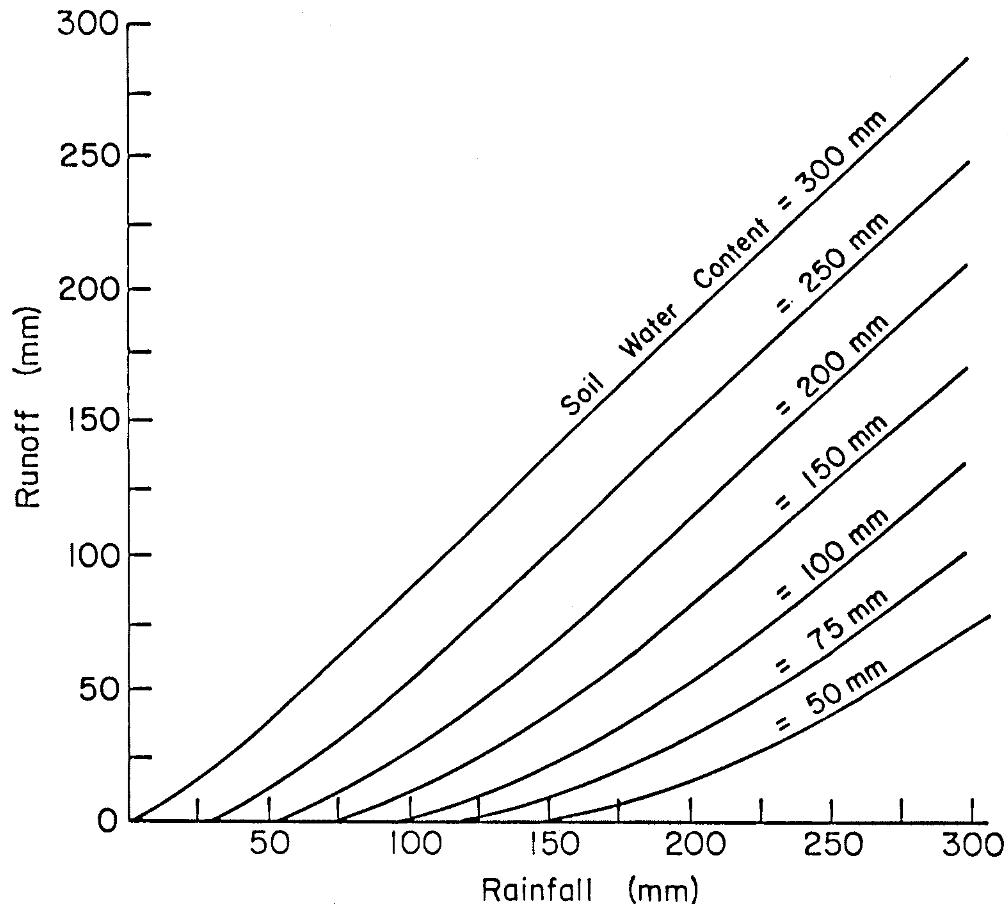


FIG. 8: RUNOFF AS FUNCTION OF SOIL WATER CONTENT AND RAINFALL AMOUNT. (After Mockus, 1972).

The outflow rate from the last layer (the overall output from the system) was computed in a similar manner to that described for layers 2 to 10 by making two more assumptions:

1. water content in the layer beneath the maximum depth remains unaltered;
2. the flow at the boundary of the system is downward only.

3.5.3.2 Soil Hydraulic Properties

In using equation 35 to describe unsaturated water flow, a fundamental problem arises. This concerns the behaviour of the transport coefficients (hydraulic conductivity and diffusivity) relative to the status of the soil. Within a dynamic framework, the soil water content, that is a state variable, is affected by overall input/output (i.e. precipitation, evapotranspiration, drainage) as well as by the flow process itself. Of the many soil characteristics that are altered over time, matric potential, volumetric water content and transport constants are of the main interest.

Under isothermal conditions, hydraulic conductivity is defined as the ratio of the flux to hydraulic gradient ($K = q/\Delta H = q/[\Delta H/\Delta X)]$. The slope of the flux (q) vs. hydraulic gradient (ΔH) is not unique and it varies with average suction (Ψ).

Childs and Collis-George (1950), by an analogy with Fick's law, defined diffusivity as the ratio of the hydraulic conductivity to the specific water capacity $D(\theta)=K(\theta)/C(\theta)$ where water capacity $C(\theta)$ is the slope of the soil moisture characteristics curve (i.e. change of water content per unit of change of matric potential). Therefore, $C(\theta) = d\theta/d\Psi$ and $D(\theta) = K(\theta) * d\Psi/d\theta$. The problem of determining the transport constants becomes more complex since the processes of wetting and drying occur simultaneously within the soil profile and sequentially in the various layers into which the soil profile has been subdivided. Consequently, a hysteresis effect occurs so that there is not a unique relationship between matric potential (Ψ) and soil wetness (θ).

As Philip (1970) pointed out, hydraulic conductivity and hence diffusivity are affected simultaneously by some soil characteristics (pore geometry), fluid attributes as well as by the direction of the process within cyclic drying and wetting.

The values of unsaturated hydraulic conductivity and diffusivity at different suctions and water contents must be experimentally measured in order to accurately apply mathematical theory to water flow. The laboratory methods and field techniques available for measurement of suction, hydraulic conductivity and diffusivity have been reviewed by Klute (1965) and Rose (1966).

Although there is not a satisfactory theory, several attempts have been made to relate unsaturated conductivity to suction and wetness and to predict the hydraulic conductivity value (K) from more basic soil parameters. Hillel (1971) presented several existing empirical equations as follows:

$$K=a/\Psi^{m} \quad ; \quad K=a/(b+\Psi^{m})$$

$$K=a\theta^{m} \quad ; \quad K=KsWs^{m} \qquad (42)$$

Where Ψ is the matric suction; θ is the volumetric water content; Ks is saturated conductivity; Ws is degree of saturation and a,b,m are empirical constants.

It is obvious that all these parameters and constants must be experimentally determined for each soil of interest. The values of exponential constants are the most important since they control the slope of the curve that represents conductivity vs. suction or wetness.

In the past, many statistical models for determining the hydraulic conductivity have been proposed. Mualem and Dagan (1978) reviewed these models and concluded that there are three general equations that might be applied to predict unsaturated hydraulic conductivity as follows:

I Childs and Collis-George (1950)

$$Kr(\theta)=Se^{x}\int_{0}^{\theta}\frac{(\theta-\zeta)d\zeta}{\Psi^{2+b}}\Bigg/\int_{0}^{\theta sat}\frac{(\theta sat-\zeta)d\zeta}{\Psi^{2+b}} \qquad (43)$$

II Burdine; Wyllie and Gardener (1958)

$$Kr(\theta)=Se^{x}\int_{0}^{\theta}\frac{d\theta}{\Psi^{2+b}}\Bigg/\int_{0}^{\theta sat}\frac{d\theta}{\Psi^{2+b}} \qquad (44)$$

III Mualem (1974)

$$Kr(\theta)=Se^{x}\left[\int_{0}^{\theta}\frac{d\theta}{\Psi^{1+b}}\Bigg/\int_{0}^{\theta sat}\frac{d\theta}{\Psi^{1+b}}\right]^{2} \qquad (45)$$

Where Kr is the relative hydraulic conductivity; Se is effective saturation; ζ is a variable of integration representing the effective water content as a function of Ψ between boundary limits (0 and θ); θ is volumetric water content; θ sat. is volumetric water content at saturation; Ψ is suction and x and b are constants.

All statistical models which use one of three generalized formulae (equation 43,44,and 45) assume a partial randomness between the pores at the two cross sections of a soil slab of a thickness Δx. Within this framework, the "effective radius" depends not only upon radius $r \rightarrow r+dr$ on one side of the slab (at x) and pores of radius $\rho \rightarrow \rho+d$ on the other side of the slab (at x + dx) but also upon the intermediate pores. Regardless of variable type, macroscopic or a microscopic term, the dependence of effective radius (r_e) on r, ρ and R is expressed using a "tortuosity factor". The ways of accounting for the tortuosity effect differ among the above equations. However, by accounting for the tortuosity effect the various Kr equations gain an additional degree of freedom; therefore, they may better represent the variability of the soil properties. Equations 43,44 and 45 are perhaps the best statistical methods for predicting the value of hydraulic conductivity. Nevertheless, as Mualem and Dagan suggested the values of x and b coefficients have to be determined experimentally before these formulae can be used as predictive tools.

Since it is difficult to obtain such measurements for a large area, Clapp and Hornberger (1978) suggested several empirical equations that might be used for estimating the hydraulic conductivity as follows:

$$\Psi=\Psi_s W \quad (46)$$

$$k=K/K_s \quad (47)$$

$$k=W^{2b+3} \quad (48)$$

$$W=\theta/\theta_s \quad (49)$$

Where Ψ is suction; Ψ_s is saturated suction; W is 'soil wetness'; K is unsaturated hydraulic conductivity; K_s is saturated hydraulic conductivity; θ is volumetric water content; θ_s is saturated volumetric water content and b is an empirical coefficient.

Since some confusion might arise relative to the term "W", which was named and expressed in many different ways in the literature, a few brief comments might be worthwhile.

Clapp and Hornberger (1978) termed "W" as "soil wetness"

$W=\theta/\theta s$ (49)

Brakenseik (1979) used a term named "effective saturation" (Se)

$Se=(\theta - \theta r)/(\theta s - \theta r)$ (50)

He accounted for residual saturation (θr). If this last term (θr) is neglected then equation 50 is equivalent to equation 49.

Mualem and Dagan (1978) use the term "Se" defined as:

$Se=\theta/\theta sat$ (51)

Where θ was considered effective moisture content ($\theta = \Theta - \Theta r$) where Θ and Θr are actual and residual water contents, respectively. By changing some of abbreviation terms, equation 51 becomes equivalent to equation 49.

In fact, all these terms (W;Se) differently named and expressed, represent the degree of saturation and are simply and well defined by Hillel (1971) as:

$\theta s=Vw/Vf=Vw/(Va + Vw)$ (52)

Where θs is degree of saturation, which ranges from zero in dry soil to 100% in a completely saturated soil; Vw is volume of water and Va is volume of air.

Equation 46 gives the relationship between suction (Ψ) and degree of saturation (W) and equations 47 and 48 provide the value of the hydraulic conductivity (K) if the saturated hydraulic conductivity (Ks) and coefficient b are known.

Clapp and Hornberger (1978) used a data set reported by Holtan et al. (1968), consisting of 176 sampled soil types, collected throughout the United States, with a total of 1800 horizons, to compute some soil hydraulic parameters as related to soil texture classes (Table 2). The figures presented are mean values. Coefficients $\bar{b}$ and $\bar{\Psi}s$ (saturated suction) have been determined for each soil textural class by taking the logarithms of both sides of equation 46 and performing a linear regression.

Brakensiek (1979) commented on the above approach. Some of the comments concern alternative ways of deriving equations 46,47,48 and 49. The main problem pointed out by Brankensiek concerned the estimation of saturated hydraulic conductivity (Ks), and its magnitude, which is crit-

TABLE 2: REPRESENTATIVE VALUES FOR HYDRAULIC PARAMETERS AS A FUNCTION OF TEXTURE (After Clapp and Hornberger,1978)

SOIL TEXTURE	No.OF SAMPLES	MEAN CLAY FRACTION	$\bar{b}$	$\bar{\Psi}s$ (cm.)	$\bar{\theta}s$ (cc/cc)	Ks** (cm/min)
SAND	13	.03	4.05(1.78)*	12.1(14.3)	.395(.056)	1.056
LOAMY-SAND	30	.06	4.38(1.47)	9.0(12.4)	.410(.068)	.938
SANDY-LOAM	204	.09	4.90(1.75)	21.8(31.0)	.435(.086)	.208
SILT -LOAM	384	.14	5.30(1.96)	78.6(51.2)	.485(.059)	.043
LOAM	125	.19	5.39(1.87)	47.8(51.2)	.451(0.78)	.042
SANDY-CLAY-LOAM	80	.28	7.12(2.43)	29.9(37.8)	.420(.059)	.038
SILTY-CLAY-LOAM	147	.34	7.75(2.77)	35.6(37.8)	.477(.057)	.010
CLAY-LOAM	262	.34	8.52(3.44)	63.0(51.0)	.476(.053)	.015
SANDY-CLAY	19	.43	10.40(1.64)	15.3(17.3)	.426(.057)	.013
SILTY-CLAY	441	.49	10.40(4.45)	49.0(62.1)	.492(.064)	.006
CLAY	140	.63	11.40(3.70)	40.5(39.7)	.482(.050)	.008

* In parentheses are presented standard deviation values.
** Ks values were taken from Li et al.(1976).

ical in estimating the value of unsaturated hydraulic conductivity using equation 47.

For predicting the value of Ks he proposed the following equation:

$$Ks=270\Phi e^2/\Psi s^2 \; 1/\{(b + 1)(2b + 1)\} \qquad (53)$$

Where Φe is effective porosity which was taken as equal to the volumetric water content at saturation (θs). All other symbols have the same significance as given for equations 46 to 49. The value of Ks determined for each soil textural class using this equation was quite different from those used by Clapp and Hornberger. Brakensiek tested predicted Ks values against observed data and found a reasonable agreement. Therefore Ks values used by Clapp and Hornberger presumably are incorrect. Consequently, we believe that it is more reliable and efficient to test all hydraulic parameters suggested by Clapp and Hornberger before using them as a practical tool.

In the recent studies, the redistribution of soil water after infiltration has become one of the more important and active topics of research. The numerical procedure for predicting the redistribution of water has been successful and some of the information from these predictions were used in the model.

Staple (1969) measured and computed moisture profiles using such a numerical method. He developed curves for diffusivity (D) and hydraulic conductivity (K) vs. volumetric water content (θ) for three soils with a fairly wide range in texture and properties of hysteresis: Uplands sand, Castor loam and Rideau clay (Figure 9 and 10). For diffusivity values (Figure 9) there are two different curves: computed and estimated. The computed curve refers to computed profiles using an explicit finite-difference form of the flow equation where the mean values of D were used directly along with gradients of θ . The estimated curve was graphed using an implicit equation where the values of D were converted from the corresponding values of K, defined as function of Ψ gradients.

However, in principle, within equation 35, which describes water flow, diffusivity and hydraulic conductivity are given functions of θ (volumetric water content) and flow is a function of θ and time. Therefore the curves developed by Staple have been used in the model. The values of K and D were estimated from Figures 9 and 10 using the inter-

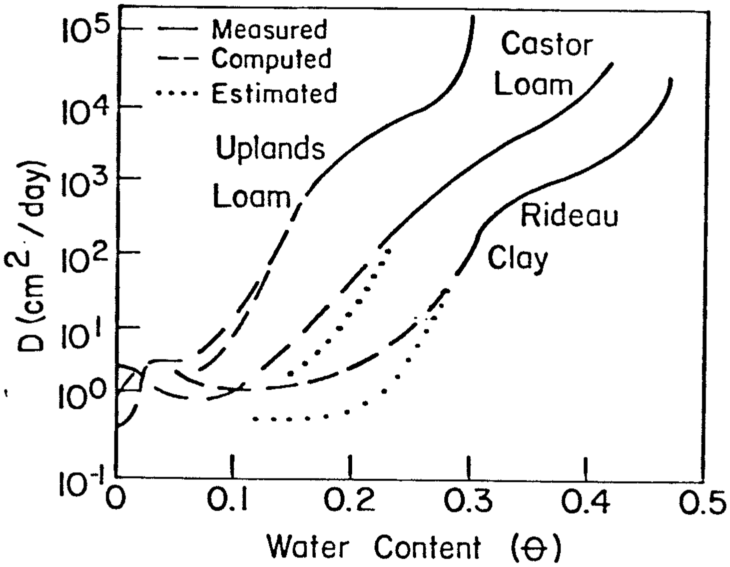


FIG. 9 DIFFUSIVITY AS FUNCTION OF WATER CONTENT.

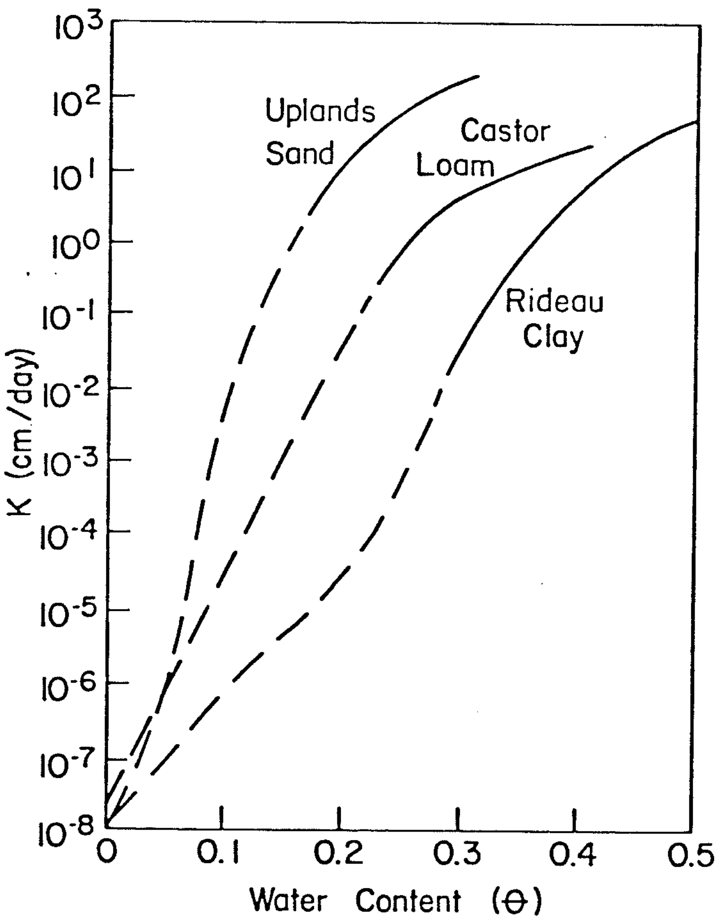


FIG.10 HYDRAULIC CONDUCTIVITY AS FUNCTION OF WATER CONTENT.
(After Staple, 1969)

polation function AFGEN. It should be noted that by choosing Staple's data, the accuracy of the model predictions depended only upon the physical soundness of the approach since no data for Manitoba soils were used.

Having obtained overall input/output variable values as well as inflow-outflow values computed for each layer, the moisture content was updated daily in the following manner:

$$WC(I) = OSM(I) + FLRT(I)/INT - FLRT(I+1)/INT - ETL(I)/INT \qquad (54)$$

Where: I -layer number;

WC -water content (cm);

OSM -water content on previous day (cm);

FLRT-flow rate (cm/day);

ETL -evapotranspiration (cm/day);

INT -integration time (1/2 day).

It was assumed that the water content in each soil layer was always between field capacity and permanent wilting point. Consequently, a restriction has been imposed in the model as follows:

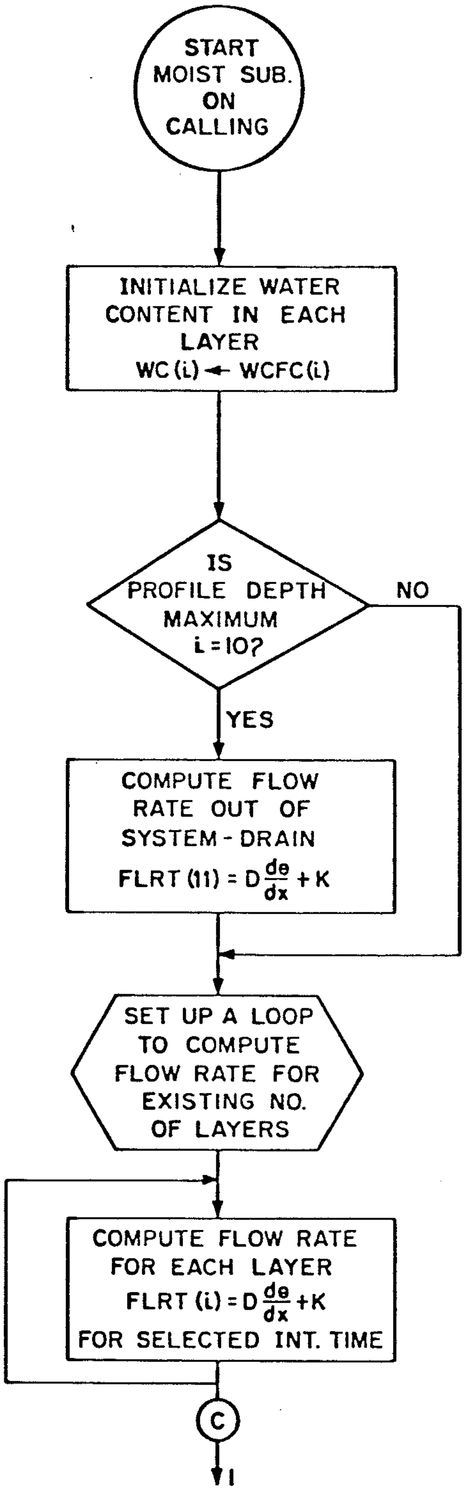
$$WILT(I) \leq WC(I) \leq WCFC(I) \qquad (54a)$$

Although it is not always true, the initial water content in each soil layer was assumed to be at the field capacity. The general flow chart of water movement is presented in Figure 11.

3.5.4 Nitrogen – Nutrient Element Considered in the Model

Based on experience of the effects of major nutrients on important crops, nitrogen is considered the most likely nutrient to limit crop growth. In the past decade the use of nitrogen in agricultural practice has increased spectacularly. In addition the available nitrate nitrogen content in soil was the only quantitative data available that descrbed, even in relatively narrow terms, the relationship of crop growth to soil fertility. Comprehensive reviews reported by McLaren (1976), Beek and Frissel (1973), van Veen (1977) and Tanji and Gupta (1977) are the more recent relevant studies dealing with modeling of the behaviour of nitrogen in soil.

MOIST


START
MOIST SUB.
ON
CALLING
INITIALIZE WATER
CONTENT IN EACH
LAYER
WC (i) ← WCFC (i)
IS
PROFILE DEPTH
MAXIMUM
i = 10?
NO
YES
COMPUTE FLOW
RATE OUT OF
SYSTEM - DRAIN
FLRT (11) = D dθ/dx + K
SET UP A LOOP
TO COMPUTE
FLOW RATE FOR
EXISTING NO.
OF LAYERS
COMPUTE FLOW RATE
FOR EACH LAYER
FLRT (i) = D dθ/dx + K
FOR SELECTED INT. TIME
C
I

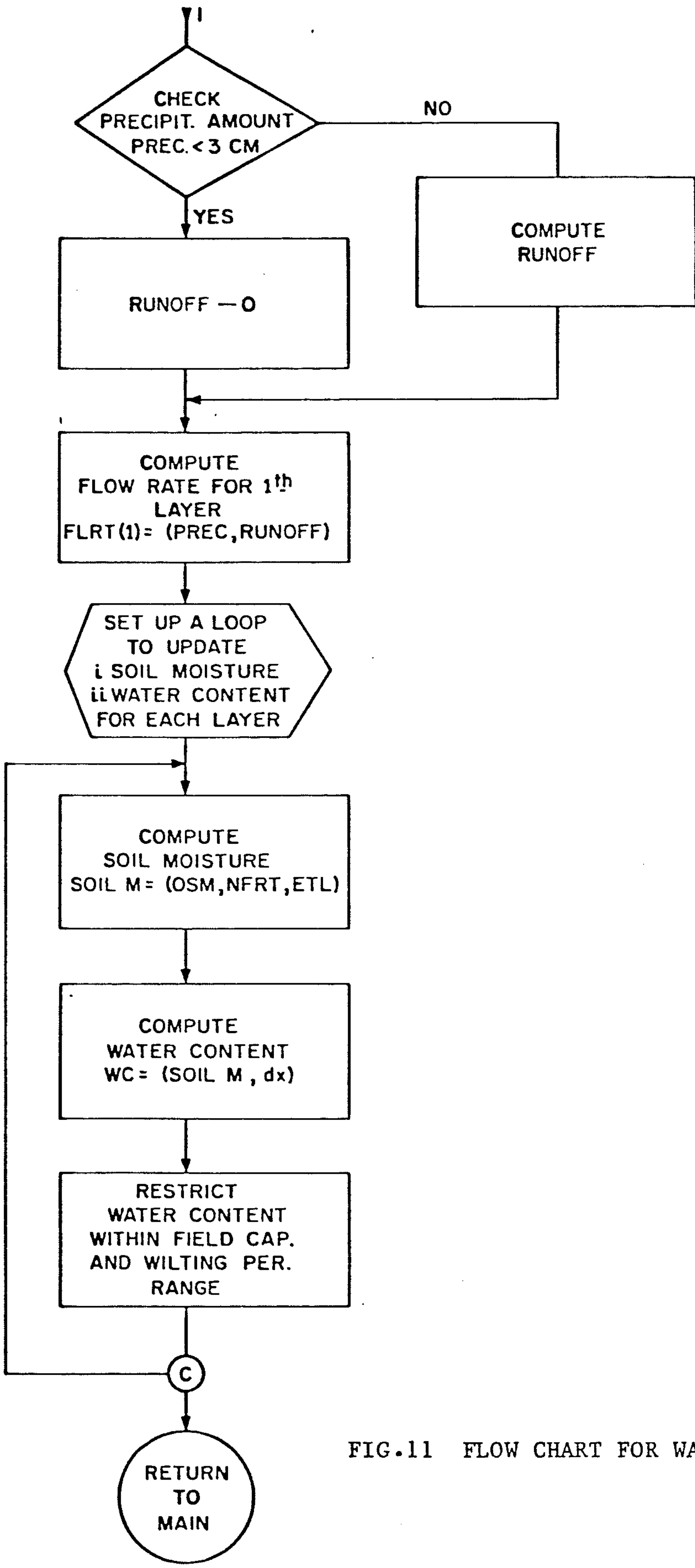


FIG.11 FLOW CHART FOR WATER MOVEMENT.

Although some of the theoretical models presented in this chapter are not strictly related to present model, they are discussed to some extent due to their importance in providing a fundamental explanation of the nitrogen cycle within a soil.

3.5.4.1 Initial Nitrogen Level in Soil and Transformations within the Nitrogen Cycle

The nitrogen cycle is so complex and dynamic that measurements of the amounts and forms of nitrogen present in soil may be considered only as snapshots of the actual situation. However, the nitrogen was an entity of interest in the system/model.Its initial level and the changes occurring during the growing season must be known. There is no doubt that the distribution of nitrogen within the soil profile is affected by well known pedogenetic factors. Within cultivated land, management practices alter the forms and amount of nitrogen quantitatively and qualitatively. Consequently, estimation of the initial nitrogen level can not based entirely on inherent soil characteristcs. Past and present management practices must also be considered. The quarter section, chosen as a unit base, was assumed to be the smallest homogenous land unit from this point of view and data generated by the Soil Testing Laboratory was considered to be the quantitative figure for the intial level of available soil nitrogen.

Having estimated the initial level of nitrogen, the second decision concerned the selection of the processes that occur within the nitrogen cycle and the manner of their description.

Based on a study by Beek and Frissel, van Veen (1977) described a computer simulation model where mineralization, nitrification, denitrification, volatilization, fixation and leaching processes were treated in separate subroutines (submodels). Since the nitrogen transformations are microbial in nature, he focussed on the biological aspects using the following kinetic rate equations:

Zero - order rate $-ds/dt=Ko$ (55)

First - order rate $-ds/dt=K_1 * S$ (56)

Michaelis-Menten $-ds/dt=Km * S/(Ks + S)$ (57)

Where ds/dt is substrate transformation rate; S is substrate concentration; Ko is the zero order rate constant (independent of substrate concentration); K_1 is the first-order rate constant; Km is the maximum transformation rate; Ks is the saturation constant (the concentration of substrate where ds/dt = 1/2Km).

Although such an approach is fundamental, due to the numerous parameters incorporated within the model, as well as because of many hypothetical environmental characteristics considered, the model can be used in research, at a micro-scale level, rather than as a practical tool.

Mehran and Tanji (1974) accounted for the same processes but they concluded that it was not a serious error to consider the reaction rate for most microbially mediated processes to be first - order. Consequently, they developed a model focussing on NO_3^- and NH_4^+ as the most frequent ions present in soil, based on an equation of the following form:

$$d(Nc)/dt = -\sum_{i=1}^{n} Ki(Nc) + \sum_{j=1}^{m} Kj(Nm) \qquad (58)$$

Where Nc is the concentration of N species of interest; Nm is the concentration of other N species; Ki and Kj are the first - order rate constants; dt is the time step considered.

A schematic representation of the possible transformation of nitrogen considered in their model is given in Figure 12. The number of the processes, numerically equal to the number of rate constants (K + KK), is very large. To account for all possible relationships between ions in the exchangeable, solution and immobilized phases is still a difficult task for a model that has to be applied to a large land unit. As Tanji and Gupta (1977) pointed out, even with a complex approach, there is no way of presenting the dynamic behavior of soil nitrogen correctly in a model. However, an extreme view, to ignore all these processes completely can not be considered a better approach.

Data from nitrogen balance sheet (Allison, 1966) shows that the main nitrogen input comes from existing soil organic matter and fertilizer applied whereas the major output consists of removal by crop, immobilization and denitrification. Most of these processes were considered and were described in the model to some extent.

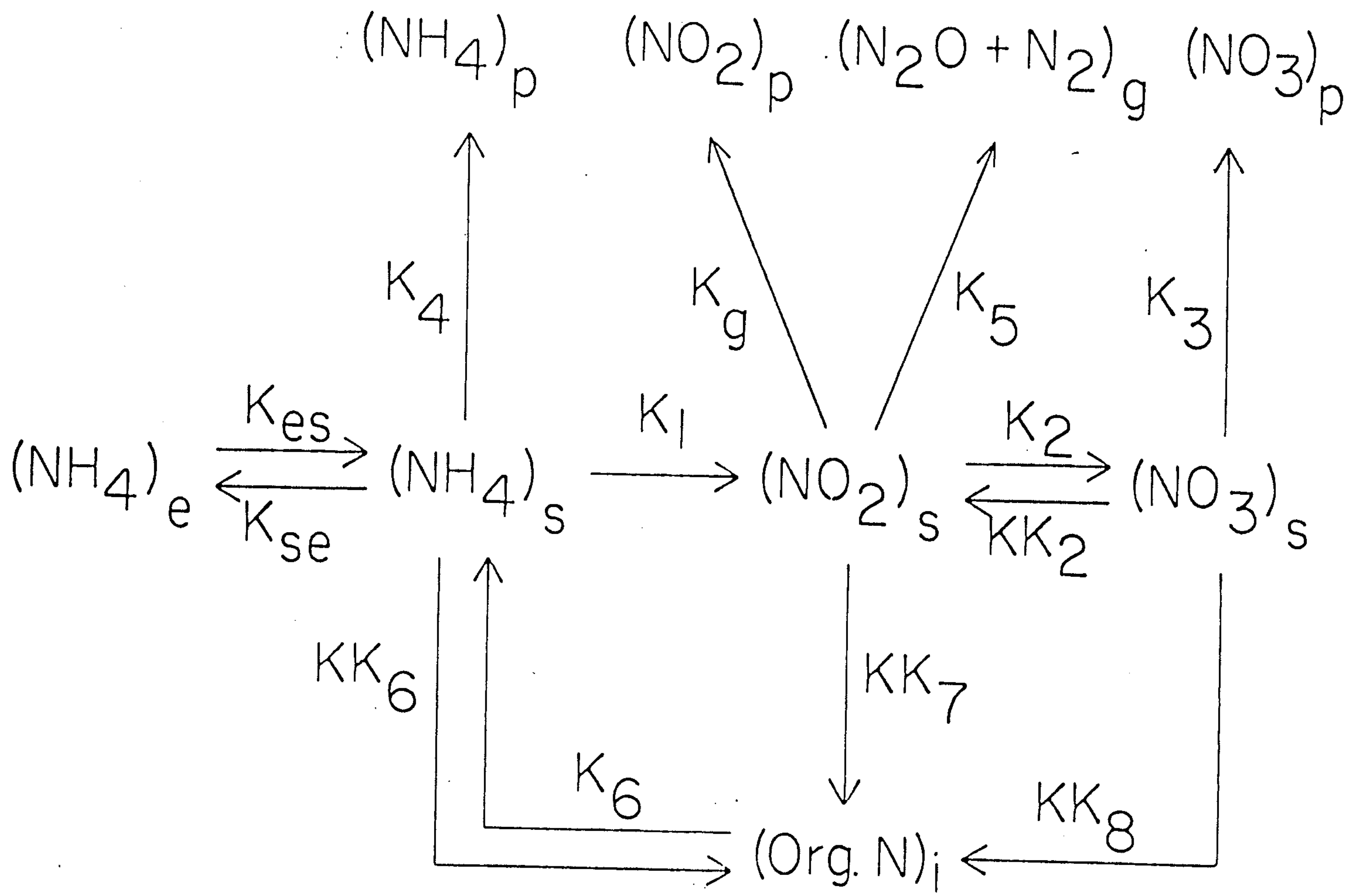


FIG.12 POSSIBLE TRANSFORMATIONS OF SOIL NITROGEN (After Mehran and Tanji, 1974)

3.5.4.2 Net Mineralization

Net mineralization is the result of two opposing processes, immobilization and mineralization, that occur simultaneously and both are intimately related to microbial activities. For these reasons most models are microbiological in nature and hence are very complex. They are important mostly from a theoretical point of view.

van Veen and Frissel (1976) described mineralization, taking into account dead biomass, fresh organic matter and soil organic matter using a general equation of the following form:

$$N_T^m = N_T^b + N_T^o + N_T^H \qquad (59)$$

Each term from the right side of equation 59 represents the amount of nitrogen mineralized from the sources mentioned. Further computation was very elaborate and this may be illustrated by showing step by step the calculations involved in computing the amount of nitrogen mineralized from dead biomass (N_T^B) and from soil organic matter (N_T^H).

$$N = \int_0^T K_B * m_T^D dt \qquad (60)$$

Where K is rate constant/day; m_T^D is amount of N in dead biomass (mg N/g soil).

$$m_T^D = \int_0^T K_D * m dt \qquad (61)$$

Where KD is the rate constant for dead biomass/day; m is the amount of nitrogen in biomass (mg N/g soil).

$$m = c_1 * n \qquad (62)$$

Where c_1 is the N concentration/cell; n is number of cells/g of soil.

From the growth rate equation:

$$n = dn/dt/\mu \qquad (63)$$

Where μ is the growth rate/day. It was expressed using the Michaelis-Menten kinetic - type equation as follows:

$$\mu = \mu max\{S/(Ks + S)\} \qquad (64)$$

Where μ max is maximum growth rate constant; S is the growth limiting substrate (carbon); Ks is a coefficient.

The amount of nitrogen mineralized from soil organic matter was represented by the following expression:

$$N_T^H = \int_0^T Kh * Ht * dt \qquad (65)$$

Where Kh is a rate constant/day and Ht is the amount of N in soil organic matter (mg N/g soil).

Equation 65 appears to be relatively simple. This is not the case. van Veen (1977) reviewed the values of the net mineralization rate constants reported in the literature and found that its values ranged from $2.58 * 10^{-2}$ to $6.59 * 10^{-5}$. Therefore, the value of the rate constant must be experimentally determined for each particular soil.

McLaren (1970) proposed a more complex description of microbial processes:

$$-dS/dt=Adm/dt + am + K\beta S/(Km + S) \quad (66)$$

Briefly, the terms on the right side of the equation account for consumption (microbial growth), maintenance and waste metabolism, respectively.

Although such models probably represent the mineralization process most corectly, they can not be used as subroutines within a large model with a practical objective. The reason for this is that such model subroutines require a very large number of coefficients, which vary widely in space and which can not be easily determined for field conditions.

A simple but very useful approach to account for mineralization process was suggested by Duffy et al. (1975). They considered that the net NO_3-N gain varies with time during the year in a certain manner. Following this approach and using some data from the Prairie region, net mineralization was represented in the model in a simple way.

According to Nyborg et al. (1976) the amount of nitrogen released from the soil during one year is about 50 lb/ac. Half of this amount was assumed to be released during the growing season and the other half during the remainder of the year (early in fall and late in spring). Consequently, the mineralization rate was computed as follows:

For $15,05 \leq T \leq 15,08$:

$$RNMIN=25\ lb/ac.=0.3077\ Kg/Ha\text{-}day=0.00308\ mg\ N\ cm^{-2}\ day^{-1} \quad (67)$$

For $15,04 \leq T < 15,05$ and $15,08 < T \leq 31,10$:

$$RNMIN=25\ lb/ac.=0.2617\ Kg/Ha\text{-}day=0.00263\ mg\ N\ cm^{-2}\ day^{-1} \quad (68)$$

Otherwise : RNMIN=0 (69)

Where RNMIN is mineralization rate and T is the day of the year.

The mineralization process was treated in a less dynamic manner than in the biological models and several other assumptions were considered:

1. the value of RNMIN reflects the effects of temperature and moisture on the process;
2. mineralization rate is constant over the growing season;
3. the process occurs only near the soil surface, in the first 30 cm of the profile. Therefore, the increment of NO_3-N was calculated only in the first two layers.

It should be noted also that the information used in the model was from an area located in North-Central Alberta assumed to be representative of the Prairie Provinces. If better information was obtained for a particular area, changes in the above rate values will be required.

3.5.4.3 Nitrification and Denitrification

One of the main processes which affects the fate of nitrogen applied as fertilizer (i.e. management input variable within the system) is nitrification. The biological character of this process was discovered more than a century ago. Two dominant microbial autotrophic genera (Nitrosomonas and Nitrobacter) are generally considered to be involved in a "step conversion process" in which reduced inorganic nitrogen forms are converted to higher oxidation states. There is no doubt that the most suitable model to describe this process is a microbiological type. There are several such models described in the literature. Basically, these models described bacterial growth using Michaelis-Menten kinetics rate and NH_4^+/NO_2^- as limiting substrates. Although the nitrification subroutine is considered one of the most successful in microbiological models, the approach has a theoretical rather than a practical value.

Agronomic experience has shown that most of the nitrogen fertilizer applied in reduced forms nitrifies within a few weeks. Duffy et al. (1975) concluded, on basis of experimental data, that in Illinois about 80% of spring-applied NH_4^+ fertilizer is nitrified in the first 20 days. Experimental data are not available under field conditions in Manitoba. Since the nitrification process is temperature dependent and because in Manitoba temperature during the spring is relatively lower than in Illinois, the nitrification rate was computed in the model as follows:

$$DNFM=(4/5) * FERT/45 * 0.1 \quad ; \quad Tf \leq T \leq Tf + 45 \qquad (70)$$

$$DNFM=.005 \quad ; \quad T>Tf + 45 \qquad (71)$$

Where DNFM is the nitrification rate (mg N/cm^2-day); FERT is fertilizer applied (Kg/Ha); Tf is the day when the fertilizer was applied and T is day of the year.

According to equations 70 and 71, in the first 45 days 80% of fertilizer is nitrified at a rate that depends only upon the amount of fertilizer applied regardless of the type (i.e. ammonium sulphate, urea). After 45 days the nitrification process continues at a lower rate until all the fertilizer is nitrified.

When attempting to obtain a soil nitrogen balance, only seldom is all of the nitrogen recovered. Loss is attributed largely to denitrification. Basically, denitrification refers to the microbes use of NO_3 as a terminal electron acceptor within the generally accepted pathway:

$$NO_3^- \longrightarrow NO_2^- \longrightarrow NO_2 \longrightarrow N_2 \quad (72)$$

Most models discussed in the literature treat denitrification as an enzymatic process described by a competitive Michaelis-Menten kinetics-type equation. Some models considered temperature, pH and oxygen effects on denitrification.

Cho and Sakdinan (1978) and Cho and Mills (1979) found that the disappearance rate of NO_3^- is independent of the initial concentration of NO_3^-, that is the rate was nearly constant (zero-order kinetics). They pointed out that N_2O, formed as an intermediate product, competes with NO_3^- as an electron acceptor. As a result, the formation of N_2 gas takes place earlier with a lower concentration of nitrate.

Since no rigorous model can be used as a subroutine, the denitrification process was empirically represented in the model. From many factors which affect denitrification, only the levels of nitrate in the soil and the water content were considered. It was assumed that denitrification will occur at a constant rate, only if the following conditions hold:

1. The nitrate within the soil is at a high level;
2. The water content is at or near field capacity.

Cho et al. (1979) related denitrification to soil depth based on oxygen diffusion and temperature. For several irrigated soils from Alberta, they found that denitrification decreases almost linearly with depth. Even in the day with the highest soil temperature (22 July) denitrification at 150 cm was very small. Consequently, within the model, denitrification was assumed to occur only in the top part of the soil profile, and changes were made only in the first 30 cm.

There are many other processes that occur within the very complex nitrogen cycle. Among them clay mineral fixation of NH_4^+ and volatilization of NO_3^- can be important in some circumstances. Also soil properties such as cation exchange capacity and pH as well as the type of fertilizer used, time and methods of application might alter the level of nitrogen within a particular land unit. In order to keep the model simple enough to be applicable to a large area, these aspects were not considered.

3.5.4.4 Nitrogen Movement

Nitrogen transport in soil is a very complex process due to the large number of N-compounds and ions involved (org-N, NH_4-N, NH_3, NO_2-N, N_2, etc.) as well as because of the various forms in which they exist i.e. insoluble, soluble, exchangeable, etc.

However, two species, nitrate and ammonium, were considered to be the most important in plant nutrition. Ammonium can be absorbed by the negatively charged soil complex, and hence very slowly leached. By contrast, NO_3^- -N is not absorbed and thus it is quite mobile. Therefore, by comparison, the movement of NH_4^+ can be practically neglected relative to NO_3^-. Consequently, the model focussed only on nitrate movement within the soil.

Transport of salt, diffusion of ions and transport of ions in soil have been described in many scientific papers. From a modeling point of view the de Wit and van Keulen (1972) and Beek and Frissel (1973) models are perhaps the best.

Following the Beek and Frissel approach, in the present model the movement of nitrate was considered to be caused by mass flow, diffusion and dispersion as follows:

$$FLRN = MFL + DIFF + DISP \quad (73)$$

Where FLRN is the total nitrate flow; MFL accounts for mass flow; DIFF stands for diffusion and DISP stands for dispersion flow. All terms are expressed in mg N/cm^2-day.

As water flows through the soil it carries nitrate and the mass flow rate was computed as a function of the water flow rate and NO_3-N concentration. The NO_3-N movement was related to NO_3-N concentration in the layer being considerd (I) as well as the concentration in the layer above (I -1).

In the real system (field conditions) cracks and relatively large holes are almost always present. Under such conditions an incomplete contact of water with the soil is to be expected, leading to lower mobility of nitrate. To overcome this, several models (Beek and Frissel, 1973; Duffy et al., 1975; Vithayathil et al., 1977) employed a weighting factor. This solution has been adopted in the present model and nitrate movement under mass flow was represented as follows:

MFL(I)=FLRT(I) * CNORT(I) * WF(I) ; FLRT(I) 0

MFL(I)=FLRT(I) * CNORT(I - 1) * WF(I) ; FLRT(I)>0 (74)

Basically, the movement by diffusion depends upon the concentration gradient (the driving force) and upon the diffusion coefficient (the constant transport). In an unsaturated soil a few particular problems must be considered when the diffusion coefficient in soil is related to the diffusion coefficient of water. First of all, diffusion is restricted to that part of the soil where pores are filled with water. Therefore the diffusion coefficient in water must be a diminished function of water content. The second problem concerns one of the characteristics of porous media - tortuosity or the labyrinths factor. The pathway of water through soil is always longer than the straight path denoted by the distance between two chosen points. Its precise measurement is a very difficult task and only an approximate magnitude can be considered in modeling. Some confusion relative to the magnitude of this dimensionless geometric parameter of porous soil arises because of different interpretations given in the literature. Scheidegger (1957) defined tortuosity as the ratio between the actual and apparent pathway. Therefore its value will always be greater than one. By contrast Frissel et al. (1970) considered tortuosity as the inverse of the above-mentioned ratio. In this case the value of tortuosity is always less than one. The latter view point was considered here. By considering the above factors, nitrogen transport by diffusion was represented as follows:

DIFF=DIF * TORT .5 * {WC(I - 1) + WC(I)} *
{CNORT(I - 1) - CNORT(I)}/15 (75)

During the flow of water through the soil some dispersion effect on nitrate movement is to be expected. According to Reiniger et al. (1972) the magnitude of dispersion is a function of the concentration gradient and the absolute flow rate of water. Consequently, dispersion was represented by the following expression:

DISPF=ABS{FLRT(I)} * DISP * {CNORT(I - 1) -
CNORT(I)}/15 (76)

By substitution of equations 74,75 and 76 into equation 73 the total nitrate was computed according to the following expression:

FLRN(I)=[FLRT(I) * CNORT(I) * WF(I)] + {[DISP * ABS
[FLRT(I)] + DIF * TORT * .5 [WC(I - 1) + WC(I)]
/INT] * [CNORT(I - 1) - CNORT(I)] /15} (77)

Where; I -the layer number (I=1,2,...,10);
FLRN-total flux (mg N/cm^2-day);
FLRT-flow rate -water (cm/day);
CNORT-nitrate concentration (mg N/cc soil);
WF -weighting factor;
DISP-dispersion coefficient- NO_3-N in water;
DIF -diffusion coefficient of NO_3-N (cm^2/day);
TORT-tortuosity coefficient (dimensionless);
WC -water content (cc/cc);
INT -integration time (day).

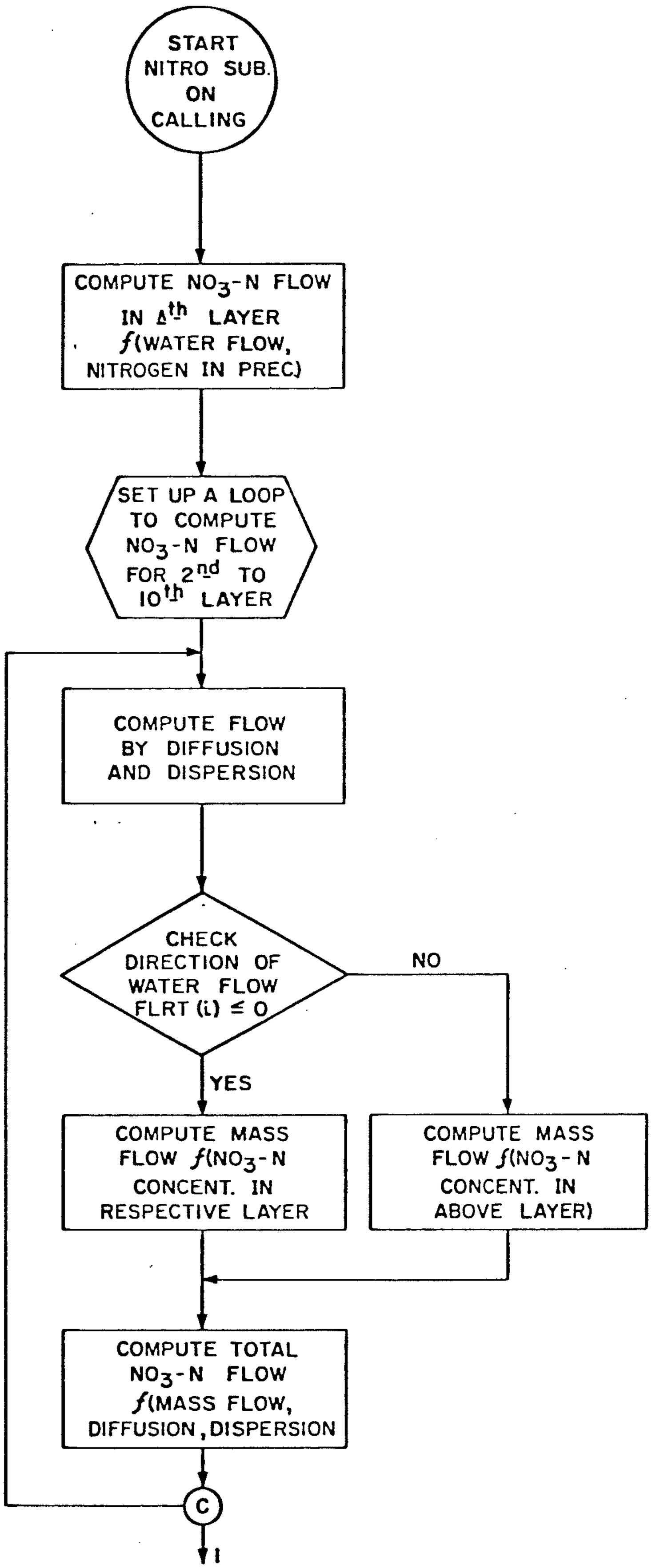
The above equation (77) holds for the 2nd to the 9th layers, with similar boundary conditions. For the first and the last layer within the soil profile the expression was modified slightly.

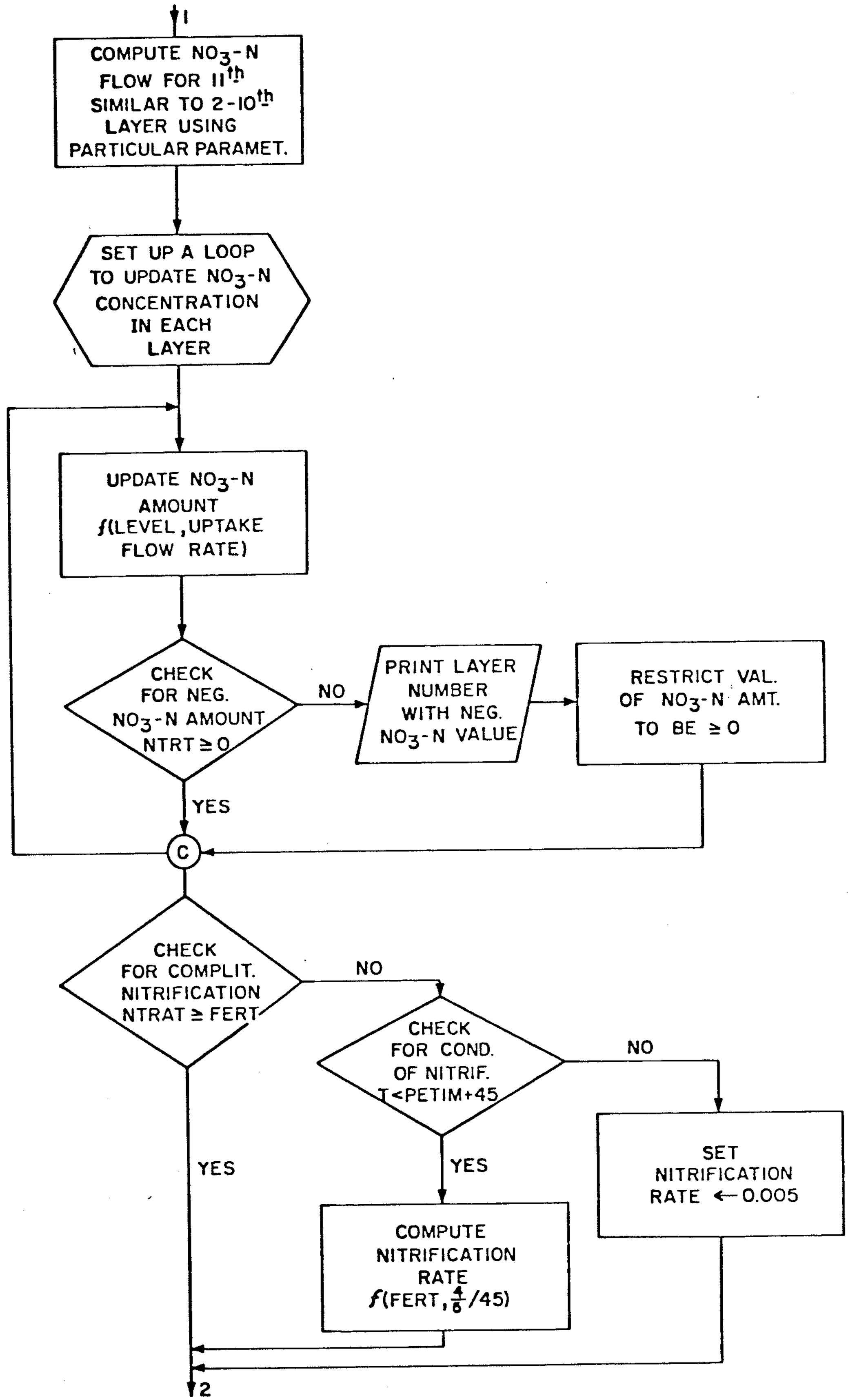
The flow chart of nitrogen movement and transformation processes considered in the model, presented in the program under the name NITRO is shown in Figure 13.

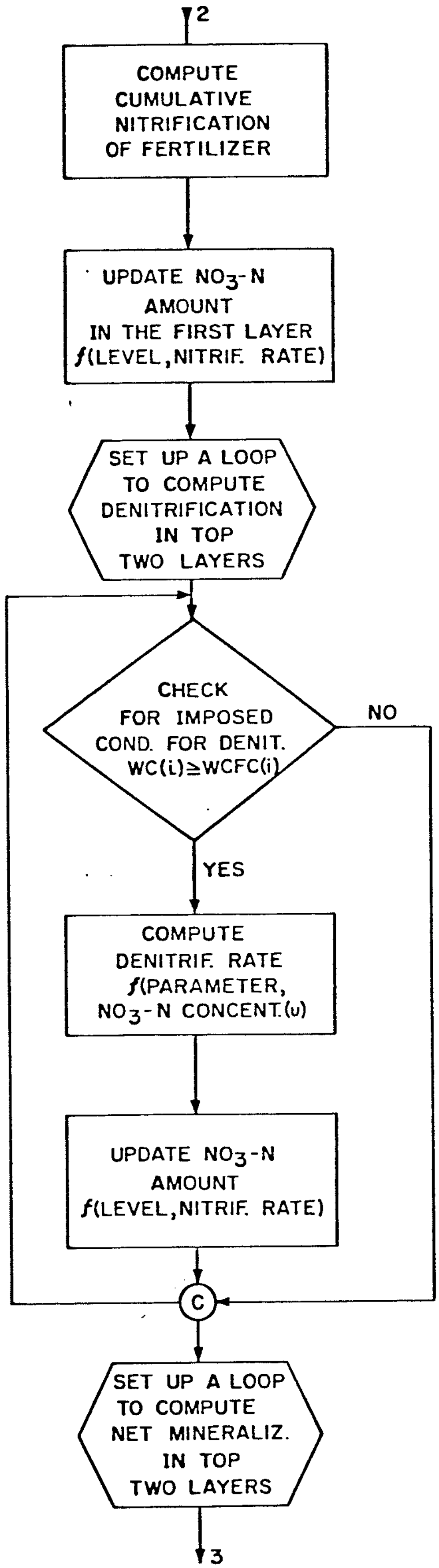
3.5.5 Plant Growth

There is no doubt that plant growth is a very important process in the system. Since the model intends to focus on soil aspects, plant growth has not been described in detail.

NITRO


START NITRO SUB. ON CALLING
COMPUTE NO3-N FLOW IN 1st LAYER f(WATER FLOW, NITROGEN IN PREC)
SET UP A LOOP TO COMPUTE NO3-N FLOW FOR 2nd TO 10th LAYER
COMPUTE FLOW BY DIFFUSION AND DISPERSION
CHECK DIRECTION OF WATER FLOW FLRT (I) ≤ 0
NO
YES
COMPUTE MASS FLOW f(NO3-N CONCENT. IN RESPECTIVE LAYER
COMPUTE MASS FLOW f(NO3-N CONCENT. IN ABOVE LAYER)
COMPUTE TOTAL NO3-N FLOW f(MASS FLOW, DIFFUSION, DISPERSION
C
1


1
COMPUTE NO3-N FLOW FOR 11th SIMILAR TO 2-10th LAYER USING PARTICULAR PARAMET.
SET UP A LOOP TO UPDATE NO3-N CONCENTRATION IN EACH LAYER
UPDATE NO3-N AMOUNT f(LEVEL, UPTAKE FLOW RATE)
CHECK FOR NEG. NO3-N AMOUNT NTRT ≥ 0
NO
PRINT LAYER NUMBER WITH NEG. NO3-N VALUE
RESTRICT VAL. OF NO3-N AMT. TO BE ≥ 0
YES
C
CHECK FOR COMPLIT. NITRIFICATION NTRAT ≥ FERT
NO
CHECK FOR COND. OF NITRIF. T<PETIM+45
NO
SET NITRIFICATION RATE ← 0.005
YES
YES
COMPUTE NITRIFICATION RATE f(FERT, 4/6/45)
2


2
COMPUTE CUMULATIVE NITRIFICATION OF FERTILIZER
UPDATE NO_3-N AMOUNT IN THE FIRST LAYER ƒ(LEVEL, NITRIF. RATE)
SET UP A LOOP TO COMPUTE DENITRIFICATION IN TOP TWO LAYERS
CHECK FOR IMPOSED COND. FOR DENIT. WC(i)≥WCFC(i)
NO
YES
COMPUTE DENITRIF. RATE ƒ(PARAMETER, NO_3-N CONCENT.(i))
UPDATE NO_3-N AMOUNT ƒ(LEVEL, NITRIF. RATE)
C
SET UP A LOOP TO COMPUTE NET MINERALIZ. IN TOP TWO LAYERS
3

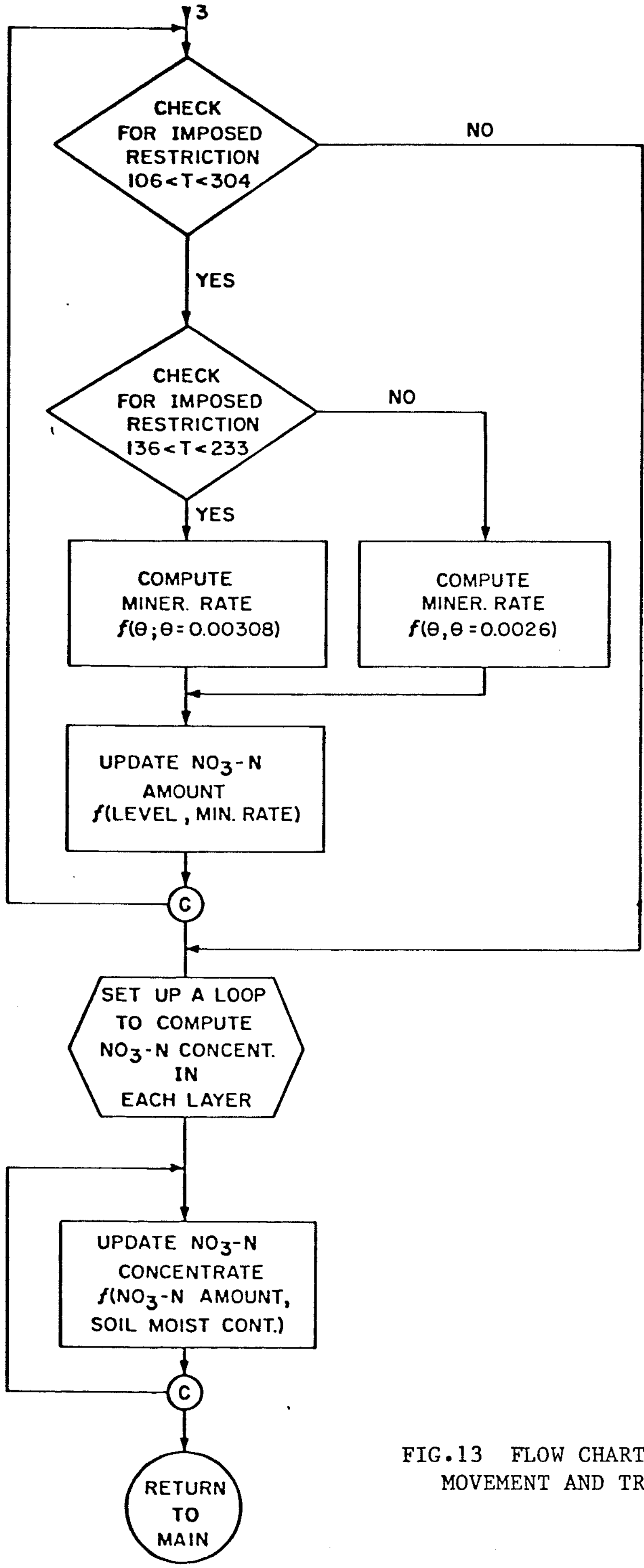


FIG.13 FLOW CHART FOR NITROGEN MOVEMENT AND TRANSFORMATIONS.

The detail chosen to describe this very complex process was treated in such a way that the plant should provide:

1. a connection between different structural parts of the system of interest;
2. a sink for water and nitrogen;
3. a biological means of describing the differences of soil conditions among land units.

As Milthorpe and Moorby (1974) pointed out, in a general sense, differentiation of plant parts (regardless of its complexity: cells, organ, etc.) appear to be under fairly strict internal control. The changes in form, over a range of conditions, are relatively small. The main differences that occur are in sizes and in the time-interval required to reach a given size - i.e. the rate of growth.

Indeed, it is very helpful to be able to identify the times (phases of the vegetation) during ontogeny,i.e. when a certain change takes place. The identification of critical events can be useful in comparing and understanding crop behaviour. The Biometeorological Time Scale (BMTS) developed by Robertson (1968) for wheat was proven to be a useful approach for determining growth stage. As Williams (1974) pointed out, the main objective of BMTS was to relate crop development to weather conditions. This does not mean that BMTS can not be used in a complex model with another particular objective. The problem is how to use it.

By treating phenological development of the crop as a state variable within the system, the yield (dry matter or grain) reflects especially the effect of weather conditions and management input (expressed by a particular seeding time). If seeding time is fixed the yield will reflect among other factors the weather pattern of a particular year. By averaging weather data over a large number of years in such a way that weather data represent a general trend of climate, then the growth stages within phenological crop development become parameters. Their values will differ only from one climatic zone to another. Consequently plant development stages in the present model were used as parameters based on data published by Baier and Robertson (1968)

Basically, the plant growth subroutine follows an approach suggested by Frere, Jensen and Carter (1970). The increase in dry matter over time is considered to follow an "S"-shaped curve similar to the integral of a normal curve. The rate of plant growth under ideal conditions was described by a normal bell-shaped curve (Figure 14) and by a general equation of the following form:

Y=Ymax EXP{- (M - X) /B } (78)

Where Y is the ideal growth rate on day X; Ymax is maximum rate on day M and B is half of the width of the peak at 37% of the maximum.

The logistic type of curve is widely used to express yield of either parts of the plant or the entire plant. However, the continuous function which provides the main feature of plant growth over an entire season can not be a perfect representation of crop growth. The function represents only the general trend; short term fluctuations are ignored.

The cumulative growth curve and the growth rate were based on data from four wheat cultivars (unpublished data McVetty,1976). Since the experiment was conducted on a irrigated area and a high fertilizer rate, the maximum yield (dry matter) approached a value of 20,000 Kg/Ha. This value is in agreement with that published by Milthrope and Moorby (1974) as a record obtained in Netherlands (20 t/ha).

The authors pointed out that, as an average for a large area, maximum yield rarely reaches half the record values reported in experimental work. Barnes et al. (1976) referring to data in the literature pointed out that the vegetative crops such as, wheat, barley and grass attained the same ceiling (10/ha). Assuming a maximum yield of 10,000 Kg/Ha and a normal curve distribution, equation 78 was expressed in the form:

IGR=210 * EXP{ -(52 - T)**2/27**2} (79)

Where IGR is ideal growth rate (Kg/ha-day) and T is the number of days after seeding.

Under field conditions ideal growth rate is virtually never reached. Recalling Blackman's equation (2) for plant growth and considering the environmental factors the rate of growth becomes:

dW/dt=G(X1,X2,...,Xn) (80)

Two questions arise: First, what factors must be considered since theoretically the number is extremely large. Plant physiology identifies several important factors such as: light, CO, temperature , water and nutrients. Due to the initial objective of this study, only the last three factors were considered in the model. The second question

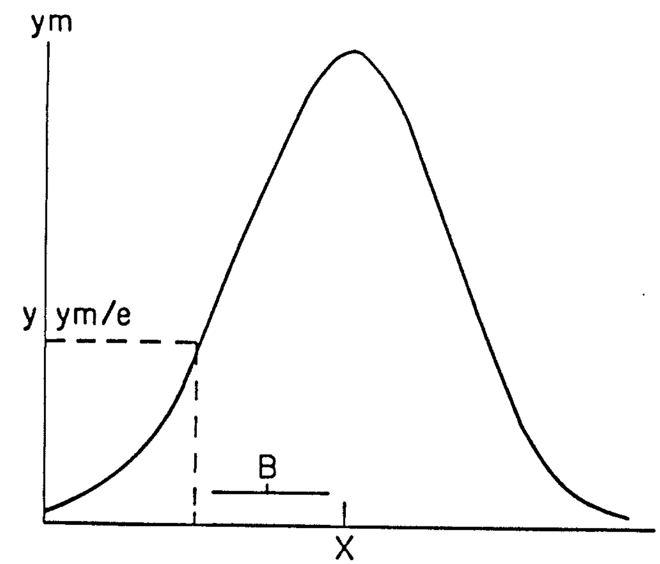


FIG.14 THE NORMAL CURVE (bell - shaped) USED FOR GROWTH AND RESPONSE TO ENVIRONMENTAL CONDITIONS. (After: Frere, Jensen, and Carter, 1970)

was how to relate the factors in order to obtain a unique value for the limiting component. In practice it has been shown that when one factor is seriously limiting, a change in other factors has a relatively small effect on plant behaviour as a whole. Consequently, Liebig's Minimum Law was extended to included environmental variables other than nutrients.

The general form of the actual growth rate used in the model was:

GR=IGR * AMIN1(LMW,LMN,LMT) (81)

Where GR is the actual growth rate (Kg/ha-day); IGR is the ideal growth rate (Kg/ha-day); AMIN1 is a computer library function that selects the minimum argument and LMW, LMN and LMT are limiting factors which account for water, nitrogen and temperature ,respectively.

All three limiting factors were chosen to vary between values of zero and one. At zero value it was assumed that plant growth ceases whereas at a value of one the actual growth rate equals the ideal groth rate, that is, all factors are optimum.

The computation of growth rate and parameters for limiting factors is a very complex process. A separate relationship between an individual factor and growth rate must be established when all other variables are held constant.

$dW/dt=WG(X1)_{x_2\,x_3}=constant$ (82)

Due to nonlinearity in the relationship of plant growth to a very large number of environmental factors which can not be controlled, and because of the complex adaptive behaviour of biological systems, the parameters for growth rate equations can best be determined using several years of experimental data.

The equations used in the model were based only on values reported in the literature and for lack of better information, the normal curve was sometimes employed.

3.5.6 Grain Yield

As a result of the plant growth approach used (equations 79 and 81) the main ouput variable within the model is the yield of above ground dry matter. Nevertheless, for validation purposes the final yield figure must represent the marketable yield.

Grain growth is too complex a process to be represented accurately by a simple plant subroutine. Even the most sophisticated models, which split up the plant into numerous subroutines and accounted for different relationships between them, have not been successful.

However, among the simple methods, two are most frequently employed. Some models predict grain yield based on the ratio between grain and grain plus straw which is known as the Harvest Index (HI). Other models predict grain based on the relationship between accumulation of dry matter from anthesis to maturity.

According to Williams (1966) the development of the inflorescence of wheat, which obviously will affect the grain yield, starts as early as 16 days after sowing. Therefore the yield, that is the number of tillers which form inflorescence, is determined at an early stage. Furthermore, Milthrop and Moorby (1974) pointed out that the environmental effects appear to work in opposite ways on the two parameters that affect the magnitude of yield - growth and development of spikelets and number of spikelets formed "... the greatest number of spikelets will form when the conditions for growth of spikelets are least favorable."

Under these conditions the use of HI to convert predicted dry matter into grain may not be seriously in error. Consequently, using a set of experimental data (unpublished data Racz, 1975) for Neepawa cultivar, an average harvest index was approximated (HI=0.40). Its value was derived from experimental plots harvested by hand. In order to obtain HI where the crop is harvested with large- scale farm equipment an average "combine loss" was employed.

Finally grain yield was expressed as follows:

GRAIN=DRY MATTER * 0.38 (83)

Indeed, under unfavorable climatic conditions for harvesting and/or inappropriate operation of harvesting equipment, the value of HI might be significantly reduced. Such a situation will affect the validation process but will affect the simulation itself to a smaller extent since none of the above conditions are related to soil characteristics.

The complete program for the model,written in FORTRAN,is presented in appendix A.

Chapter IV

RESULTS AND DISCUSSION

No model is complete without testing its performance relative to the real system it is to describe.

Two data sets were required in order to do this. The first set was the data required by the model as input, data that reflected the conditions under which the real system operated. The second set referred to the output(s) of the real system that was to be compared with the output(s) of the model. Usually, the field data recorded as the grain yield obtained by the farmer constitute the overall output of the system. Such data permit only a partial testing of the model (i.e. validation of the model in terms of grain yield). Due to the approach taken in building the model under consideration (i.e. above ground dry matter predictions at one-day timestep) as well as the importance of verifying some hypotheses used, several entities had to be measured over time. Consequently, data from a field program was considered the most appropriate means of testing the model.

4.1 FIELD PROGRAM

During the summer of 1979,a field progam was carried out on two farms (Bill Ridgeway and John Vis) located in the Winnipeg region.One of the reasons for selecting these farms was that a relatively detailed Soil Survey Study and a soil map (1:126,720) are available for the Winnipeg region. The location of these farms and some detail of the outline of the field program are shown in Table 3. Under each agricultural practice a strip of land (10 x 150 metres) received additional nitrogen applied broadcast as ammonium nitrate at the time of seeding. Sufficient nitrogen was added to these strips to bring the level of applied nitrogen to 90 Kg/Ha on fallow land and 135 Kg/Ha on nonfallow land. In each case, phosphorus, the only other element considered to be deficient, was applied at recommended rates at seeding time by the farmer.

TABLE 3: 1979,SUMMER FIELD PROGRAM SITES

	FARMER'S NAME	TOWN	LEGAL DESCRIPTION	SOIL SERIES	AGRICULT. PRACTICE	MANAGAMENT INPUT N-APPLIED(Kg/Ha)
I	BILL RIDGEWAY	GROSS ISLE	SW 33-12-IE	MARQUETTE		
					NONFALLOW	FARMING- 45 PROGRAM-135
					FALLOW	FARMING- 45 PROGRAM- 90
II	JOHN VIS	OAK-BLUFF	SW 30- 9-IE	OSBORNE		
					NONFALLOW	FARMING- 28 PROGRAM-135
					FALLOW	FARMING- 28 PROGRAM- 90

In order to have a valid comparison among sites, the initial position of the biological subsytem of interest (i.e. crop) was fixed in time. Wheat was seeded on the same day (09 June) on both farms and on all management practices. Basically, there were two climatic patterns due to the different geographic location of the farms (SW 33-12-IE and SW 30-9-IE) and two soil series (Marquette and Osborne). Within each climate-soil pattern four different management practices (past management expressed by fallow as compared to nonfallow and present management expressed by amount of fertilizer applied) were considered.

For validation and verification of the model four main entities were monitored during the growing season:

1. Above ground dry matter production;
2. Soil water content;
3. NO_3-N concentration;
4. Final grain yield.

In order to minimize errors resulting from the heterogenity of the soil (rapid spatial changes in soil characteristics), since by sampling different parts of the system were removed, two plot areas (20 square meters) were delimited at random in each site, before seeding. Sampling times during the growing season followed the Phenological Development stages of wheat as definied by Robertson (1968):

Planting (0) - the date of seeding;

Emergence (1) - the date by which 50 emerged plants per plot could be seen;

Jointing (2) - the date when the first internode elongation in the stem had occurred in at least two of the first 10 plants examined;

Heading (3) - the date when the base of the head had reached the same height as the base of the shot blade in 50 plants in a plot;

Soft-Dough (4) - the date when at least five kernels in the center part of 10 heads examined could be easily deformed;

Maturity (5)
(Harvest) — the last stage was delayed to Harvest date.

Starting with the jointing stage, the above ground portion of plants from a square metre, in each plot area, were cut, air dried and weighed. At harvest the total plant yield and grain yield were obtained. At each stage of development, as defined above, soil samples were also taken at five depths (0 - 15 cm, 15 - 30 cm, 30 - 60 cm, 60 - 90 cm, 90 - 120 cm) from two spots. One hole was made within the square metre from which plant material was harvested and one was made on the adjoining area. The two samples for each depth were mixed forming a composited sample. Gravimetric water content and NO_3-N content were determined on the composited sample from each depth.

In the present study, the site will be referred to by the farmer's name associated with soil series, agricultural practice and management input.

4.2 MODEL INPUT DATA AND THEIR SOURCES

Input data required in the model were the uncontrollable variables that must be input in order to run the model for a particular land unit/site and a chosen time interval.

The input data can be characterized from many different angles, on the basis of availability, reliability, age, etc. The main consideration in the present study was the availability of the data since this was one of the more important aspects in making the model simple enough for problem solving within a reasonable time. However, even for a simple model and a relatively large unit base (quarter-section) most of the input data can not be directly measured and some compromise and estimations must be accepted.

The input data required by the present model can be categorized in three distinct groups: climatic (weather), soil and management data.

4.2.1 Weather Data

Three main daily weather variables were required by the model: maximum temperature (TMAX); minimum temperature (TMIN) and precipitation (PREC). The basic source for these variables constituted data recorded by Atmospheric Environment Service stations. In order to relate land units of interest with a particular station, a weighting method suggested by Kraft and Senkiw (1979) was considered. A detailed description of the method can be found in the mentioned report. Basically the method permits one to relate weather data from AES stations over the Prairie Region with any particular land unit of interest.

For maximum and minimum temperatures, Ridgeway - Marquette sites were related to the Gross-Isle AES station and Vis - Osborne sites were related to the Starbuck AES station. The next variable, precipitation, was measured using rain gauges installed on each farm near the field sites. Two factors were considered in deciding to measure precipitation more precisely. First, water content was one of the most important entities within the system/model. The second factor considered was that showers make up about half of the rainfall on the Prairies and frequently fall in a very random pattern on a given day (the step interval used in the model) and often vary greatly over short distance in a given year. As will be discussed further, this variable becomes less critical when an average value is used for simulation purposes. In this case, using the weighting patterns method suggested by Kraft and Senkiw, precipitation data recorded by AES stations can readily be used.

An additional climatic variable required by the model as input data was Solar Energy at the top of the atmospher (SR). Its value was a function of latitude and day of the year and was taken from a standard table.

The weather variables for the summer of 1979 were grouped under a "weather file" formed for each farm. An example of the weather input data file, for Ridgeway - Marquette, is given in appendix B.

4.2.2 Soil Data

The main soil input data required by the model were water content at seeding time, available moisture and NO_3-N concentration values for each layer considered in the model.

With the exception of initial NO_3-N content for the 0 to 60 cm depth, soil input data were not readily available. They were estimated from basic soil properties based on two major assumptions. The first assumption made was that at seeding time the soil water content was at Field Capacity. The second assumption made was that available moisture for plant growth was the water content between Field Capacity (WCFC) and Permanent Wilting Percentage (WILT). Therefore, these two parameters were determined first.

The starting point in estimating WCFC and WILT values constituted mechanical composition and organic matter content data (Tables 4 and 5) from the Soil Survey Report (Michalyna et al.,1975). Based on these data and using equations 18,19 and 21 developed for Manitoba soils, Field Capacity, Permanent Wilting Percent and Bulk Density parameters were computed for each soil series. The last parameter was used as an intermediate variable-function in order to convert the gravimetric water content values to a volumetric basis. Computed values of the above mentioned parameters are presented in Tables 6 and 7.

Due to the subdivisions of the soil profile used in the model, the computed values of soil parameters could not be directly used in the model. In order to obtain the values for each soil layer, a graph was drawn for each parameter of interest (Figures 15, 16, 17 and 18) using data from Tables 6 and 7. From these graphs the values of Field Capacity, Permanent Wilting Percentage and Bulk Density were estimated. Field Capacity and Wilting Percentage were converted to a volumetric basis using equation 20. The values used in the model as soil variables input data are presented in Tables 8 and 9.

Finally, the initial NO_3-N content must be known for each soil layer. For the Ridegeway-Marquette sites these values were computed using results from samples submitted to the Provincial Soil Testing Laboratory by the farmer. Since for the Vis - Osborne sites such data were not available, the results from soil samples taken before seeding were used.

TABLE 4: ANALYSIS OF MARQUETTE CLAY*

DEPTH	SOIL SEPARATES (%)							ORG.C	O.M.**
(cm.)	VCS	CS	MS	FS	VFS	Si	C	(%)	(%)
0- 27	3	3	5	11	18	16	44	4.7	8.08
27- 35	2	2	2	5	10	19	60	1.2	2.06
35- 42	7	5	4	6	9	12	57		
42- 54	13	9	9	12	14	21	22		
54- 83	7	6	9	11	18	35	14		
83-104	22	39	23	10	4	2	0		
>104	9	7	10	12	16	29	17		

TABLE 5: ANALYSIS OF OSBORNE CLAY*

DEPTH	SOIL SEPARATES(%)			ORG.C	O.M.**
(cm.)	S	Si	C	(%)	(%)
0- 10	5	23	72	2.7	4.6
10- 15	3	12	85	1.1	1.9
15- 30	3	44	53	0.8	1.4
30- 60	3	21	76	0.3	0.5
60- 90	4	17	79	<.1	0.2

* Data from SOIL SURVEY WINNIPEG REGION STUDY AREA,1975(pp.223,226)
** % O.M.=% ORG.C*1.72

TABLE 6: SOIL PHYSICAL PARAMETERS.
SOIL SERIES MARQUETTE.

DEPTH (cm.)	FC (on w/w basis)	PWP	B.D. (g/cc)
0- 27	33.9	17.8	1.22
27- 35	31.0	17.8	1.39
35- 42	26.9	15.8	1.47
42- 54	18.3	7.7	1.61
54- 83	17.8	5.8	1.62
83-104	10.1	3.3	1.76
>104	17.9	6.5	1.62

TABLE 7: SOIL PHYSICAL PARAMETERS.
SOIL SERIES OSBORNE.

DEPTH (cm.)	FC (on w/w basis)	PWP	B.D. (g/cc)
0- 10	39.9	22.5	1.33
10- 15	37.7	23.7	1.35
15- 30	32.9	16.3	1.45
30- 60	34.0	20.8	1.39
60- 90	33.7	21.2	1.37

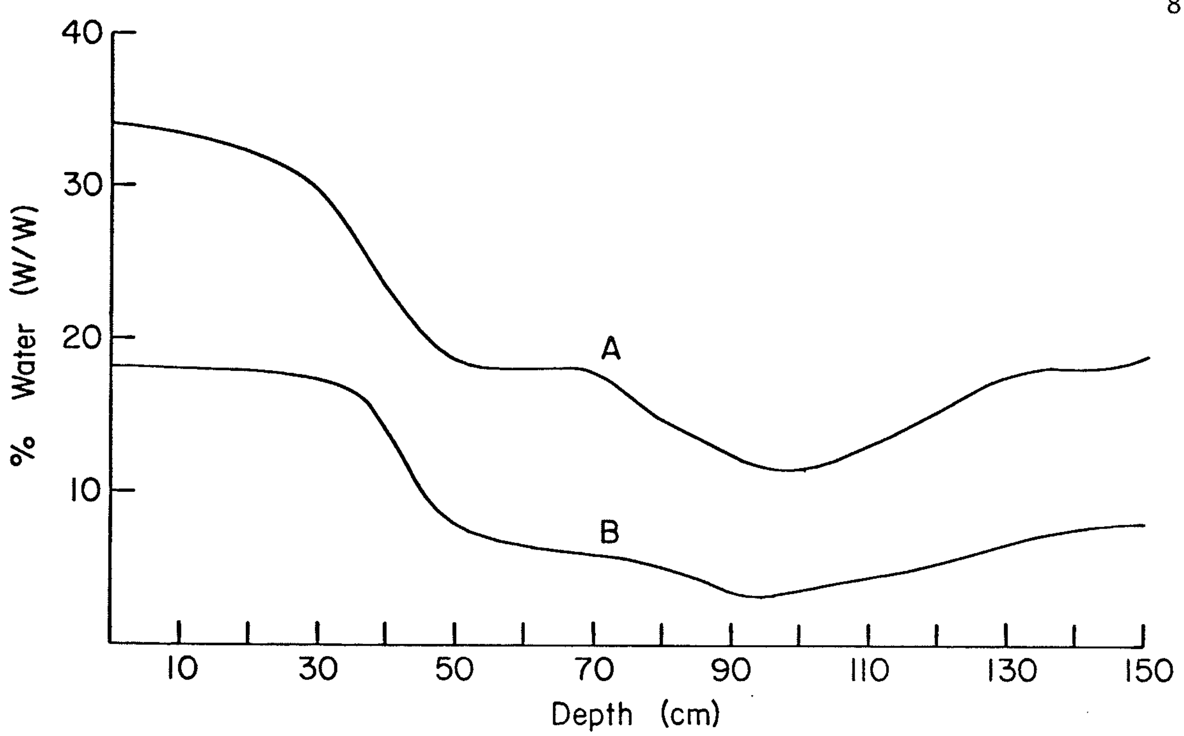


Fig. 15. Field Capacity (A) and Wilting Percentage (B) Marquette Series.

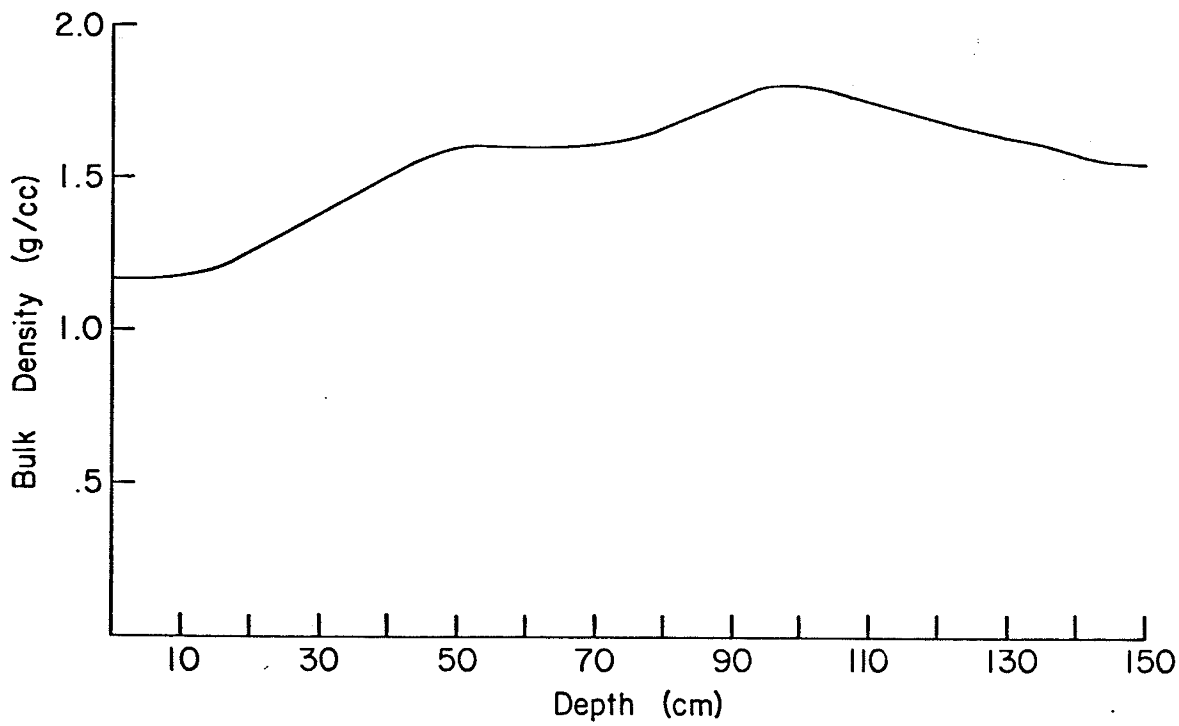


Fig. 16. Bulk Density for Marquette Series.

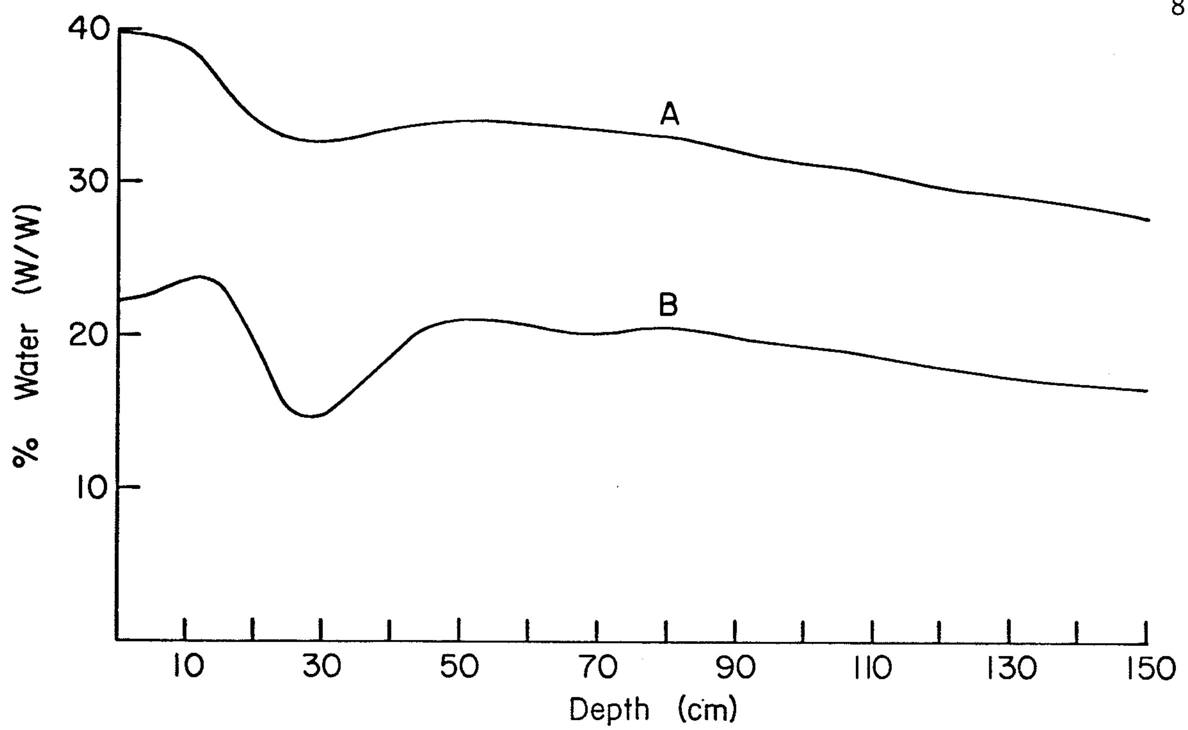


Fig. 17. Field Capacity (A) and Wilting Percentage (B) Osborne Series.

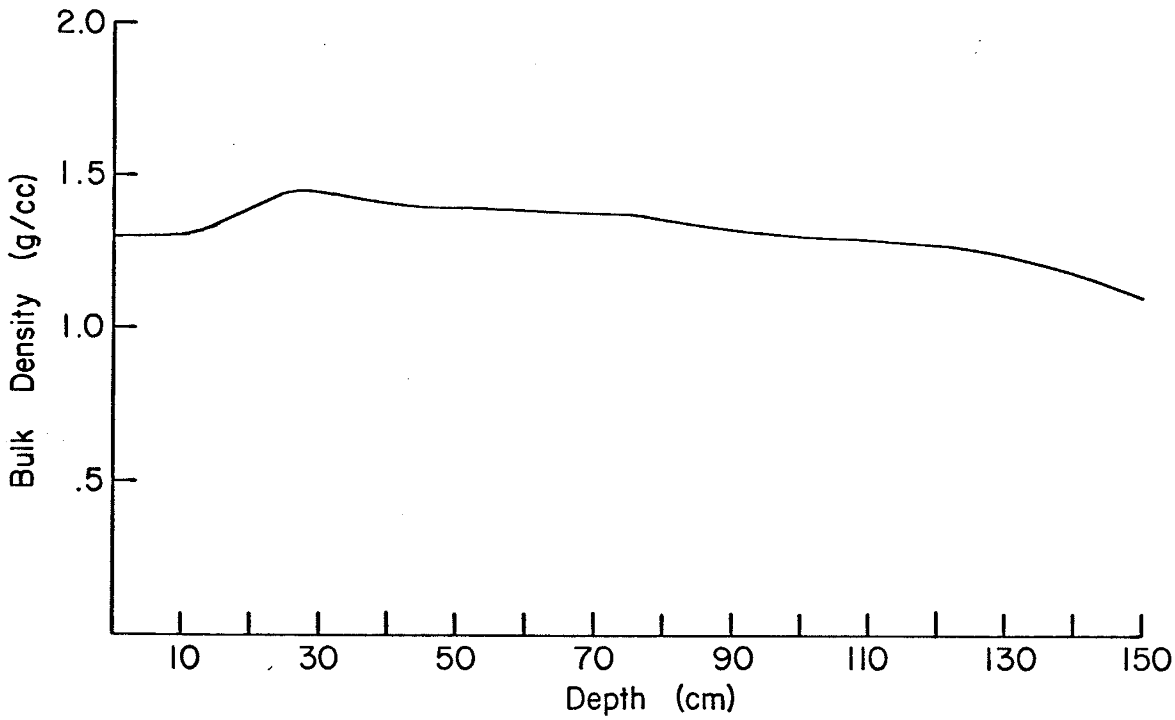


Fig. 18. Bulk Density for Osborne Series.

TABLE 8 : SOIL PARAMETERS USED IN MODEL
SOIL SERIES MARQUETTE.

LAYER NO.	DEPTH (cm.)	WCFC	WILT	B.D. (g/cc)
		(on v/v-cc/cc)		
1	0- 15	0.39	0.21	1.20
2	15- 30	0.42	0.24	1.37
3	30- 45	0.31	0.15	1.55
4	45- 60	0.27	0.11	1.60
5	60- 75	0.26	0.10	1.60
6	75- 90	0.21	0.07	1.75
7	90-105	0.23	0.08	1.75
8	105-120	0.25	0.09	1.65
9	120-135	0.27	0.11	1.55
10	135-150	0.27	0.11	1.50

TABLE 9 : SOIL PARAMETRES USED IN MODEL
SOIL SERIES OSBORNE.

LAYER NO.	DEPTH (cm.)	WCFC	WILT	B.D. (g/cc)
		(on v/v-cc/cc)		
1	0- 15	0.46	0.30	1.30
2	15- 30	0.44	0.20	1.45
3	30- 45	0.46	0.29	1.40
4	45- 60	0.46	0.27	1.38
5	60- 75	0.45	0.29	1.38
6	75- 90	0.41	0.26	1.32
7	90-105	0.40	0.25	1.30
8	105-120	0.38	0.23	1.28
9	120-135	0.33	0.21	1.20
10	135-150	0.29	0.19	1.10

For deeper layers considered in the model, for which data were not available, initial NO_3 -N concentrations were assumed to decrease with depth and to be a function of concentration in the upper layer of the soil profile. These values were computed as follows:

CNORTX(I)=CNORTX(I - 1) - 0.0005 (84)

Where I stands for layer number and CNORTX is NO_3-N concentration (mg N/cc).

The conversion of NO_3-N content expressed in Kg/Ha to mg NO_3-N/cc (as used in the model) was made using the observed water content values (WCX(I)) according to the following expression:

NO_3-N(I)mg/cc=NO_3-N(I)Kg/Ha/1500 * WCX(I) (85)

The input data used in the model for NO_3-N concentrations (CNORTX) are given in Tables 10 and 11.

4.2.3 Management Data

Management input data required in order to run the model were:

1. Seeding data (PLANTX);
2. Time of application of fertilizer (FERTMAX);
3. Amount of fertilizer used (FRTX).

Usually such data are not recorded on a quarter-section basis. For testing the model these data were collected during the Field Program. However, for simulation purposes on a large scale, as will be discussed later, these data can be treated as parameters. Therefore, management data on a small scale (quarter-section) were required only for validation and verification of the model.

It should be noted also that due to weather conditions in 1979 (low temperature and frequent precipitation in May) seeding dates in Manitoba were delayed. At both farms the crop was seeded on 09 June.

Soil and management input data as well as some details relative to the program itself, such as number of integrations per day, desirable variables to be printed and/or plotted, etc., were grouped in a file under the name SMPDATA (appendix C).

TABLE 10 : INITIAL NO_3-N CONCENTRATION AT RIDGEWAY-MARQUETTE SITES.

DEPTH (cm.)	NO_3-N (Kg/Ha)* NONFALLOW	NO_3-N (Kg/Ha)* FALLOW	LAYER No.	DEPTH (cm.)	NO_3-N (mg/cc)** NONFALLOW	NO_3-N (mg/cc)** FALLOW
0- 15	8.0	13.0	1	0- 15	.0137	.0211
15- 60: 15- 30	10.0:3.33	24.0:8.00	2	15- 30	.0053	.0127
30- 45	3.33	8.00	3	30- 45	.0072	.0172
45- 60	3.33	8.00	4	45- 60	.0082	.0198
			5	60- 75	.0077	.0193
			6	75- 90	.0072	.0188
			7	90-105	.0067	.0183
			8	105-120	.0062	.0178
			9	120-135	.0057	.0173
			10	135-150	.0052	.0168

* Data from The Provincial Soil Testing Laboratory (Recipt No. 17697).

** Values for 0-60 cm. are from S.T.L.,values for 60-150 cm. depth were computed.

TABLE 11 : INITIAL NO_3-N CONCENTRATION AT VIS-OSBORNE SITES.

DEPTH (cm.)	NO_3-N (Kg/Ha)* NONFALLOW	FALLOW	LAYER No.	DEPTH (cm.)	NO_3-N (mg/cc)** NONFALLOW	FALLOW
0- 15	16.2	36.5	1	0- 15	.0230	.0518
15- 30	18.4	25.4	2	15- 30	.0241	.0368
30- 60: 30- 45	28.6:14.3	44.4:22.2	3	30- 45	.0195	.0322
45- 60	14.3	22.2	4	45- 60	.0195	.0322
60- 90: 60- 75	17.6: 8.8	30.0:15.0	5	60- 75	.0163	.0213
75- 90	8.8	15.0	6	75- 90	.0163	.0213
90-120: 90-105	15.2: 7.6	24.0:12.0	7	90-105	.0127	.0200
105-120	7.6	12.0	8	105-120	.0127	.0200
			9	120-135	.0122	.0195
			10	135-150	.0117	.0190

* Data from soil sampled before seeding.

** Values for 0-120 cm. are from S.T.L. resultes,values for 120-150 cm.were computed.

4.3 VALIDATION OF THE MODEL

Model validation, generally, refers to the comparison of overall output of the real system with overall output of the model. First, the grain yields obtained under farming conditions were compared with the model predictions.

Since neither farmer harvested nonfallow and fallow areas separately they could only provide the actual yields as an average for two management practices and an estimated difference in yield between nonfallow and fallow. Based on each farmer's information the yield was computed for each farm and each management treatment.

Using weather, soil and management input data characteristic for each farm and agricultural practice, the model was run for each individual site. The grain yields obtained by the farmers and predicted by the model are presented in Table 12.

Generally, there was good agreement in overall output of the real system and model. Better predictions were obtained for the Ridgeway - Marquette sites. For Vis - Osborne sites the model tended to underpredict grain yield, especially on fallowed land. The deviation was as much as 272 Kg/Ha.

However, the main output variable of the model was above ground dry matter production since this was the variable that reflected daily influences of climate (weather), soil and management factors on the biological subsystem (crop) over the entire growing season. Therefore, a more realistic estimate of the model's performance can be made by comparing field program data and model predictions in terms of overall output of above ground dry matter on grain yields (Table 13).

In order to have comparable grain yield values, the predicted values were obtained by using an Harvest Index unadjusted for mechanical losses. This was the reason why the predicted values were higher than those presented in Table 12, when an allowance was made for a harvesting loss. Although the deviations of model predictions of grain yields were not exactly the same as those obtained versus the actual farming system, their general trend and order of magnitude are close to each other.

TABLE 12 : GRAIN YIELDS OBTAINED, VALUES PREDICTED BY THE MODEL AND DEVIATION OF PREDICTED FROM ACTUAL YIELD.

FARMER'S NAME-SOIL SERIES	SYSTEM-ACTUAL YIELD		MODEL-PREDICTED YIELD			
AG.PRACT.-FERT.N APPL.	(Kg/Ha)	(Bu/Ac)	(Kg/Ha)	DEV.	(Bu/Ac)	DEV.
RIDGEWAY-MARQUETTE						
NONFALLOW-45 Kg/Ha	1745	26	1811	+ 66	27	+1
FALLOW -45 Kg/Ha	2148	32	2085	- 63	31	-1
VIS-OSBORNE						
NONFALLOW-25 Kg/Ha	2013	30	1907	-106	28	-2
FALLOW -25 Kg/Ha	2349	35	2077	-272	31	-4

TABLE 13 : DRY MATTER AND GRAIN YIELDS OBSERVED, YIELDS PREDICTED AND DEVIATON OF PREDICTED FROM MEASURED YIELD.

FARMER'S NAME-SOIL SERIES AGRICULTURAL PRACTICES INPUT(FERT.N-Kg/Ha)	OBSERVED DATA DR.MAT.; Kg/Ha	GRAIN Kg/Ha	GRAIN Bu/Ac	MODEL PREDICTED VALUES DR.MAT.; Kg/Ha(DEV.)	GRAIN Kg/Ha(DEV.)	GRAIN Bu/Ac(DEV.)
RIDGEWAY-MARQUETTE						
NONFALLOW						
FARMING (45)	5280	2080	31	4766 (- 514)	1954 (-126)	29 (-2)
PROGRAM (135)	6420	2500	37	6001 (- 419)	2460 (- 40)	37 (0)
FALLOW						
FARMING (45)	5970	2280	34	5487 (- 483)	2249 (- 30)	34 (0)
PROGRAM (90)	6420	2430	36	5976 (- 444)	2450 (+ 20)	36 (0)
VIS-OSBORNE						
NONFALLOW						
FARMING (28)	4970	1980	30	5018 (+ 48)	2057 (+ 77)	31 (+1)
PROGRAM (135)	6210	2400	36	5540 (- 670)	2271 (-128)	34 (-4)
FALLOW						
FARMING (28)	6620	2520	37	5466 (-1154)	2241 (-279)	33 (-4)
PROGRAM (90)	6540	2600	39	5556 (- 984)	2278 (-322)	34 (-5)

Again, a better agreement was obtained between actual and predicted yields for the Ridgeway - Marquette sites, than for the Vis - Osborne sites.

In terms of above ground dry matter yield, with the exception of the Vis - Osborne, nonfallow, farming site, the model underestimated dry matter production by 419 to 1154 Kg/Ha. These may be accepted as reasonable estimates considering sampling errors that inevitably exist. However, the largest deviation occurred within the Vis - Osborne fallow sites. Since it was assumed that at seeding time the soil moisture content was at Field Capacity, regardless of treatment, better results were expected within fallow sites for which the above assumption is more likely to hold. Some of the reasons for these unexpected results will be discussed in further subchapters.

4.4 VERIFICATION OF SOME HYPOTHESES USED IN THE MODEL

Even with a simple model, such as the present one, which described plant growth as affected by climate, soil and management factors, a large number of hypotheses were used. Therefore, complete verification would have been a very difficult and time-consuming task. In the present study only a partial verification was possible, focussing on the main hypotheses considered in the plant growth process as affected by the status of the two major limiting factors accounted for (water and NO_3 -N).

For testing purposes,within a dynamic system, the state variable of interest had be measured at different points in time. Therefore, the entire verification was based on observed data from the 1979 field program.

The model was run using appropriate input data for each site. Every second day (T) during the growing season the value of three entitites to be compared with actual data were printed out. They were as follows:

1. Above ground dry matter (PLGRX);
2. Volumetric water content (WCX); and
3. NO_3-N concentration (CNORTX).

The last two variables were predicted for each layer considered in the model. Since for depths below 30 cm the observed data did not corresponde exactly with layered profile of the model, the predicted values chosen for comparisons were an average of two adjacent layers within the thickness and depth of interest.

A sample of output data for the Ridgeway - Marquette, nonfallow, farming site is given in appendix D.

4.4.1 Ridgeway - Marquette Sites

The differences considered among sites within each quarter-section were initial NO_3-N levels, as an effect of past management and fertilizer added under the present management. With all other variables (weather and soil) constant, the model was run for each site by changing NO_3-N content and/or amount of fertilizer applied.

The comparisons between actual above ground dry matter production (Table 14) and values predicted by the model are presented in Figures 19, 20, 21 and 22. The model seemed to be sensitive to different conditions among sites (Table 14). The highest yields were predicted for fallow vs. nonfallow farming sites, as a result of higher initial NO_3-N concentrations on the former, and for field program sites vs. farming sites, as a result of larger amount of fertilizer applied on program sites. However, the model underestimated dry matter production throughout the growing season. The largest deviation occurred early in the vegetation stage. For nonfallow sites the model gave a good prediction of dry matter yield over the entire growing season (Figures 19 and 20). Predicted values ranged from 82% to 96% of those observed. The predicted values for fallow sites were lower relative to the actual values (Figures 21 and 22) than for the nonfallow sites. However even within these sites, with the exception of program site at the jointing stage (54%), the predicted values were reasonably good.They ranged from 74% to 93% of the observed data.

Actual soil moisture content vs. predicted values for the five layers in which the largest fraction of the root was expected to be found are presented in Figure 23. Observed gravimetric water content data were converted to a volumetric basis as they were predicted by the model using the appropriate Bulk Density for each layer. Within the upper part of the profile, the predicted values showed reasonably good agreement with actual data.

TABLE 14: ABOVE GROUND DRY MATTER OBSERVED,PREDICTED AND PERCENTAGE FROM ACTUAL YIELDS AT DIFFERENT TIMES DURING 1979 GROWING SEASON AT RIDGEWAY-MARQUETTE SITES.

DATA SOURCE AND UNITS USED AGRICULTURAL PRACTICE MANG.INPUT-FERT.APPL.IN Kg/Ha	GROWTH STAGE AND DATE JOINT.(2) 12,07	HEAD. (3) 31,07	SOFT.D(4) 15,08	HARV. (5) 17,09
	ACTUAL-FIELD DATA IN Kg/Ha			
NONFALLOW				
FARMING - 45	680	2650	4740	5280
PROGRAM -135	840	2980	5090	6420
FALLOW				
FARMING - 45	910	3430	5380	5970
PROGRAM - 90	1280	3450	5870	6420
	MODEL PRED'S IN Kg/Ha(% FROM ACTUAL)			
NONFALLOW				
FARMING - 45	663(97%)	2315(87%)	3934(82%)	4766(90%)
PROGRAM -135	692(82%)	2668(89%)	4874(96%)	6001(93%)
FALLOW				
FARMING - 45	674(74%)	2563(75%)	4513(84%)	5487(92%)
PROGRAM - 90	691(54%)	2668(74%)	4864(83%)	5976(93%)

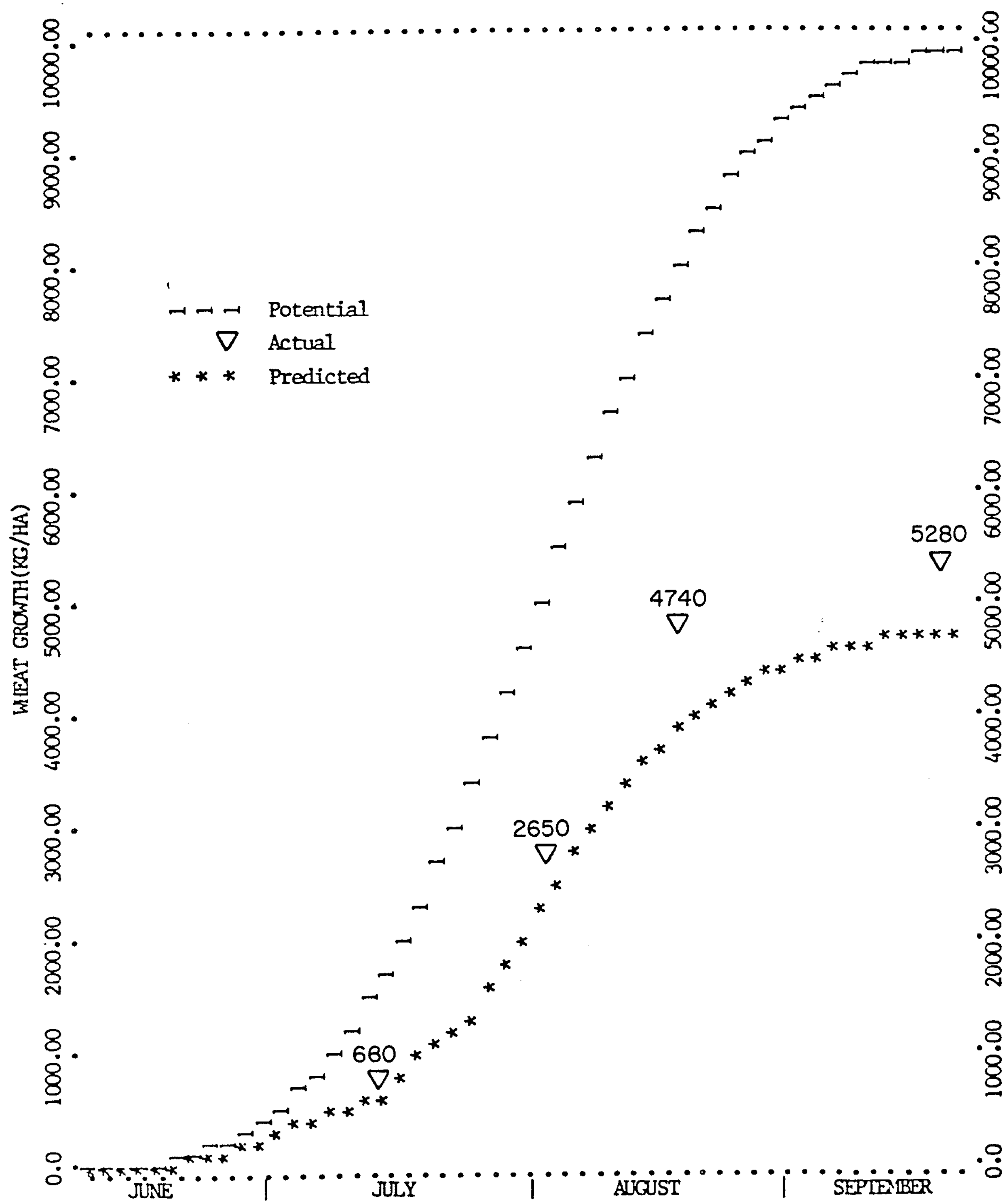


FIG. 19 : MEASURED AND PREDICTED DRY-MATTER YIELD DURING THE GROWING SEASON, 1979, AT RIDGEWAY-MARQUETTE, NONFALLOW, FARMING SITE.

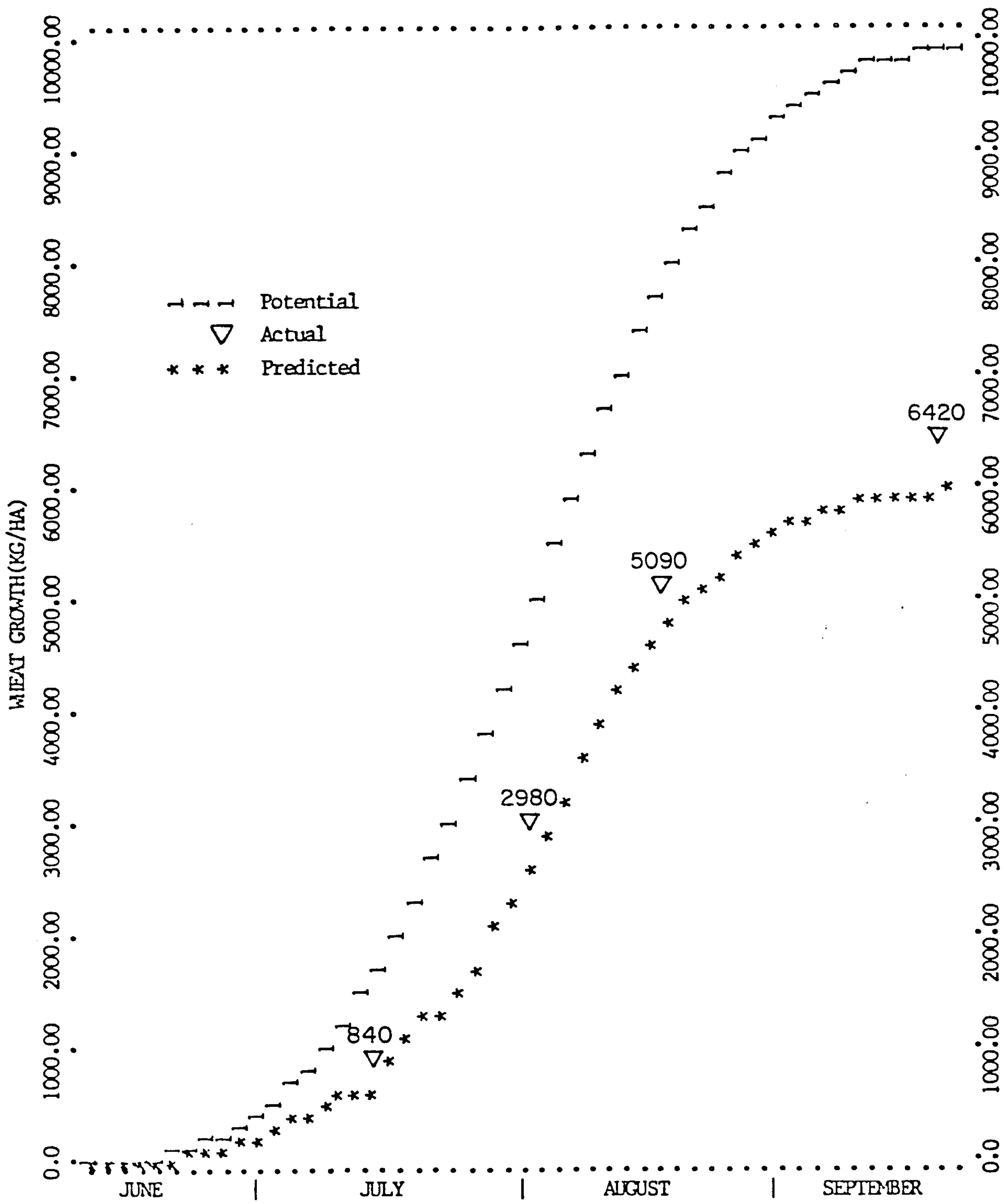


FIG. 20 : MEASURED AND PREDICTED DRY-MATTER YIELD DURING THE GROWING SEASON,1979, AT RIDGEWAY-MARQUETTE,NONFALLOW,PROGRAM SITE.

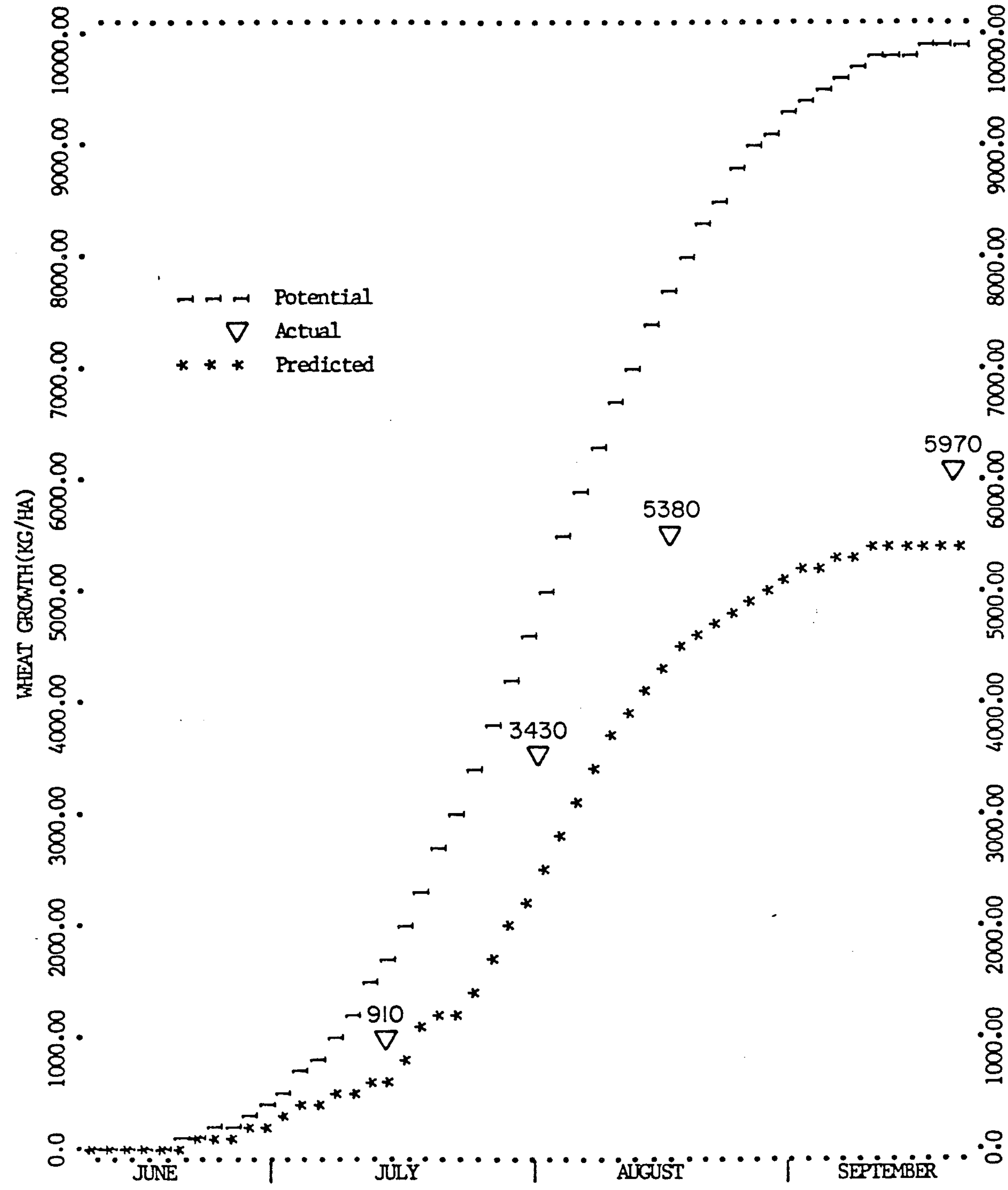


FIG. 21 : MEASURED AND PREDICTED DRY-MATTER YIELD DURING THE GROWING SEASON, 1979, AT RIDGEWAY-MARQUETTE, FALLOW, FARMING SITE.

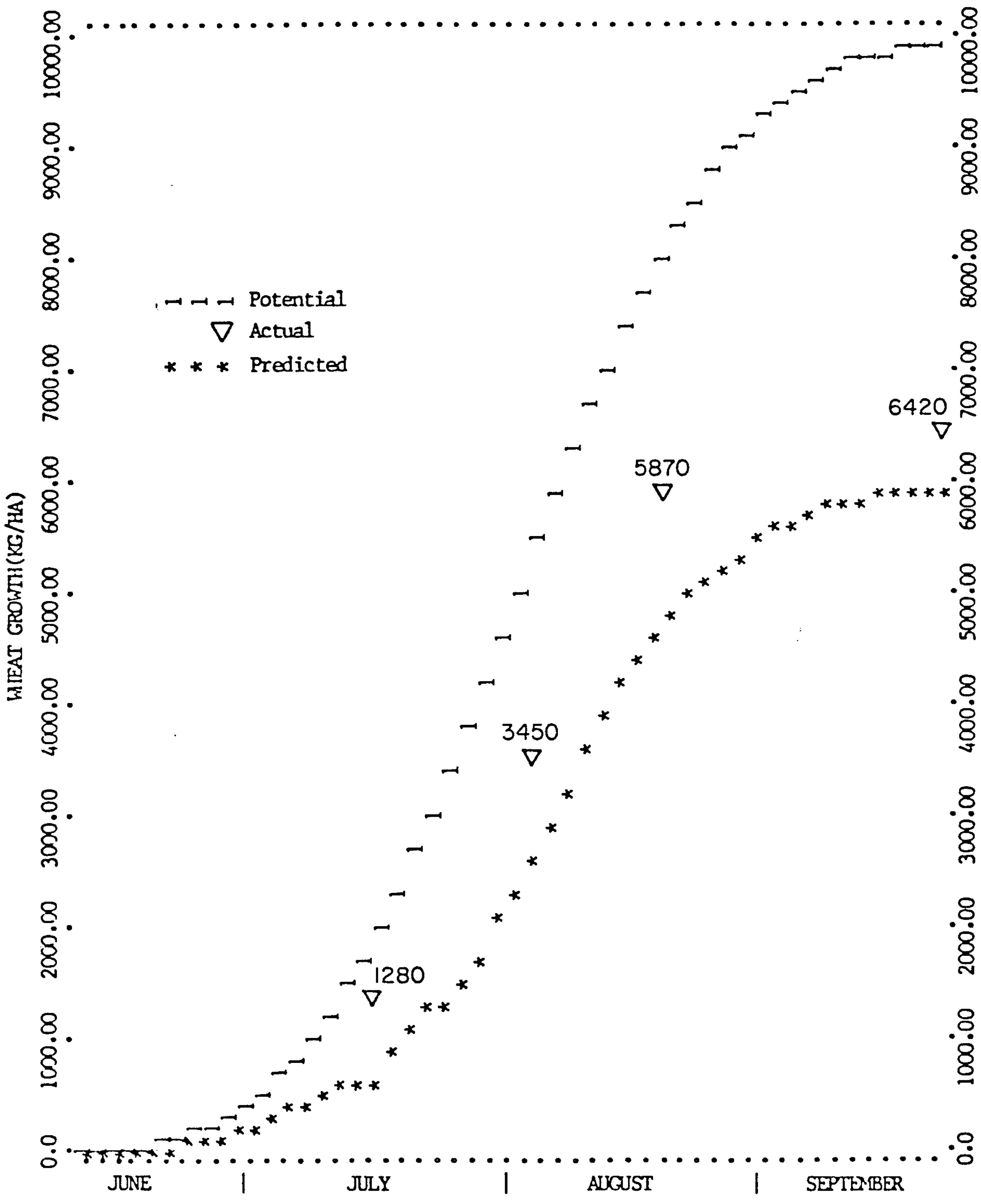


FIG. 22 : MEASURED AND PREDICTED DRY-MATTER YIELD DURING THE GROWING SEASON, 1979, AT RIDGEWAY-MARQUETTE, FALLOW, PROGRAM SITE.

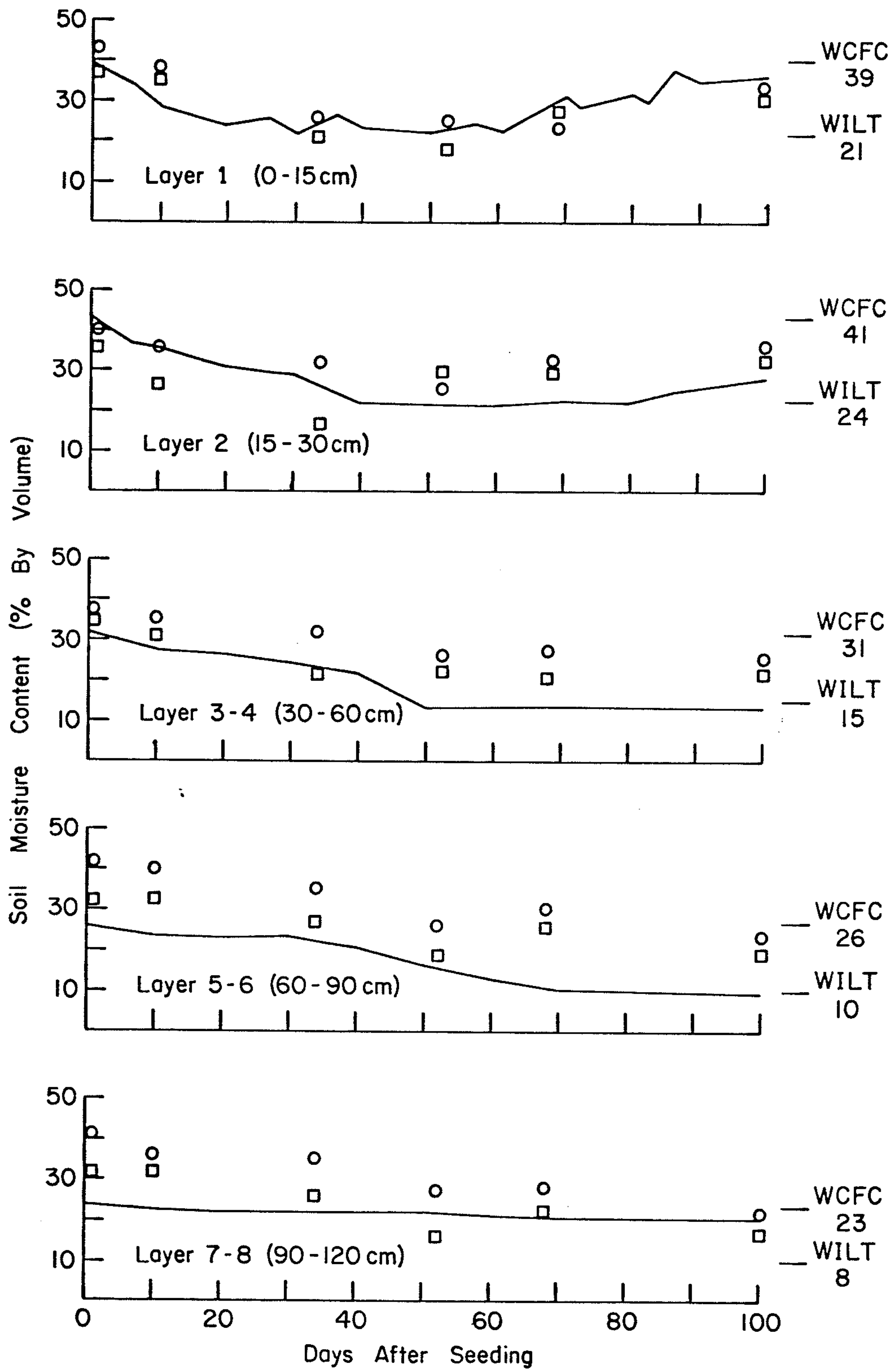


Fig. 23. Soil Moisture Content at Ridgeway - Marquette Sites.
Model prediction (———); Actual: Nonfallow (□), Fallow (○).

From the 30 cm depth down to the 120 cm the model underestimated moisture content, especially for fallow sites. This might be one of the reasons why lower dry matter yields were predicted for fallow sites than were actually obtained. Since differences between actual and predicted values showed little change as the season progressed, underpredicted values may be the result of higher actual initial water content than was approximated as initial values in the model. Indeed, such an error might have occurred for many other reasons among which heterogenous soil properties and sampling errors can not be excluded.

The NO_3-N concentrations observed as compared to those predicted were plotted over the growing season (Figures 24 and 25). Since the most dynamic changes were assumed by the model to occur in the upper layers of the soil profile, the comparisons (observed vs. predicted) were made only for the first three layers. Due to the simplicity with which nitrogen transformations were represented in the model, the predicted values did not show good agreement with observed data. However, the general trend of NO_3 -N concentration changes as well as their relative magnitude during the growing season were considered to be acceptable. Generally, the model overestimated NO_3-N concentration in the top 15 cm and underestimated the values in the 30 - 60 cm depth.

4.4.2 Vis - Osborne Sites

The quarter-section on the Vis farm was manured in 1977. As a result the initial NO_3-N concentration for both nonfallow and fallow was higher than would otherwise be expected. Also due to a large variation in NO_3 -N concentration from one square meter to another, comparisons between actual and predicted data were not made.

The comparison between measured and predicted dry matter yields, for each site, are presented in Table 15 and Figures 26, 27, 28 and 29. The predicted values were almost the same in all sites(the shape of predicted curves were similar to each other) due to the high initial level of NO_3-N (all other variables were constant). Generally, the model underpredicted dry matter at each site. The largest deviation occurred at the beginning of the growing season.

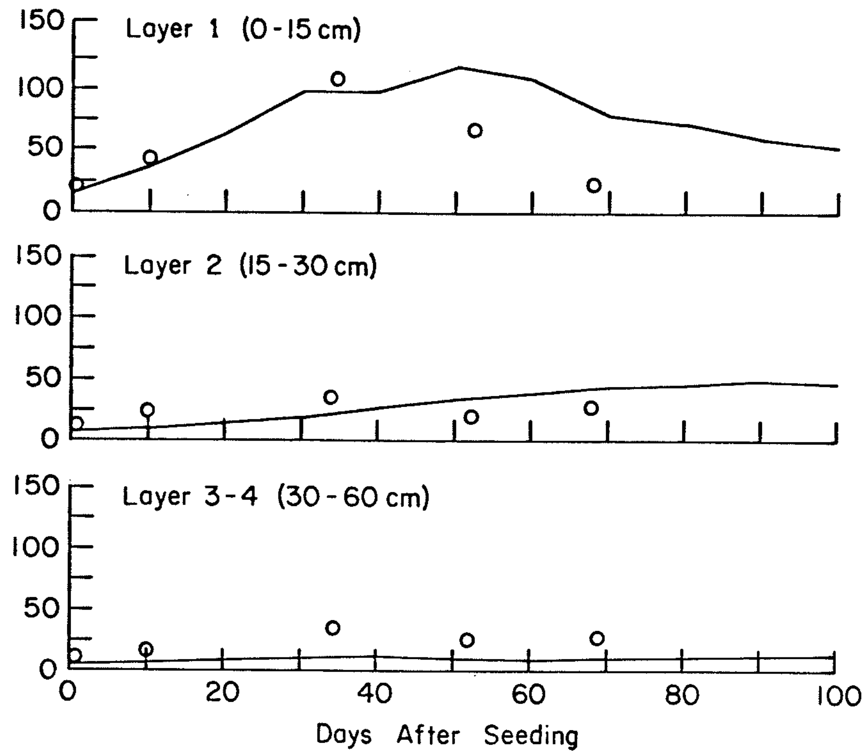


Fig. 24. NO_3-N Conc.: Ridgeway-Marquette, Nonfallow, Farming Site. Model prediction (——); Actual (o).

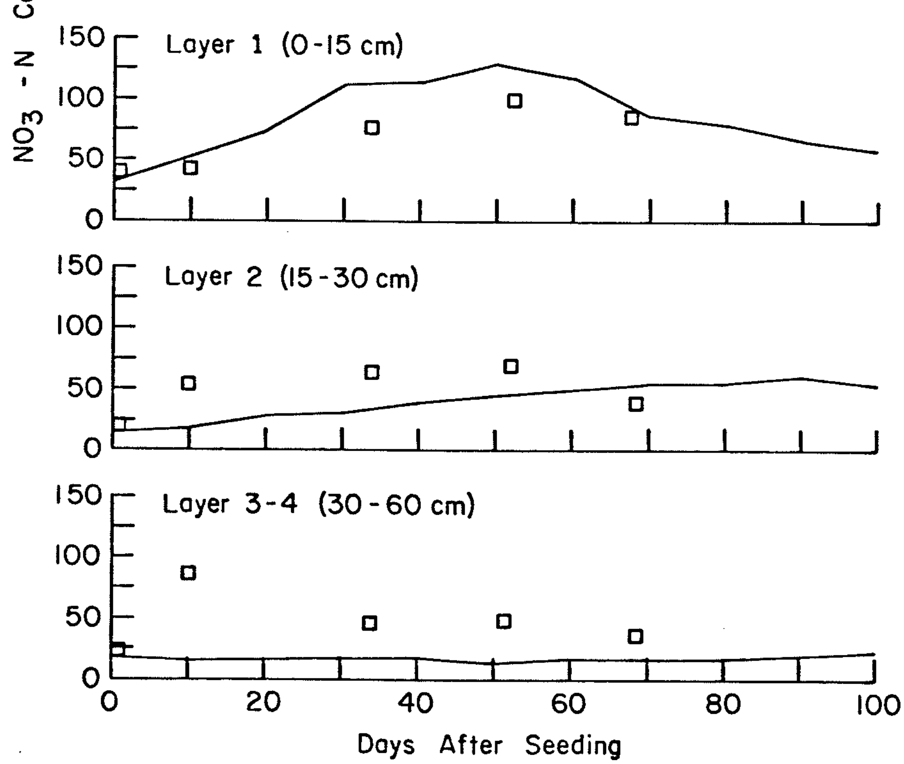


Fig. 25. NO_3-N Conc.: Ridgeway-Marquette, Fallow, Farming Site. Model prediction (———); Actual (□).

TABLE 15: ABOVE GROUND DRY MATTER OBSERVED,PREDICTED AND PERCENTAGE FROM ACTUAL YIELDS AT DIFFERENT TIMES DURING 1979 GROWING SEASON AT VIS-OSBORNE SITES.

DATA SOURCE AND UNITS USED / AGRICULTURAL PRACTICE / MANG.INPUT-FERT.APPL.IN Kg/Ha	GROWTH STAGE AND DATE JOINT.(2) 12,07	HEAD. (3) 31,07	SOFT.D(4) 15,08	HARV. (5) 17,09
	ACTUAL-FIELD DATA IN Kg/Ha			
NONFALLOW				
FARMING - 28	1150	3140	4650	4970
PROGRAM -135	1200	3830	5580	6210
FALLOW				
FARMING - 28	970	3690	5520	6620
PROGRAM - 90	1290	3920	5890	6540
	MODEL PRED'S IN Kg/Ha(% FROM ACTUAL)			
NONFALLOW				
FARMING - 28	597(52%)	2331(74%)	4160(89%)	5018(101%)
PROGRAM -135	599(50%)	2353(61%)	4424(79%)	5540(89%)
FALLOW				
FARMING - 28	599(62%)	2353(66%)	4423(80%)	5466(82%)
PROGRAM - 90	599(46%)	2353(60%)	4424(75%)	5556(85%)

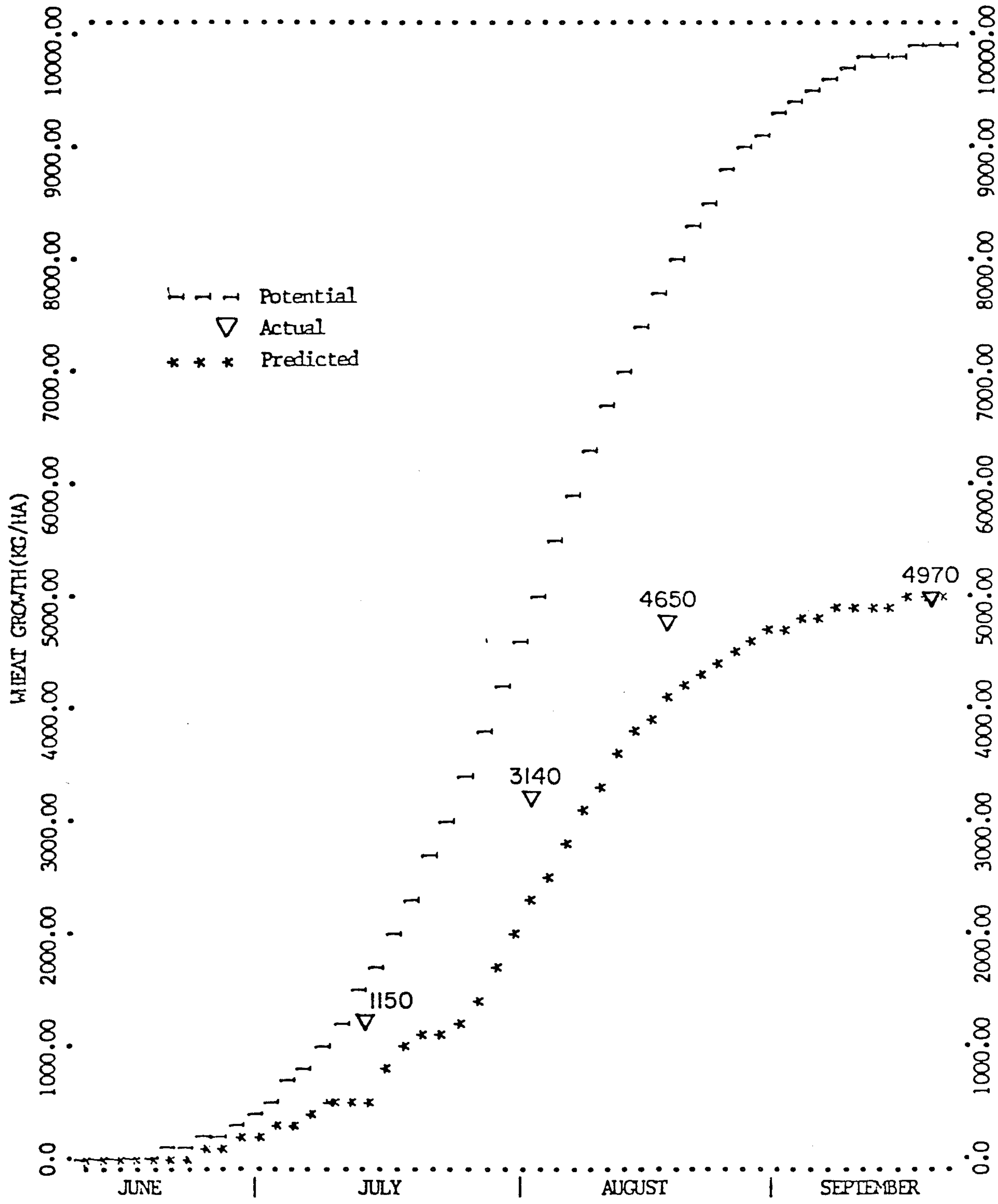


FIG. 26 : MEASURED AND PREDICTED DRY-MATTER YIELD DURING THE GROWING SEASON,1979, AT VIS-OSBORNE,NONFALLOW,FARMING SITE.

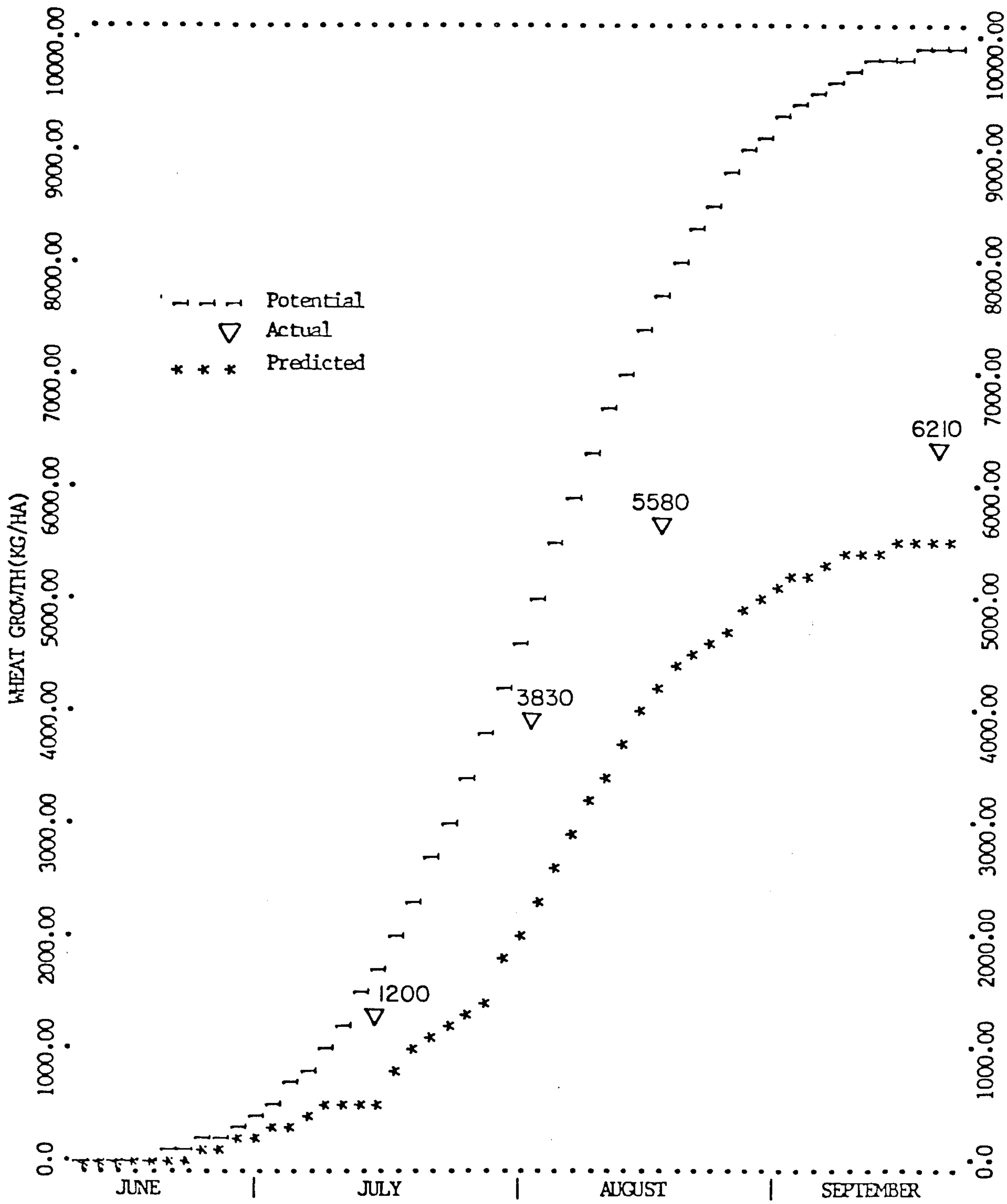


FIG. 27 : MEASURED AND PREDICTED DRY-MATTER YIELD DURING THE GROWING SEASON, 1979, AT VIS-OSBORNE, NONFALLOW, PROGRAM SITE.

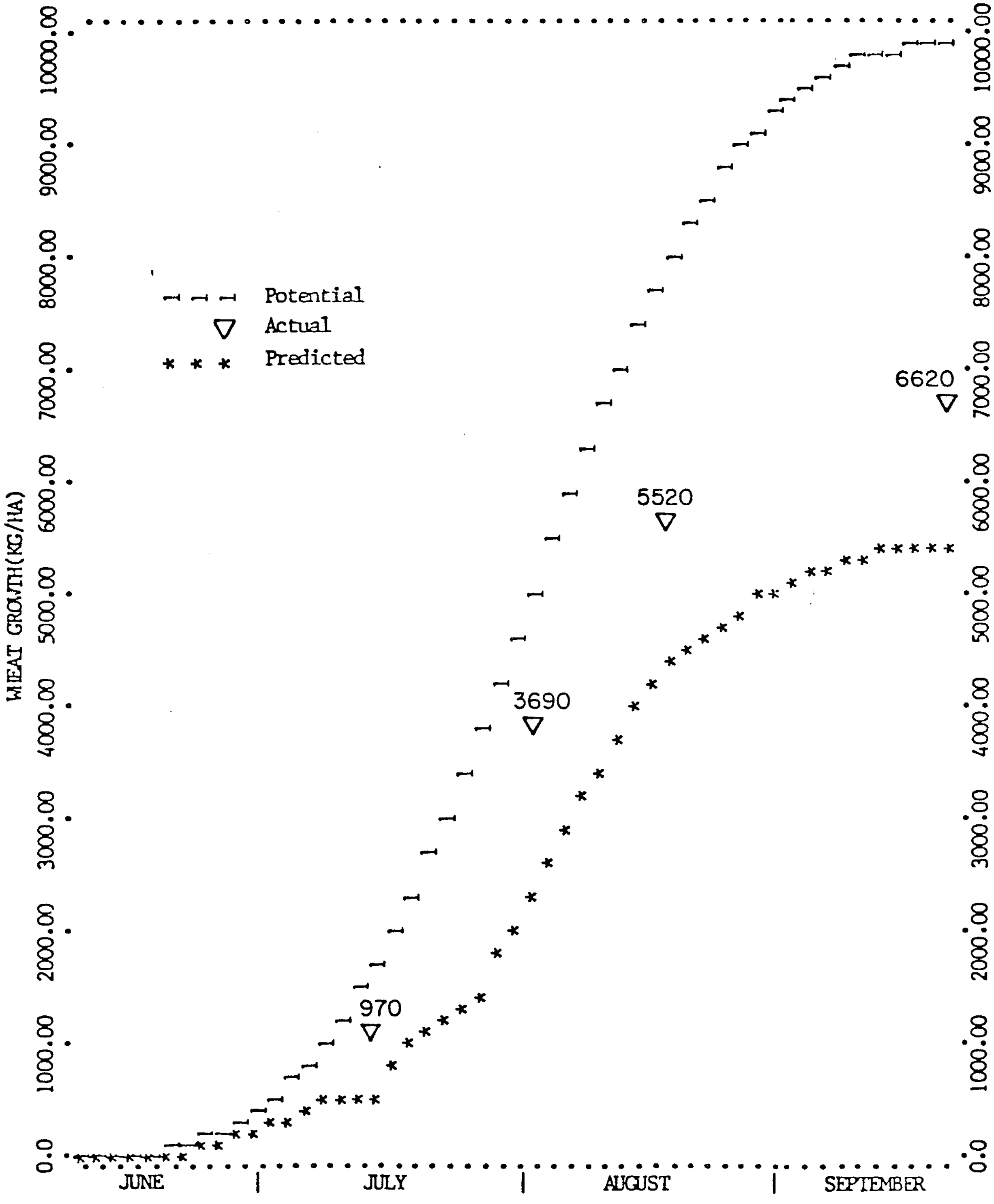


FIG. 28 : MEASURED AND PREDICTED DRY-MATTER YIELD DURING THE GROWING SEASON, 1979, AT VIS-OSBORNE, FALLOW, FARMING SITE.

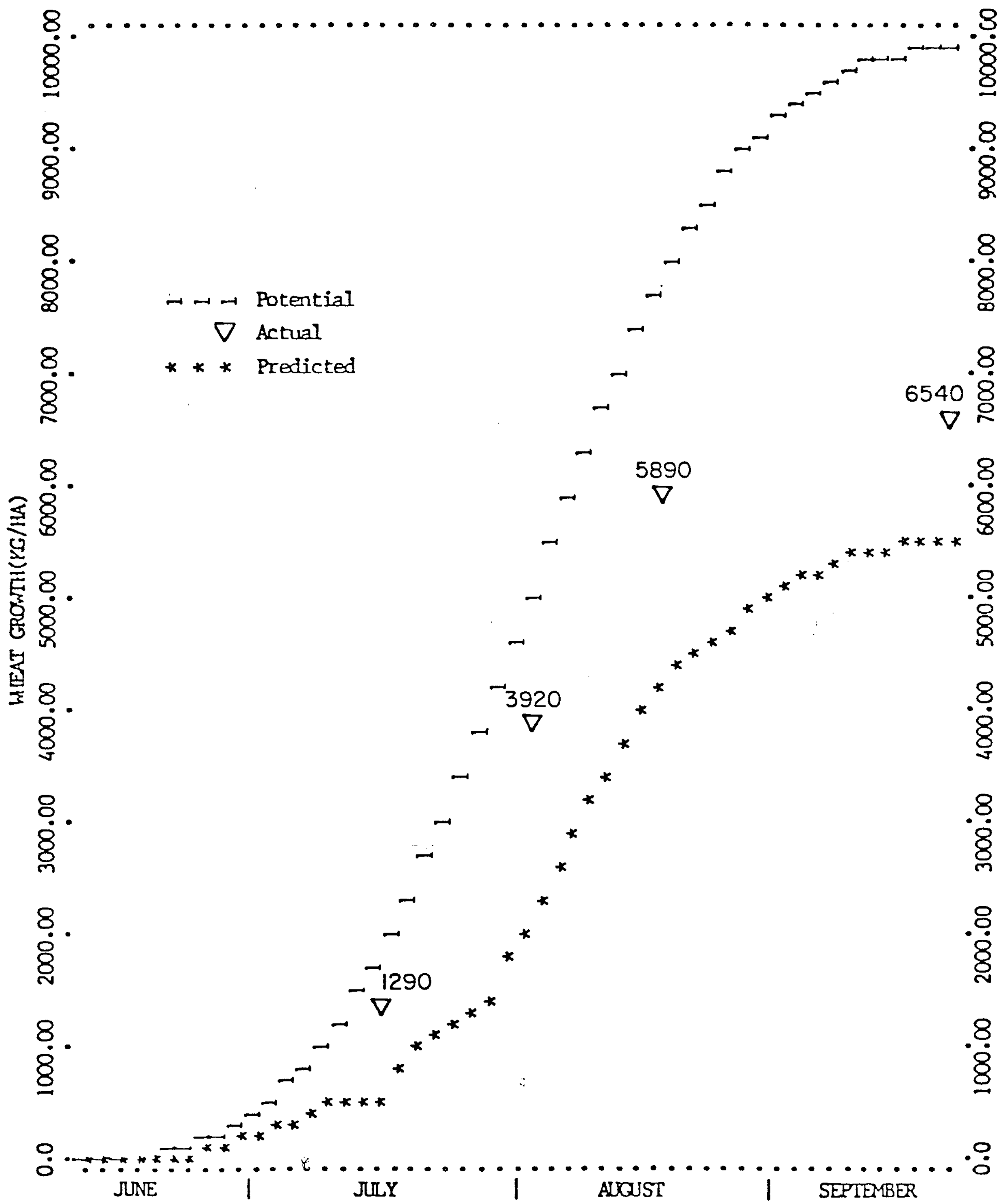


FIG. 29 : MEASURED AND PREDICTED DRY-MATTER YIELD DURING THE GROWING SEASON,1979, AT VIS-OSBORNE,FALLOW,PROGRAM SITE.

Predicted values ranged from 50% to 74% and from 46% to 63% of those observed for nonfallow and fallow sites, respectively. Later in the season, after the heading stage, the predicted values were closer to the observed data.

Some of the reasons why the model underpredicted dry matter yields may be explained by a comparison of observed soil moisture content with predicted values (Figure 30). The computed values of initial soil water content corresponded with observed values. The relationship was good throughout the season for three depths, namely, 0 to 15, 60 to 90 and 90 to 120 cm. The model consistently underestimated moisture content at the other two depths as the season progressed. This was particularly true at the 15 - 30 cm depth where a large fraction of the roots are assumed to be found especially in the early growth stages.

In a more detailed analysis of model outputs it was found that the values of transport coefficients (diffusivity and hydraulic conductivity), as they were taken from Staple's work (1969) and applied to Manitoba soils, were very high, especially in the higher range of water content. As a result, the flow of water over the relatively large time interval selected increased. It seemed that, 1/2 day integration used for water flow was still too large. The transport coefficients as a function of water content could not be adjusted rapidly enough to avoid instability that perhaps occurred within water flow.

The better prediction within the first layer was perhaps due to periodic water input from precipitation whereas for the last layer it was due to relatively lower range in water content and therefore the hydraulic parameter changes, as a function of water content, varied to a lesser extent.

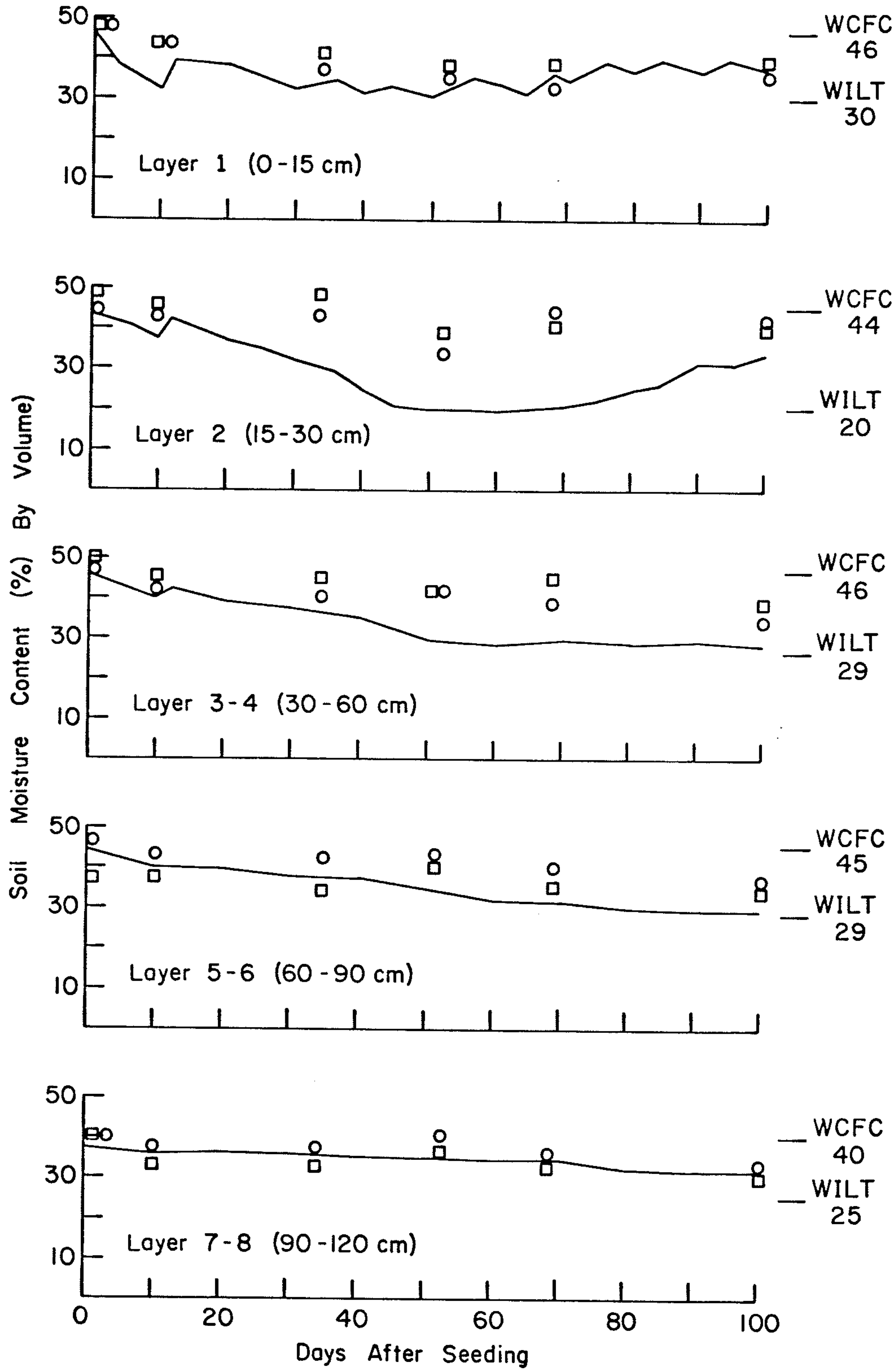


Fig. 30. Soil Moisture Content at Vis - Osborne Sites. Model prediction (———); Actual: Nonfallow (□), Fallow (o).

4.5 CONCLUSION

The model was based on the Limiting Factors hypothesis and accounted for the effects of weather, soil and management factors on crop yield. Although the model was quite simple, combining the information on climatology, soil physics and plant physiology was required. Most of the parameters used were taken from the literature and only partially from earlier experimentally derived functions for Manitoba conditions.

Due to the lack of input data the model was only tested for two soil series during 1979. Under such circumstances the overall output model, both in terms of grain and dry matter yields, as compared with actual farming system output and field program data, was found to be reasonably good. There was some disagreement between predicted and actual values of above ground dry matter production, especially at the beginning of the growing season. Due to the approach used for computing dry matter yield as a function of daily growth, which in turn was described by an exponential expression, underestimated values in the earlier stages of crop development had a relatively small effect on final predicted yield values.

As was to be expected within a complex system, there were discrepancies between model predictions, which were based mostly on theory,and the experimental data. The most serious one occurred in the soil moisture predictions. The model underestimated soil moisture content in soil layers with a relatively high Field Capacity value,i.e. with a high initial water content. The importance of an accurate prediction of soil moisture was twofold. First, from a detailed analysis of daily model output it was found that over the growing season the effect of soil moisture (limitation) on potential growth occurred when the potential growth was expected to reach the highest values. Second, the estimation of water content seemed critical for predicting final dry matter and grain yields. This was because soil moisture content was one of the major variables within the system/model that connected weather pattern (precipitation) and soil characteristics with the biological subsystem (crop growth). A more accurate prediction of soil moisture might have increased the sensitivity of the model relative to the effect of soil factors on yield and that in turn might have permitted a more realistic evaluation of the productivity of a relatively large land area based mostly on soil properties.

However, at the present time the model may be used:

1. for further validation and/or verifiction;
2. as a basis for developing a better or more comprehensive model;
3. as a tool for simulation purposes at the experimental level (i.e.pilot plant scale).

1. Since the model was tested for only two soil series in one year it is desirable that it be further tested against data collected for wheat grown on other soil series and under different weather conditions. The existing output data from a real system will establish the coordinates in time and space. An input data file in terms of weather, soil and management variables must be formed in order to run the model. It is quite unlikely that past experimental data includes records of the entities required to perform some verification of the model. Therefore, by using data from past experiments only a further validation might be achieved.

2. Of the many possible improvements that could be made to the model, the most important seems to be related to soil hydraulic parameters. There are some available data (Shaykewich - personal communication) that permit development of soil water retention curves and hydraulic conductivity and diffusivity for several Manitoba soil series. Once these parameters are incorporated into the model, a more accurate treatment of water distribution is expected, which might overcome some of the errors in predicted soil moisture content.

A second alternative for improving the performance of the model in this area may consist of predicting water movement in the soil using the "Matric Flux Potential" approach suggested by Shaykewich and Stroosnijder (1977). This approach has several virtues such as: a better estimation of water flow in coarse-textured soils; an increase in accuracy of prediction of moisture content for a thicker layer as well as more precise computation of mean hydraulic conductivity as a result of reducing the time step integration in the range of higher water content. Although such an approach requires substantial changes in the model, it should be considered since it might increase the precision and general applicability of the model.

Other aspects such as water accumulation from snowfall, drainage type and slope might be considered in order to increase the sensitivity of the model. To account for them the model must be extended to a hydrological type and predict water content over the entire year. The model can easily accomodate such modifications. The problems may occur relative to input data. The weather file must contain a fifth variable (snowfall). Continuous recording of this variable is difficult; snowgauges have several catching problems due to wind and turbulence, and the measurement of snow depth by rulers is not accurate due to uneven snowfall distribution and to the high variation in the water content of snow.

3. There is no doubt that many compromises and modifications must be accepted in order to make a model simple enough to solve a problem within a reasonable time. Indeed, the application of a model for practical purposes largely depends on the truthfulness of the model itself. It also depends on the degree of accuracy required and accepted by the user. It is difficult, if not impossible, for a model to predict accurately a large number of state variables of a complex system.

After a more extensive validation is performed and some improvements realized, the present model might be used for simulation purposes at a pilot plant scale. This can be realized at the level of two townships located in different climatic regions. Based on historical data, a weather file would have to be prepared for existing AES stations within the selected area. By using a relatively large number of years the random pattern of shower precipitation is smoothed out to some extent. Using the extrapolation method suggested by Kraft and Senkiw each quarter-section can be related to a particular weather input data set. Based on Soil Survey Reports and Soil Testing Laboratory reports soil input data can be obtained for every land unit. Although seeding dates do vary,a certain seeding time must be established. Finally, the management data in terms of amount of fertilizer applied may be computed either as a function of an average input over the past five years or based on Soil Testing Laboratory recomandations.

Having established input data, the simulation of the model may be performed for a given land unit and given circumstances. By choosing the highest predicted yield as a basis, a Producitvity Index can be ascribed to each land unit within selected areas. After the simulation is completed further analysis of the efficiency of the model might be performed using overall outputs of the real systems which are available from Crop Insurance records.

If the model is to be used for evaluation of land subject to alternative uses, the simulation must consider several crops and Productivity Indexes that are compared must represent complex factors. The structure of the model is such that a minimum number of changes are required to run it for a crop other than wheat.

BIBLIOGRAPHY

Allison, F.E.
The fate of nitrogen applied to soil. Adv.Agron., 18:219-258, 1966

Arkley, J. R.
Relationships between plant growth and transpiration. Hilg., 34:559-584, 1963.

Ashby, W. R.
Analysis of the system to be modelled 'The process of model-building in the behavioral sciences'. (R. M. Slodghill ed.) Ohio State University Press, pp. 94-114, 1970.

Baier, W. and G. W. Robertson.
estimation of latent Evaporation from simple weather observations. Can. J. Plant Sci., 45:276-284, 1965.

Baier, W.
Evaluation of latent evaporation estimates and their conversion to potential evaporation. Can. J. Plant Sci., 51:255-266, 1971.

Baier, W. and Robertson, G. W.
The performance of soil moisture estimates as compared with the direct use of climatological data for estimating crop yields. Agr. Meteorol., 5:17-31, 1968.

Baier, W.
Note on the terminology of crop weather models. Ag. Meteor. 20:137-145, 1979.

Baker, C. H. and R. B. Curry.
Structure of Agricultural Simulators: A Philosophical View - Agric. Systems (1). Applied Science Publishers Ltd., England, 1976.

Baldwin, J. P. and P. H. Nye.
Uptake of solutes by multiple root systems from soil IV. Plant and Soil, 40:703-706, 1974.

Baldwin, J. P.
Competition for plant nutrients in soil; a theoretical approach. J. Agric. Sci., Cambridge, 87:341-356, 1976.

Barnes, A., et al.
A dynamic model for the effects of potassium and nitrogen fertilizers on the growth and nutrient uptake of crops. J. Agric. Sci., Cambridge, 86:225-244, 1976.

Beaton, J. D., et al.
Fertilizer nitrogen. In: Nitrogen Symposium Proceedings. Calgary, Alberta, pp. 219-247, 1976.

Beckner, M.
The biological way of thought. University of California Press, Berkeley, 1959.

Beek, J. and M. Frissel.
Simulation of nitrogen behavior in soils. Pudoc, Wageningen. 67 pp., 1973

Blouin, G. M.
Effects of increased energy costs on fertilizer production. Costs and Technology Bull. y-84, 1974.

Brewster, J. L., et al.
The possibility of predicting solute uptake and plant growth response from independently measured soil and plant characteristics I The theoretical basis of the experiments. Pl. Soil, 42:197-226, 1976.

Brakensiek, L. D,
Comments on 'Empirical equations for some soil hydraulic properties'. Water Resources Research, 15:989-990, 1979.

Canny, M.J.
Phloem Translocation. Cambridge University Press, London, 301 pp, 1973.

Childs, E. C. and N. Collis-George.
The permeability of porous materials. Proc. Roy. Soc. Series A., 201:392-405, 1950.

Cho, C. M. and L. Sakdinan.
Mass spectrometric investigation on denitrification. Can. J. Soil Sci., 58:443-457, 1978.

Cho, C. M. and G. J. Mills.
Kinetic formulation of the denitrification process in soil. Can. J. Soil Sci., 59:249-257, 1979.

Cho, C. M., et al.
Denitrification intensity and capacity of three irrigated Alberta soils. S.S.S.A. Jour., 43:601-604, 1978.

Clapp, R. B., and G. M. Hornberger.
Empirical equation for some soil hydraulic properties. Water Resources Research, Vol. 14, No. 4, pp. 601-604, 1978.

Cooper, C. F.
Ecosystem models and environmental policy. Simulation 26:133-138, 1976.

De Vries, D.A. and N.H. Afgan (Editors)
Heat and Mass Transfer in the Biosphere I. Transfer processes in plant environment. Scripta Book Co., Washington, D.C., 494 pp., 1975.

de Wit, T. C.
Transpiration and crop yield. Verslag. van Landbouwk. Onderzoek. No. 64. VI 88 pp., 1958.

de Wit, T. C., et al.
The simulation of photosynthetic systems. In: I. Setlik (Ed.) Pudoc, Wageningen, pp. 47-70, 1970.

de Wit, T. C. and H. van Keulen.
Simulation of transport processes in soils. Pudoc, Wageningen, 1972.

de Wit, C. T. and G. W. Arnold.
Systems and models in Critical evaluation of systems analysis in ecosystems research and management. Pudoc, Wageningen, pp. 3-9, 1976.

Duffy, J., et al.
A simulation model of biophysiochemical transformations of nitrogen in tile-drained corn belt soil. J. Environ. Qual., 4:477-486, 1975.

Forrester, J. W.
Principles of Systems. Second Preliminary Edition (Text and workbook), 1976.

Fiscus, E.L.
The interaction between osmotic and pressure-induced water flow in plant roots. Plant Physiol., 55:917-922., 1975.

Frere, H. M., M. E. Jensen, and J. N. Carter.
Modelling water and nitrogen behavior in the soil-plant system. Proc. of the 1970 Summer Computer Simulation Conference, Denver, Colo., pp.746-750, 1970.

Frere, M. H., et al.
Nitrogen behaviour in soil. U.S. Dept. Agric., ARS-H-3, 54 pp., 1975.

Frissel, M. J., et al.
Chromatographic transport through soils. Pl. Soil, 33:161-176, 1970.

Frissel, M. J. and J. A. van Veen.
Nitrogen in irrigated croplands. In: Nitrogen Behaviour in Soil. Vol. 1. Academic Press ed., N.Y., pp. 145-162, 1977.

Gerwitz, A. and E. R. Page.
An empirical mathematical model to describe plant root systems. Jour. of Applied Ecology, 11:773-780, 1974.

Gold,J.H.
Mathematical modeling of biologial systems - An introductory guidebook. A Wiley - Interscience Publication,1977.

Greenwood, D. J., et al.
A dynamic model for the effects of soil and weather conditions on nitrogen response. J. of Agric. Sci., Cambridge, 82:455-467, 1974.

Hall, A.E. and O. Bjorkman.
Model of leaf photosynthesis and respiration. In: D.M. Gates and R.B. Schmerl (Editors), Perspectives of Biophysical Ecology. Vol. 12 of Ecological Studies. Analysis and Synthesis. Springer-Verlag, Berlin, Heideberg, New York, N.Y., pp. 55-72, 1975.

Hanks, R. J. and S. A. Bower.
Numerical solutions of the moisture flow equation for infiltration into layered soils. Soil Sci. Soc. of Amer., 26:530-534, 1962.

Haree, R.
The Philosophies of Science. Oxford University Press, 1972.

Hesketh, J. D. and J. W. Jones.
Some comments on computer simulators for plant growth. Ecological Modelling, 2:235-247, 1975.

Hillel, D.
Physiological Ecology. Academic Press., pp. 164, 1971.

Hiler, A. and A. Howell.
Optimization of water use efficiency through trickle irrigation and the stress day index. Texas Water Resources Institute, Technical Report No. 62, 1974.

Hiler, E. A. and R. N. Clark.
Stress day index to characterize effects of water stress on crop yields. Transactions ASAE, 14:757-761, 1971.

Holtan, et al.
Moisture-tension data for selected soils on experimental watersheds. ARS 41-144, 609 pp., 1968.

Hobbs, E. H. and K. K. Krogman.
Observed and estimated evapotranspiration in Southern Alberta. Transactions ASAE, 11:502-507, 1968.

Howell, A. T. and E. A. Hiler.
Optimization of water use efficiency under high frequency irrigation - I. Evapotranspiration and yield relationship. Trans. ASAE, 18:873-878, 1975.

Hurd, E. A.
Growth of roots of seven varieties of spring wheat at high and low moisture levels. Agron. J., 60:201-205, 1968.

Jackson, R. D., et al.
Wheat canopy temperature: a practical tool for evaluating water requirement. In press, 1977.

Jensen, M. E., et al.
Estimating soil moisture depletion from climate, crop and soil data. Transactions ASEA, 14:954-959, 1971.

Klute, A.
Laboratory measurement of hydraulic conductivity of unsaturated soil. In: Methods of Soil Analysis. Amer. Soc. Agron. Monograph 9, pp. 253-261, 1965.

Kraft, F.D. and M. Senkiw.
Productvity analysis of Canada land inventory classification. Department of Agricultural Economics, U. of M.,Winnipeg, Manitoba, 53 pp., 1979.

Lawlor, D. W.
Growth and water absorption of wheat with parts of the roots at different water potentials. New Phytol., 72:297-305, 1972.

Li, E. A., et al.
Estimating saturated hydraulic conductivity and capillary potential at the wetting front, Dep. of Agr. Eng., Va. Polytech.Inst. and State Univ.,Blacksburg, 1976.

Makkink, G. F. and H. D. J. van Heemst.
Simulation of the water balance of arable land and pastures. Pudoc, Wageningen, Netherlands, 1975.

McArthur, J. A. et al.
Cotton, In:L. T. Evans (Editor), Crop Physiology: Some Case Histories. Cambridge University Press, London, pp. 297-325., 1975.

McLaren, A. D.
Comments on an autoecological study of microorganisms. Soil Sci., 12:60-61, 1976.

McLaren, A. D.
Rate constants for nitrification and denitrification in soil. Rad. Environm. Biophsi., 13:1-6, 1976.

McLaren, A. D.
Temporal and vectorial reactions of nitrogen in soil: a review. Can. J. Soil Sci., 50:97-109, 1970.

McVetty, P.
Growth analysis of four spring wheat cultivars experiment. University of Manitoba, Unpublished data. (Plant Science Department). 1976.

Mehran, M. and K. Tanji.
Computer modelling of nitrogen transformation in soils. J. Env. Qual., 3:391-396, 1974.

Meidner, H.
Water supply, evaporation and vapor diffusion in leaves. J. of Exp. Botany., 26:666-673, 1975.

Michalyna, W. at al.
Soil of the Winnipeg region study area. Canada - Manitoba, Soil Survey., 239 pp., 1975.

Miller, H.M., et al.
Technical Report No.4-Development and Validation of Land Productivity Models for Ontario. Univ. of Guelph, Publication No. 96, 1979.

Milthorpe, F. L. and J. Moorby.
An Introduction to Crop Physiology. Cambridge University Press, 1974.

Mirreh, H. F. and J. W. Ketcheson.
Influence of soil water matric potential and resistance to penetration on corn root elongation. Can. J. Soil Sci., 53:383-388, 1973.

Minhas, B. S., et al.
Toward the structure of production function for wheat yields with date inputs of irrigation water. Water Resources Research, 10:383-393, 1974.

Monteith, J. L.
Principles of Environmental Physics. Am. Elsevir Publ.Co., New York, N.Y.,241 pp., 1972

Morgan, T. H., et al.
A dynamic model of corn yield response to water. Water Resources Research, 16:59-64, 1980.

Mockus, V.
Estimation of direct runoff from storm rainfall. In: USDA-SCS National Engineering Handbook, Section 4-Hydrology, 1972.

Mualem, Y. and G. Dragan.
Hydraulic conductivity of soils: Unified approach to the statistical models. Soil Sci. Soc. of Amer., 42:392-395, 1978.

Musick, J. T., et al.
Soil water depletion-yield relationships of irrigated sorghum, wheat and soybeans. Trans. ASAE, 19:489-493, 1976.

Nass. H. G. and B. Reiser.
Grain filling period and grain yield relationships in spring wheat. Can. J. Plant Sci., 55:673-678, 1975.

Naylor, T. H., et al.
Computer Simulation Technique. John Wiley, New York, 1966.

Newman, E. I.
A method of estimating the total length of root in a sample. J. Appl. Ecol., 3:139-143, 1966.

Nobel, P. S. et al.
Relation between mesophyll surface area, photosynthetic rate, and illumination during development of leaves of Pretranthus parviflorus Henckel. Plant Physiol., 55:1067-1070, 1975.

Nye, P. H., et al.
The possibility of predicting solute uptake and plant growth response from independently measured soil and plant characteristics I The theoretical basis of the experiments. Plant Soil, 42:161-170, 1975.

Nye, P. H., and P. B. Tinker.
Solute movement in the soil-root system. In: Studies in Ecology-Vol. 4. University of California Press, 1977.

Nyborg, M., et al.
Measuring crop available nitrogen. In: Nitrogen Symposium Proceedings. Calgary, Alberta, pp. 102-128, 1976.

Olsen, S. R. and W. D. Kemper.
Movement of nutrients to plant roots. Adv. Agron., 20:91-151, 1968.

Peel, A. J.
Transport of Nutrients in Plants. John Wiley, New York, N.Y.,258 pp., 1974.

Penning de Vries.
Respiration and growth. In: A.R. Rees, K.W.Cockhull, D.W.Hand and R.G.Hurd (Editors), Crop Processes in Controlled Environments. Academic Press, London, pp. 163-202, 1972.

Philip, J. R.
Flow in porous media. Ann. Rev. Fluid Mech., 2 (In press), 1970.

Pielou, E. C.
An Introduction to Mathematical Ecology. Wiley, New York, 1969.

Pritsker, A. A.
The Gasp IV Simulation Language. John Wiley and Sons, Inc., New York, 1974.

Racz, G. J.
Improving crop utilization of nitrogen experiment. Soil Science Department, University of Manitoba, unpublished data, 1975.

Reinger, P. et al.
„Simulation of cation exchange and movement in soils,published in "Isotopes and Radiation in Soil-Plant Relationships including Forestry",IAEA, Viena, 1972.

Richards, L. A.
Advances in soil physics. Trans. 7-th. Intern. Congr. Soil Sci., Madison, I, pp. 67-69, 1960.

Robertson, G. W.
A biometeorological time-scale for a cereal crop involving day and night temperatures and photoperiod. Int. J. Biometeor, 12:191-223, 1968.

Rose, C. W.
Agricultural Physics. Pergamon Press, pp. 69-86,193-198, 1966.

Rosen, R. (Ed.).
Foundations of Mathematical Biology. Academic, New York, 1973.

Rosemburg, N. J.
Microelemente-The Biological Environment. John Wiley, New York, N.Y.,315 pp., 1974.

Rubinow, S. I.
Introduction to Mathematical Biology. Wiley, New York, 1975.

Scheidegger, A. E.
The Physics of Flow through Porous Media. Macmillan, New York, 1957.

Sestak, Z., Catsky, J. and Jarvis, P.G. (Editors),
Plant Photosinthetic Production: Manual of Methods. W. Junk, The Hague, 815 pp., 1971.

Shaykewich, C.F. and M.A. Zwarich.
Relationships between soil physical constants and soil physical components of some Manitoba soils. Can. J. Soil Sci, 48: 199-204, 1968.

Shaykewich, C.F. and L.Stroosnijder.
The concept of matric flux potential applied to simulation of evaporation from soil. Neth. J. agric. Sci., 25:63-82,1977.

Shaw, R. H.
Estimation of soil moisture under corn. Iowa State Univ., Iowa, Res. Bull. 52, 1963.

Slatyer, R. O.
The significance of the permanent wilting percentage in studies of plant and soil water relationships. Bot. Rev., 23:585-589, 1957.

Selirio, I. S. and D. M. Brown.
Simulation of forage yield using daily soil moisture as a criterion. Final Report, 31 pp., 1976.

Selirio, I. S. and D. M. Brown.
Develpment of a corn production simulation for land evaluation purposes. Final report, Supply and Services, 44 pp., 1977.

Selirio, I. S. and D. M. Brown.
Soil moisture-based simulation of forage yield. Agric. Meteorol., 20:99-114, 1979.

Smith, J. M.
Mathematical Ideas in Biology. Cambridge Univ. Press, 1968.

Smith, J. M.
Models in Ecology. Cambridge University Press, 1975.

Smith, O. L.
Nitrogen, phosphorus and potassium utilization in the plant-soil system: An analytical model. Soil Sci. Soc. of Amer., 40:704-714, 1976.

Staple, W. J.
Comparison of computed and measured moisture redistribution following infiltration. Soil Sci. Soc. of Amer., 33:840-847, 1969.

Steenbjerg, F. and S. T. Jakobsen.
Plant nutrition and yield curves. Soil Sci., 95:69-88, 1963.

Svensson, B. H. and R. Soderlund (Eds.).
Nitrogen, phosphorus and sulphur-global cycle. Ecol. Bull. 22, 1976.

Tandon, H. L. S.
Dynamics of fertilizer nitrogen in Indian soils. Fertilizer News, 19:3-11, 1974.

Tanji, K. and S. Gupta.
Nitrogen in irrigated croplands. In: Nitrogen Behavior in Soil, Vol. 1. Academic Press ed., pp. 82-129, 1977.

Taylor, H. M. and B. Klepper.
Water uptake by cotton root systems: An examination of assumptions in the single root model. Soil Sci. 120:57-67, 1975.

Taylor, H.M. et al.
Measurement of soil-grown roots in a rhizotron. Agron.J., 62:807-809, 1970.

van Bavel, C. H. M. and J. Ahmed.
Dynamic simulation of water depletion in the root zone. Ecological Modelling, 2:189-212, 1975.

van Keulen, H.
Simulation of water use and herbage growth in arid regions. Pudoc, Wageningen, 84 pp., 1975.

van Veen, J. A. and M. J. Frissell.
Computer Simulation Model for the Behaviour of Nitrogen in Soil and Leaching to Groundwater. Pudoc, Wageningen, 26 pp., 1976.

van Veen J. A.
The behaviour of nitrogen in soil: A computer simulation model. ITAL-Wageningen, 164 pp., 1977.

Visser, W. C.
The model of the water balance and nutrient uptake as a basis for hydrological, agro-hydrological and other projects. Mathematical Models in Hydrology, IAHS-AISH, Publ. No. 101, 1974.

Vithayathil, F. J., et al.
A program for the simulation of nitrogen flow in a tile-drained corn belt agricultural field. CBNS-Washington, ST. Louis., 1977.

Walker, G. K.
Development of a wheat model for Land Evaluation. Unpublished MSc. thesis. Univ. of Saskatchewan, 1977.

Ward, R. H.
Development and Testing of a Phenological Model for Small Grains in Saskatchewan. Minutes, First Annual Meeting, Expert Committee on Soil Survey, 1979.

Williams, G. D. V.
Deriving a biophotothermal time-scale for barley. Int. J. Biometeor., 18:57-69, 1974.

Williams, R. F.
Early stages in the development of inflorescence of wheat. Aust J. Biol. Sci., 19:949-966, 1966.

Wilson, J. W.
Control of crop processes. In: Crop Processes in Controlled Environments. Academic Press, 1972.

Wood, J. T., et al.
Interactions between the beneficial effects of nitrogen, phosphate and potassium on plant growth. J. Agric Sci., 78:389-391, 1972.

Western Canada Nitrogen Symposium. Proceeding of the Alberta Soil Science Workshop. Calgary, Alberta, 1976.

Appendix A

MODEL OF WHEAT GROWTH IN MANITOBA - PIXMOD

```
C     MODEL OF WHEAT GROWTH IN MANITOBA
      PIXMOD
C
      IMPLICIT REAL*4 (A-H,J-Z)
      COMMON /COMA/
     * HEAD,IHEAD,T,WTFC,   F(10),WCFC(10),SR,TMAX,TMIN
      COMMON /COMB/       AREA,CWHT
      COMMON /COMC/      PREC,RUNOFF,
     * XX(10),DY(10),KY(10),OPTXX(7),OPTYX(7),WILT(10)
      COMMON /COMD/      CNORW,
     * DENIT,DIF,DISP,NORN,TORT,WTSAT,WF(10)
      COMMON /COME/      IKX,CNORTX(10),FLRNX(11),FLRTX(11)
      COMMON /COMF/
     1 BOX,MOX,YOX,      FERTMX,FERTX,
     2 HARVTX,NITUPX,NTRATX,PLANTX,PLGRX,WTBX,DNTUPX(10),
     3 NTRTX(10),SOILMX(10),WCX(10),         TDENTX,HIW
      COMMON /COMI/      AA(8030),INP
      LOGICAL*1 FG(42)/'(27X,F3.2,7X,2F3.0,3X,F5.1)'/
      LOGICAL*1 FMT(14,3)/'(F9.3)         (9X,F7.4)    '/,FMTA(14)
      DIMENSION ETLX(10),FRTMX(3),FRTX(3)
      DIMENSION CROP(1),CNORT(10),IXZ1(2),IXZ2(2)
      DATA CROP(1)/'CWHT'/,HEADA/'HEAD'/,SPEC/'SPEC'/,AREAA/'AREA'/,
     1 CNOX/'CNOX'/
      DIMENSION IMAGE(20)
      CALL INIT
      CALL INITX
      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(1H1,18X,19A4//)
      CALL REREAD
      READ(5,201)A,NP,NL,IDAY,INTT,IFORM,IG1,IXZ1,IG2,IXZ2
  201 FORMAT(A4,2F4.0,I4,I2,I1,2212)
      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.SPEC) GO TO 190
      IF(NP.EQ.0.) NP=2.
      IF(NL.EQ.0.) NL=2.
      IF(INTT.EQ.0) INTT=1
      IF(IFORM.EQ.0) GO TO 5
      CALL REREAD
      READ(5,202)FG
  202 FORMAT(42A1)
      READ(99,9876) (IMAGE(I),I=1,20)
```

```
      WRITE(6,9877) (IMAGE(I),I=1,20)
    5 CONTINUE
      CALL REREAD
      READ(5,206) A,CNORT
  206 FORMAT(A4,10F7.5)
      READ(99,9876) (IMAGE(I),I=1,20)
      WRITE(6,9877) (IMAGE(I),I=1,20)
      IF(A.NE.CNOX) GO TO 190
      IF(CNORT(1).EQ.0.) GO TO 15
      DO 10 I=1,10
      CNORTX(I)=CNORT(I)
   10 NTRTX(I)=CNORT(I)*SOILMX(I)
   15 CONTINUE
   35 DO 145 IJ=1,IDAY
      IF(T.GT.159..AND.T.LT.261.) GO TO 70
      CALL REREAD
      READ(5,204)A,DAREA,DCWHT
  204 FORMAT(A4,2F4.0)
      READ(99,9876) (IMAGE(I),I=1,20)
      WRITE(6,9877) (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)
      WRITE(6,9877) (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
      DO 40 I=1,IFX
   40 IF(FRTX(I).EQ.0.)FRTX(I)=50.
      ICX=0
      WRITE(6,210) AREA,CWHT,PLANTX,(FRTMX(1),FRTX(1))
  210 FORMAT(1HO  /5X,'THE UNIT AREA IS',F4.0,'HECTARS.',
     1 /5X,F4.2,' FROM THE AREA IS WHEAT.',
     2 /5X'PLANT.-DAY',5X'FERT.-DAY',5X'FERT.-AMNT.',
     3 //8X,F4.0,11X,F4.0,11X,F4.0//)
      IF(IG1.EQ.0) GO TO 70
      WRITE(6,9001)WCFC
 9001 FORMAT(' WCFC',10F7.2)
      WRITE(6,9002)WILT
 9002 FORMAT(' WILT',10F7.2)
   65 WRITE(6,220)
  220 FORMAT(1H1,'  T          PLGRX      ANCX')
   70 T=T+1
      IF(ICX.GE.IFX.OR.T.NE.FRTMX(ICX+1)) GO TO 80
      ICX=ICX+1
      FERTX=FERTX+FRTX(ICX)*1.12
```

```
      FERTMX=FRTMX(ICX)
   80 READ(11,FG,END=180)PREC,TMAX,TMIN,SR
      INT=2
      IPREC=PREC
      IF(IPREC.LE.2) GO TO 1234
      INT=IPREC+1
 1234 CONTINUE
      CALL ETX(ETLX,PAMX,HARVTX)
      DO 95 I=1,INT
      CALL MOIST(WCX,FLRTX,SOILMX,ETLX,WTBX,IKX,1,INT)
      CALL NITRO(WCX,FLRTX,SOILMX,IKX,CNORTX,FLRNX,NTRTX,DNTUPX,FERTX,
     * PLANTX,HARVTX,FERTMX,DNFMX,NTRATX,INT,TDENTX)
   95 CONTINUE
      IF(T.GE.PLANTX.AND.T.LT.HARVTX) CALL PLGRTH(PLANTX,MOX,
     1 BOX,YOX,NITUPX,PLGRX,WTBX,PAMX,ETLX,IKX,
     2 DNTUPX,CNORTX,OPTXX,OPTYX,1,WCX,WILT)
      IF(T.NE.HARVTX) GO TO 115
      DO 100 IZ=1,10
  100 DNTUPX(IZ)=0.
      RZONEX=0.
      NITUPX=0.
  115 IF(IG1.EQ.0) GO TO 140
      IF(AMOD(T,NL).GT.0.) GO TO 140
      ANCX=0.0
      DO 2000 IK=1,10
 2000 ANCX=ANCX+NTRTX(IK)
      ANCX=ANCX*10.0
      SHC2=NITUP*100.
      WRITE(6,360)T,PLGRX,ANCX
  360 FORMAT(1HO,F5.,6X,2F8.3)
      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 IF(IG2.EQ.0) GO TO 145
      IF(AMOD(T,NP).GT.0.) GO TO 145
      WRITE(12,400) PLGRX,NITUPX
  400 FORMAT(0PF9.3,2PF7.4)
      AA(II)=T
      II=II+1
  145 CONTINUE
      GYIELD=PLGRX*HIW
      BYIELD=GYIELD*0.0149
      WRITE(6,350)PLGRX,GYIELD,BYIELD
  350 FORMAT(//10X,'AVERAGE YIELD- (OVERALL OUTPUT)',
```

```
   1 //5X'DR.-MATR.(KG/HA)',5X'GRAIN (KG/HA); (BU/AC)',
   2 //9X,F9.3,9X,F8.3,8X,F3.0,//)
     IF(IG2.EQ.0) GO TO 999
     INP=IDAY/NP
     DO 175 IX=1,IG2
     REWIND 12
     DO 150 IZ=1,14
150  FMTA(IZ)=FMT(IZ,IXZ2(IX))
     DO 155 II=1,INP
155  READ(12,FMTA,END=156) AA(INP+II)
     GO TO 157
156  INP=II
157  CALL PLOT(IXZ2(IX),2)
175  CONTINUE
     GO TO 999
180  WRITE(6,500)
500  FORMAT(' INSUFFICIENT WEATHER DATA')
190  WRITE(6,550)
550  FORMAT(' CONTROL CARD ERROR')
999  STOP
     END
C
     BLOCK DATA
     IMPLICIT REAL*4 (A-H,J-Z)
     COMMON /COMA/
   * HEAD,IHEAD,T,WTFC,   F(10),WCFC(10),SR,TMAX,TMIN
     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)
     DATA XX/  0.15,0.2,0.225,0.25,0.275,0.3,0.35,0.4,0.45,0.5/,
   1 KY/  -5.5,-4.57,-4.,-3.33,-2.4,-1.5,0.,1.,1.33,1.5/,
   2 DY/  -0.25,-0.1,0.15,0.6,1.3,1.9,2.5,3.2,4.,4.4/,
   3 GRA1X/160.,169.,181.,193.,203.,211.,218.,227.,245.,261./,
   5 GRA1Y/0.30,0.38,0.54,0.80,0.96,1.02,1.04,1.00,0.55,0.32/,
   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/175.,180.,187.,191.,197.,203.,210.,217.,225.,261./,
   5 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.,
   6 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.,
   7 0.35,0.3,2*0.1,3*0.05,3*0.,2*0.3,2*0.1,4*0.05,2*0.,
   8 2*0.3,0.1,6*0.05,0.,2*0.3,0.1,5*0.05,2*0.025/
     DATA OPTXX/0.,20.,45.,55.,65.,90.,120./,
   1 OPTYX/0.031,0.052,0.029,0.022,0.021,0.022,0.020/,
```

```
     1 OPTYX/0.031,0.052,0.029,0.022,0.021,0.022,0.020/,
     2 WCFC/0.39,0.42,0.31,0.27,0.26,0.21,0.23,0.25,0.27,0.27/,
     3 WILT/0.21,0.24,0.15,0.11,0.10,0.07,0.08,0.09,0.11,0.11/
      END
C
      SUBROUTINE INIT
      IMPLICIT REAL*4 (A-H,J-Z)
      COMMON /COMA/
     *HEAD,IHEAD,T,WTFC,     F(10),WCFC(10),SR,TMAX,TMIN
      COMMON /COMB/       AREA,CWHT
      COMMON /COMD/       CNORW,
     * DENIT,DIF,DISP,NORN,TORT,WTSAT,WF(10)
      T=159.
      NORN=0.001
      DIF=1.
      TORT=0.6
      DISP=4.
      DENIT=0.0004
      CNORW=0.004
      HEAD=0.
      IHEAD=1
      WTFC=0.27
      WTSAT=0.33
      CWHT=1.
      AREA=64.
      DO 10 I=1,5
      WF(I)=0.6
   10 WF(I+5)=0.9
      DO 20 I=1,2
   20 F(I)=0.5
      DO 30 I=3,10
   30 F(I)=1.
      RETURN
      END
C
      SUBROUTINE INITX
      IMPLICIT REAL*4 (A-H,J-Z)
      COMMON /COMA/
     * HEAD,IHEAD,T,WTFC,     F(10),WCFC(10),SR,TMAX,TMIN
      COMMON /COME/       IKX,
     * CNORTX(10),FLRNX(11),FLRTX(11)
      COMMON /COMF/
     1 BOX,MOX,YOX,        FERTMX,FERTX,
     2 HARVTX,NITUPX,NTRATX,PLANTX,PLGRX,WTBX,DNTUPX(10),
     3 NTRTX(10),SOILMX(10),WCX(10),     TDENTX,HIW
      PLGRX=0.
      MOX=52.
      BOX=27.
```

```
      YOX=210.
      NTRATX=0.
      NITUPX=0.
      WTBX=500.
      IKX=MIN1(10.,WTBX/15.)
      FERTX=0.0
      PLANTX=160.
      HARVTX=261.
      TDENTX=0.
      HIW=0.38
      DO 10 I=1,IKX
   10 WCX(I)=WCFC(I)
      WRITE(6,1000)WCX
 1000 FORMAT(' WCX',10F7.3)
      IF(IKX.EQ.10) GO TO 30
      IL=IKX+1
      DO 20 I=IL,10
   20 WCX(I)=WCFC(I)+0.07
   30 DO 40 I=1,10
      SOILMX(I)=15.*WCX(I)
      DNTUPX(I)=0.
      CNORTX(I)=0.020-0.0010*I
      NTRTX(I)=SOILMX(I)*CNORTX(I)
   40 CONTINUE
      RETURN
      END
C
      SUBROUTINE ETX(ETL,PAM,HARVT)
      IMPLICIT REAL*4 (A-H,J-Z)
      COMMON /COMA/
     * HEAD,IHEAD,T,WTFC,    F(10),WCFC(10),SR,TMAX,TMIN
      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)
      DIMENSION ETL(10)
      CTMAX=TMAX*1.8+32.
      CTMIN=TMIN*1.8+32.
      LET=-87.03+(0.928*CTMAX)+(0.933*(CTMAX-CTMIN))+(0.0486*SR)
      PET=LET*0.0094
      IF(T.GE.121.AND.T.LE.288) GO TO 10
      ET=0.0375
      GO TO 40
   10 IF(T.GT.HARVT) GO TO 35
      RATIO=AFGEN(GRA1X,GRA1Y,10,T)
      IF(T.GE.178) GO TO 15
      ET=PET*RATIO
      GO TO 40
   15 IF(T.GE.212) GO TO 20
      IF(PET.LE.0.4) ET=PET*RATIO*AFGEN(GRA3L,STRES3,11,PAM)
```

```
      IF(PET.GT..4.AND.PET.LE..53)ET=PET*RATIO*AFGEN(GRAX,STRES2,11,PAM)
      IF(PET.GT.0.53) ET=PET*RATIO*AFGEN(GRAX,STRES1,11.PAM)
      GO TO 40
   20 IF(PET.LE.0.3) ET=PET*RATIO*AFGEN(GRA3L,TRESS3,11,PAM)
      IF(PET.GT..3.AND.PET.LE..41)ET=PET*RATIO*AFGEN(GRAX,TRESS2,11,PAM)
      IF(PET.LT.0.41) ET=PET*RATIO*AFGEN(GRAX,TRESS1,11,PAM)
      GO TO 40
   35 ET=0.25*PET
   40 DO 45 IJ=1,10
      IF(DATES(IJ).GE.T) GO TO 55
   45 CONTINUE
   55 DO 50 I=1,10
   50 ETL(I)=PATN(I,IJ)*ET
      RETURN
      END
C
      SUBROUTINE MOIST(WC,FLRT,SOILM,ETL,WTB,IK,IWH,INT)
      IMPLICIT REAL*4(A-H,J-Z)
      COMMON /COMA/
     * HEAD,IHEAD,T,WTFC,    F(10),WCFC(10),SR,TMAX,TMIN
      COMMON /COMB/       AREA,CWHT
      COMMON /COMC/       PREC,RUNOFF,
     *XX(10),DY(10),KY(10),OPTXX(7),OPTYX(7),WILT(10)
      DIMENSION WC(10),FLRT(11),SOILM(10),ETL(10),OSM(10)
      DIFN(X)=10.**AFGEN(XX,DY,10,X)
      CDUT(X)=10.**AFGEN(XX,KY,10,X)
      DO 10 I=1,10
   10 OSM(I)=SOILM(I)
      IL=IK+1
      IF(IK.LT.10) GO TO 20
      AVD=(DIFN(WC(10))+DIFN(WTFC))/2.
      AVC=(CDUT(WC(10))+CDUT(WTFC))/2.
      FLRT(11)=(AVD*(WC(10)-WTFC)/((WTB-150)/2.+7.5)+AVC)/INT
      IL=10
   20 DO 30 I=2,10
      AVD=(DIFN(WC(I-1))+DIFN(WC(I)))/2.
      AVC=(CDUT(WC(I-1))+CDUT(WC(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
   80 DO 100 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 100
      SOILM(I)=SOILM(I)+ETL(I)/INT
      IF(I.LT.10) ETL(I+1)=ETL(I+1)+ETL(I)
      ETL(I)=0.
      WC(I)=SOILM(I)/15.
      IF(WC(I).GE.WILT(I)) GO TO 100
      FLRT(I+1)=FLRT(I+1)-(WILT(I)-WC(I))*15.
      WC(I)=WILT(I)
      SOILM(I)=15*WILT(I)
  100 CONTINUE
      RETURN
      END
C
      SUBROUTINE NITRO(WC,FLRT,SOILM,IK,CNORT,FLRN,NTRT,DNTUP,FERT,
     * PLANT, HARVT,FERTIM,DNFM,NTRAT,INT,TDENIT)
      IMPLICIT REAL*4(A-H,J-Z)
      COMMON /COMA/
     * HEAD,IHEAD,T,WTFC,    F(10),WCFC(10),SR,TMAX,TMIN
      COMMON /COMD/      CNORW,
     * DENIT,DIF,DISP,NORN,TORT,WTSAT,WF(10)
      DIMENSION DNTUP(10),WC(10),FLRT(11),SOILM(10),CNORT(10),FLRN(11),
     * NTRT(10)
      FLRN(1)=FLRT(1)*NORN
      DO 20 I=2,10
      DFL=(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=FLRT(I)*CNORT(I)*WF(I)
      IF(FLRT(I).GT.0.) MFL=FLRT(I)*CNORT(I-1)*WF(I)
   20 FLRN(I)=MFL+DFL
      DFL=(DISP*ABS(FLRT(11))+DIF*TORT*0.5*(WC(10)+WTSAT)/INT)
     *    *(CNORT(10)-CNORW)/757.
      IF(FLRT(11).LE.0.) MFL=FLRT(11)*CNORW
      IF(FLRT(11).GT.0.) MFL=FLRT(11)*CNORT(10)
      FLRN(11)=MFL+DFL
      DO 80 I=1,10
      NFLRN=FLRN(I)-FLRN(I+1)
      NTRT(I)=NTRT(I)+NFLRN-DNTUP(I)/INT
      IF(NTRT(I).GE.0.) GO TO 80
      WRITE(6,200) I
  200 FORMAT(/26X,'**NEG.NO3-N BEING CORECTED IN LAYER',I3,'**')
      FLRN(I+1)=FLRN(I+1)+NTRT(I)
      NTRT(I)=0.
   80 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
   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
      IF(T.LT.120.OR.T.GT.289) GO TO 130
      IF(T.LT.151) GO TO 120
      IF(T.LT.228) GO TO 110
      NTRT(1)=NTRT(1)+0.0013/INT
      NTRT(2)=NTRT(2)+0.0013/INT
      GO TO 130
  110 NTRT(1)=NTRT(1)+0.0014/INT
      NTRT(2)=NTRT(2)+0.0014/INT
      GO TO 130
  120 NTRT(1)=NTRT(1)+0.0008/INT
      NTRT(2)=NTRT(2)+0.0008/INT
  130 DO 140 I=1,10
  140 CNORT(I)=NTRT(I)/SOILM(I)
      RETURN
      END
C
      SUBROUTINE PLGRTH(PLANT,MO,BO,YO,NITUP,PLGR,
     * WTB,PAM,ETL,IK,DNTUP,CNORT,OPTX,OPTY,IWH,WC,WILT)
      IMPLICIT REAL*4 (A-H,J-Z)
      INTEGER MAX1
      COMMON /COMA/
     * HEAD,IHEAD,T,WTFC,    F(10),WCFC(10),SR,TMAX,TMIN
      DIMENSION WC(10),ETL(10),DNTUP(10),CNORT(10),OPTX(7),OPTY(7),
     * WILT(10)
      RZONE=3.0+(147./(1.0+EXP(5.-(8.*((T-PLANT)/52.)))))
      IX=AMINO(MAX1(RZONE,15.)/15,10,IK)
      W=0.
      WX=0.
      DO 10 I=1,IX
      WX=WX+WCFC(I)-WILT(I)
   10 W=W+WC(I)-WILT(I)
      PAM=W/WX
      LMW=ALOG10(100*PAM+1.)/2.0043
      DO 20 I=1,10
      DNTUP(I)=ETL(I)*CNORT(I)*F(I)
   20 NITUP=NITUP+DNTUP(I)
      IF(PLGR.GT.0) GO TO 60
      LMN=1.
      GO TO 90
   60 TP=T-PLANT
      OPNIT=AFGEN(OPTX,OPTY, 7,TP)
      R=AMIN1(100.*NITUP/PLGR,OPNIT)
```

```
   80 LMN=EXP(-(OPNIT-R)**2/(0.75*OPNIT )**2)
   90 TAIR=((TMAX+TMIN)/2)+273.
      LMT=EXP(-(1.02721**TAIR*((288.-TAIR)/TAIR)**2))
      LM=AMIN1(LMT,LMW,LMN)
      GR=LM*YO*EXP(-(MO-T+PLANT)**2/BO**2)
      PLGR=PLGR+GR
      RETURN
      END
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
      WRITE(6,30) X,ARG(IDIM)
   30 FORMAT(' THE VALUE',F10.4,'IS OUTSIDE OF ARGUMENTS OF THE TABLE;'/
     * 'IT IS SET EQUAL TO LAST ARGUMENT IN TABLE:',F10.4)
   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
      SUBROUTINE PLOT(NO,M)
      COMMON /COM1/       A(8030),N
      DIMENSION YM(2),YPR(11),JP(10)
      DATA YM/10000.,150./
      LOGICAL*1 ANG(10)/'*123456789'/,BLANK/' '/,OVER/'+'/
      LOGICAL*1 OUT(101)/ 101 * ' ' /
      LOGICAL*1 HEAD(20,2)/'WHEAT GROWTH(KG/HA) N-UPTAKE (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) LL,(OUT(I),I=1,101),LL
600 FORMAT(10X,I5,'.',101A1,'.',I4)
    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
```

Appendix B

WEATHER FILE, 1979: RIDGEWAY,MARQUETTE,NONFALLOW,FARMING SITE

WEATHER: RIDGEWAY-MARQUETTE

1.	09 06	35	21	5	10085
2.	10 06		23	10	10100
3.	11 06	18	24	3	10113
4.	12 06		29	8	10125
5.	13 06		35	14	10136
6.	14 06		27	14	10145
7.	15 06		21	8	10154
8.	16 06		22	13	10161
9.	17 06		25	4	10166
10.	18 06		27	7	10171
11.	19 06		21	10	10174
12.	20 06	27	21	13	10176
13.	21 06		13	6	10177
14.	22 06		17	2	10176
15.	23 06		22	3	10174
16.	24 06		26	8	10171
17.	25 06	30	24	13	10167
18.	26 06		23	10	10161
19.	27 06		28	8	10154
20.	28 06	10	25	12	10146
21.	29 06		29	11	10136
22.	30 06		27	12	10126
23.	01 07		27	13	10114
24.	02 07		26	15	10101
25.	03 07		26	13	10086
26.	04 07		29	12	10071
27.	05 07		28	12	10054
28.	06 07		28	13	10036
29.	07 07		24	12	10027
30.	08 07		31	15	10007
31.	09 07		32	17	9985
32.	10 07		32	13	9962
33.	11 07	15	30	14	9938
34.	12 07		32	16	9913
35.	13 07	25	27	18	9887
36.	14 07		24	11	9859
37.	15 07	73	21	9	9831
38.	16 07		24	5	9801
39.	17 07		28	9	9770
40.	18 07		30	13	9738
41.	19 07	35	27	13	9705
42.	20 07		33	14	9671
43.	21 07		27	17	9636
44.	22 07		30	8	9600
45.	23 07	30	26	17	9563
46.	24 07		28	12	9525
47.	25 07	15	22	12	9486
48.	26 07		22	9	9445

C:

49.	27 07		26	9	9404
50.	28 07		30	11	9362
51.	29 07		27	13	9319
52.	30 07		22	13	9275
53.	31 07		26	5	9231
54.	01 08	25	29	10	9185
55.	02 08		24	11	9138
56.	03 08	48	18	6	9091
57.	04 08		21	10	9042
58.	05 08		23	4	8993
59.	06 08		26	9	8943
60.	07 08		24	10	8892
61.	08 08		24	5	8841
62.	09 08	27	22	12	8788
63.	10 08		21	8	8735
64.	11 08		25	3	8681
65.	12 08	25	22	12	8626
66.	13 08	81	13	5	8571
67.	14 08		18	3	8515
68.	15 08		21	1	8458
69.	16 08		22	9	8400
70.	17 08	27	25	12	8342
71.	18 08		29	13	8283
72.	19 08		28	10	8223
73.	20 08		30	12	8163
74.	21 08	7	21	11	8102
75.	22 08		21	15	8052
76.	23 08		13	7	7990
77.	24 08	25	21	5	7927
78.	25 08		21	4	7864
79.	26 08		23	7	7800
80.	27 08		27	6	7736
81.	28 08		27	12	7672
82.	29 08		19	9	7606
83.	30 08		23	1	7541
84.	31 08	15	25	10	7475
85.	01 09	17	23	14	7408
86.	02 09	93	14	8	7341
87.	03 09		16	3	7274
88.	04 09		22	9	7206
89.	05 09		25	7	7138
90.	06 09		16	3	7070
91.	07 09		18	1	7001
92.	08 09		23	6	6932
93.	09 09		18	6	6863
94.	10 09		15	4	6793
95.	11 09	88	19	6	6723
96.	12 09		15	5	6653
97.	13 09		14	1	6583
98.	14 09		22	0	6512
99.	15 09		25	3	6442

C:

100.	16 09	30 10		6371
101.	17 09	21 12		6300
102.	18 09	13	1	6229

C:

Appendix C

SMPDATA - SOIL AND MANAGEMENT INPUT DATA: RIDGEWAY - MARQUETTE,NONFALLOW,FARMING SITE

SMPDATA

```
1                        RIDGEWAY-MARQUETTE,NONFALLOW,FARMING


OSPEC   2   2 102 20 2 1 2 2 1 2

OCNOX  0137   0053   0072   0082   0077   0072   0067   0062   0057   0052

OAREA  64 1.0

OCWHT 160 2611 160  40

0
      THE UNIT AREA IS 64.HECTARS.
      1.00 FROM THE AREA IS WHEAT.
      PLANT.-DAY      FERT.-DAY      FERT.-AMNT.

         160.            160.            40.


 WCFC   0.39   0.42   0.31   0.27   0.26   0.21   0.23   0.25   0.27   0.27
 WILT   0.21   0.24   0.15   0.11   0.10   0.07   0.08   0.09   0.11   0.11
C:
```

Appendix D

OUTPUT: RIDGEWAY - MARQUETTE,NONFALLOW,FARMING SITE

```
WCX  0.375  0.250  0.150  0.111  0.101  0.100  0.201  0.234  0.261  0.266
O 248.      4669.289   6.909
 CNORT  64.75  49.28  13.09   7.57   6.56   6.61   6.79   6.32   5.82   5.35
WCX  0.364  0.256  0.150  0.110  0.100  0.100  0.201  0.233  0.261  0.266
O 250.      4696.152   6.940
 CNORT  65.58  49.99  13.42   7.56   6.55   6.66   6.79   6.32   5.82   5.35
WCX  0.358  0.257  0.150  0.110  0.100  0.099  0.200  0.233  0.260  0.266
O 252.      4717.988   6.967
 CNORT  66.34  50.72  13.81   7.61   6.56   6.59   6.78   6.32   5.82   5.35
WCX  0.353  0.258  0.150  0.110  0.100  0.099  0.199  0.233  0.260  0.266
O 254.      4735.551   7.012
 CNORT  58.33  50.66  14.14   7.65   6.57   6.59   6.78   6.31   5.82   5.35
WCX  0.390  0.276  0.150  0.110  0.100  0.099  0.199  0.232  0.260  0.266
O 256.      4746.840   7.052
 CNORT  59.67  50.58  14.54   7.70   6.58   6.55   6.78   6.31   5.82   5.36
WCX  0.374  0.289  0.150  0.110  0.100  0.099  0.198  0.232  0.260  0.266
O 258.      4757.855   7.092
 CNORT  60.53  50.97  14.94   7.75   6.59   6.55   6.77   6.31   5.82   5.36
WCX  0.367  0.293  0.151  0.110  0.100  0.099  0.198  0.232  0.259  0.265
O 260.      4766.441   7.133
 CNORT  61.27  51.45  15.33   7.79   6.59   6.55   6.77   6.31   5.82   5.36
WCX  0.362  0.295  0.151  0.110  0.100  0.099  0.197  0.232  0.259  0.265


         AVERAGE YIELD- (OVERALL OUTPUT)

      DR.-MATR.(KG/HA)     GRAIN (KG/HA); (BU/AC)

         4766.441          1811.248        27.
C:
```