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SIMULATION-MULTICRITERIA OPTIMIZATION TECHNIQUE AS A DECISION SUPPORT SYSTEM FOR RICE PRODUCTION

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ABSTRACT

SIMULATION-MULTICRITERIA OPTIMIZATION TECHNIQUE AS A DECISION SUPPORT SYSTEM FOR RICE PRODUCTION

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Low-yielding rice-growing countries can benefit from the agrotechnologies developed and made available through experimental stations and from high-yielding countries. However, the conventional method of agrotechnology transfer may be costly and time-consuming, and the farmers' perception of risk within the context of the economic environment in which they function is sometimes a major barrier to adapting high-yielding agrotechnologies.

The rice simulation model reported here is a computer software package designed to aid in the initial selection of new varieties and management practices in various soil types and climatic environments of the tropics and subtropics. Varieties and management practices which look promising in the context of the simulation are the principal technologies to be tried in the field. This procedure is expected to reduce dramatically the cost and time required in agrotechnology transfer.

The extent to which farmers are willing to adapt high-yielding

Dedicated to

my husband and best friend, Rex,

and my mother, Rosario.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION AND NEEDS ANALYSIS

While there is food surplus in some regions of the world, serious food deficiency, leading to malnutrition and starvation, is a grim reality in many others. Unfortunately, these food-deficient regions are not economically able to gain access to the food surplus. To eliminate the destructive effect of food deficiency, the concerned countries must find ways and means to increase food production in pace with population growth.

Food supply is a direct function of weather and soil environments, market system, government policies and programs, agrotechnology, and the producer's objective of profit and income stability.

Plants provide as much as 95 percent of the world's food supply (MSU Agricultural Experiment Station, 1981). To more than a third of the world's population, predominantly in Asia, rice is a primary staple in the diet and the center of existence (Barker et al., 1985). This makes rice the most important food crop in the world today. De Datta (1981) reported that in 1976-1978, rice was harvested from about 143.5 million hectares from Asia (accounting for 90 percent of the total), Africa, South and Central America, Australia, and part of the United States. Rice, grown as flooded wetland or dryland crop, has received considerable research, political and economic attention from all over the world. But in many of the Asian, African, and Latin American rice-growing countries today, production is not enough to meet the food needs of their population, making the daily food supply unreliable and driving the cost of subsistence proportionately high relative to income. Particularly for upland rice agriculture, the regional average grain yield is very low: from 0.5 to 1.5 MT/Ha in Asia, about 0.5 MT/Ha in Africa, and 1 to 4 MT/Ha in Latin America (De Datta, 1975). However, under ideal conditions in experiment stations, yields are reported to be between 5.4 to 7.2 MT/Ha.

In order to increase rice production, the low-yielding countries will have to do one or a combination of two things: increase the area devoted to production and/or increase the frequency and intensity of cultivation. At the present rate of population growth, agricultural land is continuously reduced in favor of urbanization, so increasing production by increasing land area is at best only a partial and short-term solution. Hence, rice productivity must come from increases in output per unit area, per unit input, per unit time through high-yielding, science-based technologies tailored to the unique combination of soil, climatic, biological, economic, and cultural conditions of the local area (Wortman and Cummings, 1978; Swaminathan, 1975; Ruttan, 1982). However, the generation of technology is a complex process. Plant agriculture is a complex system. It is characterized by unique properties and non-linear functions (Baker and Curry, 1976). It is a system which requires natural resources as part of the inputs, imposing their stochastic behavior in the transformation process from input to output (Amir et al., 1978). The development of science-based technologies is evolutionary in nature and requires a long-term investment (Sahal, 1980). Agricultural research techniques are costly, time-consuming, site-specific and, by its own nature, a trial-and-error undertaking. In many of the food-deficient countries, there is an increasing uncertainty as to whether the current agricultural research methods are adequate to meet the food requirements of the growing population and provide for the management skills required to keep food production going.

Thus, the complex circumstances surrounding the rice production system, particularly in narrowing the yield gap of upland rice agriculture, requires the development of a methodology that will hasten the evaluation of appropriate transferable agrotechnologies, in the form of varieties and field management practices, from high-yielding rice-growing countries to the low-yielding countries, or from its site of origin to another location, at lower cost, minimum failure, and shortest waiting time. Such a methodology can be embodied in a computer software that can simulate a rice production system for any chosen variety and management practices considering the stochastic factors of the production environment.

But increased yield per hectare is not in itself a sufficient goal. Agricultural production is increasingly dependent on the degree to which cost-effective technology is employed (Avery, 1985), and to which the farmer's vulnerability to the uncertainties of the environmental factors are reduced, rather than simply striving for maximum yield. The level and stability of income to the farmer govern the intensity of rice production. What is needed is a procedure for designing and managing the production system in such a manner as to maximize returns and minimize production risk under highly uncertain enviromental conditions. This need translates into an analytical, multicriteria, resource-allocation optimization procedure through which the tradeoffs can be evaluated between two conflicting objectives: maximum profit and minimum risk. To the author's knowledge, this is the first time that multicriteria optimization technique of the type presented here has been applied to agriculture production in general and to upland rice production in particular.

CHAPTER II

OBJECTIVES AND SCOPE OF RESEARCH

2.1. Objectives

The general objective of this dissertation research is to develop an interactive computer software on rice simulation and multicriteria-resource-allocation optimization technique (to be referred to as SMOT) as a decision support system for use by farmers, agricultural extension workers, researchers, and government policy-makers in the design and management of the rice production system.

The specific objective of the dissertation research is to develop a practical and flexible computer software for simulating an upland rice production system for use as a tool in the effective transfer of agrotechnologies among and within countries in the tropics and subtropics from its site of origin to new locations and, based on this simulation software, develop a multicriteria, resource-allocation optimization software as an analytical tool in evaluating profit and production risk, subject to constraints in resources, environment and relevant food production policies.

2.2. Scope

The rice simulation software is developed for upland condition in the tropical and sub-tropical environments. The software is designed primarily to predict:

1. the phenological development or duration of growth stages as influenced by plant genetics, weather, and environmental factors,
2. biomass production and partitioning, and
3. the effect of soil water deficit and nitrogen deficiency on the photosynthesis and photosynthate partitioning in the plant system.

The simulation software provides the foundation for the simulation-multicriteria optimization technique (SMOT). SMOT is designed as a decision support system for upland rice production where profit and production risk are quantitatively evaluated subject to the simultaneous constraints on resources, environment, and production policies. Through the use of SMOT, alternative production strategies can be identified based on the level of profit and risk as well as the capability of the producer to finance the operation.

As with all software packages, SMOT has its limitations. Diseases and insect pests, for example, which are highly variable with respect to location, are important considerations in rice production. Conceptually, the rice simulation model has been bifurcated into (1) a plant system without the destructive effect of pest, and (2) one with the influence of pest. The first system, devoid of the effect of pests, is considered here. Incorporation of pest models remains as a future activity. In the work reported here, it is assumed that pests are controlled to the extent that they have no economic effect and that the cost of this control can be represented as a fixed cost in the optimization technique.

As structured, the simulation software assumes that:

1. The production field is not bunded, i.e., runoff is allowed to occur.
2. Method of planting is by direct-seeding.
3. Fertilizer application is basal, i.e., fertilizer is to be applied once at the beginning of the planting season.
4. Except for nitrogen, all nutrients required for plant growth are non-limiting, that is, sufficient to support a normal growth.
5. There are no highly problematic soil conditions such as high salinity and acidity, heavy compaction, or deficiencies in trace elements.
6. The effects of typhoons are negligible.

As structured, SMOT assumes further that the market situation, including the price of grain and input costs, are constant over the period of the optimization. The optimization procedure, however, can be repeated as often as desired for alternative prices and costs.

For the present application, capital is assumed a constraint factor while labor is in abundant supply. This assumption is based on the fact that majority of rice production is an activity among highly populated, low-income developing countries. Consequently, harvesting is assumed to be done manually and cost of harvest is on per weight basis. Harvesting mechanization, however, can be implemented by SMOT.

The present applications of SMOT also assumes that the unavoidable by-products of rice production such as nitrate leaching, runoff, and pesticide pollution have negligible impact on the environment. However, where necessary, these by-products can be analytically incorporated as constraints on the inputs to the simulation and/or optimization processes of SMOT.

CHAPTER III

SYSTEM IDENTIFICATION

The rice production system is governed by the input-process-output relationship, as a function of time, t. The vector of inputs fall into two classes: (1) the exogenous input variables which are uncontrollable and may be stochastic in nature, and (2) the controllable input variables which are deterministic in nature. The vector of exogenous input variables is represented analytically as $\bar{e}(t)$ and the vector of controllable input variables as $\bar{u}(t)$. The vector of state variables is denoted by $\bar{x}(t)$. The vector $\bar{x}(t)$ describes the internal as well as the external behavior of the plant system. The system parameters are the coefficients in the analytical equations which define the analytical structure describing the system.

The vector of outputs also fall into two classes: (1) the desired output variables, represented as $\bar{y}(t)$, and (2) the undesired, unavoidable by-products which are generated when the system produces the desired outputs. The performance criteria are defined in order to evaluate whether the desired outputs are acceptable.

The rate of change of the state variables at time t ($\dot{\bar{x}}(t)$), as well as the output variables at time t ($\bar{y}(t)$), depend upon the inputs $\bar{u}(t)$ and $\bar{e}(t)$, the state of the system, $\bar{x}(t)$, and time, t. This relationship is expressed by the functions $\bar{g}$ and $\bar{h}$ in a state-space representation as follows:

$$\dot{\bar{x}}(t) = \bar{g}(\bar{x}(t), \bar{u}(t), \bar{e}(t), t)$$

$$\bar{y}(t) = \bar{h}(\bar{x}(t), \bar{u}(t), \bar{e}(t), t)$$

The rice production system forms a class of system characterized technically as stochastic, continuous-time, with memory, non-linear, time-varying, and dynamic. The system is stochastic because the weather variables can only be described probabilistically, that is, they can not be described exactly for all time. It is also continuous-time because the environmental-biological interactions in the plant system occur continuously during the growth process. The system has memory because the output of the system at a given time t_1 depends not only on the input applied at t_1 but also on the input applied before t_1 (Swisher, 1976). The non-linearity of the system is due to the fact that the relaxed system, or zero initial condition of the system, can only be described sufficiently with non-linear relationships as mentioned in Chapter I. In this case, the principle of superposition (Swisher, 1976) will not hold true, that is,

$$L\{a_1u_1(t) + a_2u_2(t)\} \neq a_1L\{u_1(t)\} + a_2L\{u_2(t)\}$$

for any two inputs $u_1(t)$ and $u_2(t)$ as functions of time t, and any constant scalars a_1 and a_2.

The state of the plant system during its growth vary with time, hence the system is time-varying. The rice production system is also a dynamic system because the two conditions describing a dynamic system are properties of the rice production system. The two conditions are (Swisher, 1976):

(1) A real output $\bar{y}(t)$ exists for all $t > t_o$ given a real input $\bar{u}(t)$ for all t, where t_o is initial time.

(2) Outputs do not depend on inputs $\bar{u}(\tau)$ for $\tau > t$.

Because of the second condition, rice production system is also considered as causal, that is, the output of the system at time t does not depend on the input at times after time t.

3.1. The Exogenous Input Variables

The major contribution of the exogenous input variables make rice production seasonal, geographically dispersed, and uncertain. These exogenous variables are grouped into two categories, namely: physical and socio-economic. The physical exogenous input variables are solar radiation, daylength variations, air temperature, and rainfall. The socio-economic exogenous input variables are product prices, input costs, and marketing costs.

3.2. The Controllable Input Variables

The controllable input variables in the rice production system are classified into the following: manpower (such as the farmers and hired workers); budget allocation; material flow inputs (such as seeds, fertilizers, water, pesticides), capital facilities (such as irrigation system, storage or barns, farm animals, tractors, threshers, and land); and cultural management practices (such as sowing or planting date, plant density, sowing depth, amount and frequency of fertilizer application, amount of irrigation, and type of pest control).

3.3. The Output Variables

Rice production involves the transformation of inputs into desirable outputs such as grain yield and straw. However, there are unavoidable, undesirable by-products in the process such as pesticide pollution, nitrate leaching, runoff, and sometimes, the build-up of insect populations. These by-products degrade the environment and, while there is no apparent cost to the rice producer at the moment, the future generation will pay for the damage if not dealt with now.

3.4. The System Parameters

The system parameters determine the functional relationship in the input-process-output and define the structure of the system. They are classified into two categories, namely: (1) the system design parameters, which are manageable, and (2) the natural system parameters which are unmanageable. The system design parameters depend upon the technologies used and how these technologies are organized into a production system. The design parameters for rice production are grouped into (a) genetic-dependent, and (b) labor- or mechanization-dependent. The genetic-dependent parameters, which describe the variety, are: (1) the time required for the plant to develop from seedling stage to floral initiation; (2) the rate of photo-induction; (3) optimum photoperiod; (4) the time required to complete grain filling; (5) the plant's conversion efficiency from sunlight to carbohydrates; and, (6) tillering characteristic.

The labor- or mechanization-dependent variables are: (1) method of land preparation; (2) method of fertilizer application; (3) method of pesticide control; (4) irrigation method; and, (5) method of harvesting.

The natural system parameters are: (1) the latitude of the production area; and, (2) the properties and initial conditions of the soil profile such as soil nutrition and toxicities, water saturation properties, landscape hydrology, textural profile of the soil, and the topographic position of the field.

The system parameters are affected directly or indirectly by socio-economic and institutional factors such as availability of farm inputs, access to credit and markets, inflation and interest rates, local and international market situation, consumers' demands, consumers' nutritional requirements, customs reflecting preference for certain varieties by consumers and farm practice by farmers, production policies by the government (price support, production input subsidies, government-supported storage facilities, etc.), form of government or political system (socialism, capitalism, communism, etc.), the needs of the rice industry, and the availability of agrotechnologies from research institutions.

The exogenous input variables, the system parameters and the socio-economic and institutional factors determine the type of agriculture in any particular environment.

3.5. Performance Criteria

The criteria upon which the performance of the rice production system are evaluated, are: (1) farmer's profit; and, (2) production risk. These two criteria are conflicting in the sense that production strategies that generate higher profit are usually very risky operations. Thus, the evaluation procedure will exercise tradeoffs to identify simultaneously the best acceptable values of the two objective functions. The process is called simulation-multicriteria optimization technique.

3.6. The Multicriteria Optimization

Optimization is an analytical procedure or a mathematical programming technique used to find the optimum solution that would maximize or minimize an objective function subject to some defined equality or inequality constraints. The optimization techniques were developed in response to such questions as "Are we making the most effective use of our scarce resources?" or "Are we taking risks within acceptable limits?" (Bazaraa and Shetty, 1979). The simultaneous growth of fast computing facilities had facilitated the use of these techniques. Problem optimization can either be linear or non-linear programming. Within the class of non-linear programming is another classification according to the number of objective functions: the single criterion and the multicriteria or vector optimization problem. The class of problem to be dealt with here is nonlinear, multicriteria optimization problem due to the nonlinearity of the system, the nonlinearity of some of the constraint functions, and the nonlinearity of the objective functions. In a multicriteria optimization problem, the objective functions form a vector of criteria (Osyczka, 1984). The formulation requires a definition of the objectives to be maximized or minimized, the decision variables that must be optimized, and the constraint functions surrounding the problem.

Multicriteria optimization has had its applications in engineering fields. It is an analytical procedure of finding the "optimum" solution which would give acceptable values or tradeoffs for all the objective functions to be considered simultaneously. The goal of the multicriteria optimization is to help decision-makers make the right decision in conflicting situations (Osyczka, 1984). Recently, multiple criteria or multi-objective decision-making has gained popularity and applications in management science due to the realization that a decision has more than one dimension which affects successive actions or decisions. For example, Shapiro (1984) argued that the assumption that a firm is interested only in profit is an oversimplification. He presented research results indicating that management decides upon allocation of scarce resources with reference to several, sometimes conflicting, goals such as profit, market share, balanced business portfolio, long-range growth rate, and risk, in the strategic (long-term) sense, as well as employment level, management-labor relations, and product quality, in the tactical (short-term) sense. There are also nonfinancial demands that need to be addressed to, including such issues as equal employment opportunities, pollution control, product safety, and work safety.

The nonlinear multicriteria optimization will use the Pareto optimization and min-max optimization techniques. The Monte Carlo search method, which assigns random numbers to generate new and random Points, will be employed to search the space of feasible solution.

3.6.1. Pareto Optimization

The concept of Pareto optimization originated in 1896 from a man named Vilfredo Pareto who began a study of efficient solution theory as applied to welfare economics (French et al., 1983). French et al. indicated that Pareto's study provided the earliest recognition of the difficulty of reducing decision problems to forms involving a single objective. However, its application to engineering and management science did not gain momentum until in the early 1970's, and the idea of multi-objective or multicriteria decision-making became formalized.

The original version of Pareto optimality theory was quoted by Cirillo (1979) as follows:

"*There are, as we have noted, two problems to be resolved in obtaining the maximum well-being for a collectivity. Given certain rules of distribution, we can investigate what positions, following these rules, will give the greatest well-being to the members of the collectivity. Let us consider any particular position and let us suppose that a very small move is made compatible with the relations involved. If in doing so the well-being of all the individuals is increased, it is evident that the new position is more advantageous for each one of them, vice-versa, it is less so if the well-being of all the individuals is diminished. The well-being of some may remain the same without these conclusions being affected. But, if on the other hand, this small move increases the well-being of certain individuals and diminishes that of others, it can no longer be said that it is advantageous to the community as a whole to make such a* *move. We are, hence, led to define a position of maximum ophelimity as one where it is impossible to make a small change of any sort such that the ophelimities of all individuals with the exception of those that remain constant, are either all increased or all diminished."*

In short, Pareto optimality states that an optimum position is reached when it is not possible to increase the utility of some consumers without diminishing that of others (Cirillo, 1979).

Mathematically, Osyczka (1984) defined Pareto optimization as follows:

A point $\overline{u}^* \in U$ is Pareto optimal if for every $\overline{u} \in U$ either,

$$(f_i(\overline{u}) = f_i(\overline{u}^*))$$

or, there is at least one $i \in I$ such that

$$f_i(\overline{u}) > f_i(\overline{u}^*)$$

Intuitively, Pareto optimization is that point $\overline{u}^*$ where no criterion can be improved without worsening at least one other criterion. Pareto optimum usually gives a set of non-inferior solutions. This set is denoted as U^p. F^p denotes the map of U^p in the space of objective functions.

3.6.2. Min-max Optimization

Min-max optimization procedure was developed by Osyczka (1984). It uses the information of the separately attainable minima of the objective functions. These minima can be obtained by solving the optimization problems for each criterion separately. Then the values of the objective functions are compared to these minima through their relative deviations. The min-max optimum is that point $\overline{u}^*$ which gives the smallest values of the relative increments of all the objective functions.

The detailed analytical presentations of both the Pareto and min-max optimization procedures are presented in Chapter VI.

CHAPTER IV

THE AGRONOMY OF UPLAND RICE PRODUCTION

Upland rice agriculture is the method of rice production on unbunded flat and slopping fields with land preparation and seeding under dry conditions, and that depend mostly on rainfall for moisture (De Datta, 1975). Primarily a tropical or subtropical crop, rice (*Oryza sativa L.*) is grown from 53 degrees north to 35 degrees south latitude, and from sea- or below sea-level to elevations of about 2,000 meters (Yoshida, 1981).

The growth cycle of a rice plant takes about 3-6 months depending on the climatic condition of the production area and the genetic characteristics of the variety with regards to photosensitivity and thermosensitivity (Tanaka et al., 1966; Yoshida, 1981). Because of the weather factors, especially temperature and daylength, and genetic interactions in the plant system, the growth duration is highly location and season specific.

During the growth cycle, the plant completes several stages, generally classified as the vegetative, reproductive, and ripening stages. The vegetative stage can be further sub-divided into germination, emergence, juvenile, and floral or panicle initiation, while the reproductive and ripening stages can be sub-divided into heading, grain filling, and physiological maturity. The duration of the vegetative stage varies among varieties and largely determines the growth duration of the plant (IRRI, 1964; Yoshida, 1981). The duration of the vegetative stage is said to have a minimum and maximum limit (IRRI, 1964). The minimum limit which is relatively constant for a variety, is known as the basic vegetative phase, and the duration between the minimum and maximum limits is known as the photoperiod sensitive phase. The duration of the photoperiod sensitive phase varies with the daylength or photoperiod, which is the interval between sunrise and sunset (unit: hours). Photoperiod is a function of the latitude of the production area.

The vegetative stage is characterized by active tillering, increase in plant height, leaf emergence, and increase in the leaf area (Yoshida, 1981). The reproductive and ripening stages are characterized by panicle and grain growth.

4.1. The Effect of Temperature on Rice Growth

An optimum temperature for different physiological processes has been observed (Yoshida, 1981). This optimum temperature varies with variety. The optimal temperature appears to shift from high to low as growth advances from the vegetative to the reproductive and ripening stages (IRRI, 1972; Yoshida, 1981). Within the critical high and low temperatures, high temperatures are required for active growth at early stages while low temperatures favor spikelet production during the reproductive stage, confirming the observation that the length of ripening is inversely correlated with daily mean temperature (Yoshida, 1981). However, extremely high or low temperatures are not favorable to plant growth. Yoshida (1981) reported that high percentage of spikelet sterility occurred when temperatures exceeded 35^{o}C at anthesis and lasted for more than 1 hour. Injury to rice occurred when the daily mean temperature dropped below 20^{o}C. Low temperatures, such as 12^{o}C, induced 100 percent sterility when they lasted for 6 days. Other injuries due to cold temperatures were failure to germinate, delayed seedling emergence, stunting, leaf discoloration, panicle tip degeneration, incomplete panicle exsertion, delayed flowering, and irregular maturity.

Crop duration is directly related to temperature and modelled as thermal time or degree-days (Yoshida, 1981). It is calculated as follows:

Degree-days = Σ (daily mean temperature - threshold temperature)

Rice has been observed to have a threshold temperature of 8^{o}C. Yoshida (1981) indicates that the concept of thermal time or degree-days assumes that the growth or development of a plant is linearly related to temperature or the total amount of heat to which it is exposed. However, he cautions that this concept should be handled carefully because there are some physiological and biochemical processes in the plant which are not linearly dependent on temperature. He demonstrated the presence of the "idling effect" of high temperatures, suggesting that a "ceiling temperature" existed.

4.2. Rice Phenology

Phenology is concerned with the duration of the growth stages of the plant. As mentioned in the earlier section, the growth stages are germination, emergence, juvenile, panicle initiation, heading, grain filling, and physiological maturity.

4.2.1. Germination

The concept of thermal time was applied to the germination study by Livingston and Haasis (1933) in order to determine the thermal time requirement for complete germination in rice seeds. The result showed that it took about 45 degree-days to germinate healthy rice seeds within the temperature range of 15^{o} to $37^{o}C$. At the incubation temperature of $42^{o}C$, only about 8 percent germinated in 10 days and no germination was observed in a period of 6 days at $45^{o}C$.

At germination, the coleoptile emerges and the first leaf follows (Yoshida, 1981). A study by Yoshida (1973) indicates that temperature affects the rate of leaf emergence. At $22^{o}C$ one leaf emerged every 5.4 days while a leaf emerged every 3.5 days at $31^{o}C$. The concept of thermal time was applied on the above study. The temperature ranges were converted to degree-days using a threshold temperature of $8^{o}C$. Plotting the degree-days against the number of leaves per culm or stem showed that the relationship was linear and that the slope, number of leaves per degree-day, was 0.012. The inverse of the slope is 83.3 degree days/leaf. The 83.3 is also known as the phyllocron interval. However, phytotron studies to determine the phyllocron interval for some rice varieties conducted at the Duke University during the period 1983-84 (unpublished results) showed an average value of 90 degree-days/leaf. Most varieties develop 10-22 leaves on the main culm (Yoshida, 1973, 1981).

Roots develop immediately after germination. Root growth is observed to be regulated by both varietal characteristics and root environment. A study on rice growth under controlled environment by Yoshida (1973) showed that at the very early stage of plant growth, root to shoot ratio was about 0.21, decreasing exponentially as the plant weight increased, and stabilizing at about 0.10 as the plant weighed 1 gram or more. Root weight was not markedly affected by temperature, at least within the range of 22^{o} to $31^{o}C$. However, water stress was found to increase root growth relative to shoot growth (IRRI, 1974).

4.2.2. Seedling emergence

Seedling emergence is the time when the tip of a seedling emerges from the soil surface, and so start the growth process in the field (Yoshida, 1981). Thus, the time required for emergence is a function of the sowing depth.

Until this point, plant growth is supported by the nutrients in the endosperm, often known as the seed reserve (Yoshida, 1973; IRRI, 1973). The concept of thermal time was applied on the seedling growth experiment by Yoshida (1973) in order to evaluate growth rate. The result showed that growth was linearly related to thermal time up to 120 degree-days, with a slope of 0.00008265 grams dry weight/plant/degree-day.

4.2.3. Juvenile Stage

Juvenile stage is characterized by root growth, leaf emergence, leaf growth, and tillering.

During the initial stages of seedling growth (first and second week after sowing), growth of the coleoptile and subsequent leaves is largely dependent on the seed reserve (Yoshida, 1973 and 1981). Photosynthesis takes over carbohydrate production after the second week of growth. Yoshida (1973, 1981) reported that within the temperature range of 22^{o}C to 31^{o}C, photosynthesis was responsible for about 30 percent of growth during the first week, 84 percent during the second week, and 100 percent thereafter. Yoshida also indicated that during the first week after sowing and until the middle growth stages, growth rate increased almost linearly with increasing temperatures.

Studies (IRRI, 1968) have shown that tillering is initiated when the total nitrogen uptake becomes greater than 10 mg/plant or the dry weight is greater than 300 mg/plant, demonstrating that tillering initiation depends on the size of the main tiller. The tiller number was observed to increase when the nitrogen content of the leaf blade was higher than 2 percent, but tillering stopped when nitrogen content dropped below 2 percent. Tillering ability is known to be a varietal character, that is, high-tillering varieties tiller more actively than low-tillering ones. Tillering increase by a plant population follows a curvilinear shape, increasing monotonically until the maximum tiller number stage. Tiller number decreases after the heading stage. High temperatures encourage tillering (IRRI, 1972).

Leaf area development of a rice variety is highly related to its tillering capacity at conventional plant spacing (Yoshida and Parao, 1972). A high-tillering variety tends to have a vigorous vegetative growth.

4.2.4. Panicle Initiation

Since rice is a short-day crop, rice initiates panicle primordia in response to short photoperiods (Yoshida, 1981). The duration of this stage varies with the degree of photosensitivity of the variety. Depending on the daylength condition of the production area, the duration could be at its shortest or longest. The daylength at which the duration from sowing to flowering is a minimum is called the optimum photoperiod (Yoshida, 1981; IRRI, 1966). The optimum photoperiod of most varieties is observed to be 9-10 hours (Yoshida, 1981; IRRI, 1969). The critical photoperiod is the longest photoperiod at which the plant will flower; flowering will not occur beyond the critical photoperiod (Yoshida, 1981; IRRI, 1966). The critical photoperiod of most varieties ranges from 12 to 14 hours (Yoshida, 1981; IRRI, 1969). Short photoperiods decrease the growth period of the plants. Photosensitivity is a varietal character, that is, the critical and optimum photoperiod differ among varieties. The growth of a variety that is less sensitive to photoperiod does not fluctuate as much as a highly sensitive variety under various daylength conditions (Tanaka et al., 1966).

It is usually during the panicle initiation stage that the plant reaches the maximum tiller number (Yoshida, 1981). There is a period before the maximum tiller stage when the tiller number becomes numerically equal to the panicle number at maturity.

4.2.5. Heading

Yoshida (1981) defines heading as the time when 50 percent of the panicles have exserted. From his experience, complete heading in the field takes about 10-14 days.

As the rice plant grows, the leaf area index (LAI) increases. LAI is the sum of the leaf area of all the leaves divided by the ground area where the leaves have been collected. Studies by Yoshida (1981) show that LAI increases curvilinearly with time and reaches a maximum at around heading. After heading, LAI decreases as the lower leaves senesce. The same studies demonstrate that a rice crop can attain maximum LAI values of 10 or more at heading time, with a LAI value of 5-6 at maximum crop photosynthesis.

Tiller number also starts to decrease during the heading stage. The non-bearing tillers and weak-bearing tillers are killed as a result of shading and senescence (IRRI, 1964). The number of tillers and the number of panicles become equal at harvest.

4.2.6. Grain Filling

Grain filling is characterized by increase in grain size and weight, resulting in the increase in panicle weight. It is also characterized by changes in grain color and senescence of leaves (Yoshida, 1981). The process of grain growth is quantified by the increase in dry weight and the decrease in water content. Yoshida observed that the rate of grain growth was faster and the grain filling period was shorter at higher temperatures. Grain growth was initially slow, then entered a linear phase where the growth rate was fast, and then slowed down toward maturity.

During the grain filling period, some of the assimilates from the other plant organs are translocated to the grains. Studies have shown that about 5 percent of the assimilates absorbed by the plant during the panicle development, and 30-50 percent of the assimilates absorbed after flowering, are translocated to the grains (IRRI, 1964). The duration of grain filling, that is, the time required to reach maximum weight, varies with the variety.

4.3. The Influence of Solar Radiation on Plant Growth

Aside from temperature, solar radiation influences rice yield by directly affecting the physiological processes involved in grain production. Photosynthesis in green leaves uses solar energy in wavelengths from 0.4 to 0.7 μm, often referred to as the photosynthetically active radiation (PAR) (Yoshida, 1981). The ratio of PAR to total solar radiation is close to 0.50 in both the tropics and the temperate regions. This ratio represents a weighted mean between the fractions for direct radiation and diffuse sky radiation. The solar radiation requirements of a rice crop differs from one growth stage to another with the greatest effect on grain yield during the reproductive and ripening stages (Yoshida, 1981).

4.4. Photosynthesis

Photosynthesis is a process by which solar energy is captured and converted into chemical energy and stored in the form of carbohydrates (Yoshida, 1981). It supplies organic substances which are used as building blocks in the process of plant growth and as energy sources for respiration (IRRI, 1965). About 80-90 percent of the dry matter of green plants is derived from photosynthesis; the rest (minerals) come from the soil (Yoshida, 1981). The photosynthetic activity occurs in the leaves which intercept the incident solar radiation. Thus, a rice plant with more surface leaf area is likely to intercept more solar energy than a rice plant with less surface leaf area. Yoshida (1981) outlined the factors that determine crop photosynthesis in the field. These factors were: incident solar radiation, photosynthetic rate per unit leaf area, leaf area index (LAI), and leaf orientation. The photosynthetic rate per unit leaf area is controlled by varietal characters and nitrogen nutrition at a given stage (IRRI, 1968).

The leaf area index (LAI) is estimated from one surface of the leaf blade. It is a function of (a) tiller number per unit field area; (b) leaf number per tiller; and (c) average leaf size (IRRI, 1964). An active tillering variety tends to have a large LAI. Environmental and genetic factors influence leaf size. Studies have shown that LAI increases with increase in the dry weight of the leaves (IRRI, 1964). But, while photosynthesis increases with increase in LAI, the photosynthetic activity by one plant is not linearly proportional to the total photosynthetic activity of a plant community due to the effect of mutual shading. The fully exposed leaves receive more light than they are able to utilize while the leaves further down receive less sunlight than they need (IRRI, 1964). The degree of mutual shading is expressed by the light transmission ratio (LTR) (IRRI,1964). LTR is the light intensity at the ground level of the plant population (I) divided by the light intensity at the top of the population (I_o). This ratio is expressed as the negative exponential function of the product between LAI and the extinction coefficient K. The result of the relationship is written as follows:

$$LTR = \frac{I}{I_o} = e^{-(K \cdot LAI)}$$

K measures leaf orientation. The optimum K value increases with the decrease in LAI (Tanaka et al., 1966).

Studies indicate that the LAI values necessary to intercept 95 percent of the incident light in rice canopies range from 4 to 8. A large LAI and K values imply long, wide leaves while short leaves have smaller LAI and K values (Tanaka et al., 1966). In many studies, the concept of mutual shading explain why tiller number, plant weight, LAI, and grain yield decrease when the surrounding plants increase in leafiness (IRRI, 1964).

4.5. Carbohydrate Partitioning

The distribution of assimilates or carbohydrates into the different plant organs varies with the growth stages and environmental conditions (Suzuki, 1983). Generally, the organs actively developing at the time of growth get a large proportion of the carbohydrates such as sugars and starch (IRRI, 1964). Suzuki (1983) indicated that the ratio of distribution to roots and blades was high in the early growth stages, then a higher distribution to the stem and leaf sheath was evident during the middle growth stages, and finally after heading, the distribution to the panicle was predominant. A research study (IRRI, 1964) showed that during the early growth stage and until panicle development, about 50 percent of the carbohydrates assimilated became part of the cell walls and was not translocated, however, only 10 percent was retained after flowering. Yoshida (1981) reported that carbohydrates began to accumulate sharply about 2 weeks before heading and reached a maximum concentration in the plant's vegetative parts, mainly in the leaf sheath and culm, at heading. The concentration began to decrease as ripening proceeded and rose slightly again near maturity. Another study (IRRI, 1970) on the distribution of carbohydrates revealed that, 10 days before flowering, about 18 percent went to the leaf, 22 percent to the sheath and stem, 55 percent to the panicle, and about 5 percent was lost by respiration and senescence. Carbohydrates lost from the vegetative parts during grain filling and not used for respiration, are translocated to the grains (IRRI, 1964).

4.6. Grain Yield

Rice yield is generally reported as rough rice at 14 percent moisture content (IRRI, 1964; Yoshida, 1981). Grain yield is a function of panicle number per square meter, spikelet or grain number per panicle, percent filled spikelets, and grain weight. The product of panicle number/m^2 and number of spikelets or grains/panicle is the number of spikelets or grains/m^2. The relationship is written as follows (Yoshida, 1981):

$$\text{Grain yield (MT/Ha)} = \text{Panicle No./m}^2 \cdot \text{Spikelet No./Pan.} \cdot \text{\% filled Spikelets} \cdot \text{1,000-grain weight (g)} \cdot 10^{-5}$$

$$= \text{Spikelet No./m}^2 \cdot \text{\% filled Spikelets} \cdot \text{1,000-grain weight (g)} \cdot 10^{-5}$$

The equation above shows that grain yield is directly related to spikelet or grain number. In most conditions, the 1,000-grain weight of rice is relatively constant and a very stable varietal character (IRRI, 1967; Murayama, 1979; Yoshida, 1981). The constant 1,000-grain weight of a given variety does not mean however, that individual grains have the same weight per grain. The percent filled-spikelet is also observed to be about 85 percent over a wide range of grain number (IRRI, 1971, 1972), although it has been observed to decrease to 60 percent when grain number is very large. At the wider spacing, grain yield is directly related to the panicle number, that is, the larger the panicle number, the larger is grain yield (Yoshida and Parao, 1972).

4.7. Soil-Water Condition and Water Losses

The soil conditions of upland rice are diverse. De Datta and Feuer (1975) reported that soil texture varied from sand to clay; pH, from 3 to 10; organic matter content, from 1 to 50 percent; salt content, from almost 0 to 1 percent; nutrient availability, from acute deficiency to over supply.

Soil texture affects particularly the moisture status of upland rice soils. A clayey textural profile with a medium texture on the surface horizon is suggested to be the most favorable for rice cultivation (De Datta and Feuer, 1975). Yoshida (1975) indicates that the soil texture determines the capillary ascent of water in soils. Water moves upward at a slow rate but for a longer distance in a fine soil compared to a rapid capillary action for a short distance in a coarse soil. For an illustration, he reported Kramer's work in 1969 which showed that with a water table 60 cm deep, water moved upward at 5 mm/day in a coarse-textured soil but only at 2 mm/day in a fine-textured soil.

Different soils vary in their water storage capacitites. Yoshida (1975) defined the water storage capacity as the water readily available to plants (in the range between the field capacity and permanent wilting point), measured in millimeters of water per unit depth of soil. He demonstrated that the storage capacity ranged from 4.3 to 8.6 mm/30 cm in fine sand to 77.0 mm/30 cm in a clay. As a result, plants growing in soils that had low storage capacities exhausted the readily available water and suffered from drought much sooner than plants growing in soils with high storage capacities. Yoshida further indicated that the extent to which ground water could supply the needed moisture to the root zones was primarily determined by the depth of the water table and the soil texture. A higher water table would supply more moisture to the root zones than a lower water table.

A major difference between upland rice soils and lowland rice soils is the soil water regime. Unlike lowland rice soils, Ponnamperuma (1975) explains that upland rice soils are not submerged or saturated with water for a long period of time during the growing season. However, he indicates that the rice plant is physiologically, morphologically, and anatomically adapted to submerged, anaerobic soils. So, under upland conditions, the rice plant has to adjust to a dry, aerobic soil condition. Ponnamperuma (1975) further illustrates that nutrients are delivered by mass flow and diffusion, the delivery rate decreasing with moisture content. So, the low soil moisture content in upland soils reduces the potential supply of nutrients to the roots. Thus, moisture stress is a primary limiting factor on the growth and yield of upland rice (Ponnamperuma, 1975; IRRI, 1974). This observation was supported by Chang and Vergara (1975) who reported that, under severe water stress, rice yield was poor despite heavy fertilization and effective weed control. Ponnamperuma adds that unlike submerged soils, upland soils are not able to adjust their pH levels to the favorable range of 6.5 to 7.0, a condition which could result to manganese and aluminum toxicities in strongly acid soils, and iron deficiency in alkaline soils. Finally, Ponnamperuma suggests that upland rice does best on the lower members of the toposequence of slightly acid soils, discouraging the use of sodic, calcareous, and saline soils, acid sulfate soils, and soils low in organic matter.

Consistent with Ponnamperuma's findings, Yoshida (1975) observed that nitrogen became the major limiting factor for yield if adequate water was provided either through rainfall or irrigation.

Water stress is brought about through many processes. One is by transpiration. Transpiration is the amount (grams) of water lost from plant surfaces per gram of dry matter or carbohydrate produced. It is needed for plant growth. Yoshida (1975) reported that the transpiration ratio was generally around 250 to 350 g/g, implying that dry matter production was proportional to the amount of water transpired by the plant.

Aside from transpiration, water is lost through evaporation, surface run-off, percolation, and seepage. Evaporation is the loss of water from free water surfaces (Yoshida, 1981). The combined water losses due to evaporation and transpiration are called evapotranspiration. The potential evapotranspiration, which is the amount of water lost through transpiration by a vegetation that completely covers a ground that is never water deficient, represents the maximum possible evaporative loss from a vegetative-covered surface. Yoshida presented several methods of calculating the potential evapotranspiration. These methods are the Penman equation, the Thornwaite method, and the van Bavel method. The procedure proposed by Priestley and Taylor (1972) is the method used in the CERES crop models.

Yoshida (1981) further defines percolation, seepage, and run-off. Percolation, which occurs in a vertical direction, is largely affected by the topography, soil characteristics, and depth of the water table. Seepage is the water lost through the horizontal movement of water in a levee as determined by the slope and roughness of the soil surface in upland fields. Generally, percolation and seepage are taken as a measure of the water-retaining capacity of the field. Surface run-off or overland flow occurs when rainfall intensity exceeds the surface storage capacity and the percolation-plus-seepage rate or infiltration rate.

Water stress severely affects shoot growth more than root growth, while tillering is least affected (IRRI, 1974).

The analytical relationship of the soil-water balance and the water losses by evapotranspiration, surface run-off, percolation, and seepage are presented and discussed by Ritchie (1985).

4.8. The Importance of Nitrogen Fertilization

As plants grow, they absorb nitrogen from the soil to support photosynthesis. Studies have shown that photosynthesis and respiration, and correspondingly grain yield, increase with increasing levels of nitrogen, especially in fields short of the element (IRRI, 1964). This absorption will deplete the amount of nitrogen in the soil (IRRI, 1963). In order to maintain a high leaf photosynthetic activity for assimilating a large amount of carbohydrates and to supply more nitrogenous compounds to grains during the ripening stage, Murayama (1979) indicated that additional nitrogen must be supplied from the soil to the plant. He reported that high-yielding rice plants had high nitrogen concentration throughout its growth cycle. The straw of ordinary varieties contained 0.5-0.6 percent nitrogen at maturity while the high-yielding varieties contained 0.7-1.0 percent. For a high yielding plant, he reported that the optimum nitrogen concentration in the leaf blade was 2.3-4.0 percent at the early panicle formation stage and 2.2-3.3 percent at the heading stage. He further added that about 50-60 percent of total plant nitrogen in high-yielding plants with high nitrogen concentration had been absorbed by the early panicle formation, and about 70-80 percent by heading and finally about 20-30 percent of nitrogen was absorbed during the ripening stage.

Nitrogen compounds are mobile in the plant. They are constantly translocated from old organs to new ones (IRRI, 1963). During the ripening stage, about 70 percent of the nitrogen absorbed by the straw are translocated to the grain (Yoshida, 1981). Nitrogen content of the grain does not fluctuate.

Patnaik and Rao (1979) outlined the many sources of nitrogen that could be applied to regulate nitrogen nutrition in the soil. Soil organic matter is one good source and the process of supplying nitrogen from this source to the plant is through mineralization by biochemical or microbial means. Another source of nitrogen is organic and green manures. Organic and green manures are crop residues such as straw or well-rotted compost incorporated into the soil. Chemical fertilizers, such as urea, ammonium sulfate, and ammonium phosphate to name a few, have been identified as the major sources of nitrogen. Choice of the form depends upon the availability and condition of the soil. The incorporation of fertilizer nitrogen into the reduced subsurface layer during land preparation is one method of application. This method has been observed to minimize losses resulting from runoff, volatilization, leaching, and denitrification. The amount of application is recommended to be between 40-50 Kg N/Ha with a maximum of 60 Kg N/Ha during the wet season, and 80-100 Kg N/Ha with a maximum of 120 Kg N/Ha during the dry season.

Without nitrogen fertilization in soils not able to meet the nitrogen requirements of the plant, the plant suffers a nitrogen deficiency. Nitrogen deficiency eventually results in low yield. However, higher nitrogen application does not always bring about higher yields. Many studies have shown that when plants grow taller and actively tiller, the field become crowded with leaves, especially at high nitrogen levels, resulting in serious mutual shading, and sometimes lodging. This event could cause an imbalance between photosynthesis and respiration in the later stages of the growth and reduce the effectiveness of the nitrogen applied (IRRI, 1963). Thus, the nitrogen effect tends to decrease with increase in growth duration (Tanaka et al., 1966).

The nitrogen transformation processes under upland condition, such as nitrogen mineralization, denitrification, and nitrate leaching follow that outlined for the CERES-Wheat model by Godwin and Vlek (1985).

CHAPTER V

THE ANALYTICAL STRUCTURE OF THE RICE SIMULATION MODEL

In adapting the system to a digital computer, the state-space description has to be transformed into a discrete-time system so that the problem can be solved recursively by using difference equations. In discrete-time system representation, the rice production system is described in the following state-space equation:

$$\bar{x}(kT+T) = \bar{g}(\bar{x}(kT),\ \bar{u}(kT),\ \bar{e}(kT),\ kT)$$

$$\bar{y}(kT) = \bar{h}(\bar{x}(kT),\ \bar{u}(kT),\ \bar{e}(kT),\ kT)$$

where the variable k is the discrete time and takes on positive integer values exclusively, while the variable T is the sampling period or interval. The functions $\bar{g}$ and $\bar{h}$ are vector valued and non-linear; $\bar{y}(kT)$ is the output vector at discrete time k; $\bar{u}(kT)$ is the controllable input vector at discrete time k; $\bar{e}(kT)$ is the exogenous input vector at discrete time k; and, $\bar{x}(kT)$ is the state vector at discrete time k.

The sampling interval T is one day, that is, the value of the variables is a sequence of numbers spaced at 24-hour intervals. Replacing T with 1 simplifies the state-space equation into the following:

$$\bar{x}(k+1) = \bar{g}(\bar{x}(k),\ \bar{u}(k),\ \bar{e}(k),\ k)$$

$$\bar{y}(k) = \bar{h}(\bar{x}(k),\ \bar{u}(k),\ \bar{e}(k),\ k)$$

The vector components of $\overline{u}(k)$ are the day of the year for sowing (ISOW); number of plants/m^2 (PLANTS); depth of sowing (SDEPTH, cm); day of the year (JFDAY) and amount of nitrogen fertilizer (AFERT, Kg N/Ha), depth of fertilizer application (DFERT, cm), and type (IFTYPE) of fertilizer; day of the year (JDAY) and amount of irrigation (AIRR, mm).

The vector components of $\overline{e}(k)$ are the solar radiation at time k (SOLRAD(k), MJ/m^2); maximum air temperature at time k (TEMPMX(k), ^{o}C); minimum air temperature at time k (TEMPMN(k), ^{o}C); and rainfall at time k (RAIN(k), mm/day).

The controllable input variables or signals are of the Kronecker delta sequence, that is,

$$u(k) = \delta(k) = 1 \quad \text{for } k=0$$
$$= 0 \quad \text{for } k \neq 0$$

while the exogenous input signals or variables are of the Kronecker-delta-like sequences, that is,

$$u(k) = \delta(k-p) = 1 \qquad \text{for } k=p$$
$$= 0 \qquad \text{for all other values of } k$$

where p is any fixed integer (Cadzow, 1973). The sequence $\delta(k-p)$ is equal to the sequence $\delta(k)$ shifted p discrete-time units to the right since k will take only positive integer values.

The vector $\overline{y}(k)$ has two components: grain yield (YIELD, MT/Ha) and plant straw (PSTRAW, g/m^2).

The natural system parameters are the latitude of the production area (LAT) and parameters related to the soil properties and soil water balance. The number (NLAYR) and depth of the soil layers ($DLAYR_{\lambda}$, λ=1,...,NLAYR), and the lower limit of plant extractable soil water of the soil layer (LL_{λ}) are soil-related parameters which will be mentioned in the discussion. However, there are other parameters related to the soil, water, and nitrogen fertilization which are needed for the numerical estimation of the water-related and nitrogen-related stress factors. These parameters are outlined by Ritchie (1985), Godwin and Vlek (1985), and Ritchie et al. (1986).

The system design parameters are the genetic coefficients of the variety. These coefficients are: P1 (duration, in degree-days, from emergence to end of juvenile stage), P2R (rate of photo-induction, in degree-days/hour), P2O (optimum photoperiod, in hours), P5 (duration, in degree-days, required for grain filling), G1 (conversion efficiency from intercepted photosynthetically active radiation (PAR) to dry matter production, g/MJ PAR), and TR, a unitless tillering factor.

The input-process-output relationship in the rice production system is best related to the phenological stages and growth patterns of the plant. The phenological stages describe the duration of each growth stage in the life cycle of the rice plant. Growth pertains to the production and distribution of carbohydrates to the various plant parts resulting in plant growth. Unless otherwise stated, the unit of production area is one square meter (m^2), the units of carbohydrate production and plant growth are in grams per square meter (g/m^2), and the unit of leaf area expansion is in square meter leaf area per square meter of land area occupied by the plants (m^2/m^2).

The phenological stages are numbered 1 through 9, with the active, above-ground stages numbered 1 through 5. This numerical sequencing is based on carbohydrate partitioning which varies according to stages. The phenological stages are identified as follows, namely: sowing (ISTAGE 7); germination (ISTAGE 8); emergence (ISTAGE 9); juvenile (ISTAGE 1); panicle initiation (ISTAGE 2); heading (ISTAGE 3); beginning of grain filling (ISTAGE 4); end of grain filling (ISTAGE 5); and, physiological maturity (ISTAGE 6).

As mentioned in Chapter IV, the duration of each phenological stage makes use of the concept of thermal time or degree-days at time k (DTT(k)). DTT(k) is the difference between the mean temperature (TEMPM(k)) and temperature threshold (TBASE) of one day, hence the unit degree-day. TEMPM(k) at time k is the average of TEMPMX(k) and TEMPMN(k) at time k. However, this estimation process is valid only when TEMPMN(K) is greater than TBASE and TEMPMX(k) is less than 33^{o}C. That is,

$$TEMPM(k) = \frac{TEMPMX(k) + TEMPMN(k)}{2}$$

$$DTT(k) = TEMPM(k) - TBASE, \qquad TEMPMN(k) > TBASE;$$
$$TEMPMX(k) < 33^{o}C$$

Otherwise, DTT(k) is estimated by dividing a 24-hour day into eight 3-hourly sections, calculate a temperature correction factor for each section (TMFAC), interpolate the air temperature for that section (TTMP), and then calculate the appropriate thermal time at time k. That is,

$$TMFAC(k)_i = 0.931 + 0.114i - 0.0703i^2 + 0.0053i^3, \quad i = 1, \ldots, 8$$

$$TTMP(k)_i = TEMPMN(k) + TMFAC(k)_i \cdot (TEMPMX(k) - TEMPMN(k))$$
$$i = 1, \ldots, 8$$

$$
\mathrm{DTT}(k) = \begin{cases} \dfrac{1}{8} \sum_{i=1}^{8} (\mathrm{TTMP}(k)_i - \mathrm{TBASE}) , & \mathrm{TBASE} \le \mathrm{TTMP}(k)_i \le 33^{\circ}\mathrm{C} \\[2ex] \dfrac{(33 - \mathrm{TBASE})}{8} \sum_{i=1}^{8} [1 - (\mathrm{TTMP}(k)_i - 33)/9], & 33^{\circ}\mathrm{C} < \mathrm{TTMP}(k)_i < 42^{\circ}\mathrm{C} \\[2ex] 0 , \text{ otherwise.} & \end{cases}
$$

The production and distribution of carbohydrates are affected at each phenological stage by temperature, water, and nitrogen stresses. So these stress factors have to be estimated quantitatively.

A temperature-related stress factor at time k (PRFT(k)), taking on real values in the closed interval 0-1, affects carbohydrate production. PRFT(k) is calculated from TEMPMN(k) and TEMPMX(k) weighted accordingly, with optimum at 26°C mean temperature.

$$
\mathrm{PRFT}(k) = 1 - 0.0025 \cdot [\{0.25 \cdot \mathrm{TEMPMN}(k) + 0.75 \cdot \mathrm{TEMPMX}(k)\} - 26]^2
$$

$$
\mathrm{PRFT}(k) \in [0,1]
$$

Another temperature-related stress factor at time k is SLFT(k). SLFT(k) takes on real values in the closed interval 0-1 and affects leaf senescence due to temperatures below 6°C.

$$
\mathrm{SLFT}(k) = \begin{cases} 1, & \mathrm{TEMPM}(k) > 6^{\circ}\mathrm{C} \text{ and } \mathrm{TEMPMN}(k) > 0^{\circ}\mathrm{C} \\[2ex] 1 - \dfrac{6 - \mathrm{TEMPM}(k)}{6} , & 0^{\circ} \le \mathrm{TEMPM}(k) \le 6^{\circ}\mathrm{C} \\[2ex] 0, & \mathrm{TEMPM}(k) < 0^{\circ}\mathrm{C} \text{ or } \mathrm{TEMPMN}(k) < 0^{\circ}\mathrm{C} \end{cases}
$$

The water-related stress factors at time k are SWDF1(k) and SWDF2(k), while the nitrogen-related stress factors at time k are NDEF1(k) and NDEF2(k). These factors take on real values in the closed interval 0-1. SWDF1(k) and NDEF1(k) are the water stress and nitrogen stress factors, respectively, affecting carbohydrate production, while SWDF2(k) and NDEF2(k) are the water stress and nitrogen stress factors, respectively, affecting leaf expansion. The analytical relationships of the soil-water balance and nitrogen transformation and uptake leading to the quantification of these stress factors are presented by Jones et al. (1986).

Plant competition for sunlight, nutrients and water becomes a factor in plant growth when plant population is dense, so a population density factor affecting the actual carbohydrate production (POPFAC), which takes on real values in the closed interval 0-1, is also calculated.

$$\text{POPFAC} = 0.94 + 0.0006 \cdot \text{PLANTS} \,, \qquad \text{POPFAC} \in [0,1]$$

All the stress factors, PRFT(k), SLFT(k), SWDF1(k), SWDF2(k), NDEF1(k), and NDEF2(k), and the population factor (POPFAC) are unitless.

5.1. Sowing Stage (ISTAGE 7)

Sowing stage is the point in time when seeds are sown in the ground and the discrete time k is set to 0 and will be incremented by 1 hereafter, taking on a positive integer value exclusively for every simulation step.

The location of the seeds in the soil profile is determined from the sowing depth (SDEPTH) and the thickness (cm) of the soil layers (DLAYR). The soil layer containing the seeds is indexed as $\lambda 0$. The location of the seeds in the soil profile (CUMDEP) is calculated as follows:

$$\text{CUMDEP} = \sum_{\lambda=1}^{\lambda 0} \text{DLAYR}_{\lambda}$$

At this time also, the vector components of $\bar{x}(0)$, the initial state of the system, is defined.

5.2. Germination Stage (ISTAGE 8)

Germination stage covers the period from sowing until germination. Germination will occur if all 4 conditions outlined below are satisfied:

1) $SW(k)_{\lambda 0} > LL_{\lambda 0}$, where $SW(k)_{\lambda 0}$ is the soil water content of the seed layer $\lambda 0$ at time k and $LL_{\lambda 0}$ is the lower limit of plant extractable soil water of that layer. Otherwise the extractable soil water at the sowing depth at time k (SWSD(k)), calculated proportionately between $SW(k)_{\lambda 0}$ and $LL_{\lambda 0}$ and the soil water content and lower limit of plant extractable soil water of the next layer, $SW(k)_{\lambda 0+1}$ and $LL_{\lambda 0+1}$ respectively, has a value of 0.02 or greater. That is,

$$SWSD(k) = (SW(k)_{\lambda 0} - LL_{\lambda 0}) \cdot 0.65 + (SW(k)_{\lambda 0+1} - LL_{\lambda 0+1}) \cdot 0.35$$

2) The mean air temperature at time k is between 15° and 42°C, that is, $15^{o}C \leq TEMPM(k) \leq 42^{o}C$,

3) the accumulated degree-days from sowing time (k_7) until time k is 45 or more, that is,

$$\sum_{k_7}^{k} DTT(k) \geq 45 ,$$

4) the duration of the seeds in the ground is ≤ 40 days

If germination does not occur 40 days after sowing, crop failure is assumed.

If germination occurs, the initial rooting depth (RTDEP(k), cm) is equivalent to the sowing depth (SDEPTH), that is,

$$RTDEP(k) = SDEPTH$$

5.3. Emergence Stage (ISTAGE 9)

Emergence stage covers the period from germination to emergence of the seedling from the soil surface. The duration, in degree-days, required from germination to emergence is P9. P9 is a linear function of the sowing depth (SDEPTH) with a slope of 7 degree-days/cm depth.

$$P9 = 7 \cdot SDEPTH$$

During the emergence stage, the seedling gets its food supply from the seed reserve. The potential carbohydrate production at time k (PCARB(k)) under optimum water, nitrogen, and temperature conditions is a linear function of the thermal time at time k (DTT(k)). That is, within the optimal high and low temperature range, growth is faster at higher temperatures than at lower temperatures. From Chapter IV, the slope of potential dry matter or carbohydrate production is given as 0.00008265 g carbohydrate/plant/degree-day. At this stage, seedling growth is not affected by plant competition, so the total potential carbohydrate production is the product of a single plant's production and the plant population per square meter (PLANTS).

$$PCARB(k) = 0.00008265 \cdot PLANTS \cdot DTT(k)$$

However, the actual carbohydrate production at time k (CARBO(k)) is not always equal to the potential production due to environmental constraints. The actual carbohydrate produced can be less than the potential due to reduction by the most limiting of either the temperature stress (PRFT(k)) or soil water deficit (SWDF1(k)).

$$CARBO(k) = PCARB(k) \cdot \min(PRFT(k), SWDF1(k))$$

The carbohydrates produced during this stage are distributed between the leaves and roots in proportional fractions. The fraction going to the roots at time k (PFR(k)) is represented as the negative exponential function of the seedling weight at time k-1 (PLTWT(k-1)/PLANTS), where PLTWT(k-1) is the total plant weight per square meter area at time k-1.

$$PFR(k) = 0.21 \cdot e^{-(PLTWT(k-1)/PLANTS)}$$

The fraction of carbohydrates going to the leaves at time k PFL(k)) is 1 less PFR(k).

$$PFL(k) = 1 - PFR(k)$$

Root growth (GRORT(k)) and leaf growth at time k (GROLF(k)) are rtional to the amount of carbohydrates allocated to these parts e k. That is,

$$)RT(k) = CARBO(k) \cdot PFR(k)$$

$$.F(k) = CARBO(k) \cdot PFL(k)$$

veight of the roots (RTWT(k)) and the leaves (LFWT(k)) at the sum of their respective weights at time k-1 and growth That is,

$$RTWT(k-1) + GRORT(k)$$

$$LFWT(k) = LFWT(k-1) + GROLF(k)$$

During this stage, the increase in the rooting depth at time k is a linear function of the thermal time (DTT(k)) at time k with a slope of 0.15 cm/degree-day. So the rooting depth at time k (RTDEP(k)) is the sum of the rooting depth at time k-1 and the increase in the rooting depth at time k, that is,

$$RTDEP(k) = RTDEP(k-1) + 0.15 \cdot DTT(k)$$

The nitrogen content of the roots at time k (ROOTN(k)) is determined from the actual nitrogen concentration of the roots (RANC(k-1)), in g N/g root, and total root weight (RTWT(k-1)) at time k-1.

$$ROOTN(k) = RANC(k-1) \cdot RTWT(k-1)$$

The nitrogen content of the stover at time k (STOVN(k)) is calculated from the total stover weight (STOVWT(k-1)) and the actual nitrogen concentration of the tops (TANC(k-1)), in g N/g top weight, at time k-1.

$$STOVN(k) = STOVWT(k-1) \cdot TANC(k-1)$$

The leaves will start to grow during this stage. Leaf emergence per plant at time k (TI(k)) is a linear function of the thermal time at time k (DTT(k)) with a slope equivalent to the phyllocron interval. The phyllocron interval used in the simulation model is 83 degree-days/leaf.

$$TI(k) = \frac{DTT(k)}{83}$$

The total number of fully expanded leaves from k=0 to time k (CUMPH(k)) is the sum of the daily leaf emergence (TI(k)).

$$CUMPH(k) = \sum_{k=0}^{k} TI(k)$$

5.4. Juvenile Stage (ISTAGE 1)

Juvenile stage covers the period from emergence to the end of the basic vegetative phase. The duration in degree-days is the genetic coefficient P1.

The root length density for the soil layers at time k ($RLV(k)_\lambda$), in cm root/cm^3 soil, is first estimated at this stage. $RLV(k)_\lambda$ is initialized as a function of the plant population (PLANTS) and the thickness of the soil layer ($DLAYR_\lambda$). λ is the soil layer index going from 1 through the total number of soil layers (NLAYR), $\lambda 0$ being the index for the seed layer. For each soil layer above the seed layer, RLV(k) is proportional to the plant population by a factor of 0.2 cm root/cm^2 soil/plant, that is,

$$RLV(k)_\lambda = \frac{0.2 \cdot PLANTS}{DLAYR_\lambda}, \qquad \lambda = 1, \ldots, \lambda 0\text{-}1$$

However, RLV(k) in the seed layer is reduced by a unitless fraction proportional to the difference between the cumulative depth of the seed layer (CUMDEP) and the rooting depth of the plants at time k (RTDEP(k)). That is,

$$RLV(k)_{\lambda 0} = \frac{0.2 \cdot PLANTS}{DLAYR_{\lambda 0}} \cdot \left(1 - \frac{CUMDEP - RTDEP(k)}{DLAYR_{\lambda 0}}\right)$$

RLV(k) is zero after the seed layer, that is,

$$RLV(k)_\lambda = 0, \qquad \lambda = \lambda 0+1, \ldots, NLAYR$$

When the seed reserve is still available for the plant to use, the potential carbohydrate production at time k (PCARB(k)) for each seedling is a logarithmic function of the thermal time at time k (DTT(k)) by a factor of 0.001 g carbohydrate/plant/degree-day. The total potential production is multiplied by the plant population/m^2 (PLANTS). That is,

$$PCARB(k) = 0.001 \cdot PLANTS \cdot \log(DTT(k))$$

Then CARBO(k), PFR(k), PFL(k), ROOTN(k), and STOVN(k) are calculated as in ISTAGE 9.

When the seed reserve is gone, growth is supported by photosynthesis. Photosynthesis is the process where the plant converts the intercepted light or solar radiation at time k (SOLRAD(k)) into carbohydrates. The plant utilizes the photosynthetically active radiation (PAR(k)) which is 50 percent of solar radiation (SOLRAD(k)). Thus,

$$PAR(k) = 0.50 \cdot SOLRAD(k)$$

where PAR(k) has the unit MJ/m^2.

In Chapter IV, the Light Transmission Ratio (LTR) was given as the negative exponential function of the product of the leaf area index (LAI(k)) and the extinction coefficient K. That is,

$$e^{-(K \cdot LAI(k))}$$

This means that the interception can be written as

$$1 - e^{-(K \cdot LAI(k))}$$

The intercepted light, in the form of PAR(k), is then converted into carbohydrates as inluenced by the plant's genetic or varietal character for conversion efficiency, G1. Intuitively, G1 defines the erectness or droopiness of the leaves. When used in this equation, G1 has the unit g carbohydrate/MJ of intercepted PAR(k). Thus the equation is stated as follows:

$$PCARB(k) = G1 \cdot PAR(k) \cdot [1 - e^{-(K \cdot LAI(k-1))}]$$

where LAI(k-1) is the leaf area index at time k-1. K varies with LAI(k-1), thus,

$$K = \begin{cases} e^{-(LAI(k-1))} & LAI(k-1) \le 0.6 \\ 0.58 - 0.04 \cdot LAI(k-1)\ , & 0.6 < LAI(k-1) \le 5.0 \\ 0.36 & LAI(k-1) > 5.0 \end{cases}$$

The actual carbohydrates produced at time k (CARBO(k)) can be less than the potential production due to shading (POPFAC), temperature stress (PRFT(k)), and the most limiting effect due to water (SWDF1(k)) and nitrogen (NDEF1(k)) stresses at time k. That is,

$$CARBO(k) = PCARB(k) \cdot POPFAC \cdot PRFT(k) \cdot \min(SWDF1(k), NDEF1(k))$$

When photosynthesis takes over carbohydrate production completely, a very slow growth in the stem occurs. The distribution of carbohydrate to the plant parts then changes. The fraction going to the leaves at time k (PFL(k)) is now a linear function of thermal time at time k with a slope of 0.001/degree-day.

$$PFL(k) = PFL(k-1) + 0.001 \cdot DTT(k)\ , \quad PFL(k) \le 0.84$$

PFL(k), however, is bounded on the right by 0.84. This condition ensures that a fraction of carbohydrates going to the leaves is at most 0.84, and allows for positive fractions going to the stem and roots, under a favorable growing day. The fraction going to the stem at time k (PFC(k)) is also a function of thermal time with a slope of

0.00002/degree-day, that is,

$$PFC(k) = PFC(k-1) + 0.00002 \cdot DTT(k)$$

and the fraction that goes to the roots (PFR(k)) is 1 less PFL(K) and PFC(k).

$$PFR(k) = 1 - PFL(k) - PFC(k)$$

However, during the presence of a water deficit (SWDF2(k)) or nitrogen deficiency (NDEF1(k)) at time k, the plants redistribute their carbohydrates or assimilates in favor of the roots, reducing PFL(k) by the most limiting factor of the two stresses. This redistribution is active until just before the beginning of grain filling.

Daily root growth (GRORT(k)) and leaf growth (GROLF(k)) are calculated, while root weight (RTWT(k)) and leaf weight (LFWT(k)) at time k are updated, as in ISTAGE 1. That is,

$$GRORT(k) = CARBO(k) \cdot PFR(k)$$

$$GROLF(k) = CARBO(k) \cdot PFL(k)$$

$$RTWT(k) = RTWT(k-1) + GRORT(k)$$

$$LFWT(k) = LFWT(k-1) + GROLF(k)$$

Daily stem growth (GROSTM(k)) at time k is proportional to the amount of carbohydrates distributed to the stem.

$$GROSTM(k) = CARBO \cdot PFC(k)$$

The stem weight at time k (STMWT(k)) is the sum of the weight at time k-1 and the growth at time k.

$$STMWT(k) = STMWT(k-1) + GROSTM(k)$$

The total stover weight (STOVWT(k)) is the sum of LFWT(k) and STMWT(k), that is,

$$STOVWT(k) = LFWT(k) + STMWT(k)$$

The juvenile stage is characterized by leaf expansion. When the seed reserve is used up, leaf area expansion at time k (PLAG(k)) is calculated. PLAG(k) is a function of leaf growth at time k (CARBO(k)·PFL(k)) and the number of leaves/plant emerging at time k (TI(k)). Leaf expansion is also a function of the plant's genetic characteristic for tillering (TR·G1), which is a varietal character to form tillers or new plants thus, is given the unit: number of plants. As indicated in Chapter IV, a high value of (TR·G1) indicates that the plant has a high capacity for tillering (or forming new plants) and therefore bigger capacity for leaf expansion. The conversion factor is 0.037 m^2 leaf area expansion/leaf/g of leaf growth. Leaf expansion is however reduced by the most limiting of the three stress factors at time k: soil water deficit (SWDF2(k)), nitrogen stress (NDEF2(k)), and low temperature (SLFT(k)). That is,

$$\mathrm{PLAG}(k) = 0.037 \cdot \mathrm{TR} \cdot \mathrm{G1} \cdot \mathrm{TI}(k) \cdot \mathrm{CARBO}(k) \cdot \mathrm{PFL}(k) \cdot \min[\mathrm{SWDF2}(k), \mathrm{NDEF2}(k), \mathrm{SLFT}(k)]$$

Total leaf area at time k (PLA(k)) is the sum of the leaf area at time k-1 and the expansion at time k, that is,

$$\mathrm{PLA}(k) = \mathrm{PLA}(k-1) + \mathrm{PLAG}(k)$$

In this situation, PLA(k) is numerically equal to the leaf area index at time k (LAI(k)). Thus,

$$\mathrm{LAI}(k) = \mathrm{PLA}(k)$$

Tillering is also a characteristic of the juvenile stage. The tiller number per square meter at any time k (TILNO(k)) is the sum of the tiller number at time k-1 and the tillering growth at time k. The tillering growth at time k is a function of the number of leaves/plant emerging at time k (TI(k)), the fraction of carbohydrates going to the leaves at time k (PFL(k), unitless), the plant's genetic characteristic for tillering (TR·G1, number of plants), and a population factor (100/PLANTS, per square meter). The conversion factor is 32 tillers/leaf. Thus,

$$TILNO(k) = TILNO(k-1) + 32 \cdot TI(k) \cdot PFL(k) \cdot TR \cdot G1 \cdot (100/PLANTS)$$

5.5. Panicle Initiation (ISTAGE 2)

Panicle initiation stage covers the period from end of juvenile stage to panicle initiation.

The photoperiod or daylength in hours at time k (HRLT(k)) is determined from the daylength variation at time k (DLV(k)), which is a function of the solar declination, in radians, at time k (DEC(k)), the sine and cosine of the latitude of the production area (LAT), and the angle of the sun at civil twilight (in radians). The solar declination at time k (DEC(k)) is a sine function of the day of the year (JDATE), that is,

$$(1) \quad DEC(k) = 0.4093 \cdot \sin(0.0172 \cdot (JDATE-82.2))$$

The daylength variation (DLV(k)) is calculated from the sine and cosine of both the latitude of the area (LAT) and the solar declination. DLV(k) is adjusted by the angle of the sun at civil twilight (0.1047). Thus,

$$(2) \quad DLV(k) = \frac{-\sin(LAT) \cdot \sin(DEC(k)) - 0.1047}{\cos(LAT) \cdot \cos(DEC(k))}$$

However, DLV(k) is bounded on the left by -0.87. Finally, the photoperiod is an arccosine function of the daylength variation, that is,

(3) $HRLT(k) = 7.639 \cdot \arccos(DLV(k))$

The rate of floral induction per degree-day at time k (RATEIN(k)) is a constant 1/136 if the photoperiod is less than or equal to the optimum photoperiod (P2O). However, if the photoperiod at time k (HRLT(k)) is greater than P2O, RATEIN(k) is slowed down and becomes a function of the photoperiod HRLT(k), the optimum photoperiod (P2O), and the rate of photo-induction (P2R).

$$RATEIN(k) = \frac{1}{136 + P2R \cdot (HRLT(k) - P2O))}$$

Panicle initiation stage is completed when the sum of the product of RATEIN(k) and DTT(k) from the beginning of this stage (k_2) until time k is 1.0. That is,

$$\sum_{k=k_2}^{k} RATEIN(k) \cdot DTT(k) = 1.0$$

Panicle initiation stage is characterized by root growth, leaf emergence and leaf growth, stem growth, and tillering. The fraction going to the roots is set to 0.15. The fraction going to the leaves is decreasing, with a negative slope of 0.001/degree-day, in favor of the stem. That is,

$PFR(k) = 0.15$

$PFL(k) = PFL(k-1) - 0.001 \cdot DTT(k)$

$PFC(k) = 1 - PFR(k) - PFL(k)$

As in ISTAGE 1, PFL(k) is adjusted in favor of PFR(k) whenever there is a water deficit or nitrogen deficiency.

Daily root growth (GRORT(k)), leaf growth (GROLF(k)), stem growth (GROSTM(k)), root weight (RTWT(k)), leaf weight (LFWT(k)), stem weight (STMWT(k)), and stover weight (STOVWT(k)) at time k are updated, as in

ISTAGE 1. That is,

$$GRORT(k) = CARBO(k) \cdot PFR(k)$$

$$GROLF(k) = CARBO(k) \cdot PFL(k)$$

$$GROSTM(k) = CARBO \cdot PFC(k)$$

$$RTWT(k) = RTWT(k\text{-}1) + GRORT(k)$$

$$LFWT(k) = LFWT(k\text{-}1) + GROLF(k)$$

$$STMWT(k) = STMWT(k\text{-}1) + GROSTM(k)$$

$$STOVWT(k) = LFWT(k) + STMWT(k)$$

5.6. Heading Stage (ISTAGE 3)

Heading stage covers the period from the end of panicle initiation to heading where 50 percent of the panicles have exserted. The duration of this stage is P3. It is equivalent to 450 degree-days plus 15 percent of the accumulated degree-days from the beginning of the juvenile stage (k_1) until just before heading stage (k_3), that is,

$$P3 = 450 + 0.15 \cdot \sum_{k=k_1}^{k_3} DTT(k)$$

The heading stage is characterized by root growth, leaf growth, emergence of last leaf, stem elongation, increase in plant height, panicle growth, and decline in tiller formation.

PFR(k) is set to 0.10 during this stage. PFL(k) is reduced linearly with thermal time by a slope of 0.0014/degree-day, but bounded on the left by 0, while PFC(k) is increasing monotonically as a linear function of thermal time with a slope of 0.00072/degree-day. That is,

$PFR(k) = 0.10$

$PFL(k) = PFL(k-1) - 0.0014 \cdot DTT(k)$

$PFC(k) = PFC(k-1) + 0.00072 \cdot DTT(k)$

Since panicle growth is also a characteristic of this stage, the fraction going to the panicles at time k (PFP(k)) is positive. The positive fraction is guaranteed because the rate of decrease from PFL(k) is greater than the rate of increase for PFC(k).

$PFP(k) = 1 - PFR(k) - PFL(k) - PFC(k)$

The panicle growth at time k (PAWT(k)) is proportional to the amount of carbohydrates allocated to it, that is,

$PAWT(k) = CARBO(k) \cdot PFP(k)$

The panicle weight at time k (PPAWT(k)) is the sum of the weight at time k-1 and growth at time k.

$PPAWT(k) = PPAWT(k-1) + PAWT(k)$

One panicle is allowed to grow as a linear function of thermal time with a slope of 0.00095 g/degree-day. This single panicle will be used to estimate the total number of panicles during harvest. Thus, the single panicle growth at time k (PNWT(k)) and the single panicle weight at time k (PERPAWT(k)) are estimated and updated as follows:

$PNWT(k) = 0.00095 \cdot DTT(k)$

$PERPAWT(k) = PERPAWT(k-1) + PNWT(k)$

As in ISTAGE 1, PFL(k) is adjusted in favor of PFR(k) whenever there is a water deficit or nitrogen deficiency.

Daily root growth (GRORT(k)), leaf growth (GROLF(k)), stem growth (GROSTM(k), root weight (RTWT(k)), leaf weight (LFWT(k)), stem weight (STMWT(k)), and stover weight (STOVWT(k)) at time k are updated, as in

ISTAGE 2. That is,

$$GRORT(k) = CARBO(k) \cdot PFR(k)$$

$$GROLF(k) = CARBO(k) \cdot PFL(k)$$

$$GROSTM(k) = CARBO \cdot PFC(k)$$

$$RTWT(k) = RTWT(k-1) + GRORT(k)$$

$$LFWT(k) = LFWT(k-1) + GROLF(k)$$

$$STMWT(k) = STMWT(k-1) + GROSTM(k)$$

$$STOVWT(k) = LFWT(k) + STMWT(k)$$

The biomass at time k (BIOMAS(k)) is the sum of LFWT(k), STMWT(k), and PPAWT(k), while the total plant weight at time k (PLTWT(k)) is the sum of BIOMAS(k) and RTWT(k), that is,

$$BIOMAS(k) = LFWT(k) + STMWT(k) + PPAWT(k)$$

$$PLTWT(k) = BIOMAS(k) + RTWT(k)$$

At the end of heading stage, the leaves stop to grow.

5.7. Beginning of Grain Filling (ISTAGE 4)

Beginning of grain filling stage covers the period from the time when 50 percent of the panicles have exserted to beginning of grain filling. The duration is 170 degree-days.

A temperature-related stress factor is modelled to affect the percentage of grain filling (FERTILE). When the mean temperature at time k (TEMPM(k)) is between 17^{o}C and 35^{o}C, FERTILE is a constant 85.3 percent, however this percentage is reduced by shading effects due to plant population (PLANTS). That is,

$$FERTILE = 0.853 - 0.00028 \cdot PLANTS$$

Otherwise, at extremely high or low temperatures, the percentage of grain filling is estimated as follows:

$$\text{FERTILE} = 0.75-0.1 \cdot (\text{TEMPM}-35)\ , \qquad \text{TEMPM} > 35^{o}\text{C}$$

$$= 0.75-0.1 \cdot (17-\text{TEMPM})\ , \qquad \text{TEMPM} < 17^{o}\text{C}$$

PFR(k) is set to a fixed fraction of 0.10 during this stage. PFL(k) continues to decrease linearly with thermal time by a slope of 0.0006/degree-day.

$$\text{PFL(k)} = \text{PFL(k-1)} - 0.0006 \cdot \text{DTT(k)}$$

During this growth stage, there is a possibility of assimilate translocation from the leaves to the panicle. This event occurs when the value of PFL(k) becomes negative. The absolute value is added to the fraction allocated to the panicle. The negative value of PFL(k) causes a negative value of leaf growth and leaf expansion. This negative growth and negative leaf expansion represents leaf senescence. Although leaf senescence has occurred slightly during the previous growth stages as part of a natural process, it is during this stage that leaf senescence is clearly demonstrated since leaves have stopped to grow. Leaf senescence at time k (PLAG(k)), in m^2 leaf area senescence/m^2 of land area, is estimated to be influenced by the weight of leaf senescence at time k (CARBO(k)·PFL(k)) in proportion to the varietal characteristic for tillering (TR·G1). Leaf senescence is hastened in the presence of water, nitrogen, and temperature stresses. The conversion factor is 0.004 m^2 leaf area senescence/gram-weight of leaf senescence/plant. Thus, leaf senescence is modelled as follows:

$$\text{PLAG(k)} = 0.004 \cdot \text{CARBO(k)} \cdot \text{PFL(k)} \cdot \text{TR} \cdot \text{G1} \cdot$$
$$\{2 - \min[\text{SWDF2(k)}, \text{NDEF2(k)}, \text{SLFT(k)}]\}$$

Since PLAG(k) is negative, leaf area (PLA(k)) and leaf area index (LAI(k)) at time k are correspondingly reduced.

$PLA(k) = PLA(k-1) + PLAG(k)$

$LAI(k) = PLA(k)$

PFC(k) is also starting to decline linearly with thermal time by a slope of 0.00215/degree-day but bounded on the left by 0. PFP(k) is increasing monotonically. That is,

$PFC(k) = PFC(k-1) - 0.00215 \cdot DTT(k)$

$PFP(k) = 1 - PFR(k) - PFL(k) - PFC(k)$

As in ISTAGE 1, PFL(k) is adjusted in favor of PFR(k) whenever there is a water deficit or nitrogen deficiency.

Daily root growth (GRORT(k)), leaf growth (GROLF(k)), stem growth (GROSTM(k)), panicle growth (PAWT(k)), single panicle growth (PNWT(k)), root weight (RTWT(k)), leaf weight (LFWT(k)), stem weight (STMWT(k)), panicle weight (PPAWT(k)), single panicle weight (PERPAWT(k)), stover weight (STOVWT(k)), biomass (BIOMAS(k)), total plant weight (PLTWT(k)) at time k are updated, as in ISTAGE 3. That is,

$GRORT(k) = CARBO(k) \cdot PFR(k)$

$GROLF(k) = CARBO(k) \cdot PFL(k)$

$GROSTM(k) = CARBO(k) \cdot PFC(k)$

$PAWT(k) = CARBO(k) \cdot PFP(k)$

$PNWT(k) = 0.00095 \cdot DTT(k)$

$RTWT(k) = RTWT(k-1) + GRORT(k)$

$LFWT(k) = LFWT(k-1) + GROLF(k)$

$STMWT(k) = STMWT(k-1) + GROSTM(k)$

$PPAWT(k) = PPAWT(k-1) + PAWT(k)$

$PERPAWT(k) = PERPAWT(k-1) + PNWT(k)$

$STOVWT(k) = LFWT(k) + STMWT(k)$

$BIOMAS(k) = LFWT(k) + STMWT(k) + PPAWT(k)$

$PLTWT(k) = BIOMAS(k) + RTWT(k)$

Beginning this stage until maturity, the leaves stop to grow, that is,

$TI(k) = 0.$

5.8. End of Grain Filling (ISTAGE 5)

End of grain filling stage covers the period of grain filling. The duration, in degree-days, is 95 percent of the genetic coefficient P5.

This stage is characterized by grain growth, leaf senescence, and the rate of root growth being equal to the rate of root senescence. The latter event is represented as PFR(k)=0.

During this stage, there is a translocation of assimilates from both the leaves and the stem to the panicles where the grains are growing. PFL(k) and PFC(k) continue to decrease as a function of thermal time while PFP(k) continues to increase. The translocation from both the leaves and the stem trigger an equivalent amount of senescence in those organs as will be demonstrated by the reduction of their respective weights.

$PFL(k) = PFL(k-1) - 0.7 \cdot 0.0009 \cdot DTT(k)$

$PFC(k) = PFC(k-1) - 0.3 \cdot 0.0009 \cdot DTT(k)$

$PFP(k) = PFP(k-1) + 0.0009 \cdot DTT(k)$

Daily root growth (GRORT(k)), leaf growth (GROLF(k)), stem growth (GROSTM(k)), panicle growth (PAWT(k)), single panicle growth (PNWT(k)), root weight (RTWT(k)), leaf weight (LFWT(k)), stem weight

(STMWT(k)), panicle weight (PPAWT(k)), single panicle weight (PERPAWT(k)), stover weight (STOVWT(k)), biomass (BIOMAS(k)), total plant weight (PLTWT(k)) at time k are updated, as in ISTAGE 4. That is,

GRORT(k) = CARBO(k) · PFR(k)

GROLF(k) = CARBO(k) · PFL(k)

GROSTM(k) = CARBO(k) · PFC(k)

PAWT(k) = CARBO(k) · PFP(k)

PNWT(k) = 0.00095 · DTT(k)

RTWT(k) = RTWT(k-1) + GRORT(k)

LFWT(k) = LFWT(k-1) + GROLF(k)

STMWT(k) = STMWT(k-1) + GROSTM(k)

PPAWT(k) = PPAWT(k-1) + PAWT(k)

PERPAWT(k) = PERPAWT(k-1) + PNWT(k)

STOVWT(k) = LFWT(k) + STMWT(k)

BIOMAS(k) = LFWT(k) + STMWT(k) + PPAWT(k)

PLTWT(k) = BIOMAS(k) + RTWT(k)

A single grain-growth concept is introduced during this stage. The rate of grain growth is a linear function of thermal time with a slope of 0.000083/degree-day. This single grain size will be used to estimate the number of grains per square meter during harvest. Grain growth at time k (GROGRN(k)) and grain weight at time k (GRNWT(k)) are calculated as follows:

GROGRN(k) = 0.000083 · DTT(k)

GRNWT(k) = GRNWT(k-1) + GROGRN(k)

During this growth stage, the nitrogen concentration in the panicle and grain are estimated. The estimation process is part of the nitrogen transformation and uptake which are outlined by Jones et al. (1986).

5.9. Physiological Maturity (ISTAGE 6)

The duration of the physiological maturity is the time required to complete P5 or when DTT(k) is less than or equal to 0. The latter condition allows for maturity even with insufficient degree-days accumulation due to low temperatures. When the time is completed, the grains are harvested. At harvest time, k=h.

Panicle number per square meter at harvest (PNO(h)) is calculated from the total plant panicle weight (PPAWT(h)) divided by the weight of 1 panicle (PERPAWT(h)).

$$PNO(h) = \frac{PPAWT(h)}{PERPAWT(h)}$$

Grain number per square meter at harvest (GRAIN(h)) is calculated from 90 percent of PPAWT(h), divided by a single grain weight in grams per grain (GRNWT(h)), and multiplied by the percentage of grain filling (FERTILE).

$$GRAIN(h) = \frac{PPAWT(h) \cdot 0.9}{GRNWT(h)} \cdot FERTILE$$

The total weight of straw at harvest (PSTRAW(h)) is the sum of the total stover weight (STOVWT(h)) and 10 percent of the panicle weight (PPAWT(h)).

$$PSTRAW(h) = STOVWT(h) + (PPAWT(h) \cdot 0.1)$$

Plant-straw ratio at harvest (PSRATIO(h)) is the ratio of the total panicle weight to the total straw.

$$PSRATIO(h) = \frac{PPAWT(h)}{PSTRAW(h)}$$

Dry grain yield (DYIELD(h)) is calculated as a product of the grain number (GRAIN(h)) and single grain weight (GRNWT(h)), adjusted to MT/Ha by multiplying with 0.01.

$$DYIELD(h) = GRAIN(h) \cdot GRNWT(h) \cdot 0.01$$

Commercial grain (YIELD(h)) is dry grain yield adjusted to 14 percent moisture.

$$YIELD(h) = \frac{DYIELD(h)}{0.86}$$

CHAPTER VI

THE ANALYTICAL STRUCTURE OF THE MULTICRITERIA OPTIMIZATION PROCEDURE

The multicriteria optimization procedure is a two-objective function resource allocation technique. It uses the Monte Carlo search method to explore the space of decision variables, $\bar{u}(k)$, for feasibility. While the Pareto optimization procedure is conducted to identify a set of optimal, non-inferior solutions, the ideal vector of objective functions is also generated. From the set of Pareto optimal solutions, the min-max optimization procedure is used to identify the best compromise solution considering all the criteria simultaneously and on equal terms of importance.

The general analytical structures of the algorithms of the Monte Carlo search method, the generation of the ideal vector, the Pareto optimization, and the min-max optimization used here were developed by Dr. Andrezj Osyczka (1984). The analytical structures were modified, when necessary, to incorporate the simulation model and to fit the peculiar structure of the problem. Hence, the definitions and the basic structure of the equations were taken from Osyczka's publication.

The multicriteria optimization problem is formulated as follows: find a vector of input decision variables, $\bar{u}(k)$, which satisfies constraints and optimizes a vector of objective functions, $\bar{f}(\bar{u})$. That is,

Find $\overline{u^*}$ such that

$$\overline{f}(\overline{u^*}) = \text{opt } \overline{f}(\overline{u}) \tag{6.1}$$

subject to:

$$g_m(\overline{u}) \geq 0 \qquad m = 1,2, \ldots, M \tag{6.2}$$

where $\overline{u}(k) = [u_1(k),\ldots,u_n(k)]^T$ is a vector of decision variables defined in n-dimensional Euclidean space of variables E^n, where n=3. The 3 decision variables are: $u_1(k)$ = day of the year for planting; $u_2(k)$ = amount of nitrogen fertilizer, in Kg N/Ha; and, $u_3(k)$ = plant population, in plants/m^2. All 3 decision variables are input signals of the Kronecker delta sequence at k=0. Hence, $\overline{u}(k)$ is $\overline{u}(0)$ at k=0. The vector $\overline{u}(0)$ will be hereinafter represented as $\overline{u}$, $u_1(k)$ will be written as u_1, $u_2(k)$ as u_2, and $u_3(k)$ as u_3. The variable k will be redefined as will be seen next. $\overline{f}(\overline{u}) = [f_1(\overline{u}),\ldots,f_k(\overline{u})]^T$ is a vector function defined in k-dimensional Euclidean space of objectives E^k, where k=2, and which are non-linear functions of the variables u_1, u_2, and u_3. This vector function represents the criteria that will be considered in the optimization. The two criteria or objective functions are to maximize profit ($f_1(\overline{u})$) and to minimize production risk ($f_2(\overline{u})$) as a function of $\overline{u}$.

The inequality constraints $g_m(\overline{u})$ given by (6.2) define the feasible region U and represent the restriction imposed on the decision variables, $\overline{u}$. $g_m(\overline{u})$ are linear and non-linear functions of the variables u_1, u_2, and u_3. Any point $\overline{u} \in U$ defines a feasible solution and the vector function $\overline{f}(\overline{u})$ maps the set U in the set F, which represents all possible values of the objective functions.

The optimal solution (or set of optimal solutions) is denoted by

$\bar{u}^*$. I=[1,2] is used to denote the set of indices for the two objective functions; i will be used as a generic index for any variable.

6.1. The Monte Carlo Search Method

The Monte Carlo search method is an exploratory method used to randomly generate new values of the vector $\bar{u}$ by using the formula (Osyczka, 1981, pp.70-71):

$$u_i = u_i^a + \alpha_i(u_i^b - u_i^a) \qquad \text{for} \quad i = 1,2,3 \tag{6.3}$$

where $u_i{}^a$ is the given lower limit for u_i, $u_i{}^b$ is the given upper limit for u_i, and α_i is a random number between 0 and 1. If λ^a points of decision variables are desired to be evaluated, then the optimization procedure will generate λ^a random numbers, one random number for each point. Equation (6.3) is used to obtain a new value of the decision variable u_i. Each generated point will be tested for constraint violation and discarded if it is not a feasible solution. If the point is in the feasible region, the simulation and optimization will proceed.

The random number generator is taken from the weather generator component of the CERES crop models.

6.2. Pareto Optimization

As Osyczka (1984) presented it, Pareto optimization is based on the contact theorem which says that given a negative cone in E^k which is the set

$$C^{-} = \{\bar{f} \in E^k \mid \bar{f} \le 0\}$$

a vector $\bar{f}$ is a Pareto optimal solution for the multicriteria optimization problem if and only if

$$(C^{-} + \bar{f}^{*}) \cap F = \{\bar{f}^{*}\}.$$

Then he defines a Pareto optimum as follows: a point $\bar{u}^{*} \in U$ is Pareto optimum if for every $\bar{u} \in U$ either,

$$\bigwedge_{i \in I} (f_i(\bar{u}) = f_i(\bar{u}^{*})) \tag{6.4}$$

or, there is at least one $i \in I$ such that

$$f_i(\bar{u}) > f_i(\bar{u}^{*}) \tag{6.5}$$

To demonstrate the Pareto optimization concept, Osyczka's illustration is presented (1984, pp.66). Consider two solutions $\bar{u}^{(1)}$ and $\bar{u}^{(2)}$ for which there may be two specific cases

$$(1) \quad (C^{-} + \bar{f}(\bar{u}^{(1)})) \subset (C^{-} + \bar{f}(\bar{u}^{(2)})) \tag{6.6}$$

$$(2) \quad (C^{-} + \bar{f}(\bar{u}^{(1)})) \supset (C^{-} + \bar{f}(\bar{u}^{(2)})) \tag{6.7}$$

The following are defined:

$\bar{u}^{(\lambda)} = [u_1^{(\lambda)}, u_2^{(\lambda)}, \ldots, u_n^{(\lambda)}]^T$ = any given point in U,

$\bar{f}(\bar{u}^{(\lambda)}) = [f(\bar{u}_1^{(\lambda)}), f(\bar{u}_2^{(\lambda)}), \ldots, f(\bar{u}_k^{(\lambda)})]^T$ = vector of objective functions for the point $\bar{u}^{(\lambda)}$

$\bar{u}_j^p = [u_{1j}^p, u_{2j}^p, \ldots, u_{nj}^p]^T$ = the jth Pareto optimal solution,

$\bar{f}_j^p = [f_{1j}^p, f_{2j}^p, \ldots, f_{kj}^p]^T$ = vector of objective functions

for the jth Pareto optimal solution.

The problem is to choose from any given set of solutions

$\Lambda = \{1,2,\ldots,\lambda,\ldots,\lambda^a\}$, the set of Pareto optimal solutions

$J = \{1,2,\ldots,j,\ldots,j^a\}$.

Let $\bar{u}^{(\lambda)}$ be a vector of new solution to be considered. If in the set of Pareto optimal solutions there is a solution $\bar{u}_j{}^P$ such that it

(1) satisfies (6.6) then $\bar{u}^{(\lambda)}$ is substituted for $\bar{u}_j{}^P$, or

(2) satisfies (6.7) then $\bar{u}^{(\lambda)}$ is discarded.

If none of the solutions from the set of Pareto optimal solutions satisfies either (6.6) or (6.7), then $\bar{u}^{(\lambda)}$ becomes a new Pareto optimal solution.

This intuitively means that the point $\bar{u}^*$ is chosen as the optimum if no criterion can be improved without worsening at least one other criterion. A set of these optimal, non-inferior solutions is generated to form a Pareto optimal curve.

6.3. Min-max optimization

Min-max optimization uses the information of the optimum values of each objective function when solved separately. These values form the ideal vector of objective functions. The vector of objective functions for each point in the Pareto optimal curve is compared with the ideal vector. Relative deviations are calculated and the best solution is the one whose objective functions are as close as possible to their separately attainable minima.

Following Osyczka's outline (1984, pp.32-33), the min-max optimization concept is presented as follows:

Consider the ith objective function for which the relative deviation can be calculated from

$$z_i'(\bar{u}) = \frac{\left| f_i(\bar{u}) - f_i^0 \right|}{\left| f_i^0 \right|} \tag{6.8}$$

$$z_i''(\bar{u}) = \frac{\left| f_i(\bar{u}) - f_i^0 \right|}{\left| f_i(\bar{u}) \right|} \tag{6.9}$$

For (6.8) and (6.9) to be valid we have to assume that for every $i \in I$ and for every $u \in U$, $f_i^0 \neq 0$ and $f_i(\bar{u}) \neq 0$.

Let $\bar{z}(\bar{u}) = [z_1(\bar{u}), z_2(\bar{u})]^T$ be a vector of relative increments which are defined in E^2. The components of the vector $\bar{z}(\bar{u})$ will be evaluated from the formula

$$\bigwedge_{i \in I} (z_i(\bar{u}) = \max\{z_i'(\bar{u}), z_i''(\bar{u})\} \tag{6.10}$$

Then the min-max optimum is defined as follows:

A point $\bar{u}^* \in U$ is min-max optimal, if for every $\bar{u} \in U$ the following recurrence formula (6.11) is satisfied:

Step 1

$$\nu_1(\bar{u}^*) = \min_{u \in U} \max_{i \in I} \{z_i(\bar{u})\}$$

and then $I_1 = \{i_1\}$, where i_1 is the index for which the value of $z_i(\bar{u})$ is maximal.

If there is a set of solutions $U_1 \in U$ which satisfies Step 1, then

Step 2

$$\nu_2(\overline{u^*}) = \min_{u \in U_1} \max_{\substack{i \in I \\ i \notin I_1}} (z_i(\bar{u}))$$

and then $I_2 = (i_1, i_2)$, where i_2 is the index for which the value of $z_i(\bar{u})$ in this step is maximal. ______________________________ (6.11)

Intuitively, this optimum means that knowing the extremes of the objective functions which can be obtained by solving the optimization problems for each criterion separately, the desirable solution is the one which gives the smallest values of the relative increments of all the objective functions.

6.4. Function Minimization

For the sake of convenience, all the objective functions will be minimized, so the first objective function, to maximize profit, will be converted into a form which will allow for its minimization. This is done by employing the identity

$$\max f_1(\bar{u}) = \min(-f_1(\bar{u})) \tag{6.12}$$

Now, the first objective function is to minimize the negative function of profit.

In the same way, the inequality constraints of the form

$$g_m(\bar{u}) \leq 0 \qquad m = 1,2,\ldots,M$$

can be multiplied with -1 to convert them to the form

$$-g_m(\bar{u}) \geq 0 \qquad m = 1,2,\ldots,M$$

if necessary.

6.5. The Analytical Representation of the Objective Functions

The purpose of the simulation-multicriteria optimization technique (SMOT) is to be able to predict grain yield, and correspondingly estimate profit and production risk, under a highly stochastic agricultural environment. Profit will be calculated from the expected value of grain yield, which is its mean. Production risk will be quantitatively expressed through a measure of the dispersion or variability from the mean, known as the standard deviation. The probability that a grain yield of one cropping season is within ± 1 standard deviation is 0.682. To illustrate the concept, an example is presented. Suppose a certain production strategy is expected to yield 5 MT/Ha of grain with a standard deviation of ± 0.5 MT/Ha. The probability that the actual yield will be in the range 4.5-5.5 MT/Ha (± 1 standard deviation) is 0.682. That is, for every 100 trials, 68 of those trials will yield between 4.5-5.5 MT/Ha. Compare this data with a second production strategy which is expected to yield 6 MT/Ha with a standard deviation of ± 1.0 MT/Ha, and which is more costly. The probability of the actual yield being within the ± 1 standard deviation is still 0.682. However, the actual yield could be in the range 5-7 MT/Ha. The first production strategy has a smaller dispersion or variability (± 0.5 MT/Ha) compared to the second production strategy which has a wider dispersion or variability (± 1.0 MT/Ha). Thus, a larger value of the standard deviation corresponds to a more risky operation.

The probability distribution of the occurrence of grain yield must be known in order to find the maximum likelihood estimators of its mean and standard deviation. A goodness-of-fit test with two parameters (mean and variance) unknown, as outlined by Larsen and Marx (1981), was used to test the hypothesis (H_o) that rice grain yield can be described by a normal probability distribution with mean, μ, and variance, σ^2.

Since there was no available actual yield data for a period long enough to be useful in the goodness-of-fit test, the simulation model was run for 25 years using actual weather conditions. The simulated grain yield data were used in the goodness-of-fit test. The underlying theorems and detailed calculations are in Appendix A. The hypothesis testing showed that grain yield (y) is normally distributed, that is,

$$y_1, y_2, \ldots, y_{NCYCLE}$$

has $N(\mu, \sigma^2)$ distribution, where NCYCLE is the sample size. This probability distribution is described as follows:

$$p_Y(y) = \frac{1}{\sqrt{2\pi}\,\sigma} e^{-(\frac{1}{2})[(y-\mu)/\sigma]^2}, \qquad 0 < y < \infty \tag{6.13}$$

The maximum likelihood estimators for the mean, μ, and variance, σ^2, are $\hat{\mu}$ and $\hat{\sigma}^2$, respectively (Larsen and Marx, 1981, p.269-271):

$$\hat{\mu} = \frac{1}{NCYCLE} \sum_{i=1}^{NCYCLE} y_i \tag{6.14}$$

$$\hat{\sigma}^2 = \frac{1}{NCYCLE} \sum_{i=1}^{NCYCLE} (y_i - \hat{\mu})^2 \tag{6.15}$$

Larsen and Marx indicated that $\hat{\mu}$, the maximum likelihood estimator for μ, is unbiased, efficient, and consistent. If σ^2 is known, $\hat{\mu}$ is sufficient. However, while $\hat{\sigma}^2$, the maximum likelihood estimator for σ^2, is consistent, and sufficient if μ is known, the estimator is biased; specifically, it tends to underestimate σ^2.

In practice, σ^2 is estimated by the sample variance, s^2, which can be expressed as follows:

$$s^2 = \frac{\mathrm{NCYCLE} \cdot \sum_{i=1}^{\mathrm{NCYCLE}} y_i^2 - \left(\sum_{i=1}^{\mathrm{NCYCLE}} y_i \right)^2}{\mathrm{NCYCLE}\ (\mathrm{NCYCLE} - 1)} \tag{6.16}$$

Therefore, profit ($f_1(\bar{u})$) and risk ($f_2(\bar{u})$) is mathematically represented as follows:

$$f_1(\bar{u}) = \mathrm{PRICE} \cdot \hat{\mu} - \mathrm{TOTAL\ COST} \tag{6.17}$$

$$f_2(\bar{u}) = s \tag{6.18}$$

where

PRICE = market price of grain (\$/MT),

TOTAL COST = total cost of production per hectare (\$/Ha)

s = standard deviation, which is the square root of s^2 (MT/Ha)

6.6. The Economic Scenario of the Rice Farm

For an application of SMOT, the economic scenario is patterned after a rice farm in Laguna, Philippines, except that the dollar (\$) sign is used in the monetary value instead of the Philippine peso sign. The farm could be briefly outlined as follows (Capule and Herdt, 1983):

- the farmer is renting the land at \$ 699/Ha
- land preparation, \$ 200/Ha
- cost of seeds, \$ 80.00/Ha
- hired labor for land preparation and weed control, \$ 606.00/Ha
- complete pest (except weeds) control, \$ 133/Ha
- weed control, \$ 385/Ha
- cost of maintenance, \$ 156.00/Ha
- opportunity cost of owned capital, \$ 215.00/Ha
- imputed value of family labor, \$221.00/Ha
- cost of nitrogen fertilizer, \$ 70 per 50 Kg bag
- no irrigation (water from rain)
- hired labor for harvesting, \$ 148/MT
- the farmer has at most \$ 1400/Ha to spend for fertilizer
- effective farm price of grain, \$ 1020/MT
- the allowable limit of fertilizer is 900 Kg nitrogen as urea in one hectare of land area

CHAPTER VII

THE ALGORITHM OF THE SIMULATION-MULTICRITERIA OPTIMIZATION TECHNIQUE

The algorithm of the simulation-multicriteria optimization technique (SMOT), will be discussed by module. One module can be made up of one or more subroutines. There are 10 modules, namely: the initialization module, the Monte Carlo search module, the random number generator module, the constraint function module, the simulation module, the objective function module, the ideal vector module, the Pareto optimization module, the min-max optimization module, and the Print module.

The general algorithm of SMOT is outlined as follows:

A. Initialization Module

(1) Set IPAR = 1, IWRITE = 1

(2) Read n, λ^a, IPARCRV, NCYCLE, $u_1{}^a$, $u_1{}^b$, $u_2{}^a$, $u_2{}^b$, $u_3{}^a$, $u_3{}^b$ from subroutine LIMITS

(3) Set $k = 2$, $j^a = 1$, $f_i{}^0 = \infty$ and $f_{i1}{}^P = \infty$ for $i=1,2$

(4) Set $\lambda = 1$

(5) If IWRITE = 1, read the initial values of the decision variables $\overline{u}^{(\lambda)}$, and other input data needed to run the rice simulation model.

Do steps 6 through 15 for $\lambda = 1,2,\ldots,\lambda^a$

B. Simulation Module

(6) Run the rice simulation model NCYCLE times to generate the mean grain yield, $\hat{\mu}$.

C. Objective Function Module

(7) Calculate $f_i(\overline{u}^{(\lambda)})$ for $i = 1,2$

(8) Print λ, $\overline{u}^{(\lambda)}$, $\hat{\mu}$, $f_i(\overline{u}^{(\lambda)})$ for $i=1,2$

(9) Set IWRITE = 0

D. Ideal Vector Module

(10) Replace f_i^0 by $f_i(\overline{u}^{(\lambda)})$ for every i for which $f_i(\overline{u}^{(\lambda)}) < f_i^0$.

E. Pareto Optimization Module

(11) Call subroutine PARETO to check if the point $\overline{u}^{(\lambda)}$ is Pareto optimum.

(12) If $\lambda < \lambda^a$ then $\lambda = \lambda + 1$ and go to 13, otherwise go to 16.

F. Monte Carlo Search Module

(13) Call subroutine RANDOM to generate new values for $u_2^{(\lambda)}$ and $u_3^{(\lambda)}$.

G. Constraint Function Module

(14) Check constraint functions for feasibility.

(15) If the point $\overline{u}^{(\lambda)}$ is in the feasible region go to 6, otherwise go to 12.

Do step 16 for $j = 1,2,\ldots,j^a$

H. Min-max Optimization Module

(16) Call subroutine MINMAX to check if the point $\overline{u}_j{}^P$ is the min-max optimum.

I. Print Module

(17) Print $\overline{u}_j{}^P$ and $\overline{f}_j{}^P$ for $j = 1,2,\ldots,j^a$ and $\overline{u^*}$, λ^*, $\overline{f}(\overline{u^*})$, $\overline{z}(\overline{u^*})$.

Do steps 18,19 if IPARCRV > 1.

(18) If IPAR < IPARCRV then IPAR=IPAR+1 and go to 19, otherwise end.

(19) Call subroutine RANDOM to generate a new value for $u_1{}^{(\lambda)}$. Go to 3.

The algorithm of subroutine PARETO is as follows:

(1) Read k, n, j^a, $\overline{u}^{(\lambda)}$, $\overline{f}(\overline{u}^{(\lambda)})$, and $\hat{\mu}$

(2) Set $j = 1$

(3) If for every $i \in I$ we have $f_i(\overline{u}^{(\lambda)}) < f_{ij}{}^P$ then substitute $\overline{u}_j{}^P = \overline{u}^{(\lambda)}$, $\overline{f}_j{}^P = \overline{f}(\overline{u}^{(\lambda)})$, and $\hat{\mu}_j{}^P = \hat{\mu}$, and go to 7, otherwise go to 4.

(4) If for every $i \in I$ we have $f_i(\overline{u}^{(\lambda)}) > f_{ij}{}^P$ then go to 8, otherwise go to 5.

(5) Set $j = j + 1$

(6) If $j > j^a$ then $j^a = j^a + 1$ and $\overline{u}_{j^a}{}^P = \overline{u}^{(\lambda)}$, $\overline{f}_{j^a}{}^P = \overline{f}(\overline{u}^{(\lambda)})$, and $\hat{\mu}_j{}^P = \hat{\mu}$, and go to 8, otherwise go to 3.

(7) If $j < j^a$ then $j = j + 1$, and go to 3.

(8) Return

The algorithm of subroutine MINMAX is outlined as follows:

(1) Read k, n, j, j^a, $\bar{f}^0$, $\bar{u}_j{}^P$, $\bar{f}_j{}^P$, and $\hat{\mu}_j{}^P$ for $j = 1,2,\ldots,j^a$

(2) Evaluate the vector $\bar{z}(\bar{u}_j{}^P)$ using formula (6.10) (subroutine MAX)

(3) If $\bar{z}(\bar{u}_j{}^P) = 0$, then retain this solution as the optimum since there is no better solution, and go to 5, otherwise go to 4.

(4) Find the maximal values of all the steps of formula (6.11) for the point $\bar{u}_j{}^P$.

(5) Return

The algorithm of subroutine RANDOM is as follows:

(1) Read $u_1{}^a$, $u_1{}^b$, $u_2{}^a$, $u_2{}^b$, $u_3{}^a$, $u_3{}^b$

(2) Generate random number α_i (subroutine RANDN)

(3) Generate the point $\bar{u}^{(\lambda)}$ following formula (6.3)

(4) Return

A flowchart of the SMOT algorithm is presented in Figure 7.1. The Fortran program of SMOT is in Appendix B.

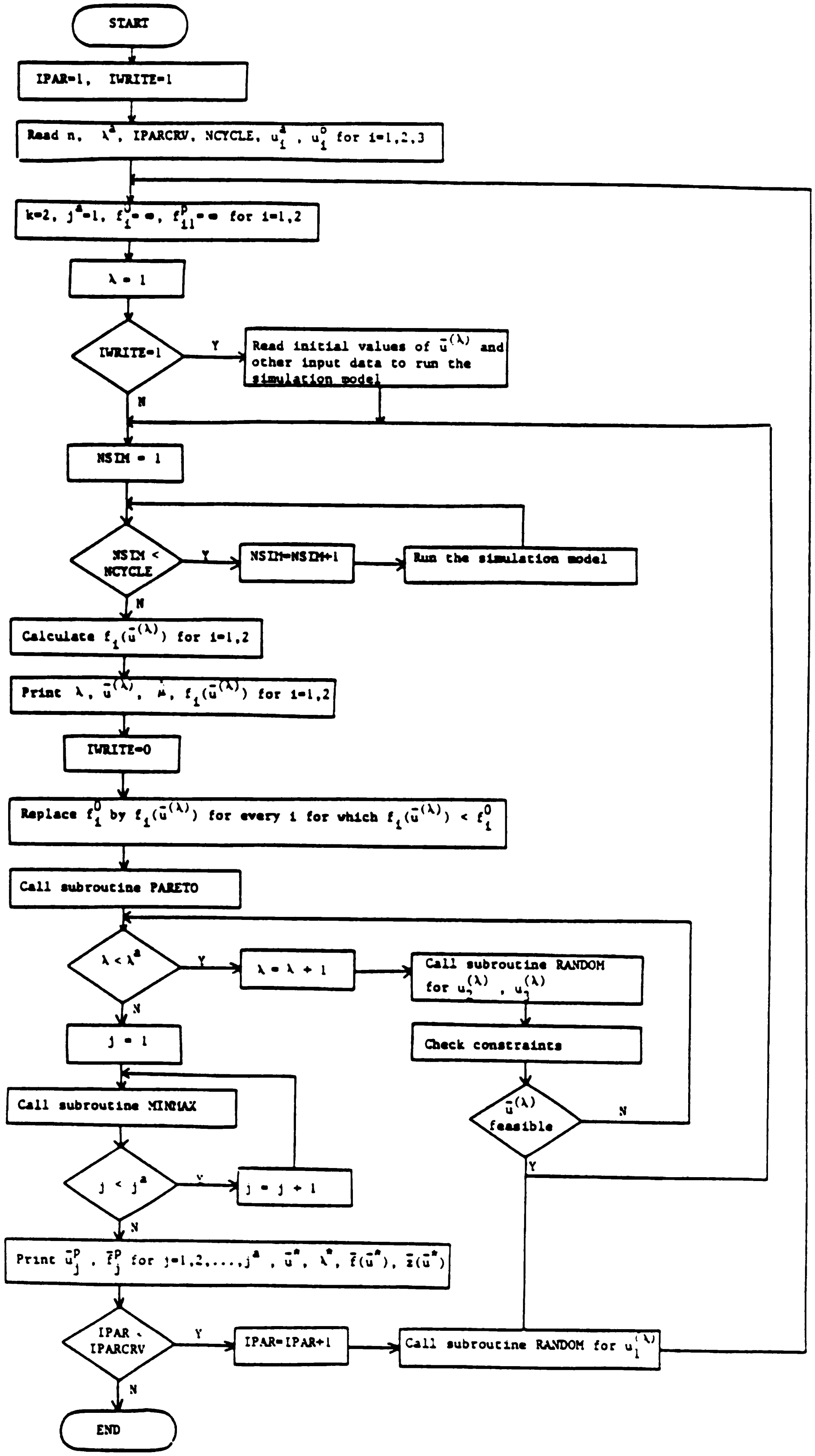

Figure 7.1. Flowchart of the simulation-multicriteria optimization technique (SMOT)

CHAPTER VIII

DISCUSSION OF RESULTS

Two computer software packages have been developed as output of this dissertation research. These are the rice crop growth simulation model and the multicriteria optimization procedure. These two software packages comprise the simulation-multicriteria optimization technique (SMOT) as a decision support system to evaluate profit and production risk for use by agricultural research scientists, extension workers, farmers, and policy-makers involved in rice production under upland condition.

8.1. The Rice Growth Simulation Model

The rice simulation model is a growth simulation model for upland condition. It is designed to predict the growth components and yield of different rice varieties under the tropical and sub-tropical agroclimatic environments. The simulation model is programmmed in Fortran 77 and set-up to run interactively in any IBM-compatible microcomputer with at least 256 K bytes of random access memory (RAM). In a Compaq microcomputer with 640 K bytes RAM, simulation time of one cropping season takes about 25 to 40 seconds. In the Hewlett Packard (HP) 9000 minicomputer system, the user time is between 9.3 to 9.9

seconds. For instructions on how to run the simulation model, a user documentation has been developed (Appendix C).

Model validation is based on observed, field-measured data, whenever available, and intuitive knowledge of experts, whenever data is lacking. The validation covers the phenology, growth and partitioning, leaf area index, and grain yield under water and nitrogen constraints.

Table 8.1.1 presents a comparison between the predicted (P, model) and the observed (O, field-measured) phenological occurrence, days after sowing (DAS), of 3 upland rice varieties, namely: IR43, UPLRI5, and UPLRI7. The data were the result of a series of experiments for drought tolerance conducted at the upland experimental farm of the International Rice Research Institute (IRRI), Los Baños, Philippines during the period 1983-1984. Actual weather data, collected from the site, were used in the simulation. Due to lack of information, some of the soil parameters were estimated based on expert opinion. The sowing dates were based on actual information. For each simulation, plant population was 400 plants/m^2 and was applied with 60 Kg N/Ha of fertilizer a day before sowing time. The three phenological events being compared are the time of emergence, heading, and physiological maturity. The comparison showed that from an average of six experiments, the predicted time of emergence was one day less than the observed for the three varieties. However, the predicted time of heading was one day earlier for IR43, two days later for UPLRI5, and four days earlier for UPLRI7, compared with the observed data. The predicted occurrence for physiological maturity was very good: on the average of six experiments, only a day earlier

TABLE 8.1.1. COMPARISON BETWEEN PREDICTED AND OBSERVED PHENOLOGICAL OCCURRENCE OF 3 RICE VARIETIES, DAYS AFTER SOWING (DAS)

Variety Name	Sowing Date (1983)	Emergence P	Emergence O	Heading P	Heading O	Maturity P	Maturity O
IR43	May 26	4	8	99	97	128	125
	Jun 30	4	6	96	99	127	134
	Jul 8	4	4	97	99	128	127
	Aug 4	4	4	95	100	127	123
	Aug 28	4	4	94	100	127	127
	Nov 10	4	6	98	93	129	134
	(Average)	4	5	97	98	127	128
UPLRI5	Jun 20	4	4	98	95	121	119
	Jun 30	4	6	98	92	120	116
	Jul 8	4	4	97	95	120	120
	Aug 4	4	4	94	100	118	123
	Aug 28	4	4	93	93	117	116
	Nov 10	4	6	96	91	119	125
	(Average)	4	5	96	94	119	120
UPLRI7	May 26	4	8	92	91	119	116
	Jun 20	4	4	89	88	117	112
	Jun 30	4	6	88	91	116	116
	Jul 8	4	4	88	89	117	119
	Aug 4	4	4	86	99	115	123
	Aug 28	4	4	84	93	115	116
	(Average)	4	5	88	92	117	117

than the observed for IR43 and UPLRI5 while about the the same for UPLRI7.

A rice simulation model that is able to predict the phenological occurrence of the crop will provide good opportunities for a rice farmer to plan out and optimize the farm operations. Some farmers may want to apply fertilizer and/or irrigation just before heading. A good prediction on the physiological maturity will also allow the farmer to plan for harvesting and marketing. In the Philippines and other Asian countries where harvesting and marketing are mostly done manually with the help of hired labor, an advanced planning will ensure early contracts for hired labor and hence, harvest operation and marketing transportation may be done on schedule. Other farmers may want to plant cash crops following rice to make use of the residual fertilizer and soil moisture. An evaluation of the maturity duration of the different varieties within the climatic area will give the farmer insight as to the kind of rice variety appropriate for the season in order to maximize the cropping pattern.

The next set of comparison between predicted and observed is on IR36 variety. The data were from a Ph.D. dissertation by A. Chinchest (1981) on the effects of water regimes and amount of nitrogen on the growth of some selected rice varieties. The experiment was replicated four times and conducted at the upland farm of IRRI during the 1980 dry season. Actual weather data for the duration of the experiment, collected from the site, were used in the simulation run. Some of the soil parameters needed in the model were estimated. The simulation inputs include sowing date, plant population, fertilizer application, and irrigation levels, according to actual information.

Table 8.1.2 presents the result of the phenological comparison. Model predictions regarding the time of occurrence for floral initiation and heading were a day earlier while the occcurrence for maturity was two days earlier compared to the observed time of occurrence.

TABLE 8.1.2. COMPARISON BETWEEN PREDICTED AND OBSERVED PHENOLOGICAL OCCURRENCE OF IR36 VARIETY (Sowing Date: January 9,1980)

Phenological stage	Predicted Date	Observed Date
Floral Initiation	Febuary 27, 1980	Febuary 28, 1980
Heading or Flowering	March 29, 1980	March 30, 1980
Maturity	April 26, 1980	April 28, 1980

Using Chinchest's observed data, more comparisons between the predicted output of the simulation model and the observed data were done on the growth components of IR36 with 4 nitrogen treatments (0, 30, 60, and 120 Kg N/Ha) and 2 irrigation levels (about 810 and 795 mm of water). A biomass comparison, from 4 sampling dates on the 4 nitrogen treatments and irrigation of about 795 mm water, was conducted. The predicted and observed values are presented in Table 8.1.3. From an average of 4 sampling intervals, the comparison showed 12.6 percent, 18.1 percent, 21.2 percent, and 21.0 percent difference in biomass between the predicted and observed for 0, 30, 60, and 120 Kg N/Ha, respectively. The simulation model tends to underpredict biomass at all sampling intervals as demonstrated graphically in Figures 8.1.1 (0 N), 8.1.2 (30 Kg N/Ha), 8.1.3 (60 Kg N/Ha), and 8.1.4 (120 Kg N/Ha).

TABLE 8.1.3. PREDICTED AND OBSERVED BIOMASS OF IR36 VARIETY AT 4 TREATMENTS OF NITROGEN FERTILIZER ON 4 SAMPLING INTERVALS. 795 mm WATER APPLIED.

Nitrogen Treatment (Kg N/Ha)	Sampling Interval (DAS)	Predicted (g/m^2)	Observed (g/m^2)	Percent Difference
0	57	202.	228.	11.4
	69	343.	349.	1.7
	89	604.	829.	27.1
	106	850.	946.	10.1
(Average)				12.6
30	57	268.	318.	15.7
	69	427.	501.	14.8
	89	722.	983.	26.6
	106	1009.	1192.	15.3
(Average)				18.1
60	57	319.	366.	12.8
	69	496.	548.	9.5
	89	821.	1233.	33.4
	106	1145.	1614.	29.1
(Average)				21.2
120	57	381.	390.	2.3
	69	589.	793.	25.7
	89	963.	1302.	26.0
	106	1342.	1920.	30.1
(Average)				21.0

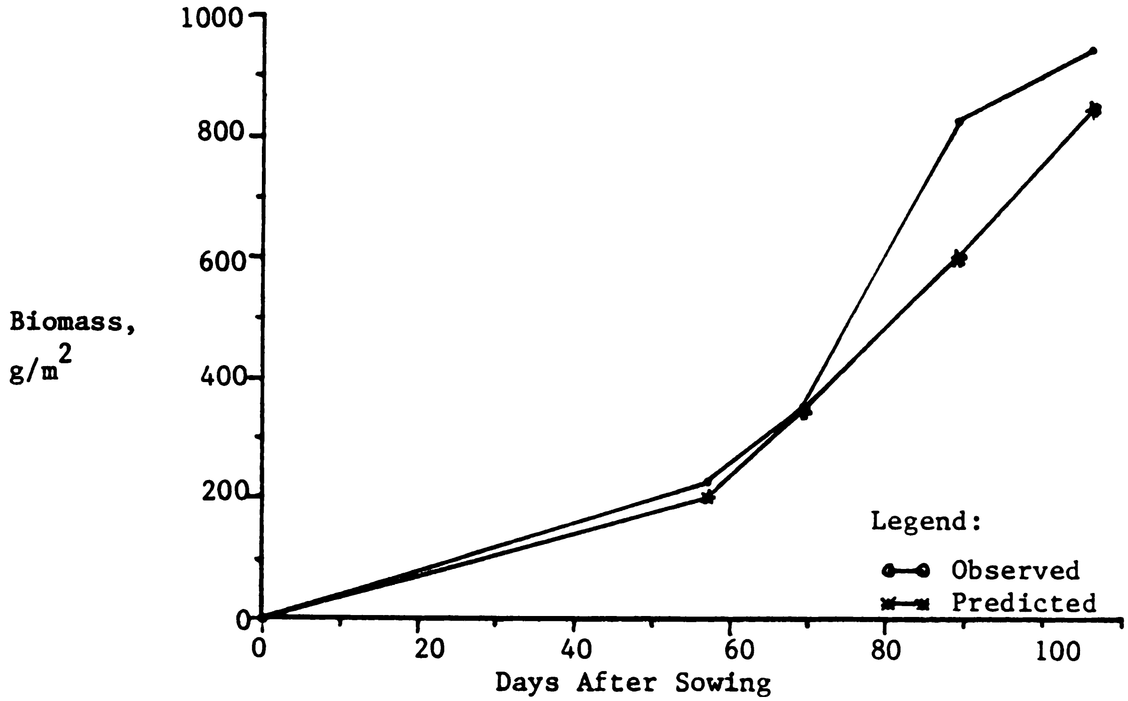

Figure 8.1.1. Comparison between predicted and observed biomass of IR36 variety with 0 N.

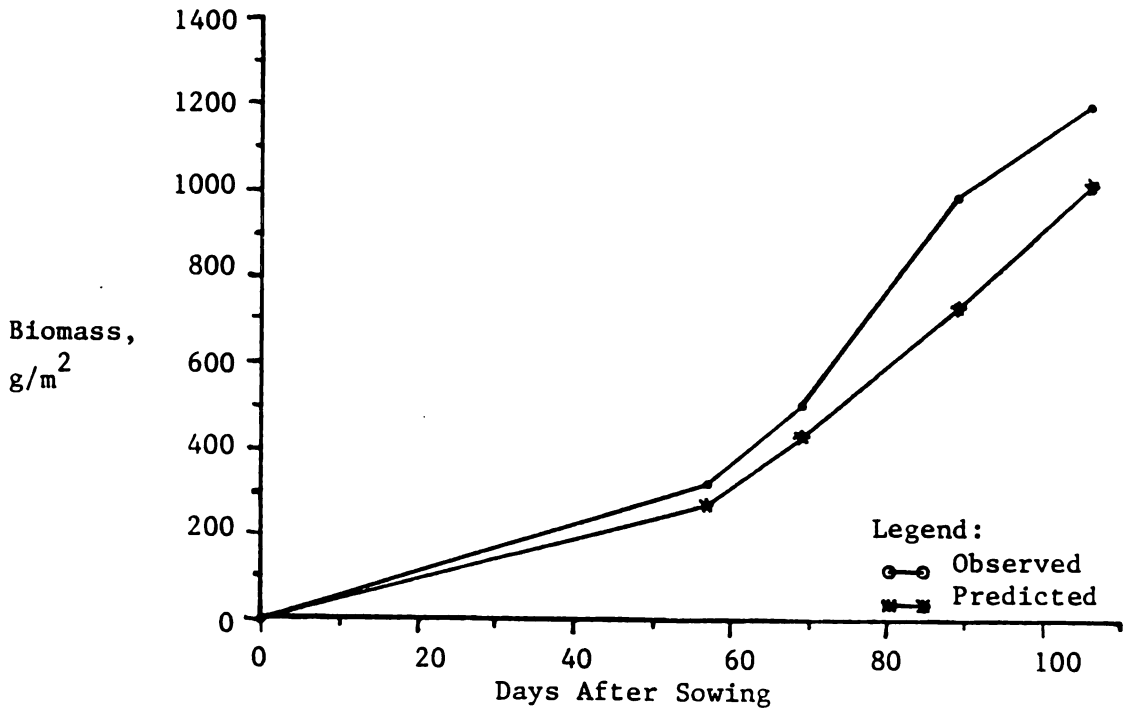

Figure 8.1.2. Comparison between predicted and observed biomass of IR36 variety with 30 Kg N/Ha.

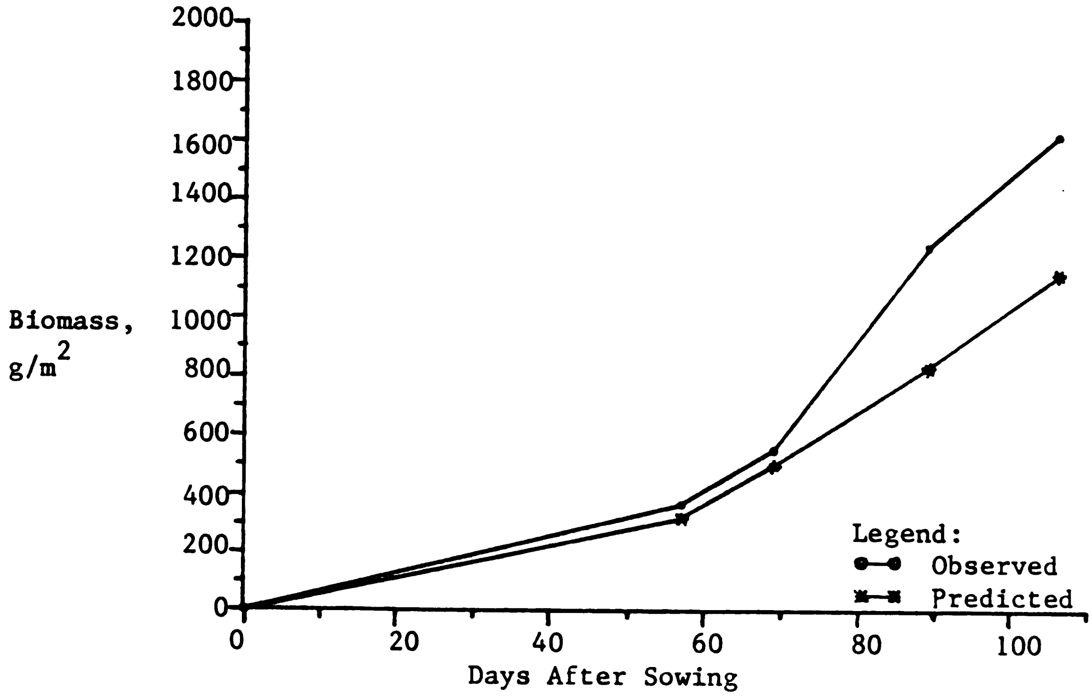

Figure 8.1.3. Comparison between predicted and observed biomass of IR36 variety with 60 Kg N/Ha.

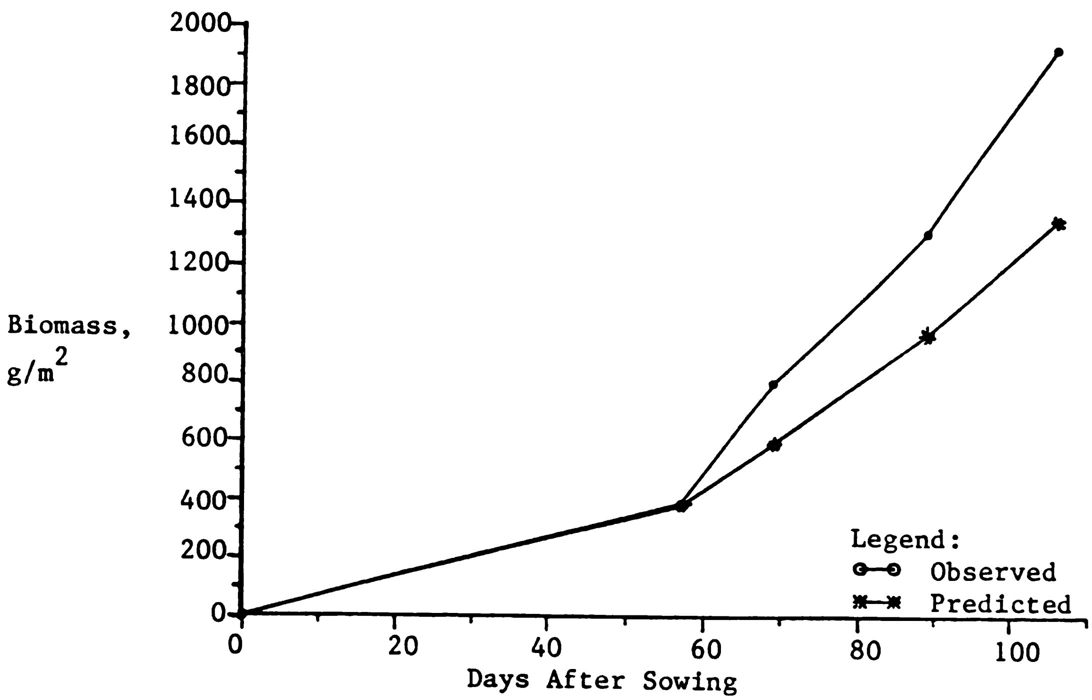

Figure 8.1.4. Comparison between predicted and observed biomass of IR36 variety with 120 Kg N/Ha.

Table 8.1.4 shows a comparison on the straw weight at harvest on the 4 fertilizer treatments and 2 irrigation levels, 810 mm (W1) and 795 mm (W2) water applied. From an average of 4 nitrogen treatments, the difference in straw weight between predicted and observed is 3.1 percent for W1 and 4.7 percent for W2.

TABLE 8.1.4. PREDICTED AND OBSERVED STRAW WEIGHT AT HARVEST OF IR36 VARIETY AT 2 IRRIGATION LEVELS AND 4 NITROGEN TREATMENTS.

Irrigation Level (mm)	Nitrogen Treatment (Kg N/Ha)	Predicted (g/m^2)	Observed (g/m^2)	Percent Difference
810 mm (W1)	0	419.	405.	3.4
	30	512.	523.	2.1
	60	589.	564.	4.4
	120	700.	683.	2.5
(Average)				3.1
795 mm (W2)	0	416.	420.	1.0
	30	506.	490.	3.3
	60	581.	600.	3.2
	120	683.	613.	11.4
(Average)				4.7

Table 8.1.5 is a rearrangement of the entries in Table 8.1.4 in order to demonstrate the effect of nitrogen treatments on the prediction of straw. It shows that the simulation model is able to predict consistently better at fertilizer treatments 0, 30, and 60 Kg N/Ha (2.2, 2.7, and 3.8 percent difference, respectively) than at the 120 Kg N/Ha treatment (7.0 percent difference).

TABLE 8.1.5. PREDICTED AND OBSERVED STRAW WEIGHT AT HARVEST OF IR36 VARIETY AT 4 NITROGEN TREATMENTS AND 2 IRRIGATION LEVELS.

Nitrogen Treatment (Kg N/Ha)	Irrigation Level (mm)	Predicted (g/m^2)	Observed (g/m^2)	Percent Difference
0	810	419.	405.	3.4
	795	416.	420.	1.0
(Average)				2.2
30	810	512.	523.	2.1
	795	506.	490.	3.3
(Average)				2.7
60	810	589.	564.	4.4
	795	581.	600.	3.2
(Average)				3.8
120	810	700.	683.	2.5
	795	683.	613.	11.4
(Average)				7.0

Grain yield comparison between predicted and observed, at 14 percent moisture content, on the 4 nitrogen treatments (0, 30, 60, and 120 Kg N/Ha), and 2 irrigation levels (810 and 795 mm, W1 and W2 respectively), is shown in Table 8.1.6. From an average of 4 nitrogen treatments, the difference in yield is 8.8 percent for W1 and 8.6 percent for W2.

TABLE 8.1.6. GRAIN YIELD OF IR36 VARIETY AT 2 IRRIGATION LEVELS AND 4 NITROGEN TREATMENTS.

Irrigation Level (mm)	Nitrogen Treatment (Kg N/Ha)	Predicted (g/m^2)	Observed (g/m^2)	Percent Difference
810 mm (W1)	0	4.3	4.6	6.5
	30	5.0	5.6	10.7
	60	5.6	6.7	16.4
	120	6.6	6.7	1.5
(Average)				8.8
795 mm	0	4.3	4.6	6.5
	30	4.9	5.3	7.5
	60	5.5	6.9	20.3
	120	6.5	6.5	0.0
(Average)				8.6

The entries of Table 8.1.6 were rearranged and presented in Table 8.1.7 in order to show the effect of nitrogen treatments on the prediction of yield. Table 8.1.7 shows that grain yield prediction is best at 120 Kg N/Ha treatment (0.8 percent difference); prediction is poorest at 60 Kg N/Ha treatment (18.4 percent difference).

TABLE 8.1.7. GRAIN YIELD OF IR36 VARIETY AT 4 NITROGEN TREATMENTS AND 2 IRRIGATION LEVELS.

Nitrogen Treatment (Kg N/Ha)	Irrigation Level (mm)	Predicted (g/m^2)	Observed (g/m^2)	Percent Difference
0	810	4.3	4.6	6.5
	795	4.3	4.6	6.5
(Average)				6.5
30	810	5.0	5.6	10.7
	795	4.9	5.3	7.5
(Average)				9.1
60	810	5.6	6.7	16.4
	795	5.5	6.9	20.3
(Average)				18.4
120	810	6.6	6.7	1.5
	795	6.5	6.5	0.0
(Average)				0.8

The predicted leaf area index (LAI) on the 4 fertilizer treatments and 795 mm water irrigation for 7 sampling dates is shown in Table 8.1.8. The graphical illustration of the LAI curve is shown in Figure 8.1.5.

TABLE 8.1.8. PREDICTED LAI OF IR36 VARIETY ON 7 SAMPLING INTERVALS, DAYS AFTER SOWING (DAS).

DAS	0 N	30 Kg N/Ha	60 Kg N/Ha	120 Kg N/Ha
4	0.	0.	0.	0.
35	0.9	1.6	2.0	2.2
49	2.1	3.0	3.7	4.4
80	2.9	4.0	4.9	5.9
89	2.7	3.8	4.7	5.7
107	1.9	2.8	3.5	4.4
108	1.9	2.8	3.5	4.4

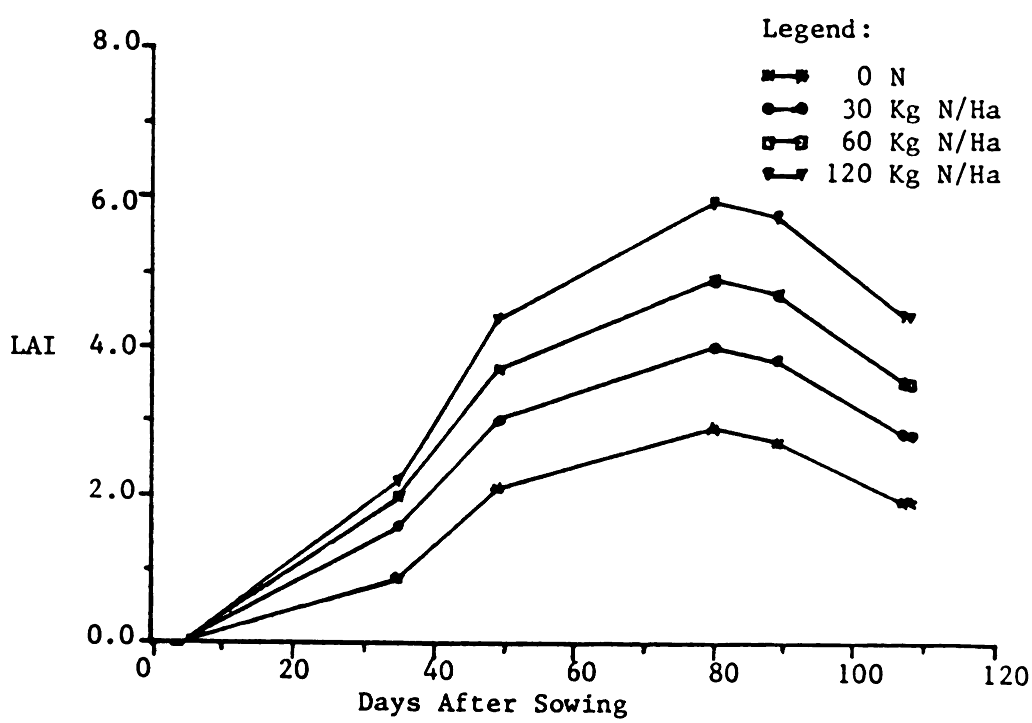

Figure 8.1.5. Leaf area index (LAI) of IR36 variety with 0 N, 30, 60, and 120 Kg N/Ha.

For lack of observed (field-measured) data on LAI of this experiment, the observed LAI values of IR36 sown on November 6, 1984 with 100 Kg N/Ha in flooded condition at the IRRI experimental farm, is presented in column 6 of Table 8.1.9. The corresponding LAI curve is presented in Figure 8.1.6. The purpose of presenting this observed data is to provide aproximate comparison with the predicted results in Table 8.1.8 and Figure 8.1.5. The shape of the predicted LAI curve (Figure 8.1.5) approximates that of the observed LAI (Figure 8.1.6). The maximum LAI of the predicted at 60 Kg N/Ha is 4.9 while the maximum LAI of the observed is 4.6. Both maxima occurred 80 days after sowing.

TABLE 8.1.9. ROOT WEIGHT, LEAF WEIGHT, STEM WEIGHT, PANICLE WEIGHT, AND LAI OF IR36 VARIETY ON 9 SAMPLING INTERVALS, DAYS AFTER SOWING (Sown on Nov. 6, 1984, with 100 Kg N/Ha in flooded condition, IRRI, Philippines).

DAS	Root Weight (g/m^2)	Leaf Weight (g/m^2)	Stem Weight (g/m^2)	Panicle Weight (g/m^2)	LAI
30	4.0	4.8	3.6	0.	0.1
40	9.8	11.4	9.4	0.	0.3
50	19.8	44.2	34.3	9.8	1.2
60	53.5	107.6	94.7	25.5	2.9
70	82.0	173.3	214.3	46.9	4.3
80	73.0	195.7	341.0	60.9	4.6
90	93.1	193.4	537.9	82.4	4.6
100	99.7	178.5	302.9	591.4	3.7
110	105.3	162.3	242.0	652.6	3.4

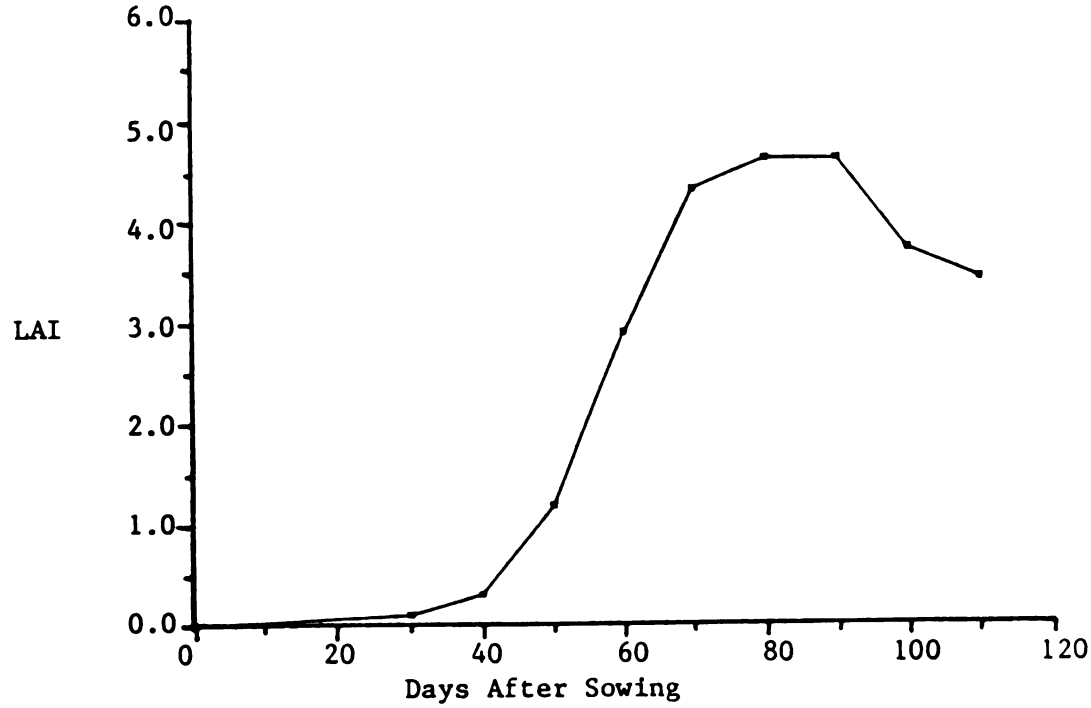

Figure 8.1.6. Observed LAI of IR36 variety sown on Nov. 6, 1984 in flooded condition with 100 Kg N/Ha.

To evaluate growth and partitioning, the predicted results of root weight, leaf weight, stem weight, and panicle weight of 7 sampling dates on the 4 nitrogen treatments are presented in Table 8.1.10 (0 N), Table 8.1.11 (30 Kg N/Ha), Table 8.1.12 (60 Kg N/Ha), and Table 8.1.13 (120 Kg N/Ha). For graphical illustration, the plant parts with 0 N and 120 Kg N/Ha are shown in Figures 8.1.7 and 8.1.8, respectively. For an approximate comparison, the root weight, leaf weight, stem weight, and panicle weight of IR36 sown on November 6, 1984 in flooded condition are presented in Table 8.1.9 and Figure 8.1.9.

TABLE 8.1.10. PREDICTED ROOT WEIGHT, LEAF WEIGHT, STEM WEIGHT, AND PANICLE WEIGHT OF IR36 VARIETY ON 7 SAMPLING INTERVALS, DAYS AFTER SOWING (DAS), WITH 0 N.

DAS	Phenological Stage	Root Weight (g/m^2)	Leaf Weight (g/m^2)	Stem Weight (g/m^2)	Panicle Weight (g/m^2)
4	EMERGENCE	0.0	0.1	0.0	0.0
35	END JUVENILE STAGE	32.6	49.7	0.4	0.0
49	FLORAL INITIATION	103.4	110.3	24.0	0.0
80	HEADING	180.8	150.3	220.0	92.5
89	START GRAIN FILL	187.6	144.3	291.7	168.4
107	END GRAIN FILL	171.4	92.7	274.2	491.0
108	PHYSIOLOGICAL MATURITY	171.4	92.7	274.2	491.0

TABLE 8.1.11. PREDICTED ROOT WEIGHT, LEAF WEIGHT, STEM WEIGHT, AND PANICLE WEIGHT OF IR36 VARIETY ON 7 SAMPLING INTERVALS, DAYS AFTER SOWING (DAS), WITH 30 Kg N/Ha.

DAS	Phenological Stage	Root Weight (g/m^2)	Leaf Weight (g/m^2)	Stem Weight (g/m^2)	Panicle Weight (g/m^2)
4	EMERGENCE	0.0	0.1	0.0	0.0
35	END JUVENILE STAGE	45.8	82.8	0.7	0.0
49	FLORAL INITIATION	135.4	159.4	30.4	0.0
80	HEADING	222.6	205.0	252.5	104.7
89	START GRAIN FILL	229.9	197.9	333.3	190.4
107	END GRAIN FILL	210.1	136.7	312.8	568.2
108	PHYSIOLOGICAL MATURITY	210.1	136.7	312.8	568.2

TABLE 8.1.12. PREDICTED ROOT WEIGHT, LEAF WEIGHT, STEM WEIGHT, AND PANICLE WEIGHT OF IR36 VARIETY ON 7 SAMPLING INTERVALS, DAYS AFTER SOWING (DAS), WITH 60 Kg N/Ha.

DAS	Phenological Stage	Root Weight (g/m^2)	Leaf Weight (g/m^2)	Stem Weight (g/m^2)	Panicle Weight (g/m^2)
4	EMERGENCE	0.0	0.1	0.0	0.0
35	END JUVENILE STAGE	49.8	103.5	0.8	0.0
49	FLORAL INITIATION	148.6	195.1	34.9	0.0
80	HEADING	242.6	248.4	281.0	116.0
89	START GRAIN FILL	251.1	240.1	370.1	210.6
107	END GRAIN FILL	229.5	170.0	346.9	638.9
108	PHYSIOLOGICAL MATURITY	229.5	170.0	346.9	638.9

TABLE 8.1.13. PREDICTED ROOT WEIGHT, LEAF WEIGHT, STEM WEIGHT, AND PANICLE WEIGHT OF IR36 VARIETY ON 7 SAMPLING INTERVALS, DAYS AFTER SOWING (DAS), WITH 120 Kg N/Ha.

DAS	Phenological Stage	Root Weight (g/m^2)	Leaf Weight (g/m^2)	Stem Weight (g/m^2)	Panicle Weight (g/m^2)
4	EMERGENCE	0.0	0.1	0.0	0.0
35	END JUVENILE STAGE	48.5	114.3	0.9	0.0
49	FLORAL INITIATION	153.3	231.9	41.0	0.0
80	HEADING	254.8	302.1	325.9	134.3
89	START GRAIN FILL	266.2	291.5	428.7	243.2
107	END GRAIN FILL	243.2	207.7	400.9	746.8
108	PHYSIOLOGICAL MATURITY	243.2	207.7	400.9	746.8

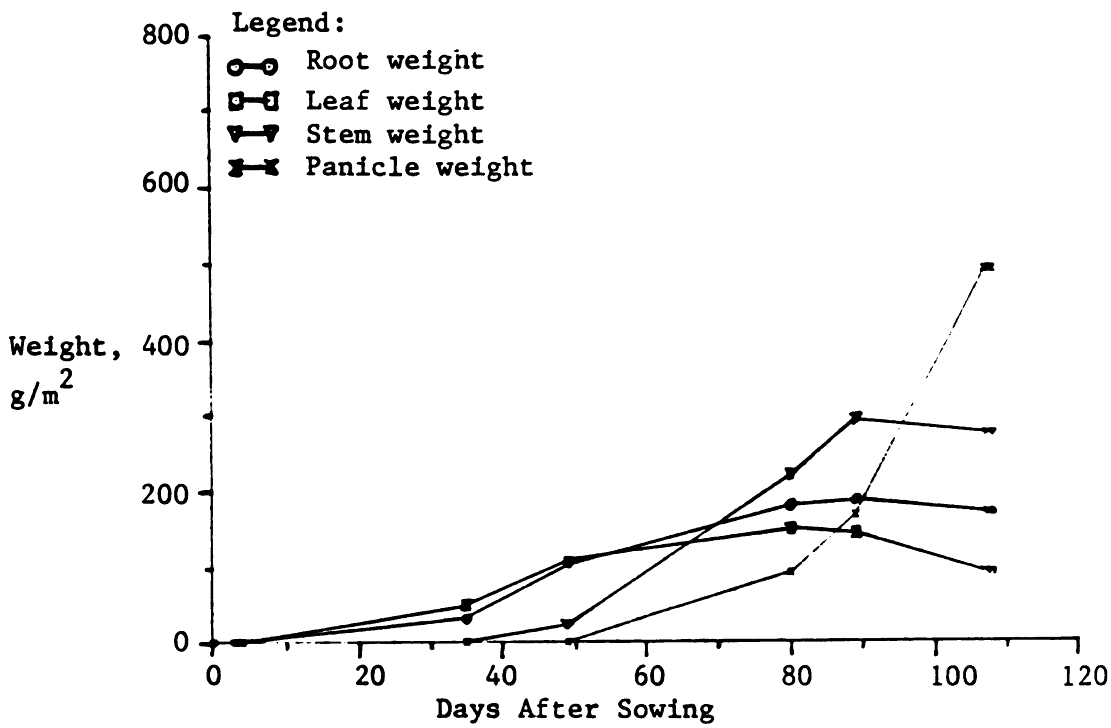

Figure 8.1.7. Predicted root weight, leaf weight, stem weight, and panicle weight of IR36 variety with 0 N.

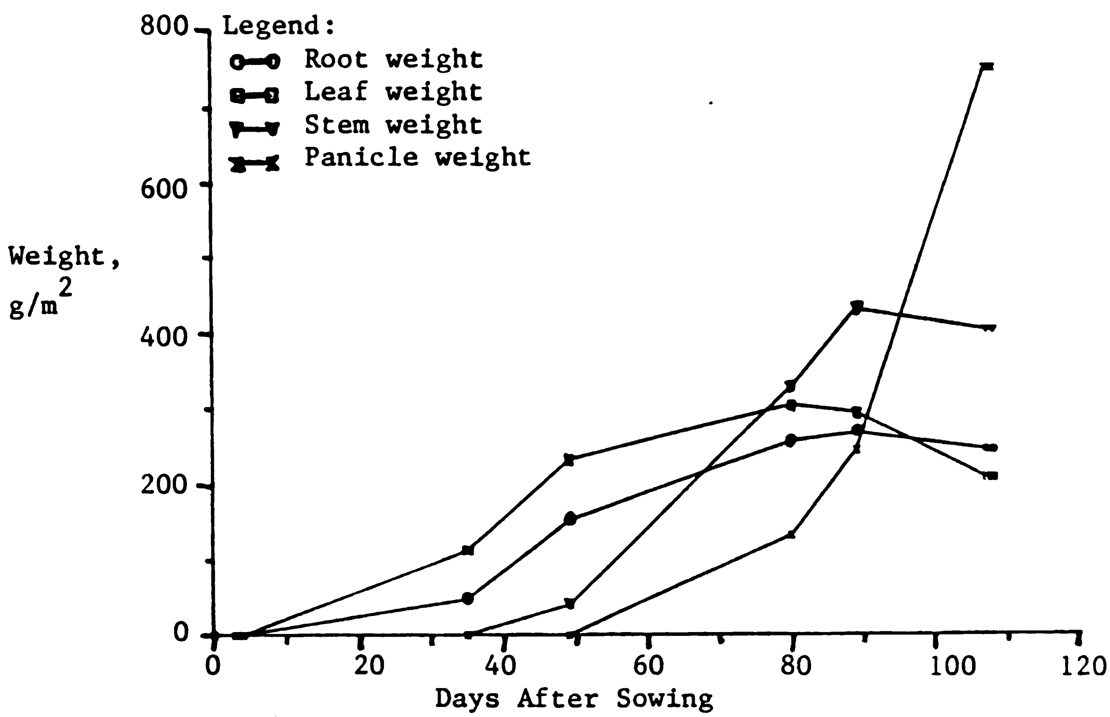

Figure 8.1.8. Predicted root weight, leaf weight, stem weight, and panicle weight of IR36 variety with 120 Kg N/Ha.

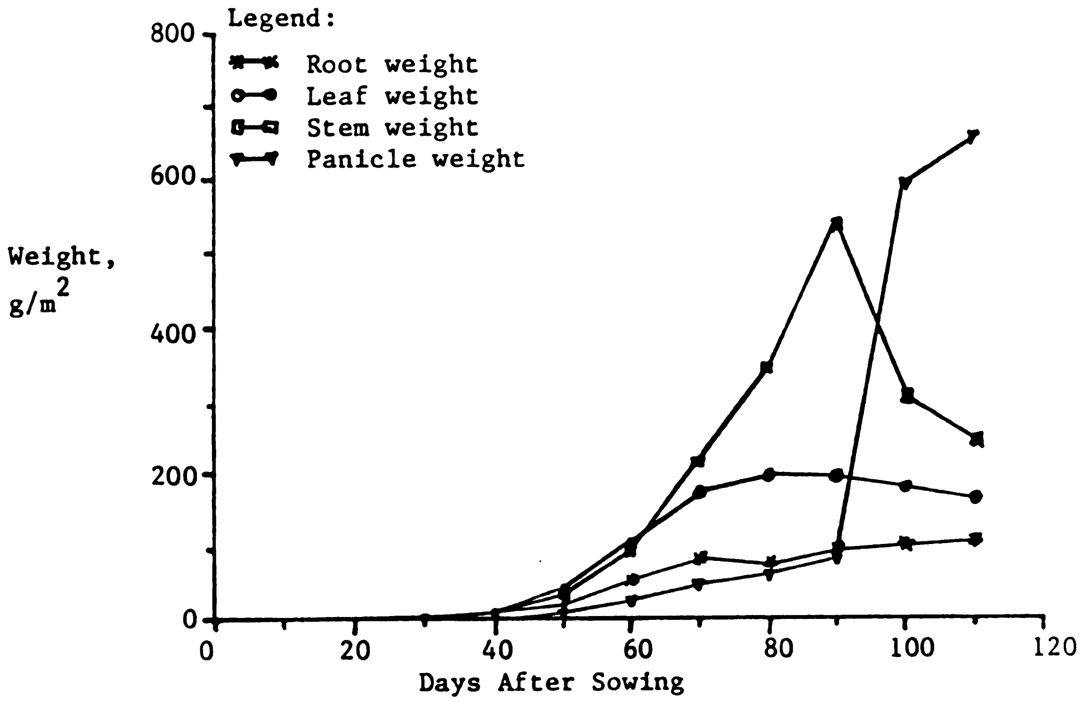

Figure 8.1.9. Observed plant parts of IR36 variety sown on Nov. 6, 1984 in flooded condition with 100 Kg N/Ha.

A simulation model that is able to predict the yield of rice will be useful to farmers and agricultural extension workers in evaluating the economic farm plans. A more extensive discussion on the economics of rice production will be covered in the next section.

The rice simulation model will also provide insight to rice physiologists and agronomists as to the rice plant's mechanism to respond to various climatic environments.

8.2. The Simulation-Multicriteria Optimization Technique (SMOT)

To demonstrate the capability of SMOT, it was implemented three times in a farm environment representative of the Philippines. SMOT, however, can be reparameterized to fit the different agricultural environments in the tropics and subtropics. The first implementation had the following conditions: $u_1=171$ (June 20), u_2 and u_3 varying randomly; the second implementation had $u_1=171$ (June 20), u_2 varying randomly, and $u_3=400$ plants/m^2; and, the third implementation had $u_1=244$ (September 1), u_2 and u_3 varying randomly.

For each u_1, SMOT is run 200 times to generate 200 new points of u_2 and u_3. Every feasible combination of u_1, u_2, and u_3 represents a point $\bar{u} \in U$. Thus, a maximum of 200 $\bar{u}$ points are generated. Let every point $\bar{u} \in U$ be called a production strategy. Each point $\bar{u} \in U$ goes through 25 simulations of the rice model (with actual weather data collected from Los Baños, Philippines), and comprises one SMOT run. Hence, the maximum total number of iterations for each implementation is 5000 (200 x 25). For every 25 simulations, that is, one SMOT run, the user time in the HP 9000 minicomputer system is about 165 seconds, thus, the total user time for the 200 runs is estimated to be 33,000 seconds or 9 hours and 12 minutes.

For each SMOT run, the mean yield ($\hat{\mu}$), profit (f_1), and sample standard deviation (f_2) are calculated. As indicated earlier, the sample standard deviation is used as a measure of risk: a low value of the standard deviation means a lower risk relative to a high value which means a higher risk.

During the 200 SMOT runs, the set of Pareto optimal solutions is generated and the ideal solutions are identified. From the set of Pareto optimal solutions, the min-max optimum solution is determined. The min-max optimum solution is the solution where profit and risk are considered simultaneously and of equal importance. A sample of SMOT output is shown in Appendix D.

SMOT output for the first implementation is presented in Table 8.2.1 and Figure 8.2.1. Table 8.2.1 presents the ideal vector of objective functions, the set of Pareto optimal solutions, and the min-max optimum solution. Figure 8.2.1 shows the corresponding Pareto optimal curve and the min-max optimum point. In Figure 8.2.1, the vertical axis is profit ($/Ha) and the horizontal axis is the sample standard deviation (MT/Ha) as a measure of risk. Each point in the Pareto optimal curve represents a set of production strategy including the sowing date (u_1), nitrogen fertilizer treatment (u_2) and plant population (u_3). The Pareto optimal curve shows that profit increases with risk. The curve then provides a range of feasible strategies, depending on the choice of profit and risk level. In this case, for example, the SMOT user who is risk-averse would probably choose a lower value of the sample standard deviation, with corresponding lower profit. The min-max optimum point represents the "best compromise" production strategy where both profit and risk are equally weighted. In this particular example, $\overline{u}^*$ (the min-max optimum solution) has the components: u_1^*=June 20, u_2^*=100 Kg N/Ha; u_3^*=761 plants/m^2. The corresponding grain yield is 4.94 MT/Ha, with a profit of \$ 1473.72/Ha and a standard deviation of ± 0.708.

The ideal vector of objective functions provides an estimate as to the maximum profit (f_1^0) if risk is not a factor to consider, and

TABLE 8.2.1. IDEAL VECTOR OF OBJECTIVE FUNCTIONS, PARETO OPTIMAL SOLUTIONS, AND MIN-MAX OPTIMUM SOLUTION FOR u_1=June 20, u_2 AND u_3 VARYING

A. The ideal vector of objective functions are: f_1^0 = \$ 3494.49/Ha

f_2^0 = 0.302 MT/Ha

B. The set of Pareto optimal solutions are:

u_2	u_3	yield	f_1	f_2
0.	400.	3.16	61.42	.302
498.	792.	7.33	2996.08	1.021
526.	611.	7.63	3191.91	1.060
463.	541.	7.69	3313.68	1.091
195.	574.	6.46	2662.32	.966
544.	333.	7.84	3367.96	1.098
153.	480.	5.96	2225.57	.882
399.	434.	7.74	3494.49	1.134
490.	394.	7.84	3439.37	1.109
111.	530.	5.24	1666.77	.749
100.	761.	4.94	1473.72	.708
120.	256.	5.38	1787.71	.781
621.	847.	7.29	2751.00	.996
62.	436.	4.37	971.67	.574
631.	411.	7.92	3304.15	1.089
137.	508.	5.69	2058.25	.834
136.	744.	5.54	1928.86	.824
82.	561.	4.71	1269.66	.645
613.	499.	7.85	3241.00	1.077
150.	583.	5.86	2201.54	.869
102.	639.	5.04	1487.94	.717
23.	164.	3.49	282.49	.407
594.	652.	7.60	3090.10	1.042
12.	770.	3.25	68.09	.356
179.	888.	6.01	2266.04	.905
104.	311.	5.12	1563.28	.729
172.	665.	6.11	2352.64	.910
123.	344.	5.46	1858.83	.794
203.	500.	6.62	2726.58	.991
59.	705.	4.22	845.24	.558
539.	795.	7.35	2942.21	1.013
571.	595.	7.68	3163.56	1.058
203.	443.	6.66	2763.21	.997
490.	394.	7.84	3439.37	1.109
563.	829.	7.30	2832.90	1.003
415.	607.	7.53	3243.11	1.087
441.	761.	7.33	3066.80	1.040
491.	769.	7.36	3023.54	1.028
93.	173.	4.87	1408.66	.694
550.	779.	7.38	2968.53	1.016

TABLE 8.2.1 (cont'd.)

u_2	u_3	yield	f_1	f_2
529.	810.	7.32	2917.11	1.012
30.	288.	3.68	442.14	.442
518.	660.	7.55	3119.84	1.049
13.	728.	3.28	92.30	.360
523.	435.	7.89	3416.33	1.102
29.	738.	3.60	370.97	.434
442.	713.	7.41	3132.38	1.052
472.	736.	7.40	3056.69	1.039
45.	217.	3.98	703.75	.510
527.	402.	7.87	3399.84	1.100
487.	751.	7.39	3046.25	1.033
484.	463.	7.84	3437.63	1.106
107.	268.	5.16	1597.54	.736
174.	313.	6.23	2460.17	.938
485.	872.	7.19	2878.69	1.005
75.	407.	4.62	1189.65	.622
186.	461.	6.44	2640.77	.960
221.	655.	6.67	2768.19	1.000
49.	517.	4.08	793.04	.520
67.	258.	4.43	1025.08	.598
192.	508.	6.48	2676.35	.967
125.	297.	5.48	1874.90	.799
17.	586.	3.39	187.69	.379
574.	617.	7.65	3133.53	1.052

C. The min-max optimum solution is:

$u_1^* = 171$ $\quad$ $yield^* = 4.94$ $\quad$ $f_1^* = \$\ 1473.72/Ha$

$u_2^* = 100.$ $\quad$ $f_2^* = 0.708\ MT/Ha$

$u_3^* = 761.$

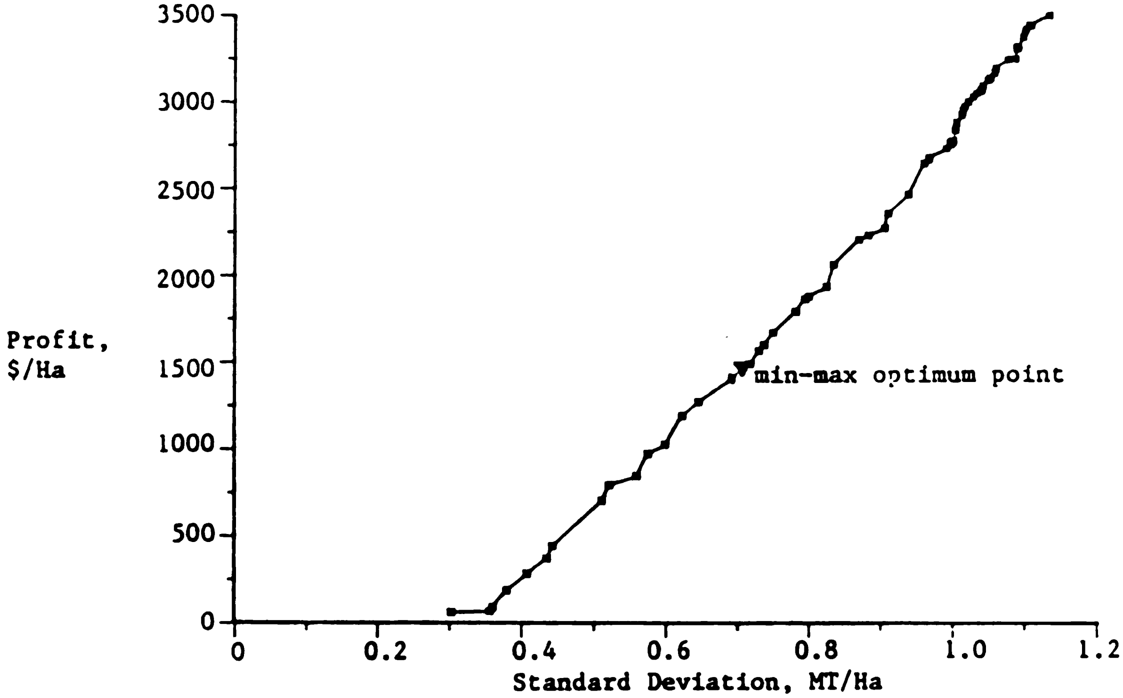

Figure 8.2.1. Pareto optimal curve and min-max optimum point for u_1=June 20, u_2 and u_3 varying.

the minimum risk ($f_2{}^0$) if profit is not an issue. Their corresponding production strategies can be generated from the SMOT output. For example, Table 8.2.1 shows that the maximum possible profit ($f_1{}^0$) is $ 3494.49. But this profit level has the largest standard deviation (± 1.134), equivalent to the highest point in the Pareto optimal curve of Figure 8.2.1. In the same manner, Table 8.2.1 also shows that the minimum possible risk ($f_2{}^0$) is ± 0.302, which has the lowest profit ($ 61.42), and equivalent to the lowest point in the Pareto optimal curve of Figure 8.2.1.

In most rice production, the conventional plant population is 400 plants/m^2. SMOT was, therefore, run with a fixed plant population (u_3) of 400 plants/m^2 with the same planting date (u_1). The objective is to see how changes in nitrogen treatments with fixed plant population affect the shape of the Pareto optimal curve and the values of the min-max optimum solution. The ideal vector of objective functions, the set of Pareto optimal solutions, and the min-max optimum solution are presented in Table 8.2.2. The corresponding Pareto optimal curve and min-max optimum point are shown in Figure 8.2.2. The shape of the Pareto optimal curve in Figure 8.2.2 is smoother, although the slope is about the same, compared to that of Figure 8.2.1. This result is expected because u_2 is the only component of $\bar{u} \in U$ that varied randomly in the second implementation. The min-max optimum solution, $\overline{u}^*$, has the components: u_1^*=June 20, u_2^*=93 Kg N/Ha, and u_3^*=400 plants/m^2, with a mean yield of 4.95 MT/Ha, profit of $ 1481.91/Ha, and sample standard deviation of ± 0.689. This optimum solution shows a higher profit and lower standard deviation compared to the first implementation implying that the min-max strategy of the second implementation is better than the min-max strategy of the first implementation. The maximum profit (f_1^0) and the minimum risk (f_2^0), however, are about the same as the first implementation.

The SMOT results of the third implementation are presented in Table 8.2.3 and Figure 8.2.3. The ideal vector of objective functions, the set of Pareto optimal solutions, and the min-max optimum solution are presented in Table 8.2.3 while the corresponding Pareto optimal curve and the min-max optimum point are illustrated in Figure 8.2.3. The Pareto optimal curve in Figure 8.2.3 is more "wigly" compared to the Pareto optimal curve in Figure 8.2.1. The min-max optimum solution has the components: u_1^*=September 1, u_2^*=100

TABLE 8.2.2. IDEAL VECTOR OF OBJECTIVE FUNCTIONS, PARETO OPTIMAL SOLUTIONS, AND MIN-MAX OPTIMUM SOLUTION FOR u_1=June 20, u_2 VARYING, u_3=400 plants/m^2

A. The ideal vector of objective functions are: f_1^0 = $ 3474.44/Ha

f_2^0 = 0.302 MT/Ha

B. The set of Pareto optimal solutions are:

u_2	yield	f_1	f_2
0.	3.16	61.42	.302
232.	6.95	3011.83	1.056
697.	7.93	3238.97	1.086
790.	7.94	3105.74	1.084
735.	7.93	3172.52	1.085
647.	7.92	3301.45	1.088
848.	7.94	3037.29	1.084
498.	7.85	3449.08	1.107
157.	6.03	2284.67	.896
211.	6.73	2824.97	1.018
399.	7.72	3474.44	1.134
195.	6.55	2734.82	.983
550.	7.89	3411.44	1.097
111.	5.27	1693.38	.755
100.	5.08	1593.38	.717
120.	5.43	1831.05	.785
150.	5.92	2260.32	.878
62.	4.36	966.22	.575
137.	5.72	2080.42	.840
136.	5.70	2066.19	.837
82.	4.75	1304.92	.648
23.	3.54	322.74	.407
226.	6.89	2962.85	1.046
12.	3.33	135.00	.355
215.	6.78	2862.83	1.026
594.	7.91	3358.43	1.092
179.	6.34	2556.99	.949
108.	5.22	1647.29	.745
181.	6.37	2581.14	.955
123.	5.48	1875.97	.795
200.	6.61	2785.95	.993
59.	4.30	913.88	.564
213.	6.75	2844.60	1.022
442.	7.79	3465.82	1.122
162.	6.11	2350.64	.911
93.	4.95	1481.91	1.097
30.	3.69	456.70	.437
13.	3.34	150.54	.360
29.	3.67	437.34	.433
165.	6.15	2387.97	.918

TABLE 8.2.2 (cont'd.)

u_2	yield	f_1	f_2
45.	4.01	735.57	.507
209.	6.71	2805.33	1.013
107.	5.20	1631.93	.742
174.	6.28	2498.11	.939
172.	6.25	2473.83	.934
75.	4.61	1188.65	.622
186.	6.44	2636.92	.966
227.	6.90	2971.29	1.048
221.	6.84	2918.30	1.038
231.	6.94	3004.23	1.054
222.	6.85	2927.71	1.040
10.	3.29	103.74	.346
49.	4.10	807.57	.523
67.	4.46	1053.06	.595
192.	6.51	2702.20	.977
125.	5.52	1906.28	.801
17.	3.42	214.89	.378

C. The min-max optimum solution is:

$u_1^* = 171$ $yield^* = 4.95$ $f_1^* = \$\ 1481.91/Ha$

$u_2^* = 93.$ $f_2^* = 0.689\ MT/Ha$

$u_3^* = 400.$

TABLE 8.2.3. IDEAL VECTOR OF OBJECTIVE FUNCTIONS, PARETO OPTIMAL SOLUTIONS, AND MIN-MAX OPTIMUM SOLUTION FOR u_1=Sept. 1, u_2 AND u_3 VARYING

A. The ideal vector of objective functions are: f_1^0 = \$ 3126.53/Ha

f_2^0 = 0.246 MT/Ha

B. The set of Pareto optimal solutions are:

u_2	u_3	yield	f_1	f_2
0.	400.	3.07	-15.81	.246
316.	513.	7.06	2970.00	1.114
313.	454.	7.12	3025.78	1.124
150.	583.	5.69	2055.24	.759
195.	574.	6.24	2467.26	.869
399.	434.	7.32	3126.53	1.189
261.	393.	6.86	2871.07	1.056
329.	578.	7.01	2927.71	1.108
111.	530.	5.12	1561.51	.643
100.	761.	4.83	1374.12	.582
136.	744.	5.39	1794.18	.702
153.	480.	5.79	2076.28	.784
62.	436.	4.27	887.41	.480
137.	508.	5.54	1929.93	.736
82.	561.	4.61	1187.92	.532
319.	496.	7.09	2997.05	1.121
155.	722.	5.67	1968.50	.757
102.	639.	4.92	1388.01	.599
29.	738.	3.51	292.40	.355
203.	500.	6.39	2524.22	.906
12.	770.	3.16	-8.35	.284
215.	365.	6.50	2621.61	.958
179.	888.	5.81	2089.00	.800
108.	777.	4.94	1406.35	.611
172.	665.	5.92	2184.92	.805
232.	462.	6.68	2778.49	.977
59.	705.	4.13	765.88	.450
203.	443.	6.43	2562.01	.914
288.	649.	6.79	2803.41	1.051
273.	512.	6.89	2892.13	1.057
30.	268.	3.58	354.92	.384
13.	728.	3.19	16.64	.289
29.	738.	3.51	292.40	.355
49.	517.	3.99	711.70	.436
75.	407.	4.51	1100.68	.525
355.	413.	7.23	3045.74	1.163
227.	436.	6.65	2753.33	.971
319.	560.	7.01	2924.41	1.105
341.	593.	7.02	2934.89	1.113
315.	432.	7.13	3035.39	1.131

TABLE 8.2.3 (cont'd.)

u_2	u_3	yield	f_1	f_2
67.	258.	4.32	930.99	.522
192.	508.	6.26	2486.76	.876
104.	311.	5.00	1457.61	.640
17.	586.	3.30	111.72	.311

C. The min-max optimum solution is:

$u_1^* = 244$ yield$^* = 4.83$ $f_1^* = \$ 1374.12$/Ha

$u_2^* = 100.$ $f_2^* = 0.582$ MT/Ha

$u_3^* = 761.$

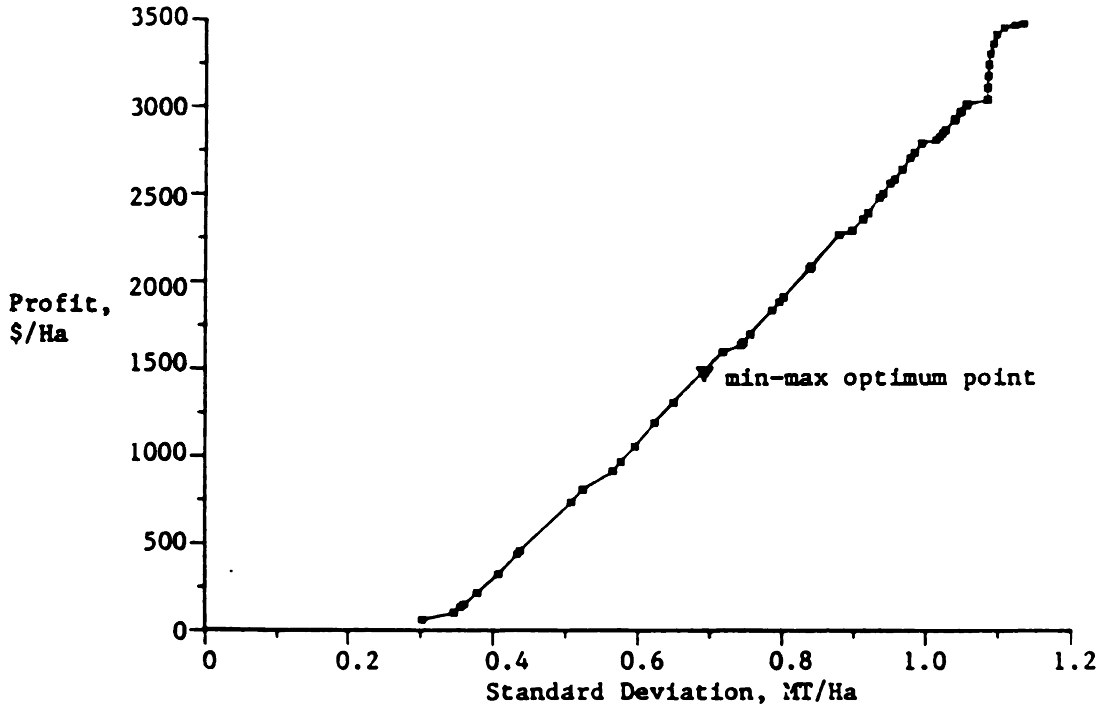

Figure 8.2.2. Pareto optimal curve and min-max optimum point for u_1=June 20, u_2 varying, u_3=400 plants/m^2

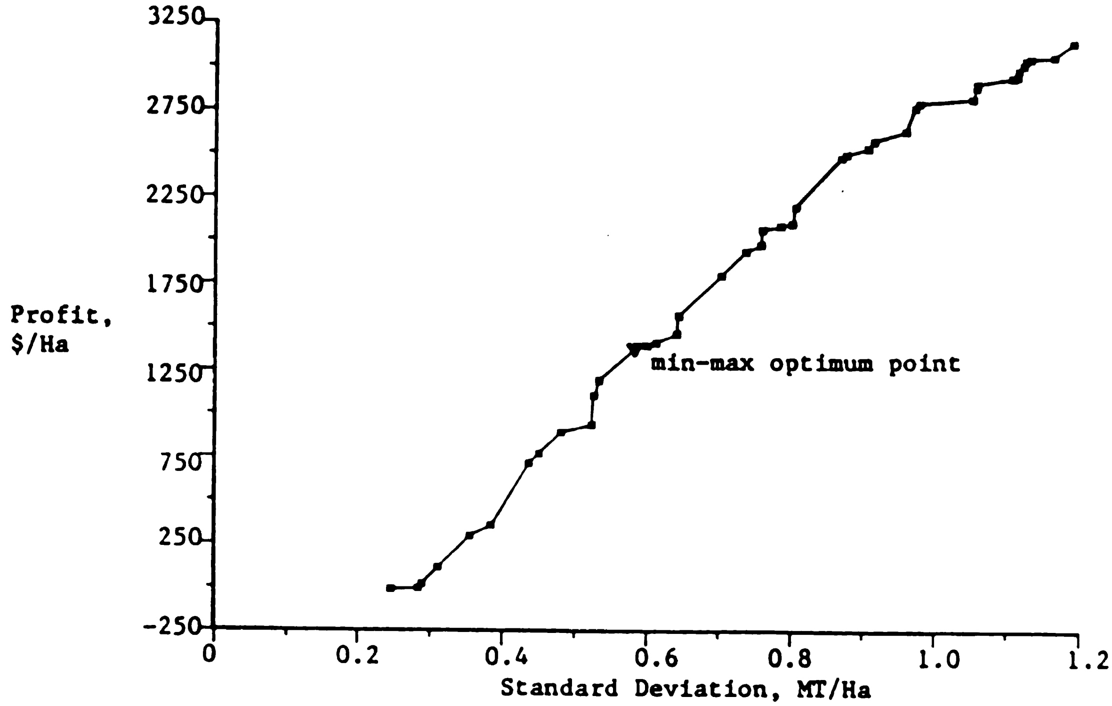

Figure 8.2.3. Pareto optimal curve and min-max optimum point for u_1=Sept. 1, u_2 and u_3 varying.

Kg N/Ha, and $u3^{*}$=761 plants/m^2, with a mean yield of 4.83 MT/Ha, profit of \$ 1374.12, and a standard deviation of ± 0.582. Except for a difference in the value of u_1^*, the min-max optimum u_2^* and u_3^* for the first and third implementations have the same values. However, the mean yield, and correspondingly profit, of the first implementation is higher than that of the third implementation. Their standard deviations are inversely related to profit.

To provide more comparison between the Pareto optimal curves of the first and third implementations, Figure 8.2.1 and Figure 8.2.3 were drawn on the same x,y axes, and illustrated in Figure 8.2.4. It is demonstrated that the Pareto optimal curve of the first implementation (curve 1) is always to the right of the Pareto optimal curve of the third implementation (curve 2) until about the point (1.000,2750). The position of curves 1 and 2 relative to each other shifted after this point, that is, curve 1 is now to the left of curve 2. This graph demonstrates that as long as the farmer chooses a point of risk less than ± 1.0 standard deviation, a production strategy along curve 2 is always as or more profitable than a production strategy along curve 1. However, for a risk level higher than ± 1.0 standard deviation, a production strategy along curve 1 will give more profit than those along curve 2. There is another way of looking at the graph in Figure 8.2.4. Note that, except for a difference in the sowing date (u_1), all other treatments corresponding to the min-max points of both curves 1 and 2 are the same. But the min-max point in curve 1 gives a higher profit (\$ 1473.72) than the min-max point in curve 2 (\$ 1374.12), although the standard deviation in curve 1 is higher (± 0.708) than in curve 2 (± 0.582). Tables 8.2.1 and 8.2.3

show that for the same treatments including fertilizer and plant population, rice sown on June 20 (curve 1) gives a higher profit than rice sown on September 1 (curve 2). Their corresponding standard deviation, however, are inversely related.

Tables 8.2.1 and 8.2.3 also reveal that the Pareto optimal curve is highly influenced by the amount of nitrogen fertilizer applied. The fertilizer level of the production strategies along the lower portion of the two curves (between ± 0.2-0.4 standard deviation) range between 0-30 Kg N/Ha while the fertilizer level around the top portion of the curves (above ± 1.0 standard deviation) range between 260-630 Kg N/Ha. Thus, if fertilizer is not a constraint and the risk level is above 1.0, sowing on June 20 is a better strategy over sowing on September 1.

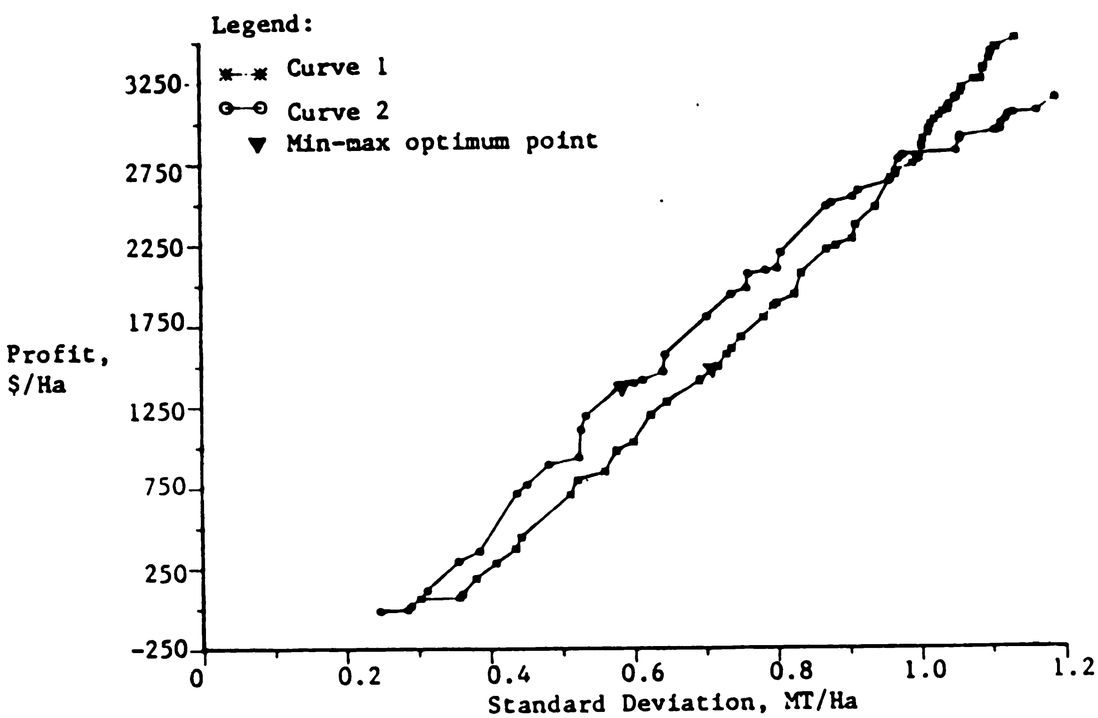

Figure 8.2.4. Pareto optimal curves and min-max optimum points for u_1=June 20 (curve 1) and u_1=Sept. 1 (curve 2).

To illustrate the concept of utilizing the standard deviation of a mean as a measure of risk, 3 representative points (lowest, highest, and min-max) from the Pareto optimal curve in Figure 8.2.1 were chosen for variability analysis. The mean ($\hat{\mu}$) and standard deviation (s) of each of the 3 points were fitted in a normal probability distribution function ($N(\hat{\mu},s^2)$). Column 3 of Table 8.2.4 gives the calculated probability density values. The 3 normal curves are shown in Figure 8.2.5. In this graph, the horizontal axis represents the mean grain yield, while the vertical axis represents the probability density. The normal curve to the left has a mean yield of 3.16 (profit of $ 61.42) and a sample standard deviation of ± 0.302. The components of $\bar{u}$ are: u_1=June 20; u_2=0 Kg N/Ha; u_3=400 plants/m^2, equivalent to the strategy with the lowest risk. The normal curve to the right has a mean yield of 7.74 (profit of $ 3494.49) and a sample standard deviation of ± 1.134. The components of $\bar{u}$ are: u_1=June 20; u_2=399 Kg N/Ha; u_3=434 plants/m^2, equivalent to the strategy with the highest risk. The normal curve at the middle has a mean yield of 4.94 (profit of $ 1473.72) and a sample standard deviation of ± 0.708. The components of $\bar{u}$ are: u_1=June 20; u_2=100 Kg N/Ha; u_3=761 plants/m^2, equivalent to the min-max optimum strategy. It is demonstrated that associated with a larger mean yield is a wider dispersion or variability, or for this application, greater risk. It should be noted that the right tail of the low-risk normal curve ceases to have a positive probability density at the grain yield interval (4.2-4.4 MT/Ha) where the left tail of the high-risk normal curve starts to have a positive probability density. This interval is the "convergence interval" between the low-risk and high-risk strategies.

TABLE 8.2.4. GRAIN YIELD, PROBABILITY DENSITY, AND PROFIT

Description	Yield (MT/Ha)	Probability Density	Profit ($/Ha)
$\hat{\mu}$ = 3.16, S = ± 0.302	2.00	0.00	-951.00
(0 N, 400 plants/m^2)	2.20	0.01	-776.60
	2.40	0.06	-602.20
	2.60	0.24	-427.80
	2.80	0.65	-253.40
	3.00	1.15	-79.00
	3.20	1.31	95.40
	3.40	0.96	269.80
	3.60	0.46	444.20
	3.80	0.14	618.60
	4.00	0.03	793.00
	4.20	0.00	967.40
$\hat{\mu}$ = 4.94, S = ± 0.708	2.60	0.00	-567.80
(100 Kg N/Ha,	2.80	0.01	-393.40
761 plants/m^2)	3.00	0.01	-219.00
	3.20	0.03	-44.60
	3.40	0.05	129.80
	3.60	0.09	304.20
	3.80	0.15	478.60
	4.00	0.23	653.00
	4.20	0.33	827.40
	4.40	0.42	1001.80
	4.60	0.50	1176.20
	4.80	0.55	1350.60
	5.00	0.56	1525.00
	5.20	0.53	1699.40
	5.40	0.46	1873.80
	5.60	0.36	2048.20
	5.80	0.27	2222.60
	6.00	0.18	2397.00
	6.20	0.12	2571.40
	6.40	0.07	2745.80
	6.60	0.04	2920.20
	6.80	0.02	3094.60
	7.00	0.01	3269.00
	7.20	0.00	3443.40

TABLE 8.2.4. (cont'd.)

Description	Yield (MT/Ha)	Probability Density	Profit ($/Ha)
$\hat{\mu}$ = 7.74, S = ± 1.134	4.40	0.00	511.80
(399 Kg N/Ha,	4.60	0.01	686.20
434 plants/m^2)	4.80	0.01	860.60
	5.00	0.02	1035.00
	5.20	0.03	1209.40
	5.40	0.04	1383.80
	5.60	0.06	1558.20
	5.80	0.08	1732.60
	6.00	0.11	1907.00
	6.20	0.14	2081.40
	6.40	0.18	2255.80
	6.60	0.21	2430.20
	6.80	0.25	2604.60
	7.00	0.28	2779.00
	7.20	0.31	2953.40
	7.40	0.34	3127.80
	7.60	0.35	3302.20
	7.80	0.35	3476.60
	8.00	0.34	3651.00
	8.20	0.32	3825.40
	8.40	0.30	3999.80
	8.60	0.26	4174.20
	8.80	0.23	4348.60
	9.00	0.19	4523.00
	9.20	0.15	4697.40
	9.40	0.12	4871.80
	9.60	0.09	5046.20
	9.80	0.07	5220.60
	10.00	0.05	5395.00

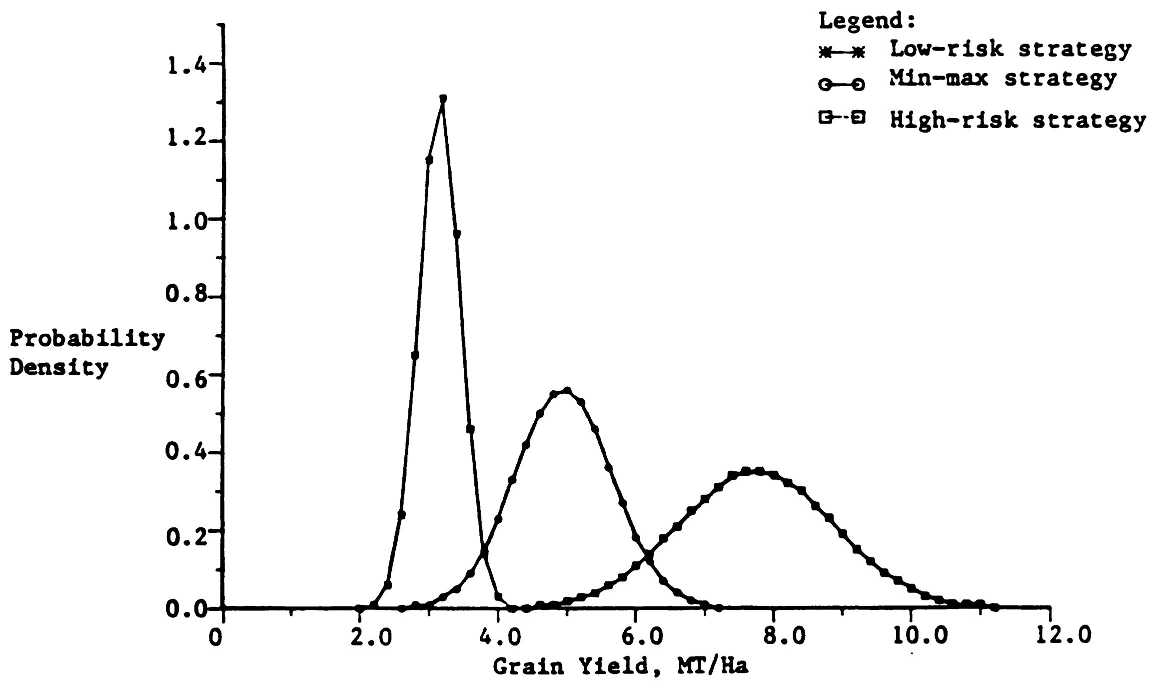

Figure 8.2.5. Normal curves of low-risk, min-max, and high-risk strategies.

Extending the analysis to profit, each point on the normal curve corresponding to grain yield with positive probability density (Figure 8.2.5) was converted into profit (column 4 of Table 8.2.4). The 3 normal curves in Figure 8.2.5 are now represented by 3 profitlines in Figure 8.2.6, where the horizontal axis is grain yield and the vertical axis is profit. The low-risk strategy has the leftmost profitline and consistently to the left, while the high-risk strategy has the rightmost profitline and consistently to the right. The profitline of the min-max strategy is consistently at the middle. The 3 profitlines do not cross each other. The low-risk profitline has its maximum at the point where the high-risk profitline has its minimum. The yield interval between the two profit points is the convergence interval. Figure 8.2.6 shows that if the yield is between

3.4-4.0 MT/Ha, the low-risk strategy is more profitable than the min-max strategy. However, the low-risk strategy has only a maximum profit of \$ 793/Ha and can loss as much as \$ 776.60 (as indicated by a negative profit), whereas the min-max strategy can have a maximum profit of \$ 3269/Ha (maximum yield of 7.0 MT/Ha) with a possible loss of as much as \$ 393.40. If the yield is between 4.6-7.0 MT/Ha, the min-max strategy is more profitable than the high-risk strategy. However, the min-max strategy can only yield at most 7.0 MT/Ha while the high-risk strategy can yield at most 10 MT/Ha or a profit of as much as \$ 5395. If the yield is within the convergence interval, the min-max strategy provides for an alternative between the low-risk strategy and the high-risk strategy.

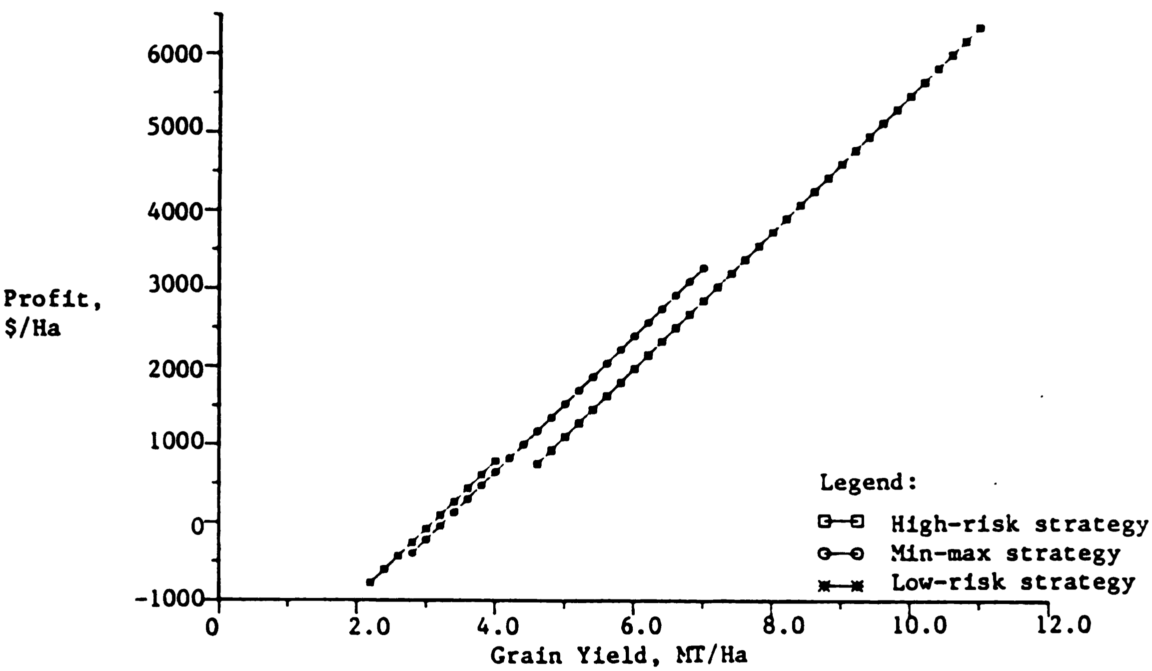

Figure 8.2.6. Profitlines of low-risk, min-max, and high-risk strategies.

To give a more concrete handle on the use of standard deviation as a measure of risk, Table 8.2.5 presents ± 1 standard deviation within the mean of the low-risk, high-risk, and min-max strategies so far discussed. The low-risk strategy is expected to yield 3.16 MT/Ha with a standard deviation of ± 0.302 MT/Ha. The probability of the actual yield being between 2.86-3.46 MT/Ha is 0.682. However, the profit range is between $ -201.08 - 322.12. Thus, the low-risk strategy has 0.682 probability of lossing as much as $ 201.08 or gaining up to $ 322.12. The min-max strategy is expected to yield 4.94 MT/Ha with a standard deviation of ± 0.708 MT/Ha. It has 0.682 probability that the actual yield will be between 4.23-5.65 MT/Ha, with profit between $ 853.56 - 2091.80. In the same manner, the high-risk strategy is expected to yield 7.74 MT/Ha with a standard deviation of ± 1.134 MT/Ha. It has 0.682 probability that the actual yield will be between 6.61-8.87 MT/Ha, with profit between $ 2508.92-4479.64.

TABLE 8.2.5. WITHIN ± 1 STANDARD DEVIATION FOR LOW-RISK, MIN-MAX, AND HIGH-RISK STRATEGIES

Strategy	Yield Range (MT/Ha)	Profit Range ($/Ha)
Low-risk ($\hat{\mu}$=3.16, S=± 0.302)	2.86-3.46	-201.08 - 322.12
Min-max ($\hat{\mu}$=4.94, S=± 0.708)	4.23-5.65	853.56 - 2091.80
High ($\hat{\mu}$=7.74, S=± 1.134)	6.61-8.87	2508.92 - 4479.64

Each point in the Pareto optimal curve and the min-max optimum solution represents an average condition over the 25 simulations. For example, in Table 8.2.1 and Figure 8.2.1, the min-max strategy is more profitable than the low-risk strategy "on the average." But is the min-max solution always more profitable than the low-risk strategy over the 25 simulation runs? In the same way, is the min-max solution always less profitable than the high-risk strategy ? To answer this question, a yearly comparison was done in such a way that the only difference were the specification of the production strategy, $\bar{u}$. Since SMOT is using actual weather data and field-measured soil data, these conditions provide for a "common scenario" in the yearly comparison. This yearly comparisons are presented in Tables 8.2.6 and 8.2.7; the graphical illustrations are shown in Figures 8.2.7 and 8.2.8. The vertical axis in Figure 8.2.7 is profit for the low-risk strategy while the horizontal axis is the profit for the min-max strategy. The vertical axis in Figure 8.2.8 is profit for the high-risk strategy while the horizontal axis is the profit for the min-max strategy. The 45^{o} line in Figures 8.2.7 and 8.2.8 is a path along which there is no difference in performance between the two strategies (Manetsch, 1986). Figure 8.2.7 shows that the yearly profit of the min-max strategy are consistently greater than the low-risk strategy, while Figure 8.2.8 illustrates that the yearly profit of the high-risk strategy is consistently greater than the min-max strategy. These results, however, do not provide for an outright conclusion in favor of high profit due to the high-risk strategy because of cost functions, model limitations, and greater variability. The high-risk strategy involves high inputs and, consequently, high cost. Capital and input

TABLE 8.2.6. YEARLY COMPARISON BETWEEN LOW-RISK AND MIN-MAX STRATEGIES

Simulation Run No.	Profit for Low-Risk ($)	Profit for Min-max ($)
1	-105.16	1211.08
2	-61.56	1681.96
3	200.04	2161.56
4	200.04	1533.72
5	-9.24	1298.28
6	-113.88	993.08
7	479.08	2632.44
8	69.24	1647.08
9	383.16	2196.44
10	278.52	1908.68
11	173.88	1080.28
12	313.40	1795.32
13	-715.56	173.40
14	-183.64	435.00
15	-70.28	1141.32
16	139.00	2013.32
17	173.88	1516.28
18	452.92	2623.72
19	304.68	1926.12
20	182.60	1716.84
21	-218.52	1219.80
22	-87.72	1333.16
23	-201.08	914.60
24	104.12	818.68
25	-157.48	862.28

TABLE 8.2.7. YEARLY COMPARISON BETWEEN HIGH-RISK AND MIN-MAX STRATEGIES

Simulation Run No.	Profit for Min-Max ($)	Profit for High-Risk ($)
1	1211.08	3267.56
2	1681.96	3677.40
3	2161.56	5656.84
4	1533.72	4061.08
5	1298.28	3668.68
6	993.08	2805.40
7	2632.44	5116.20
8	1647.08	3703.56
9	2196.44	4470.92
10	1908.68	3721.00
11	1080.28	2979.80
12	1795.32	3433.24
13	173.40	1671.80
14	435.00	2430.44
15	1141.32	2474.04
16	2013.32	4235.48
17	1516.28	2988.52
18	2623.72	4793.56
19	1926.12	4436.04
20	1716.84	3572.76
21	1219.80	2726.92
22	1333.16	4148.28
23	914.60	3093.16
24	818.68	2055.48
25	862.28	2168.84

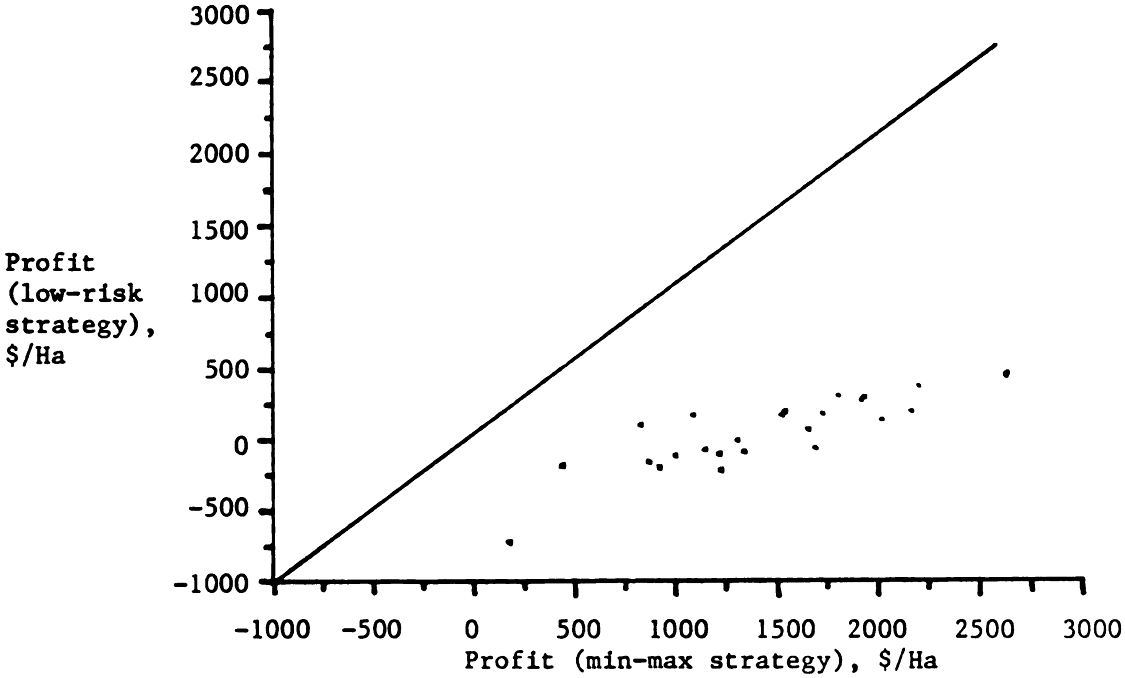

Figure 8.2.7. Yearly comparison between low-risk and min-max strategies.

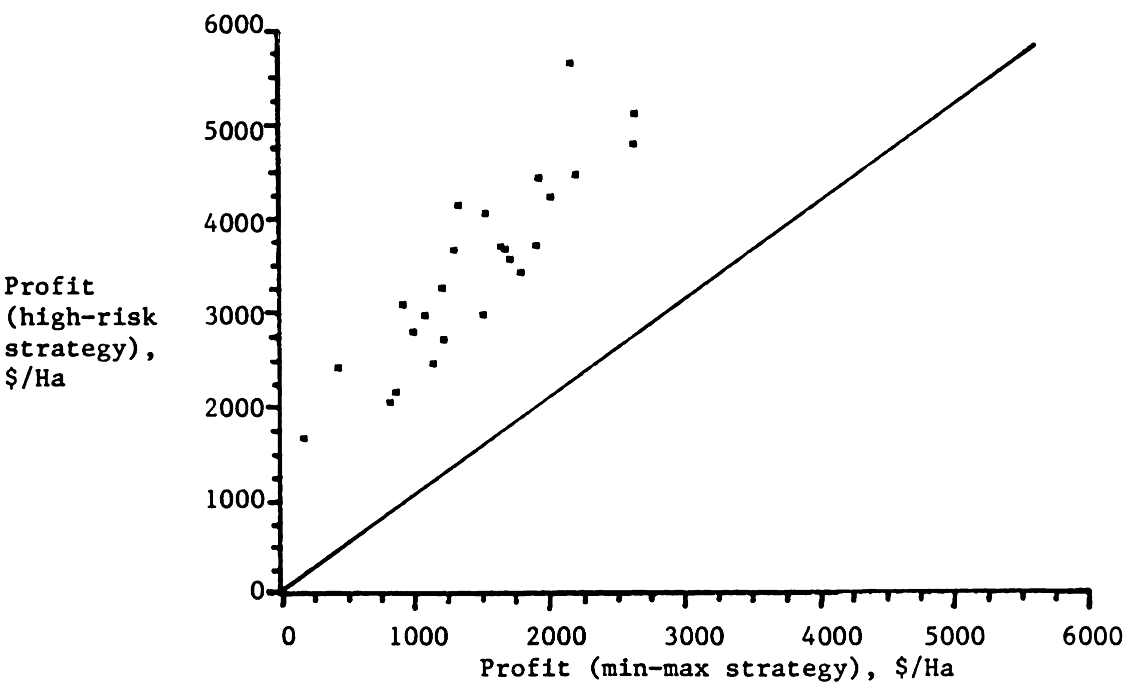

Figure 8.2.8. Yearly comparison between min-max and high-risk strategies.

availability are major constraints in developing countries. The possibilities of typhoons, pest infestation, and other natural catastrophies, which are assumed to have no destructive effect on the simulation, are major contributors to the risk factor for the producer. These risks are in addition to an already existing variability of ± 1.134 MT/Ha due to the stochastic weather conditions. The market system, which has been assumed constant in the model, introduces additional uncertainty with which the rice producer will have to reckon. Thus, the high-risk strategy is good only if the producer has (1) access to capital and inputs, and (2) courage to "play the high-risk game." To "play well" the user of SMOT must incorporate information derived from this tool with information on the market situation, forecasts on pest infestation and occurrence of typhoon, government policies, and other factors to arrive at a final production strategy.

CHAPTER IX

CONCLUSION

The needs analysis indicates that rice deficiency in many countries is due largely to low yields and that the technology exists for increasing yields commensurate with population growth in the near future. The primary barrier to implementation of high-yielding agrotechnologies is the economic environment of the farmer and his/her perceptions of profit and risk in this environment. Under present economic conditions, the farmer cannot, and does not, strive for maximum yields or maximum profit alone because the perceived risks are too high and the cost of inputs may be beyond reach. Both issues, profit and risk, must be dealt with simultaneously at policy levels as well as the farm level to overcome the low-yield syndrome. The rice simulation model and the simulation-multicriteria optimization technique presented here are developed as computer software tools in support of analysis and strategic planning at both the policy and farm levels of organization.

The rice simulation model is a first approximation to a practical and flexible computer software for simulating upland rice production. The simulation software is intended to be used as a tool in assessing the yield potential of alternative agrotechnologies from high-yielding countries to low-yielding countries, or from its site of origin to new locations within the tropical and subtropical regions of the world. The conventional research/demonstration method of transferring new rice varieties and management practices from one soil type and climatic environment to another requires time, money, and careful field evaluation. In using the simulation model, the initial trial-and-error experimentation in selecting new varieties and management practices under a specific soil type and climatic environment can, to a degree, be done in the computer. Those varieties and management practices that look promising are the principal technologies to be tried in the field. This procedure is expected to reduce dramatically the cost, time, and risks involved in agrotechnology transfer.

The simulation-multicriteria optimization technique (SMOT), using the rice simulation model, is an initial attempt to develop a software package that quantifies the trade-offs between profit and risk of alternative rice technologies under farm conditions. SMOT is presented as a first generation decision support system for use by extension workers, researchers, and policy-makers in the economic analysis of rice farms. Alternative production strategies can be tested through SMOT to help identify problems and issues before they actually occur in the field.

As with all computer software packages, a note of caution is in order when using SMOT. SMOT will not, and is not, intended to eliminate all the uncertainties in decision-making. It will help to illuminate some of its dimensions. The value of SMOT in the decision-making process depends upon the user's understanding of its strength and limitations as well as his/her attitude toward profit and risk. Attitude is conditioned by the user's expectations of the performance of SMOT, the amount of information available at the time the choice of production strategy is made, and the user's access to the controllable inputs. SMOT is not intended to replace the vital role of the farmer or farm advisor or the policy-maker in the decision-making process. SMOT is not a decision-making instrument. It should be viewed as a tool to increase the farm advisor's or policy-maker's understanding of the system performance, help quantify preferences, and improve overall decision-making ability.

As an initial work, SMOT can provide a base for further research activities in order to improve its capability and usefulness. The rice simulation software has been structured in a modular form so that a pest module or other "plant stress" modules hopefully can be added as a logical and useful extension with minimum effort. An upcoming addition is the nitrogen transformations under lowland, flooded condition. Consequently, the method of planting will include transplanting of seedlings from seedbeds. This particular addition will expand the utility of SMOT to paddy rice production. Another area of planned expansion is in the timing of fertilizer application, i.e., fertilizers to be applied at different times during the growing season. Phosphorus, potassium, and zinc are nutrients which are important in rice production. These nutrients can be modelled and incorporated in the simulation software.

SMOT is set up in such a way that any of the CERES crop simulation models can be incorporated in place of the rice simulation model. Hence, SMOT as a decision support system can be expanded to include the evaluation of profit and production risk involving other crops.

To the extent that the price of grain, input costs, marketing costs, and interest rates can be characterized by stochastic parameters, these parameters can be included as non-deterministic factors in SMOT. Incorporation of these factors will increase the usefulness of SMOT among the market-oriented rice producers.

In many Asian countries, the occurrence of typhoon during the monsoon season is practically a yearly event which can completely destroy production areas. To the extent that these events can be characterized stochastically, they can also be incorporated into SMOT with a concomitant increase in its utility.

One procedure for including environmental issues such as nitrate leaching and runoff in SMOT is to include them as constraint functions. Any production strategy violating these constraints will be discarded from the set of Pareto optimal solutions. An alternate procedure is to redefine the objective functions in SMOT so that it can be used to evaluate profit versus nitrate leaching in the soil, or profit versus run-off.

APPENDICES

APPENDIX A

GOODNESS-OF-FIT TEST TO DETERMINE THE PROBABILITY DISTRIBUTION OF GRAIN YIELD

In the analytical evaluation of the two objective functions, to maximize profit and to minimize production risk, information of the mean and standard deviation of grain yield is necessary. The probability distribution of grain yield, that is, its probability density function, must be known in order to find the best (maximum likelihood) estimators for its mean and standard deviation. This information can be generated by applying the goodness-of-fit test.

The hypothesis that the probability distribution of grain yield is normal was evaluated. That is,

$$H_o: \ p_Y(y) = p_o(y) = \frac{1}{\sqrt{2\pi}\,\sigma} e^{-(\frac{1}{2})[(y-\mu)/\sigma]^2}, \ 0 < y < \infty$$

$$H_1: \ p_Y(y) \neq p_o(y)$$

The test was based on whether the random variable grain yield (Y) would satisfy the conditions imposed by Theorems 9.2 and 9.3 from Larsen and Marx (1981, pp. 361, 366).

Theorem 9.2 states that:

"Let $(X_1, X_2, \ldots, X_k)$ be a multinomial random variable with parameters $n, p_1, p_2, \ldots, p_k$. Then:

(a) The cdf of the random variable

$$\sum_{i=1}^{k} \frac{(X_i - np_i)^2}{np_i}$$

converges to the cdf of the χ^2 distribution with k-1 degrees of freedom. (For approximation purposes when n is finite, it is usually recommended that the k classes be defined so that np_i is greater than or equal to 5, for all i.)

(b) At the α level of significance, H_o: $p_1 = p_{1o}, \ldots, p_k = p_{ko}$ is rejected in favor of H_1: at least one $p_i \neq p_{io}$ if

$$c = \sum_{i=1}^{k} \frac{(x_i - np_{io})^2}{np_{io}} \geq \chi^2_{1-\alpha,k-1} \text{ ."}$$

Theorem 9.3 states that:

"Suppose $p_1(\theta), p_2(\theta), \ldots,$ and $p_k(\theta)$ are continuously differentiable functions for θ in some interval I, satisfying the following conditions for each $\theta \in I$:

(a) $\sum_{i=1}^{k} p_i(\theta) = 1.$

(b) $p_i(\theta) > \epsilon > 0,\ 1 \leq i \leq k.$

(c) $p_i'(\theta) \neq 0,\ 1 \leq i \leq k.$

Then for each n there is a maximum-likelihood estimator, $\hat{\theta}_n$, such that $\hat{\theta}_n$ converges to θ. Furthermore, the cdf of

$$C_1 = \sum_{i=1}^{k} \frac{[X_i - np_i(\hat{\theta}_n)]^2}{np_i(\hat{\theta}_n)}$$

converges to the cdf of a χ^2 distribution with k-2 degrees of freedom."

Larsen and Marx made a comment that "*in the more general case, where the p_i's are functions of r unknown parameters, the analogous C_1 is asymptotically chi square with k-1-r degrees of freedom.*"

In these theorems, *n* represents the total number of observations, *k* represents the grouping or class of the *n* observations, *i* is used to index the *p*'s, and cdf means cumulative distribution function.

Table A.1 presents the predicted grain yield of the 25 simulation runs.

TABLE A.1. PREDICTED GRAIN YIELD (MT/Ha) OF IR36 VARIETY OVER 25 SIMULATION RUNS WITH ACTUAL WEATHER DATA

5.12	5.74	6.25	5.45	5.30
4.83	6.84	5.67	6.42	6.05
4.88	5.79	3.81	4.10	5.00
6.22	5.48	6.83	6.03	5.71
5.11	5.26	4.80	4.54	4.56

A histogram of these data is shown in Figure A.1. The distribution looks normal ($N(\hat{\mu}, s^2)$) with $\hat{\mu}$ = 5.43 MT/Ha and s^2 = $(0.78)^2$. Figure A.2 shows the $N[5.43, (0.78)^2]$ density superimposed over the histrogram of Figure A.1.

Following Theorems 9.2 and 9.3, the data from Table A.1 was grouped into a set of nonoverlapping intervals and the probability associated with each one was determined from H_o. Table A.2 presents the grouping into k=4 classes.

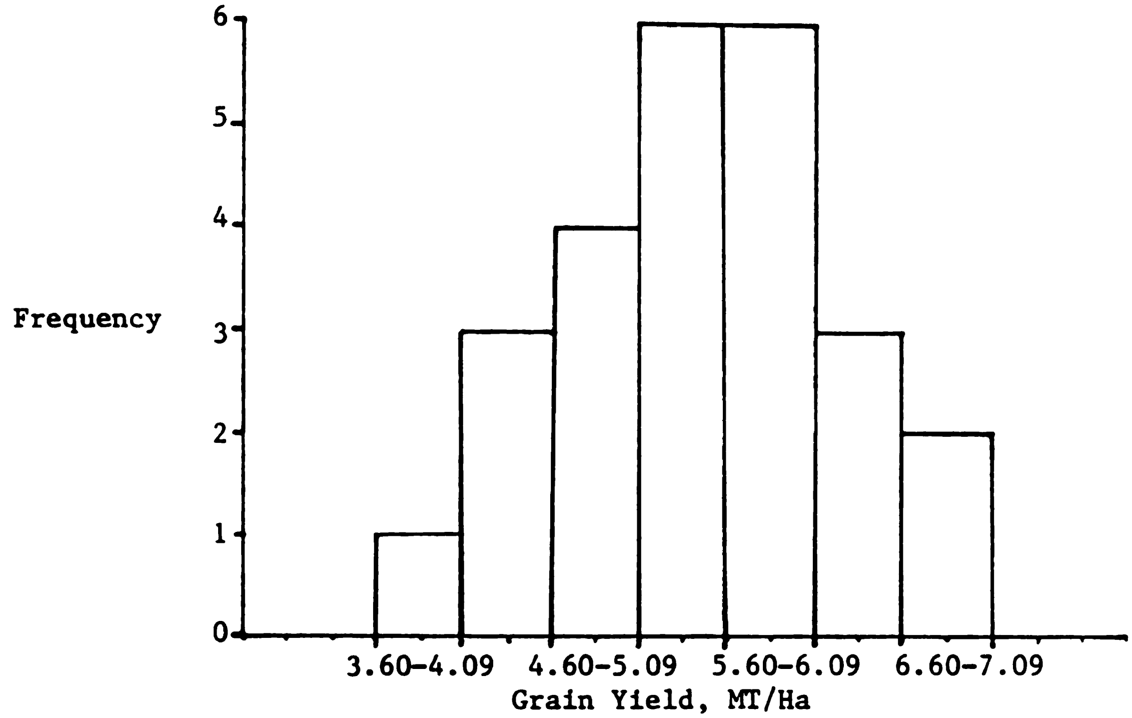

Figure A.1. Histogram of grain yield data.

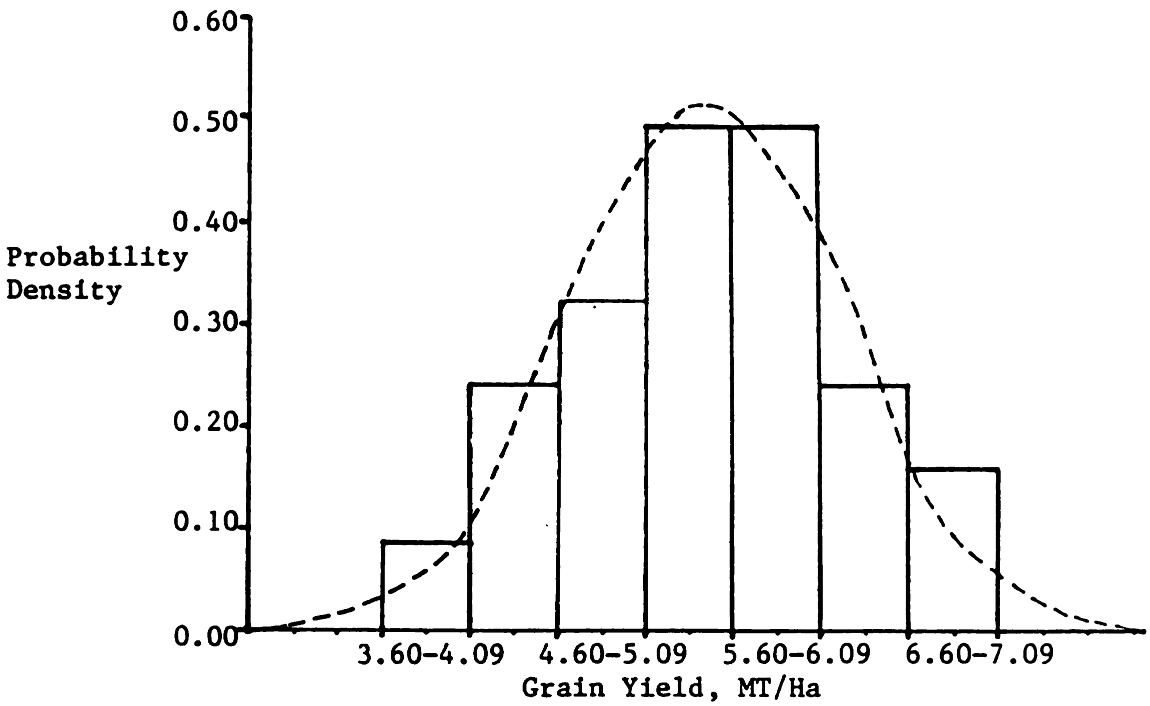

Figure A.2. Normal distribution function superimposed on histogram of grain yield data.

TABLE A.2. GROUPING OF GRAIN YIELD DATA INTO k CLASSES

i	Grain Yield	Observed frequency, y_i
1	$\leq$ 4.80	5
2	4.81-5.30	7
3	5.31-5.80	6
4	$\geq$ 5.81	7
---		--
k=4		25

Using the continuity correction together with the usual Z transformation, and given $\hat{\mu} = 5.43$ and $s = 0.78$, the expected frequency is calculated as follows:

For class 1:

$$P(Y < 4.80) = P(-\infty < Y < 4.80)$$

$$= P\left(-\infty < Z < \frac{4.805-5.43}{0.78}\right)$$

$$= P(-\infty < Z < -0.80)$$

$$= 0.2119 - 0 \quad \text{(from Table A.1 of Larsen and Marx, 1981)}$$

$$= 0.2119 = \hat{p}_{1o}$$

The expected frequency is 5.2975:

$$n\hat{p}_{1o} = 25(0.2119) = 5.2975$$

For class 2:

$$P(4.81 < Y < 5.30) = P\left(\frac{4.805-5.43}{0.78} < Z < \frac{5.305-5.43}{0.78}\right)$$

$$= P(-0.80 < Z < -0.16)$$

$$= 0.4364 - 0.2119 \quad \text{(from Table A.1)}$$

$$= 0.2245 = \hat{p}_{2o}$$

And the expected frequency is 25(0.2245) = 5.6125.

For class 3:

$$P(5.31 < Y < 5.80) = P\left(\frac{5.305-5.43}{0.78} < Z < \frac{5.805-5.43}{0.78} \right)$$

$$= P(-0.16 < Z < 0.48)$$

$$= 0.6844 - 0.4364 \quad \text{(from Table A.1)}$$

$$= 0.2480 = \hat{p}_{3o}$$

And the expected frequency is 25(0.2480) = 6.2000.

For class 4:

$$P(Y > 5.81) = P(5.81 < Y < \infty)$$

$$= P\left(\frac{5.805-5.43}{0.78} < Z < \infty \right)$$

$$= 1.0 - 0.6844 \text{ (from Table A.1)}$$

$$= 0.3156 = \hat{p}_{4o}$$

The expected frequency is 25(0.3156) = 7.890.

Table A.3 lists the $\hat{p}_{io}$'s and the expected frequencies ($n\hat{p}_{io}$'s) for the 4 classes in Table A.2. Table A.3 also shows that the calculated value of C_1 is 0.4666.

TABLE A.3. OBSERVED AND EXPECTED FREQUENCIES OF GRAIN YIELD

i	Grain Yield	y_i	$\hat{p}_{io}$	$n\hat{p}_{io}$	$C_1=(y_i-25\hat{p}_{io})^2/n\hat{p}_{io}$
1	≤ 4.80	5	0.2119	5.2975	0.0167
2	4.81-5.30	7	0.2245	5.6125	0.3430
3	5.31-5.80	6	0.2480	6.2000	0.0065
4	≥ 5.81	7	0.3156	7.8900	0.1004
---		--	------	-------	------
k=4		25	1.0000	25.0000	0.4666 = C_1

Since there were r=2 parameters estimated and k=4 classes, the number of degrees of freedom associated with C_1 is 4-1-2, or 1. At the $\alpha = 0.05$ and $\alpha = 0.10$ levels of significance, the corresponding critical values are 3.841 ($\chi^2_{0.95,1}$) and 2.706 ($\chi^2_{0.90,1}$), respectively. Based on theorems 9.2 and 9.3, the conclusion is to accept the normality assumption of grain yield.

APPENDIX B

FORTRAN PROGRAM OF THE

SIMULATION-MULTICRITERIA OPTIMIZATION TECHNIQUE

Jun 30 14:40 1987 optiml.f Page 1

```
      PROGRAM SMOT
C
C THIS IS THE SIMULATION-MULTICRITERIA OPTIMIZATION TECHNIQUE, VERSION 1.0
C *** DEVELOPED AND PROGRAMMED BY E. C. ALOCILJA *************************
C *** WITH FINANCIAL SUPPORT FROM IBSNAT *********************************
C *** MICHIGAN STATE UNIVERSITY, EAST LANSING, MI 48824 ******************
C
      DIMENSION XO(2,10),FO(2),X(10),F(2),XOP(10),FOP(2),XSTAR(10),
     + FSTAR(2),G(20),XP(10,500),FP(2,500),XA(10),XB(10),YMEANP(500)
C
C THE OPTIMIZATION MODEL IS SET-UP FOR THE FOLLOWING:
C     MAX. NO. OF OBJECTIVE FUNCTIONS, K = 2, i.e. F(1),F(2)
C     MAX. NO. OF DECISION VARIABLES, N = 10, i.e. X(1),X(2),...,X(N)
C     MAX. NO. OF CONSTRAINT FUNCTIONS, G = 20, i.e. G(1),G(2),...,G(20)
C     MAX. NO. OF SEARCH RUNS, LA = 500
C     THE FOLLOWING VARIABLES ARE DEFINED:
C        L = COUNTER FOR NO. OF RUNS, i.e. L=1,2,...,LA
C        J = COUNTER FOR NO. OF PARETO OPTIMAL SOLUTIONS
C        JA = MAX. NO. OF PARETO OPTIMAL SOLUTIONS, i.e. J=1,2,...,JA
C        NCYCLE = MAXIMUM NO. OF SIMULATION RUNS FOR EVERY SET OF DECISION VARIA
C        M = MAXIMUM NO. OF CONSTRAINTS
C
C THE USER-SUPPLIED SUBROUTINES ARE: CONST, FUNC, LIMITS
C
C SUBROUTINE CONST MUST BE CALLED FIRST BEFORE ANY SIMULATION RUN TO CHECK IF
C   THE INPUTS (DECISION VARIABLES, X) ARE WITHIN THE LIMITS OF THE CONSTRAINT
C   FUNCTIONS.  IN THIS CASE, INPUT FILES MUST BE READ FIRST BEFORE CALLING
C   SUBROUTINE CONST.
C
C ******* OPEN STATEMENTS ***************************************************
C
      OPEN (100,FILE='OUTOPT',ACCESS='SEQUENTIAL',STATUS='OLD')
C
C ***** INITIALIZATION FOR NUMBER OF PARETO CURVES TO BE GENERATED **********
C
      IWRITE=1
      IPAR=1
      CALL LIMITS (IPARCRV,LA,N,NCYCLE,XA,XB)
C
C ****** INITIALIZATION OF VARIABLES *****************************************
C
    1 DO 5 JL=1,20
        G(JL)=0.+1.E-10
    5 CONTINUE
      K=2
      JA=1
      FO(1)=1000000000.
      FO(2)=1000000000.
      FP(1,1)=1000000000.
      FP(2,1)=1000000000.
      L=1
C
C *********** SUBROUTINE RANDOM WILL GENERATE RANDOM POINTS OF X'S ***********
C
      IF (IPAR.GT.1.AND.IPAR.LE.IPARCRV) CALL RANDOM (1,1,XA,XB,X)
   10 IF (L.GT.1) CALL RANDOM (2,N,XA,XB,X)
```

Jun 30 14:40 1987 optim1.f Page 2

```
C
C ************ SUBROUTINE CONST WILL CHECK FOR FEASIBLE POINTS **************
C
      IF (NCYCLE.GT.1.AND.IWRITE.NE.1) THEN
         CALL CONST (G,M,X)
         DO 20 JL=1,M
           IF (G(JL).LT.0.) THEN
              L=L+1
              IF (L.LE.LA) GO TO 10
              L=L-1
              GO TO 50
           END IF
   20    CONTINUE
      END IF
C
C ***** SUBROUTINE RICE IS THE CERES-RICE MODEL WHICH WILL ESTIMATE YIELD ****
C ***** GIVEN FEASIBLE INPUT VARIABLES ****************************************
C
      NSIM=0
      YSUM=0.
      YSQRSUM=0.
      DO 25 I=1,NCYCLE
         YIELD=0.
         NSIM=NSIM+1
         CALL RICE (IPAR,IWRITE,NCYCLE,NSIM,X,YIELD)
         YSUM=YSUM+YIELD
         YSQRSUM=YSQRSUM+(YIELD**2)
         IF (LA.EQ.1.AND.NCYCLE.GT.1) WRITE (100,200) I,YIELD
  200    FORMAT (5X,'I = ',I5,5X,'YIELD = ',F6.2)
   25 CONTINUE
      YSUMSQR=YSUM**2
      YMEAN=YSUM/NCYCLE
C
C *********** SUBROUTINE FUNC CONTAINS THE OBJECTIVE FUNCTIONS ***************
C *********** THIS SECTION WILL GENERATE THE IDEAL VECTOR FO ****************
C
      IF (NCYCLE.EQ.1) GO TO 999
C
      CALL FUNC (F,YMEAN,YSQRSUM,YSUMSQR,NCYCLE,X)
C
      CALL OUTP (F,IPAR,IPARCRV,IWRITE,L,LA,NCYCLE,X,YMEAN)
C
      DO 30 I=1,K
         IF (F(I).LT.FO(I)) THEN
            FO(I)=F(I)
            DO 40 I1=1,N
               XO(I,I1)=X(I1)
   40       CONTINUE
         END IF
   30 CONTINUE
C
C ****** SUBROUTINE PARETO WILL CREATE A SET OF PARETO OPTIMAL SOLUTIONS *****
C
      CALL PARETO (K,N,X,F,JA,XP,FP,YMEAN,YMEANP)
      IF (L.LT.LA) THEN
         L=L+1
```

```
         GO TO 10
      END IF
C
   50 DO 60 J=1,JA
         DO 70 J1=1,N
            X(J1)=XP(J1,J)
   70    CONTINUE
         DO 80 J2=1,K
            F(J2)=FP(J2,J)
   80    CONTINUE
         CALL MINMAX (K,N,J,JA,FO,X,F,XOP,FOP,YMEANP,YSTAR,ZMIN)
   60 CONTINUE
C
      ZSTAR=ZMIN
      CALL OUTPT (FO,XO,FP,XP,FOP,XOP,JA,K,L,N,YMEANP,YSTAR,ZSTAR)
C **** END OF EACH PARETO OPTIMAL CURVE AND MIN-MAX OPTIMUM EVALUATION ***
C
      IF (IPAR.LT.IPARCRV) THEN
         IPAR=IPAR+1
         GO TO 1
      END IF
C ***THE ABOVE SECTION DETERMINES THE NUMBER OF PARETO OPTIMAL CURVES TO
C       BE GENERATED AS AFFECTED BY THE SOWING OR PLANTING DATE **********
C
 999  END


      SUBROUTINE MINMAX (K,N,J,JA,FO,X,F,XOP,FOP,YMEANP,YSTAR,ZMIN)
      DIMENSION XO(1),FO(2),X(10),F(2),XOP(10),FOP(2),ZI(2),ZMAX(500),
     + ZI2(500),XTEMP(10),FTEMP(2),YMEANP(500)
C
      CALL MAX (K,ZI,F,FO)
      IF (ZI(1) .EQ. 0 .AND. ZI(2) .EQ. 0) THEN
         ZMIN=0.
         DO 5 JJ=1,N
            XOP(JJ)=X(JJ)
    5    CONTINUE
         DO 7 II=1,K
            FOP(II)=F(II)
    7    CONTINUE
         J=JA
         YSTAR=YMEANP(J)
         GO TO 88
      END IF
      ZMAX(J)=AMAX1(ZI(1),ZI(2))
      DO 10 I=1,K
      IF (ZI(I) .NE. ZMAX(J)) ZI2(J)=ZI(I)
   10 CONTINUE
      IF (J .EQ. 1) THEN
         ZMIN=ZMAX(J)
         DO 20 J1=1,N
            XOP(J1)=X(J1)
   20    CONTINUE
         DO 30 J2=1,K
            FOP(J2)=F(J2)
```

```
   30    CONTINUE
         YSTAR=YMEANP(J)
         GO TO 88
      END IF
      IF (ZMAX(J) .LE. ZMIN) THEN
         IF (ZMAX(J) .EQ. ZMIN) THEN
         DO 40 J3=1,N
            XTEMP(J3)=XOP(J3)
   40    CONTINUE
         DO 50 J4=1,K
            FTEMP(J4)=FOP(J4)
   50    CONTINUE
            ZI2MIN=AMIN1(ZI2(J),ZI2(J-1))
            IF (ZI2MIN .EQ. ZI2(J)) THEN
               ZMIN=ZMAX(J)
               DO 60 J5=1,N
                 XOP(J5)=X(J5)
   60          CONTINUE
               DO 70 J6=1,K
                 FOP(J6)=F(J6)
   70          CONTINUE
               YSTAR=YMEANP(J)
            ELSE
               DO 80 J7=1,N
                 XOP(J7)=XTEMP(J7)
   80          CONTINUE
               DO 90 J8=1,K
                 FOP(J8)=FTEMP(J8)
   90          CONTINUE
               YSTAR=YMEANP(J)
            END IF
         ELSE
            ZMIN=ZMAX(J)
            DO 100 J9=1,N
               XOP(J9)=X(J9)
  100       CONTINUE
            DO 110 J10=1,K
               FOP(J10)=F(J10)
  110       CONTINUE
            YSTAR=YMEANP(J)
         END IF
      END IF
   88 RETURN
      END
C
C     ****** SUBROUTINE MAX CALCULATES THE FUNCTION RELATIVE INCREMENTS
C            AND CHOOSES THE MAXIMUM INCREMENT ************************
C
      SUBROUTINE MAX(K,ZI,F,FO)
      DIMENSION ZI(2),F(2),FO(2)
      DO 10 I=1,K
         FO(I)=FO(I)+1.0E-10
         F(I)=F(I)+1.0E-10
         ZI(I)=ABS(F(I)-FO(I))/ABS(FO(I))
         Z=ABS(F(I)-FO(I))/ABS(F(I))
         IF (Z .GT. ZI(I)) ZI(I)=Z
```

```
   10 CONTINUE
      RETURN
      END
C
C     **** PARETO SUBROUTINE SELECTS THE SET OF PARETO OPTIMAL SOLUTIONS ****
C
      SUBROUTINE PARETO (K,N,X,F,JA,XP,FP,YMEAN,YMEANP)
      DIMENSION X(10),F(2),XP(10,500),FP(2,500),YMEANP(500)
C
      J=1
   25 KA=0
      DO 20 I=1,K
      IF (F(I) .LE. FP(I,J)) KA=KA+1
   20 CONTINUE
      IF (KA .EQ. K) GO TO 30
      IF (KA .EQ. 0) GO TO 40
      J=J+1
      IF (J .GT. JA) THEN
          JA=JA+1
          DO 55 JJ=1,N
            XP(JJ,JA)=X(JJ)
   55     CONTINUE
          DO 65 II=1,K
            FP(II,JA)=F(II)
   65     CONTINUE
          YMEANP(JA)=YMEAN
           GO TO 40
      ELSE
         GO TO 25
      END IF
   30 DO 50 J1=1,N
      XP(J1,J)=X(J1)
   50 CONTINUE
      DO 60 I=1,K
      FP(I,J)=F(I)
   60 CONTINUE
      YMEANP(J)=YMEAN
      IF (J.LT.JA) THEN
         J=J+1
         GO TO 25
      END IF
   40 RETURN
      END
C
C ************ SUBROUTINE TO GENERATE RANDOM POINTS ******************
C
      SUBROUTINE RANDOM (N1,N,XA,XB,X)
      DIMENSION XA(10),XB(10),X(10)
      DO 10 I=N1,N
        CALL RANDN(RAN)
        X(I)=XA(I)+INT(RAN*(XB(I)-XA(I)))
   10 CONTINUE
      RETURN
      END
C
C*****THE FOLLOWING SUBROUTINE GENERATES A UNIFORM RANDOM NUMBER ON
```

Jun 30 14:40 1987 optim1.f Page 6

```
C*****THE INTERVAL 0 - 1
      SUBROUTINE RANDN(YFL)
      DIMENSION K(4)
      DATA K/2510,7692,2456,3765/
      K(4) = 3*K(4)+K(2)
      K(3) = 3*K(3)+K(1)
      K(2)=3*K(2)
      K(1) = 3*K(1)
      I=K(1)/1000
      K(1)=K(1)-I*1000
      K(2)=K(2) + I
      I = K(2)/100
      K(2)=K(2)-100*I
      K(3) = K(3)+I
      I = K(3)/1000
      K(3)=K(3)-I*1000
      K(4)=K(4)+I
      I = K(4)/100
      K(4)=K(4)-100*I
      YFL=(((FLOAT(K(1))*.001+FLOAT(K(2)))*.01+FLOAT(K(3)))*.001+FLOAT
     *(K(4)))*.01
      RETURN
      END
```

May 26 14:53 1987 optim2.f Page 1

```
$OPTION TRACE OFF
C     ****** OBJECTIVE FUNCTION SUBROUTINE ************************************
C     ****** THE OBJECTIVE FUNCTIONS ARE DEFINED AS FOLLOWS:
C              F(1) = -(MAXIMIZE PROFIT (REVENUE-COST))
C              F(2) = MINIMIZE THE YIELD STANDARD DEVIATION
C     ****** THE FOLLOWING DECISION VARIABLES HAVE BEEN DEFINED:
C              X(1) = DATE OF SOWING
C              X(2) = KG. N/HA. OF FERTILIZER (THE RICE MODEL IS SET
C                       FOR BASAL APPLICATION)
C              X(3) = PLANT POPULATION, HILLS/SQ.M. (TRANSPLANTED)
C                                       PLANTS/SQ.M. (DIRECT-SEEDED)
C *****VARIABLE & FIXED COST PER HA. INCLUDES THE FOLLOWING :
C              IRRIGATION : IF IIRR = 1 - (NO IRRIGATION APPLIED) NO COST
C                                     2 - (IRRIGATION APPLIED USING FIELD
C                                         SCHEDULE) CORRESPONDING COST
C                                     3 - (AUTOMATIC IRRIGATION AT THRESHOLD
C                                         SOIL WATER) FIXED COST
C              LAND PREPARATION
C              PEST CONTROL : WEEDING, INSECT AND DISEASE CONTROL
C              FERTILIZER APPLICATION
C              SEEDS
C              HARVESTING
C              INTEREST OF LOANS
C              OPPORTUNITY COSTS
C              IMPUTED COSTS
C
C ********* OTHER DEFINITIONS:
C              PRICE=price of grain/ton
C
      SUBROUTINE FUNC (F,YMEAN,YSQRSUM,YSUMSQR,NCYCLE,X)
      DIMENSION F(2),X(10)
      PRICE=1020.00
      FIXCOST=2695.00
      TRCOST=0.
      IRCOST=0.
      FERBAG=X(2)/50
      HARCOST=YMEAN*74.*2.
      IF ((FERBAG-AINT(FERBAG)).GT.0) FERBAG=AINT(FERBAG)+1
      F(1)=-(YMEAN*PRICE-TRCOST-IRCOST-FERBAG*70.-HARCOST-FIXCOST)
      F(2)=SQRT((NCYCLE*YSQRSUM-YSUMSQR)/(NCYCLE*(NCYCLE-1)))
      RETURN
      END
C
C     ******** CONSTRAINTS SUBROUTINE *********************************
C     ******** CONSTRAINTS ARE LIMITS IMPOSED ON THE DECISION VARIABLES USUALLY
C              BY THE ENVIRONMENT SUCH AS FARMER'S FINANCIAL CAPACITY, INPUT
C              COSTS, MARKETING COST, AVAILABILITY OF INPUT PRODUCTS, ACCESS TO
C              LENDING INSTITUTIONS, PRODUCTION PRACTICES, CONSUMER PREFERENCE,
C              GOVERNMENT PRODUCTION POLICIES, AVAILABLE TECHNOLOGY,
C              AVAILABILITY OF LABOR, ETC.
C     M = TOTAL NO. OF CONSTRAINT VARIABLES (MAXIMUM IS 20)
C
      SUBROUTINE CONST (G,M,X)
      DIMENSION X(10),G(20)
      FERBAG=X(2)/50
      IF ((FERBAG-AINT(FERBAG)).GT.0) FERBAG=AINT(FERBAG)+1
```

```
      G(1)=1400.00-70.00*FERBAG
      M=1
      RETURN
      END
C
C *********** SUBROUTINE LIMITS DEFINE UPPER AND LOWER LIMITS OF X'S ****
C *********** THE FOLLOWING VARIABLES HAVE BEEN DEFINED:
C  XA(1) = LOWER LIMIT OF SOWING DATE;    XB(1) = UPPER LIMIT OF SOWING DATE
C  XA(2) = LOWER LIMIT OF N FERTILIZER;  XB(2) = UPPER LIMIT OF N FERTILIZER
C  XA(3) = LOWER LIMIT OF PLANT POPULATION; XB(3) = UPPER LIMIT OF PLANT POPULAT
C  N = NO. OF DECISION VARIABLES DEFINED
C  LA = MAXIMUM NO. OF RUNS TO SEARCH FOR X(2)-X(3) POINTS (MAXIMUM IS 500)
C  NCYCLE = MAXIMUM NO. OF SIMULATION RUNS FOR EVERY SET OF
C                            DECISION VARIABLES
C  IPARCRV = MAXIMUM NO. DEFINED TO SEARCH FOR X(1)-POINT, WHERE X(1)=ISOW
C
      SUBROUTINE LIMITS (IPARCRV,LA,N,NCYCLE,XA,XB)
      DIMENSION XA(10),XB(10)
C
      OPEN (30,FILE='LIMITS',ACCESS='SEQUENTIAL',STATUS='OLD')
      REWIND 30
      READ (30,200) IPARCRV,LA,N,NCYCLE
      READ (30,210) XA(1),XB(1)
      I=2
   10 READ (30,220) XA(I),XB(I)
      IF (XA(I).GE.0) THEN
         I=I+1
         GO TO 10
      END IF
      RETURN
C
200   FORMAT (I6,1X,I6,2(1X,I2))
210   FORMAT (I6,1X,I6)
220   FORMAT (F6.2,1X,F6.2)
      END
```

May 29 11:47 1987 optim3.f Page 1

```
C ******** WRITES OUTPUT OF THE OPTIMIZATION PROCEDURE ************
C
      SUBROUTINE OUTP (F,IPAR,IPARCRV,IWRITE,L,LA,NCYCLE,X,YMEAN)
      DIMENSION F(10),X(10)
      ISOW=X(1)
      IF (IWRITE.EQ.1) WRITE (100,500) IPARCRV,LA,NCYCLE
      IF (L.EQ.1) WRITE (100,510) IPAR,ISOW
      F1=-F(1)
      WRITE (100,520) L,X(2),X(3),YMEAN, F1,F(2)
      IWRITE=0
      RETURN
C
500   FORMAT (15X,'FARM PRODUCTION MULTICRITERIA OPTIMIZATION',/,
     +    15X,'********************************************',///,
     +    5X,'OBJECTIVE FUNCTIONS:',/,
     +    8X,'1) MAXIMIZE PROFIT, F(1) ($/Ha)',/,
     +    8X,'2) MINIMIZE FARM PRODUCTION RISK, F(2) (std. deviation',
     +     ' from the ',/,15X,'mean yield)',//,
     +    5X,'DECISION VARIABLES:',/,
     +    8X,'1) SOWING DATE, U(1), (Julian day)',/,
     +    8X,'2) AMOUNT OF N FERTILIZER APPLIED, U(2), (Kg N/Ha)',/,
     +    8X,'3) PLANT POPULATION, U(3), (hills/sq.meter - transplanted)',
     +      /,35X,'(plants/sq.meter - direct-seeded)',//,
     +    5X,'NO. OF U(1)-POINT SEARCH : ',I3,/,
     +    5X,'NO. OF U(2),U(3)-POINT SEARCH :',I5,/,
     +    5X,'NO. OF SIMULATION CYCLES TO GET AVE.YIELD (MT/Ha):',I5)
510   FORMAT (//,5X,'SET NO. ',I3,/,5X,'=======',/,
     +    5X,'THE SET OF FEASIBLE SOLUTIONS ARE :',/,
     +    5X,'-----------------------------------',//,
     +    5X,'U(1)          : ',I3,/,
     +       5X,'(SOWING DATE)',//,
     +    5X,'RUN NO.',5X,'U(2)',9X,'U(3)',22X,'F(1)',6X,'F(2)',/,
     +    14X,'(N FERT.)',2X,'(POPULATION)',2X,'AVE. YIELD',
     +    5X,'(PROFIT)',3X,'(RISK)')
520   FORMAT (6X,I5,5X,F6.0,5X,F7.0,3X,F8.2,6X,F10.2,4X,F5.3)
      END
```

May 29 11:50 1987 optim4.f Page 1

```
      SUBROUTINE OUTPT (FO,XO,FP,XP,FOP,XOP,JA,K,L,N,YMEANP,YSTAR,ZSTAR)
      DIMENSION FO(2),XO(2,10),FP(2,500),XP(10,500),FOP(2),XOP(10),
     +   YMEANP(500)
C
      WRITE (100,220)
      FO1=-FO(1)
      FO2=FO(2)
      WRITE (100,230) FO1,FO2
      WRITE (100,240)
      DO 41 J2=1,JA
        FP1=-FP(1,J2)
        WRITE (100,250) J2,INT(XP(1,J2)),XP(2,J2),XP(3,J2),YMEANP(J2),
     +      FP1,FP(2,J2)
   41 CONTINUE
C
      WRITE (100,270)
      WRITE (100,300) L,ZSTAR
      WRITE (100,280)
      WRITE (100,310) INT(XOP(1)),XOP(2),XOP(3),YSTAR
      WRITE (100,290)
      FOP1=-FOP(1)
      WRITE (100,320) FOP1,FOP(2)
      RETURN
C
  220 FORMAT (//,5X,'THE IDEAL VECTOR OF OBJECTIVE FUNCTIONS ARE: '/,
     +   5X,'---------------------------------------------'/)
  230 FORMAT (5X, 'FO(1)= ',F10.2,5X,'FO(2)= ',F6.3)
  240 FORMAT (//,5X,'THE SET OF PARETO OPTIMAL SOLUTIONS ARE: '/,
     +   5X,'----------------------------------------',/,
     +   7X,'POINT NO.',5X,'U(1)',5X,'U(2)',5X,'U(3)',5X,'YIELD',
     +   5X,'F(1)',5X,'F(2)',/)
  250 FORMAT (11X,I5,4X,I5,3X,F6.0,3X,F6.0,5X,F5.2,1X,F8.2,1X,F8.3)
  270 FORMAT (//,5X,'THE SET OF OPTIMAL SOLUTION IN THE MIN-MAX SENSE:'/,
     +   5X,'------------------------------------------------')
  280 FORMAT (/,5X,'A) OPTIMAL VALUES OF DECISION VARIABLES:'/)
  290 FORMAT (/,5X,'B) OPTIMAL VALUES OF OBJECTIVE FUNCTIONS:'/)
  300 FORMAT (5X,'L* = ',I3,2X,'Z* = ',F10.2)
  310 FORMAT (5X,'U*(1)= ',I3,5X,'U*(2)= ',F5.0,8X,'U*(3)= ',F5.0,5X,
     +        'YIELD* = ',F5.2)
  320 FORMAT (5X,'F*(1)= ',F10.2,8X,'F*(2)= ',F6.3,//,
     +   5X,'#########################################################')
      END
```

May 28 13:24 1987 cerice1.f Page 1

```
$OPTION TRACE OFF
      SUBROUTINE RICE (IPAR,IWRITE,NCYCLE,NSIM,X,YIELD)
C *** CERES-RICE GROWTH AND DEVELOPMENT MODEL  ************************
C     Version 1.10 - for Upland Condition
C     DEVELOPED BY E.C. ALOCILJA, J.T. RITCHIE, AND U. SINGH
C     NITROGEN ROUTINES DEVELOPED BY GODWIN, JONES, ET AL
C     IBSNAT STANDARDIZED I/O STRUCTURES
C ******************************************************************
      CHARACTER *12 FILE1,FILE2,FILE3,FILE4,FILE5,FILE6,FILE7,FILE8,
     +   FILE9,FILEA,FILEB
      CHARACTER *7 OUT1,OUT2,OUT3,OUT4
      CHARACTER PEDON*12,TAXON*60,VARTY*16
      CHARACTER ANS*1,INSTS*2,SITES*2,YR*2,EXPTNO*2,TITLER*20
      CHARACTER INSTE*2,SITEE*2,TITLEE*40,TITLET*40
      CHARACTER INSTW*2,SITEW*2,TITLEW*40,BDATE*8,EDATE*8,DWFILE*12
      CHARACTER *1 IECHC,IEHVC,IFIN
      CHARACTER FTYPE*40
C
      INTEGER TRTNO,YEAR
C
      REAL IFOM,IFON,LAT,LAI,LL,LFWT,NDEM,NFAC,NDEF1,NDEF2,NDEF3,
     +   NH4,NO3,NNOM,NHUM,INSOIL,NOUT,NUP,MF

      COMMON/OBDATA/ XYIELD,XGRNWT,XPNO,XPPAWT,XLAI,XBIOMAS,
     +   XSTRAW,XPSRAT,JDHEAD,JDMAT,XAPTNUP,XATANC
      COMMON/SOIL1/ IDUMSL,PEDON,TAXON
      COMMON/TITLE1/ INSTE,SITEE
      COMMON/TITLE2/ TITLEE,TITLET
      COMMON/TITLE3/ INSTS,SITES
      COMMON/TITLE4/ YR,EXPTNO
      COMMON/TITLE5/ INSTW,SITEW
      COMMON/TITLE6/ TITLEW,TITLER
      COMMON/TITLE7/ BDATE,EDATE,DWFILE
      COMMON/NWRIT/ ATLCH,ATMIN,ATNOX,ATANC,ANFAC
      COMMON/WRIT1/ AES,AEP,AET,AEO
      COMMON/WRIT2/ ASOLR,ATEMX,ATEMN,ARUNOF,ADRAIN,APRECP
      COMMON/WRIT3/ ASWDF1,ASWDF2
      COMMON/WRIT4/ IOUTGR,IOUTWA,JHEAD,KHEAD
      COMMON/IPEXP1/ NFEXP,NWFILE,NSFILE
      COMMON/IPEXP2/ FILE1,FILE2,FILE4,FILE5,FILE6,FILE7,FILE8,FILE9
      COMMON/IPEXP3/ FILEA,FILEB
      COMMON/IPEXP4/ OUT1,OUT2,OUT3,OUT4
      COMMON/IPEXP5/ EFFIRR
      COMMON/IPEXP6/ DSOIL,THETAC
      COMMON/IPTRT1/ PHFAC3
      COMMON/IPTRT2/ P1,P2R,P5,P2O
      COMMON/IPTRT3/ G1,TR
      COMMON/IPTRT4/ STRAW,SDEP,SCN,ROOT
      COMMON/IPTRT5/ NFERT,JFDAY,AFERT,DFERT,IFTYPE
      COMMON/IPTRT6/ SWCON1,SWCON2,SWCON3
      COMMON/IPTRT7/ NIRR,JDAY,AIRR
      COMMON/IPWTH1/ S1,C1
      COMMON/PROGR1/ NDEF1,NDEF2
      COMMON/PROGR2/ SWDF1,SWDF2,SWDF3
      COMMON/OPSEA1/ AMTMIN
      COMMON/IPFRE1/ KOUTGR,KOUTNU,KOUTWA
```

```
      COMMON/SOILR1/ CEP,CES,CET
      COMMON/SOILR2/ NH4,NO3
      COMMON/SOILR3/ SUMES1,SUMES2
      COMMON/SOILN1/ FOM,FON
      COMMON/SOILN2/ IFOM,IFON
      COMMON/SOILN3/ RDCARB,RDCELL,RDLIGN
      COMMON/SOILN4/ SNH4,SNO3
      COMMON/SOILN5/ TEMPMN,TEMPMX
      COMMON/SOILN6/ TIFOM,TIFON
      COMMON/CALDA1/ MO,ND,IYR,JDATE,JDATEX
      COMMON/MINIM1/ TIMOB,TMINF,TMINH,TNNOM
      COMMON/WATBA1/ EO,EP,ES,ET
      COMMON/PHENO2/ CSD1,CSD2
      COMMON/PHENO3/ RNO3U,RNH4U
      COMMON/PHENO4/ CNSD1,CNSD2
C
      DIMENSION ESW(10),RLV(10),PNUP(10),
     +   NNOM(10),DTNOX(10),CNI(10),WFY(10),TFY(10),RNTRF(10),
     +   FOM(10),FON(10),IFOM(10),IFON(10),NHUM(10),HUM(10),FLUX(10),
     +   FLOW(10),SWX(10),NOUT(10),NUP(10),DECR(10),CNR(10),SCNR(10),
     +   RNFAC(10),RNLOSS(10),TMFAC(8),LOC(4),WRN(10),RNO3U(10),
     +   RNH4U(10),RLDF(10),JFDAY(10),AFERT(10),DFERT(10),IFTYPE(10),
     +   OC(10),SNH4(10),SNO3(10),NH4(10),NO3(10),
     +   FAC(10),BD(10),PH(10),ST(10),TO(5),JDAY(26),AIRR(26),
     +   JCNT(12),DLAYR(10),DUL(10),LL(10),SW(10),SAT(10),WF(10),
     +   WR(10),RWU(10),FOCNR(10),SWINIT(10),X(3)
C
      LOGICAL IECHON,IHVON
C
C *** THE SAVE COMMAND (COMMENTED SECTION BELOW) WILL HAVE TO BE
C     ACTIVATED WHEN RUNNING THIS MODEL IN THE HP SYSTEM         *******
C ***********************************************************************
      SAVE DLAYR,LL,DUL,SAT,SWINIT,WR,BD,OC,SW,PH,NSENS,NREP,
     +   NTRT,TRTNO,ISOILT,KVARTY,ISIM,SDEPTH,IIRR,ISWNIT,ISWSWB,
     +   CUMDEP,NLAYR,DEPMAX,SALB,U,SWCON,CN2,TAV,AMP,DMOD,RWUMX,
     +   IVAR,IVARTY,LAT,IPY,INITDA,DSFILE,YEAR
C ***********************************************************************
C
C **** SECTION ADDED WHEN RUN WITH OPTIMIZATION ************************
C
         ISOW=X(1)
         AFERT(1)=X(2)
         PLANTS=X(3)*0.25*0.90
         JFDAY(1)=ISOW-1
C
      IF (NSIM.EQ.1.AND.IWRITE.EQ.1) THEN
C ***********************************************************************
      NREP=0
      KOUTGR=7
      KOUTNU=7
      KOUTWA=7
C
      OPEN (40,FILE='SIM.DIR',STATUS='OLD')
C
C      WRITE (*,101)
C101   FORMAT (//,5X,'  C E R E S   R I C E   M O D E L ',/
```

```
C     +   5X,'  Version 1.10 - Upland Condition ')
C
C      PAUSE
C *** Version 1.10 is for upland rice incorporating a standardized I/O
C      with variables passed as argument List ****************
C
      END IF
C *** END OF IF-THEN BLOCK FOR (NSIM.EQ.1) ****************************
C ****** BEGINNING OF SIMULATION LOOP OF ONE TREATMENT ******************
C
  10  NREP=NREP+1
      NSENS=0
      ICOUNT=1
      IQUIT=0
C
      IF (NSIM.EQ.1.AND.IWRITE.EQ.1) THEN
      CALL IPEXP (NSENS,NREP,NTRT,TRTNO,ISOILT,KVARTY,ISIM,ISOW,
     +   PLANTS,SDEPTH,IIRR,ISWNIT,ISWSWB,YEAR,IPLANT,JTRANSP)
C
120   WRITE (*,105)
105   FORMAT (30(/),2X,'RUN-TIME OPTIONS? ',
     +   //2X,'0)  RUN SIMULATION ',
     +   //2X,'1)  SELECT SIMULATION OUTPUT FREQUENCY ',
     +   //2X,'2)  MODIFY SELECTED MODEL VARIABLES INTERACTIVELY ',
     +   //2X,'<===== CHOICE ? [ DEFAULT = 0 ]')
      READ (5,110) NSENS
110   FORMAT (I2)
      IF (NSENS.LT. 0 .OR. NSENS.GT. 2) THEN
         GO TO 120
      ELSE IF (NSENS.EQ.1) THEN
         CALL IPFREQ (KOUTGR,KOUTNU,KOUTWA)
         GO TO 120
      ELSE IF (NSENS.EQ.2) THEN
         CALL IPEXP (NSENS,NREP,NTRT,TRTNO,ISOILT,KVARTY,ISIM,ISOW,
     +   PLANTS,SDEPTH,IIRR,ISWNIT,ISWSWB,YEAR,IPLANT,JTRANSP)
      END IF
C
      CALL IPTRT (IIRR,NTRT,NSENS,CUMDEP,NLAYR,ISOILT,DEPMAX,SALB,U,
     +   SWCON,CN2,TAV,AMP,DMOD,RWUMX,DLAYR,LL,DUL,SAT,SWINIT,WR,BD,
     +   OC,KVARTY,IVAR,VARTY)
C
      END IF
C *** END OF IF-THEN BLOCK FOR (NSIM.EQ.1) ***********************
C
      IF (NSIM.EQ.1) CALL IPWTH (FILE1,LAT,IPY,INITDA,ISOW,ISIM)
C
C
      CALL IPSWIN (FILE5,DSFILE,DLAYR,SW,PH,SWINIT,NTRT)
C
C *** THE IF-THEN CONDITION BELOW IS ADDED WHEN RUN WITH OPTIMIZATION **
C
      IF (NCYCLE.EQ.1) THEN
      WRITE (*,130)
130   FORMAT (T21,'<===== ENTER RUN IDENTIFIER, HIT <CR> FOR NONE.')
      READ (5,140) TITLER
140   FORMAT (A20)
```

```
      WRITE (*,150)
150   FORMAT ('   Do you want input data echoed to screen (Y/N)?')
      READ (5,160) IECHC
160   FORMAT (A1)
      IF (IECHC.EQ.'Y'.OR.IECHC.EQ.'y') IECHON=.TRUE.
      WRITE (*,170)
170   FORMAT ('   Do you want post harvest comparison with observed',
     +   ' data ',/,'   displayed on the screen (Y/N) ?')
      READ (5,180) IEHVC
180   FORMAT (A1)
      IF (IEHVC.EQ.'Y'.OR.IEHVC.EQ.'y') IHVON=.TRUE.
C
      END IF
C **** END OF CONDITION ****************************************************
C
   30 CALL PROGRI (APTNUP,CRAIN,CUMDTT,CUMPH,DTT,GNP,GRAINN,GPP,
     +   GRN,GRNWT,ISTAGE,ICSDUR,INSOIL,ITRANS,IOUTNU,JDATEX,LAI,LFWT,
     +   NFAC,NHDUP,PA,PAN,PLA,PDL,PDLWT,PERPAWT,PLANTS,PLTWT,
     +   PPAWT,PRECIP,RANC,RNFAC,ROOTN,RTWT,SEEDRV,STMWT,STOVN,STOVWT,
     +   SUMDTT,TANC,TBASE,TILNO,TMNC,TMFAC,TNUP,TRWU,XSTAGE,WTLF)
C
      IF (NCYCLE.EQ.1) CALL OPSEAS (NREP,NTRT,VARTY,IIRR,IECHON,YEAR)
C
      IF (ISWSWB.NE.0) CALL SOILRI (AIRR,CN2,CRAIN,CUMDEP,DEPMAX,
     +   DLAYR,DUL,ESW,FLOW,FLUX,IDRSW,IIRR,INSOIL,JDAY,LL,NLAYR,
     +   RTDEP,RWU,RWUMX,SALB,SAT,SMX,SW,SWEF,SWCON,T,TLL,U,WF,WR)
C
   40 READ (11,70,END=50) IYR,JDATE,SOLRAD,TEMPMX,TEMPMN,RAIN
      SOLRAD=SOLRAD*23.87
C
      IF (ISWNIT.NE.0.AND.ICOUNT.EQ.1) CALL SOILNI (ABD,ALX,AMP,ANG,
     +   BD,CNI,CTNUP,CUMDEP,DD,DEPMAX,DLAYR,DMINR,DMOD,DT,DTNOX,
     +   DUL,HUM,JDATE,LL,NHUM,NLAYR,NNOM,NOUT,NUP,OC,PESW,PH,PNUP,
     +   RCN,RNLOSS,SALB,SAT,SOLRAD,ST,STO,SW,TO,TA,TAV,TFY,
     +   TMN,TPESW,WFY,WRN,Z)
C
      IF (NCYCLE.EQ.1.AND.ICOUNT.EQ.1) CALL ECHO (IECHON,ISWNIT,
     +   YEAR,NTRT,VARTY,LAT,SDEPTH,IIRR,SALB,U,SWCON,CN2,NLAYR,DUL,
     +   DLAYR,LL,SW,SAT,ESW,WR,DEPMAX,TLL,PLANTS,IPLANT,JTRANSP)
C
      IF (JDATEX.EQ.367) CALL CALDAT (IYR,JDATE,JDATEX,MO,ND)
C
      IF (ISWNIT.NE.0) CALL MINIMO (ABD,ALX,AMP,ANG,BD,CNI,
     +   CNR,CUMDEP,DD,DECR,DLAYR,DMINR,DT,DUL,FAC,FOCNR,HUM,
     +   IFOM,JDATE,LL,NHUM,NLAYR,NNOM,PESW,POMR,PONR,RNTRF,
     +   SALB,SAT,SCNR,ST,STO,SOLRAD,SW,TA,TAV,TMN,TO,TFY,WFY,Z)
C
      IF (ISWSWB.NE.0) CALL WATBAL (BD,CUMDEP,DEPMAX,DLAYR,DRAIN,
     +   DTNOX,DTT,DUL,ESW,FAC,FLOW,FLUX,GRORT,HUM,ICSDUR,IDRSW,
     +   IIRR,ISTAGE,ISWNIT,JDATE,LAI,LL,MU,NLAYR,NO3,NOUT,NUP,PESW,
     +   PRECIP,RAIN,RNFAC,RNLOSS,RLDF,RLV,RTDEP,RUNOFF,RWU,RWUMX,
     +   SALB,SAT,SMX,SOLRAD,ST,SW,SWCON,SWX,SWEF,T,TLL,TSW,TRWU,U,
     +   WF,WR)
C
      IF (JDATE.EQ.ISOW.OR.ISTAGE.NE.7) CALL PHENOL (ISWNIT,ISWSWB,
     +   IQUIT,JTRANSP,NCYCLE,PLANTS,SDEPTH,YIELD,SOLRAD,TMFAC,TEMPM,
```

May 28 13:24 1987 cericel.f Page 5

```
     +    IVARTY,VARTY,CUMDTT,SUMDTT,DTT,ISTAGE,TBASE,CUMPH,SWSD,
     +    PLTWT,PPAWT,PERPAWT,PDLWT,WTLF,GRNWT,PLA,LAI,PDL,SEEDRV,GRN,
     +    PA,PAN,TILNO,GPP,GRORT,LFWT,RTWT,STMWT,CUMDEP,ESW,ICSDUR,RLV,
     +    CRAIN,RTDEP,TANC,TCNP,RCNP,RANC,TMNC,VANC,VMNC,XSTAGE,GNP,
     +    NFAC,DSTOVN,ROOTN,STOVN,PDWI,STOVWT,PGRORT,NDEM,PANN,RNFAC,
     +    RNLOSS,TNUP,KOUTGR,FAC,PNUP,DLAYR,LL,SW,NLAYR,RWU,IHVON,
     +    BIOMAS)
C
      IF (ISWNIT.NE.0.AND.NCYCLE.EQ.1) CALL NWRITE (APTNUP,STOVN,
     +    PLANTS,NOUT,TMINF,TMINH,DTNOX,KOUTNU,ISTAGE,IOUTNU,
     +    TANC,NDEF2,NHDUP,APANN,PANN,NO3,NH4,JDATE,NLAYR)
C
      IF (NCYCLE.EQ.1) CALL WRITE (CRAIN,PRECIP,KOUTGR,KOUTWA,ISTAGE,
     +    SOLRAD,RUNOFF,DRAIN,JTRANSP,JDATE,SW,PESW,CUMDTT,CUMPH,LAI,
     +    BIOMAS,RTWT,STMWT,LFWT,PPAWT,TILNO,RTDEP,RLV,ITRANS)
C
      ICOUNT=0
      IF (IQUIT.NE.1) GO TO 40
C
C  ********* END OF DAILY SIMULATION LOOP ***********************
C
C ***** THIS SECTION ADDED WHEN RUN WITH OPTIMIZATION ************
C
      X(1)=ISOW
      X(2)=AFERT(1)
      X(3)=PLANTS/(0.25*0.90)
      IF (NSIM.EQ.NCYCLE) CLOSE (11)
      IF (NCYCLE.NE.1) GO TO 99
C
      WRITE (*,190)
 190  FORMAT (//,'  Simulation complete for this treatment',/,
     +    '    Do you want to simulate another treatment (Y/N) ?')
      READ (5,200) IFIN
 200  FORMAT (A1)
      IF (IFIN.EQ.'Y'.OR.IFIN.EQ.'y') THEN
         CLOSE (11)
         GO TO 10
      ELSE
         WRITE (*,210)
210      FORMAT ('    END OF SIMULATION RUN.')
      END IF
      GO TO 99
C
  50  WRITE (41,220)
      WRITE (*,220)
      CLOSE(11)
C
   70 FORMAT (5X,I2,1X,I3,1X,F5.2,3(1X,F5.1))
   60 FORMAT (5X,F6.2)
  220 FORMAT (15X,' END OF WEATHER DATA. ')
  99  RETURN
      END
```

```
C **********************************************************************
C ************* PROGRAM INITIALIZATION *********************************
C **********************************************************************
      SUBROUTINE PROGRI (APTNUP,CRAIN,CUMDTT,CUMPH,DTT,GNP,GRAINN,GPP,
     +   GRN,GRNWT,ISTAGE,ICSDUR,INSOIL,ITRANS,IOUTNU,JDATEX,LAI,LFWT,
     +   NFAC,NHDUP,PA,PAN,PLA,PDL,PDLWT,PERPAWT,PLANTS,PLTWT,PPAWT,
     +   PRECIP,RANC,RNFAC,ROOTN,RTWT,SEEDRV,STMWT,STOVN,STOVWT,SUMDTT,
     +   TANC,TBASE,TILNO,TMNC,TMFAC,TNUP,TRWU,XSTAGE,WTLF)
C
      REAL INSOIL,LAI,LFWT,NDEF1,NDEF2,NFAC
      COMMON/PROGR1/ NDEF1,NDEF2
      COMMON/PROGR2/ SWDF1,SWDF2,SWDF3
      COMMON/WRIT4/ IOUTGR,IOUTWA,JHEAD,KHEAD
      DIMENSION RNFAC(10),TMFAC(8)
C
      DO 20 L=1,10
        RNFAC(L)=1.0
   20 CONTINUE
      IOUTGR=0
      IOUTWA=0
      IOUTNU=0
      ITRANS=0
      JHEAD=0
      KHEAD=0
      NHDUP=0
      PLTWT=0.0044
      STMWT=0.
      PPAWT=0.
      PDLWT=0.
      TILNO=0.
      PLA=0.
      LAI=0.
      PA=0.
      PERPAWT=0.
      GRNWT=0.
      PDL=0.
      LFWT=0.0035
      RTWT=0.0009
      STOVWT=0.0035
      WTLF=0.4
      CUMPH=0.8
      SEEDRV=0.024*PLANTS
      PAN=0.00095
      GRN=0.000083
      GPP=0.
      ISTAGE=7
      TBASE=8.
      JDATEX=367
      CUMDTT=0.
      SUMDTT=0.
      OUTDTT=0.
      DTT=0.
      GRAINN=1.0
      APTNUP=0.0
      TMNC=0.0045
      XSTAGE=0.1
```

```
      DO 30 I=1,8
        TMFAC(I)=0.931+0.114*I-0.0703*I**2+0.0053*I**3
   30 CONTINUE
      SWDF1=1.0
      SWDF2=1.0
      SWDF3=1.0
      INSOIL=1.1
      TRWU=0.0
      NFAC=1.0
      ICSDUR=0
      NDEF1=1.0
      NDEF2=1.0
      TANC=0.0
      RANC=0.0
      STOVN=0.0
      ROOTN=0.0
      GNP=1.0
      TNUP=0.0
      CRAIN=0.
      PRECIP=0.
      RETURN
      END
C *********************************************************************
C ******* OUTPUT FREQUENCY SELECTION **********************************
C *********************************************************************
      SUBROUTINE IPFREQ (KOUTGR,KOUTNU,KOUTWA)
      WRITE (*,100)
  100 FORMAT(30(/))
  200 WRITE (*,300) KOUTWA
  300 FORMAT(1X,I2,' Days  ','<=== OUTPUT FREQUENCY FOR WATER BALANCE ',
     +'COMPONENTS.', /10X,'<--- NEW VALUE?')
      READ (5,400,ERR = 500) IOUTWA
  400 FORMAT(I2)
      IF (IOUTWA  .LE. 0 .OR. IOUTWA .GE. 100) GO TO 500
      KOUTWA = IOUTWA
C
  900 WRITE (*,1000) KOUTGR
 1000 FORMAT(1X,I2,' Days  ','<=== OUTPUT FREQUENCY FOR GROWTH ',
     +'COMPONENTS.',/10X,'<--- NEW VALUE?')
      READ (5,400,ERR = 700) IOUTGR
      IF (IOUTGR  .LE. 0 .OR. IOUTGR .GE. 100) GO TO 700
      KOUTGR = IOUTGR
C
 1400 WRITE (*,1100) KOUTNU
 1100 FORMAT(1X,I2,' Days  ','<=== OUTPUT FREQUENCY FOR NITROGEN ',
     +'COMPONENTS.',/10X,'<--- NEW VALUE?')
      READ (5,400,ERR = 1200) IOUTNU
      IF (IOUTNU  .LE. 0 .OR. IOUTNU .GE. 100) GO TO 1200
      KOUTNU = IOUTNU
      RETURN
C
  500 WRITE (*,600)
  600 FORMAT(10X,'Output frequency must be an integer number between',
     + ' 1 and 99')
      GO TO 200
C
```

May 20 15:10 1987 cerice2.f Page 3

```
  700 WRITE (*,800)
  800 FORMAT(10X,'Output frequency must be an integer number between',
     + ' 1 and 99')
      GO TO 900
C
 1200 WRITE (*,1600)
 1600 FORMAT(10X,'Output frequency must be an integer number between',
     + ' 1 and 99')
      GO TO 1400
C
      END
C ************************************************************************
C ***********  EXPERIMENT AND TREATMENT SELECTION ********************
C ******************** READS FILE8 ***********************************
C ************************************************************************
      SUBROUTINE IPEXP (NSENS,NREP,NTRT,TRTNO,ISOILT,KVARTY,ISIM,ISOW,
     +   PLANTS,SDEPTH,IIRR,ISWNIT,ISWSWB,YEAR,IPLANT,JTRANSP)
C
      COMMON/TITLE1/ INSTE,SITEE
      COMMON/TITLE2/ TITLEE,TITLET
      COMMON/TITLE4/ YR,EXPTNO
      COMMON/IPEXP1/ NFEXP,NWFILE,NSFILE
      COMMON/IPEXP2/ FILE1,FILE2,FILE4,FILE5,FILE6,FILE7,FILE8,FILE9
      COMMON/IPEXP3/ FILEA,FILEB
      COMMON/IPEXP4/ OUT1,OUT2,OUT3,OUT4
      COMMON/IPEXP5/ EFFIRR
      COMMON/IPEXP6/ DSOIL,THETAC
      CHARACTER INSTE*2,SITEE*2,EXPTNO*2,TITLEE*40,TITLET*40,ANS*1
      CHARACTER *12 FILE1,FILE2,FILE3,FILE4,FILE5,FILE6,FILE7,FILE8,
     +   FILE9,FILEA,FILEB
      CHARACTER *7 OUT1,OUT2,OUT3,OUT4
    . CHARACTER SOWING*1
      INTEGER TRTNO,YEAR
C
      IF (NSENS.EQ.0) THEN
         IF (NREP .EQ. 1) THEN
            NFEXP=1
            NWFILE = 1
            NSFILE = 1
            NTRT  = 1
         END IF
         NFEOLD = NFEXP
         DSFILE = -1
         OPEN (1, FILE = 'RIEXP.DIR',STATUS = 'OLD')
         WRITE (*,200)
  200    FORMAT (30(/),T47,'INST.',T54,'SITE',T60,'EXPT.',
     +   /T6,'LIST OF EXPERIMENTS TO BE SIMULATED',T48,'ID',T55,'ID',
     +   T61,'NO',T66,'YEAR',/T6,35('-'),T47,'----',T54,'----',
     +           T60,'----',T66,'----')
         DO 500 I = 1 , 50
           READ (1,300, END = 600) INSTE,SITEE,YEAR,EXPTNO,TITLEE
  300      FORMAT (2A2,I2,A2,1X,A40,//)
           WRITE (*,400) I,TITLEE,INSTE,SITEE,EXPTNO,YEAR
  400      FORMAT ( T2,I2,')',T7,A40,T48,A2,T55,A2,T61,A2,T66,'19',I2)
  500    CONTINUE
  600    REWIND 1
```

May 20 15:10 1987 cerice2.f Page 4

```
        I = I - 1
C
  700   WRITE (*,800) NFEXP
  800   FORMAT(/,1X,I2,']',2X,'<=== CURRENT EXPERIMENT SELECTION.',
     +  /6X,'<--- NEW SELECTION?  ')
        READ (5,900,ERR = 700) N
  900   FORMAT(I2)
        IF (N .LE. 0 .OR. N .GT. I) GO TO  700
        NFEXP=N
        DO 1300 I = 1,NFEXP
          READ (1,1000) INSTE,SITEE,YEAR,EXPTNO,TITLEE,FILE1,FILE2
          READ (1,1100) FILE4,FILE5,FILE6,FILE7,FILE8,FILE9
          READ (1,1200) FILEA,OUT1,OUT2,OUT3,OUT4
 1000     FORMAT (2A2,I2,A2,1X,A40,2(1X,A12))
 1100     FORMAT (A12,5(1X,A12))
 1200     FORMAT (A12,13X,4(1X,A7))
 1300   CONTINUE
        CLOSE (1)
        NWFILE = 1
        NSFILE = 1
        IF (NFEXP .EQ. NFEOLD) THEN
          NWFILE = 0
          NSFILE = 0
          IF (NREP .GT. 1) GO TO 1600
        ELSE IF (NREP .GT. 1) THEN
           ENDFILE (41)
           ENDFILE (42)
           ENDFILE (43)
           ENDFILE (44)
        END IF
        OPEN (41,FILE = OUT1,STATUS = 'OLD')
        OPEN (42,FILE = OUT2,STATUS = 'OLD')
        OPEN (43,FILE = OUT3,STATUS = 'OLD')
        OPEN (44,FILE = OUT4,STATUS = 'OLD')
        WRITE (40,1500) TITLEE,OUT1,OUT2,OUT3,OUT4
 1500   FORMAT(1X,A40,4(1X,A7))
C
 1600   NLTRT = NTRT
        OPEN (18, FILE = FILE8,STATUS = 'OLD')
        WRITE (*,1700) TITLEE
 1700   FORMAT (30(/),T2,'TRT',T47,'INST.',T54,'SITE',T60,'EXPT.',
     +  /,T2,'NO.',T7,A40,T48,'ID',T55,'ID',T61,'NO',
     +          T66,'YEAR',/,T2,'---',T7,40('-'),T47,'----',
     +          T54,'----',T60,'----',T66,'----')
 1800   READ  (18,1900, END = 2100) TRTNO,TITLET
        WRITE (*,2000) TRTNO,TITLET,INSTE,SITEE,EXPTNO,YEAR
 1900   FORMAT (9X,I2,1X,A40,/)
 2000   FORMAT ( T2,I2,')',T7,A40,T48,A2,T55,A2,T61,A2,T66,'19',I2)
        GO TO 1800
 2100   REWIND 18
        IF (NTRT .GT. TRTNO) NTRT = 1
C
 2200   WRITE (*,2300) NTRT
 2300   FORMAT(/,1X,I2,']',2X,'<=== CURRENT TREATMENT SELECTION ',
     +  /6X,'<--- NEW SELECTION?' )
        READ (5,2400,ERR = 2200) N
```

```
 2400    FORMAT(I2)
         IF (N .LE. 0 .OR. N .GT. TRTNO) GO TO  2200
         NTRT=N
 2500    READ (18,2600,END = 2700) TRTNO,TITLET,ISOILT,KVARTY
 2600    FORMAT (9X,I2,1X,A40,2(1X,I4))
         READ (18,2650,END = 2700) ISIM,ISOW,PLANTS,ROWSPC,SDEPTH,IIRR,
     +     ISWNIT,EFFIRR,DSOIL,THETAC
 2650    FORMAT (I4,1x,I3,1x,F6.2,1x,F6.3,1x,F5.2,2(1x,I2),1x,F6.2,1x,
     +     F5.2,1x,F6.1)
         ISWSWB=1
         IF(IIRR.EQ.4)ISWSWB=0
         IF (TRTNO .NE. NTRT) GO TO 2500
         IF (NTRT .NE. NLTRT) NSFILE = 1
C ************************************************************************
C ******* SECTION TO ATTACH TRANSPLANTING ROUTINE ***********************
C ********* WITH COMMENTED LINES *******************************************
C3000     WRITE (*,2850)
C2850     FORMAT(5X,'Is rice transplanted or direct-seeded ?',
C     +    /,6X,'(Press T for transplanted, D for direct-seeded.)')
C         READ (*,'(A1)') SOWING
C         IF (SOWING.EQ.'T'.OR.SOWING.EQ.'t') THEN
C            WRITE (*,2860)
C2860        FORMAT (5X,'Input number of days in seedbed.')
C            READ (*,2870) NSBED
C2870        FORMAT (I5)
C            JTRANSP=ISOW+NSBED
C            IPLANT=1
C         ELSE IF (SOWING.EQ.'D'.OR.SOWING.EQ.'d') THEN
C ******* THIS SECTION IS FOR DIRECT-SEEDED OR UPLAND CONDITION *******
           IPLANT=0
           DPLANTS=PLANTS
           PLANTS=DPLANTS*0.25*0.90
           JTRANSP=0
C *** REMOVE THE COMMENTS BELOW WHEN ACTIVATING TRANSPLANTING SECTION ****
C         ELSE
C            GO TO 3000
C         END IF
C ******* END OF TRANSPLANTING IF-THEN-ELSE BLOCK ********************
         CLOSE (18)
         RETURN
C
 2700    WRITE (*,2800) NTRT,FILE8
 2800 FORMAT(1X,'Error! Treatment no. ',I2,' missing in file ',A12,'.',
     +1X,'Fix the problem first. Program execution will terminate.')
         CLOSE (18)
         STOP
C
C      NEW SECTION TO MODIFY VALUES FOR ISOW, PLANTS, AND ISWNIT
C
       ELSE IF (NSENS .EQ. 2) THEN
         WRITE (*,'(//,A,I3,A/)')' Current Sowing Date is ',ISOW,
     +     ' day of the year '
         WRITE (*,'(A,$)')' Modify Sowing Date ? (Y,N) : '
         READ (5,'(A1)') ANS
         IF (ANS .EQ. 'Y' .OR. ANS .EQ. 'y') THEN
            WRITE (*,'(A,$)')'   Enter New Value  : '
```

```
            READ (5,'(I3)')ISOW
         END IF
         WRITE (*,'(/A,F6.2,A)')' Current Plant Population is ',DPLANTS,
     +      ' plants per sq. meter '
         WRITE (*,'(A,$)')     ' Modify Plants ?      (Y,N) : '
         READ (5,'(A1)') ANS
         IF (ANS .EQ. 'Y' .OR. ANS .EQ. 'y') THEN
            WRITE (*,'(A,$)') '   Enter New Value   : '
            READ (5,'(F6.2)') DPLANTS
            PLANTS=DPLANTS*0.25*0.90
         END IF
         IF (ISWNIT .EQ. 1) THEN
            WRITE (*,'(/,A,/,A$)')' Inadequate nitrogen is assumed.
     +Nitrogen subroutines are used. ',
     + ' Do you want to suppress use of nitrogen subroutines ? (Y,N) : '
            READ (5,'(A1)') ANS
            IF (ANS .EQ. 'Y' .OR. ANS .EQ. 'y') THEN
               ISWNIT = 0
               WRITE (*,'(A/)')' Adequate nitrogen is assumed. Nitrogen
     +subroutines are not used. '
            END IF
         ELSE
            WRITE (*,'(/,A$/)')' Adequate nitrogen is assumed. ',
     +         ' Do you want to use the nitrogen subroutines ? (Y,N) : '
            READ (5,'(A1)') ANS
            IF (ANS.EQ.'Y' .OR. ANS.EQ.'y') THEN
               ISWNIT=1
               WRITE (*,'(A)')'  Nitrogen subroutines are used. '
            END IF
         END IF
         RETURN
      END IF
C
      END
```

May 20 15:31 1987 cerice3.f Page 1

```
$OPTION TRACE OFF
C *******************************************************************
C ************* TREATMENT SELECTION *********************************
C ************* READS FILE6 AND FILEA *******************************
C *******************************************************************
      SUBROUTINE IPTRT (IIRR,NTRT,NSENS,CUMDEP,NLAYR,ISOILT,DEPMAX,
     +   SALB,U,SWCON,CN2,TAV,AMP,DMOD,RWUMX,DLAYR,LL,DUL,SAT,SWINIT,
     +   WR,BD,OC,KVARTY,IVAR,VARTY)
C
      COMMON/OBDATA/ XYIELD,XGRNWT,XPNO,XPPAWT,XLAI,XBIOMAS,
     +   XSTRAW,XPSRAT,JDHEAD,JDMAT,XAPTNUP,XATANC
      COMMON/SOIL1/ IDUMSL,PEDON,TAXON
      COMMON/TITLE1/ INSTE,SITEE
      COMMON/TITLE3/ INSTS,SITES
      COMMON/TITLE4/ YR,EXPTNO
      COMMON/TITLE5/ INSTW,SITEW
      COMMON/TITLE6/ TITLEW,TITLER
      COMMON/TITLE7/ BDATE,EDATE,DWFILE
      COMMON/IPEXP2/ FILE1,FILE2,FILE4,FILE5,FILE6,FILE7,FILE8,FILE9
      COMMON/IPEXP3/ FILEA,FILEB
      COMMON/IPTRT1/ PHFAC3
      COMMON/IPTRT2/ P1,P2R,P5,P20
      COMMON/IPTRT3/ G1,TR
      COMMON/IPTRT4/ STRAW,SDEP,SCN,ROOT
      COMMON/IPTRT5/ NFERT,JFDAY,AFERT,DFERT,IFTYPE
      COMMON/IPTRT6/ SWCON1,SWCON2,SWCON3
      COMMON/IPTRT7/ NIRR,JDAY,AIRR
C
      CHARACTER *12 FILE1,FILE2,FILE4,FILE5,FILE6,FILE7,FILE8,FILE9,
     +   FILEA,FILEB
      CHARACTER PEDON*12,TAXON*60,VARTY*16
      CHARACTER ANS*1,INSTS*2,SITES*2,YR*2,EXPTNO*2,
     + INSTE*2,SITEE*2,TITLER*20
      CHARACTER INSTW*2,SITEW*2,TITLEW*40,BDATE*8,EDATE*8,DWFILE*12
C
      INTEGER TRTNO
      REAL LL
C
      DIMENSION JDAY(26),AIRR(26),DLAYR(10),LL(10),DUL(10),SAT(10),
     +   SWINIT(10),WR(10),BD(10),OC(10),JFDAY(10),AFERT(10),DFERT(10),
     +   IFTYPE(10),SW(10)
C
      NIRR = 0
      IF (IIRR .EQ. 2 ) THEN
         OPEN (16,FILE = FILE6,STATUS = 'OLD')
  400    READ (16,410,END = 900,ERR = 1100) TRTNO
  410    FORMAT (I2)
         IF (TRTNO .EQ. NTRT) THEN
            NIRR = 0
  700       NIRR = NIRR + 1
            READ (16,420,END = 900,ERR = 1100) ITEMP,AMT
  420       FORMAT (I4,1X,F4.0)
            IF (ITEMP .GT. 0) THEN
C **CONVERT AMT FROM MM TO CM *************************
               JDAY(NIRR) = ITEMP
               AIRR(NIRR) = AMT
```

```
            GO TO 700
          ELSE
            NIRR = NIRR - 1
            CLOSE (16)
          END IF
        ELSE
  500     READ (16,420,END = 900,ERR = 1100) ITEMP
          IF (ITEMP .GT. 0) GO TO 500
          GO TO 400
        END IF
C
C
C     NEW BLOCK ALLOWING IRRIGATION DATA MODIFICATION
C
        IF (NSENS .EQ. 2) THEN
1301      WRITE (*,'(//,17x,A,//,17X,A,//,17X,A))')
     +       '      SELECTED IRRIGATION MANAGEMENT DATA ',
     +       'Event No.      DAY OF EVENT    AMOUNT ADDED (mm)',
     +       '---------      ------------    -----------------'
          DO 1305 MM = 1, NIRR
            WRITE (*,'(20x,I2,14x,I4,16x,F4.0)')MM,JDAY(MM),AIRR(MM)
1305      CONTINUE
          WRITE (*,'(/,A,$)')
     +       '  Do You Want To Modify Any Event Data ? (Y,N) : '
          READ (5,'(A1)') ANS
          IF (ANS .EQ. 'Y' .OR. ANS .EQ. 'y') THEN
           WRITE (*,'(/,A,/)')
     +         '  Enter 0 for Event No. To Continue Simulation.'
            DO 1310 MM = 1,NIRR
              WRITE (*,'(A,$)')'  Enter Event No.           : '
              READ (5,'(I2)')NUMEVENT
              IF (NUMEVENT .EQ. 0 ) GO TO 1400
              IF (NUMEVENT .LT. 1 .OR. NUMEVENT .GT. NIRR) THEN
                WRITE (*,*)' Event No. Not Valid ! '
                GO TO 1301
              END IF
              WRITE (*,'(a,$)')'  Modify Julian Day ? (Y,N) : '
              READ (5,'(A1)')ANS
              IF (ANS .EQ. 'Y' .OR. ANS .EQ. 'y') THEN
                WRITE (*,'(A,$)')'  Enter New Day             : '
                READ (5,'(I4)')JDAY(NUMEVENT)
              END IF
              WRITE (*,'(A,$)')'  Modify Amount ?     (Y,N) : '
              READ (5,'(A1)')ANS
              IF (ANS .EQ. 'Y' .OR. ANS .EQ. 'y') THEN
                WRITE (*,'(A,$)')'  Enter New Amount (mm)     : '
                READ (5,'(F4.0)')AIRR(NUMEVENT)
              END IF
1310        CONTINUE
          END IF
        END IF
      END IF
C
 1400 OPEN (8,FILE = FILEA,STATUS = 'OLD')
 1500 READ (8,1600,ERR = 1900,END = 1700) TRTNO,XYIELD,XGRNWT,XPNO,
     +  XPPAWT,XLAI,XBIOMAS,XSTRAW,XPSRAT,JDHEAD,JDMAT
```

```
1600  FORMAT (9X,I2,1X,F7.1,1X,F5.2,1X,F4.0,1X,F6.0,1X,F5.2,
     + 2(1X,F7.1),1X,F4.2,2(1X,I3))
      IF (TRTNO .EQ. NTRT) THEN
         CLOSE (8)
         CALL IPSOIL (FILE2,NSENS,CUMDEP,NLAYR,ISOILT,DEPMAX,
     +      SALB,U,SWCON,CN2,TAV,AMP,DMOD,SWCON1,SWCON2,SWCON3,RWUMX,
     +      PHFAC3,DLAYR,LL,DUL,SAT,SWINIT,WR,BD,OC,SW)
         CALL IPVAR (FILE9,KVARTY,IVAR,VARTY,P1,P2R,P5,P2O,G1,TR)
         CALL IPNIT (FILE4,FILE7,NTRT,STRAW,SDEP,SCN,ROOT,NFERT,
     +      JFDAY,AFERT,DFERT,IFTYPE,NSENS)
         CALL IDWTH  (FILE1,NSENS)
      ELSE
         GO TO 1500
      END IF
C
      RETURN
C
  900 WRITE (*,1000) NTRT,FILE6
 1000 FORMAT(/10X,'Data on treatment no. ',I3,' missing in ',
     +A12,'Fix the file and re-run the simulation. Program execution',
     + 'will terminate.' )
      CLOSE (16)
      STOP
C
 1100 WRITE (*,1200) FILE6
 1200 FORMAT(/10X,'Error! FORMAT DATA MISS-MATCH IN FILE: ',A12,/10X,
     +          'Fix the file.  Program execution will terminate.')
      CLOSE (16)
      STOP
C
 1700 WRITE (*,1800) NTRT,FILEA
 1800 FORMAT(/,' Error! TREATMENT NO ',I3,' NOT FOUND IN FILE :',A12,
     +    /T8, 'Fix the file. Program execution will terminate.')
      CLOSE (8)
      STOP
C
 1900 WRITE (*,1200) FILEA
      CLOSE (8)
      STOP
C
      END
C **********************************************************************
C *************** SOIL SELECTION ***************************************
C ***************** READS FILE2 ****************************************
C **********************************************************************
      SUBROUTINE IPSOIL (FILE2,NSENS,CUMDEP,NLAYR,ISOILT,DEPMAX,
     +  SALB,U,SWCON,CN2,TAV,AMP,DMOD,SWCON1,SWCON2,SWCON3,RWUMX,
     +  PHFAC3,DLAYR,LL,DUL,SAT,SWINIT,WR,BD,OC,SW)
C
      COMMON/SOIL1/ IDUMSL,PEDON,TAXON
      CHARACTER FILE2*12,PEDON*12,TAXON*60
      REAL LL
      DIMENSION DLAYR(10),LL(10),DUL(10),SAT(10),SWINIT(10),WR(10),
     +   BD(10),OC(10),SW(10)
C
      OPEN (12,FILE = FILE2,STATUS = 'OLD')
```

May 20 15:31 1987 cerice3.f Page 4

```
C
      IF (NSENS .EQ. 0) THEN
  200    READ (12,400,END = 600) IDUMSL,PEDON,TAXON
  400    FORMAT (1X,I2,1X,A12,1X,A60)
         READ (12,201) SALB,U,SWCON,CN2,TAV,AMP,DMOD,SWCON1,
     +      SWCON2,SWCON3,RWUMX,PHFAC3
201      FORMAT(F6.2,1x,F5.2,2(1x,F6.2),2(1x,F5.1),1x,F3.1,1x,
     +      E9.2,1x,F6.1,2(1x,F5.2),1x,F4.2)
C
         J = 0
         CUMDEP=0
  300    J = J + 1
         READ (12,301) DLAYR(J),LL(J),DUL(J),SAT(J),SWINIT(J),
     +      WR(J),BD(J),OC(J)
301      FORMAT(F6.0,5(1x,F6.3),2(1x,F5.2))
         CUMDEP=CUMDEP+DLAYR(J)
         IF (DLAYR(J) .GT. 0) GO TO 300
C
         NLAYR = J - 1
         IF (IDUMSL .EQ. ISOILT) THEN
            DEPMAX=CUMDEP
            CLOSE (12)
            RETURN
         ELSE
            GO TO 200
         END IF
      ELSE
         WRITE (*,100)
  100    FORMAT (30(/),t20,'SOILS IN THE DATA BASE',
     +   /T2,'REF',T20,22('='),/T2,'NO.',T6,'TAXONOMY NAME',T67,
     +   'PEDON NUMBER',/T2,3('-'),T6,60('-'),T67,12('-'))
  401    READ (12,400,END = 800) IDUMSL,PEDON,TAXON
         READ (12,201) SALB,U,SWCON,CN2,TAV,AMP,DMOD,SWCON1,
     +      SWCON2,SWCON3,RWUMX,PHFAC3
C
         J = 0
  302    J = J + 1
         READ (12,301) DLAYR(J),LL(J),DUL(J),SAT(J),SWINIT(J),
     +      WR(J),BD(J),OC(J)
         IF (DLAYR(J) .GT. 0) GO TO 302
         WRITE (*,500) IDUMSL,TAXON,PEDON
  500    FORMAT ( T2,I2,')',T6,A60,T67,A12)
         GO TO 401
C
  800    REWIND 12
C
         ITEMP = ISOILT
  900    WRITE (*,1000) ISOILT
 1000    FORMAT(/1X,I2,']',2X,'<=== SOIL AT THE EXPERIMENTAL SITE',
     +   /6X,'<---  NEW SELECTION? ')
         READ (5,1100,ERR = 900) N
 1100    FORMAT(I2)
         IF (N .LE. 0 .OR. N .GT. IDUMSL) GO TO  900
         ISOILT = N
 1200    READ (12,400,END = 1500) IDUMSL,PEDON,TAXON
         READ (12,201 ,END = 1500) SALB,U,SWCON,CN2,TAV,AMP,DMOD,
```

```
     +       SWCON1,SWCON2, SWCON3,RWUMX,PHFAC3
         J = 0
         CUMDEP=0.
1300     J = J + 1
         READ (12,301,END = 1500) DLAYR(J),LL(J),DUL(J),SAT(J),SW(J),
     +      WR(J),BD(J),OC(J)
         CUMDEP=CUMDEP+DLAYR(J)
         IF (DLAYR(J) .GT. 0) GO TO 1300
         NLAYR = J - 1
         IF (IDUMSL .NE. ISOILT) GO TO 1200
         DEPMAX=CUMDEP
         IF (ISOILT .EQ. ITEMP ) GO TO 1400
         NSFILE = 1
         DSFILE = 1
 1400    CLOSE (12)
         RETURN
      END IF
C
  600 WRITE (*,700) ISOILT,FILE2
  700 FORMAT(/,' Error! SOIL NO ',I3,' NOT FOUND IN FILE :',A12,
     +    /T8, 'Fix the file. Program execution will terminate.')
       CLOSE (12)
       STOP
C
 1500 WRITE (*,1600) FILE2
 1600 FORMAT(/,' Error! END OF DATA IN FILE :',A12,
     +   /T8, 'Fix the file. Program execution will terminate.')
       CLOSE (12)
      STOP
C
      END
C *********************************************************************
C ************ VARIETY SELECTION ***************************************
C ************** READS FILE9 *******************************************
C *********************************************************************
      SUBROUTINE IPVAR (FILE9,KVARTY,IVAR,VARTY,P1,P2R,P5,P2O,G1,TR)
      CHARACTER FILE9*12,VARTY*16
C
      NVARS = 0
      OPEN (19,FILE = FILE9,STATUS = 'OLD' )
      IF (NSENS .EQ. 0) THEN
  200    READ (19,300,END = 500) IVAR,VARTY,P1,P2R,P5,P2O,G1,TR
  300    FORMAT(I4,1X,A16,3F7.2,F6.1,2F6.3)
         IF (IVAR .NE. KVARTY) GO TO 200
         CLOSE (19)
         RETURN
      ELSE
         WRITE (*,10)
10       FORMAT (30(/),23X,'===========================',/
     +                  23X,' VARIETIES IN THE DATA BASE ',/
     +                  23x,'===========================',/)
         NVARS = NVARS + 1
         IF (NVARS .EQ. 1) WRITE (*,100)
  100    FORMAT(/,23x,'   NO.     VARIETY NAME     ',
     +          /,23x,'  ----   ----------------   ')
         IF (NVARS .GT. 14) THEN
```

```
            WRITE (*,'(/,a,$)')'  PRESS <Enter> TO CONTINUE LISTING'
            READ (5,'(A1)')ANS
            WRITE (*,'(7(/))')
            NVARS = 1
            WRITE (*,100)
         END IF
  205    READ (19,300,END = 505) IVAR,VARTY,P1,P2R,P5,P2O,G1,TR
         WRITE (*,400) IVAR,VARTY
  400    FORMAT(25x,I4,3X,A16)
         GO TO 205
  505    REWIND 19
C
  800    WRITE (*,900) KVARTY
  900    FORMAT(/1X,I4,']',1X,'<========= VARIETY SELECTED. ',/5X,
     +   '<-------- NEW SELECTION? ')
         READ (5,1000,ERR = 800) N
 1000    FORMAT(I4)
         IF (N .LE. 0 .OR. N .GT. IVAR) GO TO 800
         KVARTY = N
 1100    READ (19,300,END = 500) IVAR,VARTY,P1,P2R,P5,P2O,G1,TR
         IF (IVAR .NE. KVARTY) GO TO 1100
         CLOSE (19)
         RETURN
      END IF
C
  500 WRITE (*,600) KVARTY,FILE9
  600 FORMAT(/,' Error! VARTY NO ',I3,' NOT FOUND IN FILE :',A12,
     +        /T8, 'Fix the file. Program execution will terminate.')
      CLOSE (19)
      STOP
C
      END
C ********************************************************************
C **************** READS FILE4 & FILE7 *******************************
C ********************************************************************
      SUBROUTINE IPNIT (FILE4,FILE7,NTRT,STRAW,SDEP,SCN,ROOT,NFERT,
     +  JFDAY,AFERT,DFERT,IFTYPE,NSENS)
C         This module will first read variables from File4 and
C       check for existing treatment number choice and issue the
C       appropriate message.  Secondly, the variables from File7
C       will be read and echoed, giving the user an option to
C       change JFDAY, AFERT, DFERT or IFTYPE.
C
      COMMON/TITLE1/ INSTE,SITEE
      COMMON/TITLE3/ INSTS,SITES
      COMMON/TITLE4/ YR,EXPTNO
C
      INTEGER TRTNO
      CHARACTER FILE4*12,FILE7*12,ANS*1,INSTS*2,SITES*2,YR*2,EXPTNO*2,
     +   INSTE*2,SITEE*2
      DIMENSION JFDAY(10),AFERT(10),DFERT(10),IFTYPE(10)
C      -----------------------------------------------------------------
C      FILE4 SECTION
C      -----------------------------------------------------------------
       OPEN (14,FILE = FILE4,STATUS='OLD')
       DO 50 K = 1,10000
```

```
         READ (14,1000,END=99,ERR=98) INSTS,SITES,YR,EXPTNO,TRTNO,
     +                            STRAW,SDEP,SCN,ROOT
         IF (TRTNO .EQ. NTRT) GO TO 97
50    CONTINUE
99    WRITE (*,2000) NTRT,FILE4
      CLOSE (14)
      STOP
C
98    WRITE (*,2006) FILE4
      CLOSE (14)
      STOP
C
97    CLOSE (14)
C
C     ------------------------------------------------------------
C     FILE7 SECTION
C     ------------------------------------------------------------
C
      OPEN (17,FILE = FILE7,STATUS='OLD')
C
100  READ (17,1001,END=999,ERR=998) TRTNO,INSTE,SITEE,YR,EXPTNO
        IF (TRTNO .EQ. NTRT) THEN
           ICOUNT=0
           DO 200 J = 1,10000
              READ (17,1002,ERR=998) JFDAY(J),AFERT(J),
     +                              DFERT(J),IFTYPE(J)
              IF (JFDAY(J) .LT. 0) THEN
                 NFERT=J-1
                 CLOSE (17)
                 RETURN
              END IF
              IF (NSENS .EQ. 2) THEN
                 ICOUNT=ICOUNT+1
                 IF (ICOUNT.EQ.1) THEN
                    WRITE (*,2003) TRTNO
                    WRITE(*,2004)
                 END IF
                 WRITE(*,2005) JFDAY(J),AFERT(J),DFERT(J),IFTYPE(J)
                 WRITE(*,'(/A$)')
     +              ' Do You Want To Modify These Data ? (Y,N) : '
                 READ  (5,2001) ANS
                 IF (ANS .EQ. 'Y' .OR. ANS .EQ. 'y') THEN
                    WRITE (*,'(/A$)')'   Modify Day    ? (Y,N) : '
                    READ (5,2001) ANS
                    IF (ANS .EQ. 'Y' .OR. ANS .EQ. 'y') THEN
                       WRITE (*,'(a$)')'   Enter New Day          : '
                       READ (5,*) JFDAY(J)
                    END IF
                    WRITE (*,'(A$)')'   Modify Amount ? (Y,N) : '
                    READ (5,2001) ANS
                    IF (ANS .EQ. 'Y' .OR. ANS .EQ. 'y') THEN
                       WRITE (*,'(a$)')'   Enter New Amount       : '
                       READ (5,*) AFERT(J)
                    END IF
                    WRITE (*,'(A$)')'   Modify Depth  ? (Y,N) : '
                    READ (5,2001) ANS
```

```
                        IF (ANS .EQ. 'Y' .OR. ANS .EQ. 'y') THEN
                           WRITE (*,'(a$)')'   Enter New Depth       : '
                           READ (5,*) DFERT(J)
                        END IF
                        WRITE (*,'(A$)')'   Modify Type   ? (Y,N) : '
                        READ (5,2001) ANS
                        IF (ANS .EQ. 'Y' .OR. ANS .EQ. 'y') THEN
                           WRITE (*,'(a$)')'   Enter New Type        : '
                           READ (5,*) IFTYPE(J)
                        END IF
                     END IF
                  END IF
200         CONTINUE
         ELSE
            DO 300 M = 1,10000
                READ (17,1002,ERR=998) MDAY
                IF (MDAY .LT. 0) GO TO 100
300         CONTINUE
         END IF
C
999   WRITE (*,2000) NTRT,FILE7
      CLOSE (17)
      STOP
C
998   WRITE (*,2006) FILE7
      CLOSE (17)
      STOP
C
1000  FORMAT (3(A2),a2,1x,I2,4(1x,F5.0))
1001  FORMAT (I2,1x,3(A2),a2)
1002  FORMAT (I4,2(1x,F5.1),1x,I2)
2000  FORMAT (3x,'***** TREATMENT NO. ',I2,' MISSING IN FILE ',A,' !!',
     +/,'Add Missing Treatment to File and Restart.')
2001  FORMAT (A1)
2003  FORMAT (///,15x,'FERTILIZER APPLICATION DATA FOR TREATMENT NO. ',
     +I2,' ')
2004  FORMAT (/,20x,'DAY',5X,'AMOUNT',5X,'DEPTH',5X,'TYPE',/,
     +        20X,'---',5X,'------',5X,'-----',5X,'----')
2005  FORMAT (20X,I3,6X,F5.0,5X,F5.0,6X,I2,/,
     +   ' Note: 1 = Urea ',/,
     +   '       2 = Ammonium nitrate',/,
     +   '       3 = Anhydrous ammonia or Ammonium sulphate',/,
     +   '       4 = Calcium ammonium nitrate',/)
2006  FORMAT (3x,'** READ ERROR ENCOUNTERED ON INPUT FILE ',A12,' !!',
     +/,3x,'Check File Formats and Data. Program will terminate.')
      END
C ***********************************************************************
C ************** WEATHER FILE SELECTION *********************************
C **************** SELECTS FILE1 ****************************************
C ***********************************************************************
      SUBROUTINE IDWTH  (FILE1,NSENS)
      COMMON/TITLE5/ INSTW,SITEW
      COMMON/TITLE6/ TITLEW,TITLER
      COMMON/TITLE7/ BDATE,EDATE,DWFILE
      CHARACTER INSTW*2,SITEW*2,TITLEW*40,BDATE*8,EDATE*8,FILE1*12,
     + DWFILE*12,TITLER*20
```

```
C
      OPEN (2,FILE = 'WTH.DIR',STATUS = 'OLD')
C
      IF (NSENS .EQ. 0) THEN
  200    READ (2,300,END = 600) INSTW,SITEW,TITLEW,BDATE,EDATE,DWFILE
  300    FORMAT (2A2,1X,A40,A8,1X,A8,1X,A12)
         IF (DWFILE .NE. FILE1) GO TO 200
         CLOSE (2)
         RETURN
C
  600    WRITE (*,601) FILE1
  601    FORMAT (1X,'Weather file ',A12,' is missing in WTH.DIR.',
     +1X,'Fix the problem first. Program execution will terminate.')
         CLOSE (2)
         STOP
C
      ELSE
         WRITE (*,100)
  100    FORMAT (30(/),T73,'WEATHER',
     +     /T49,'DATES AVAILABLE',
     +     T66,'INST',T73,'STATION',/T5,'WEATHER DATA SETS AVAILABLE',
     +     T50,'FROM',T56,'UNTIL',T67,'ID',T76,'ID',
     +     /T5,28('-'),T47,8('-'),T56,8('-'),T66,'----',T73,'------')
         DO 501 I = 1,50
          READ (2,300,END = 610) INSTW,SITEW,TITLEW,BDATE,EDATE,DWFILE
          WRITE (*,400) I,TITLEW,BDATE,EDATE,INSTW,SITEW
  400     FORMAT (T2,I2,')',T6,A40,T47,A8,' ',T56,A8,T67,A2,T76,A2)
          IF (DWFILE .EQ. FILE1) IITEMP = I
  501    CONTINUE
  610    REWIND 2
         I = I - 1
         ITEMP = IITEMP
  700    WRITE (*,800) IITEMP
  800    FORMAT(/1X,I2,']',1X,'<=== CURRENT WEATHER FILE SELECTION',
     +     /5X, '<--- NEW SELECTION? ')
         READ (5,900,ERR = 700) N
  900    FORMAT(I2)
         IF (N .LE. 0 .OR. N .GT. I) GO TO 700
         IITEMP = N
         DO 1100 I = 1,IITEMP
           READ (2,1000) INSTW,SITEW,TITLEW,BDATE,EDATE,FILE1
 1000      FORMAT (2A2,1X,A40,A8,1X,A8,1X,A12)
 1100    CONTINUE
         IF (IITEMP .NE. ITEMP) NWFILE = 1
         CLOSE (2)
         RETURN
      END IF
C

      END
C ********************************************************************
C ************** READS INITIAL INFORMATION IN FILE1 ******************
C ********************************************************************
      SUBROUTINE IPWTH (FILE1,LAT,IPY,INITDA,ISOW,ISIM)
      COMMON/IPWTH1/ S1,C1
      CHARACTER FILE1*12
```

May 20 15:31 1987 cerice3.f Page 10

```
      REAL LAT
C
C     READ NEW WEATHER RECORD, IF APPROPRIATE
C
      OPEN (11,FILE = FILE1,STATUS = 'OLD')
      READ (11,600) LAT,XLONG,PARFAC,PARDAT
600   FORMAT(4x,2(1x,f6.2),2(1x,f5.2))
      READ (11,700)  IPY,INITDA
  700 FORMAT(5X,I2,1X,I3,1X,F5.2,2(1X,F5.1),F5.1,1X,F6.2)
      REWIND 11
      IF (ISOW .GE. INITDA .AND. ISIM .GE. INITDA) THEN
         IF (ISOW .GE. ISIM) THEN
            READ (11,600) LAT,XLONG,PARFAC,PARDAT
            S1=SIN(LAT*0.01745)
            C1=COS(LAT*0.01745)
         ELSE
            WRITE (*,300)
  300       FORMAT(/10X,'Water balance must begin on or before the',
     +     'planting date.',/10X,'Fix the crop management file.',
     +     ' Program will terminate.')
            CLOSE (11)
            STOP
         END IF
      ELSE
         WRITE (*,100)
  100    FORMAT(/10X,
     +  'Planting and/or simulation date specified is before the',/10x,
     +  'first available weather day. Fix the file. Program execution',
     +   'will terminate.')
         CLOSE (11)
         STOP
      END IF
C
      RETURN
      END
C ******************************************************************
C ***************** READS FILE5 ************************************
C ******************************************************************
      SUBROUTINE IPSWIN (FILE5,DSFILE,DLAYR,SW,PH,SWINIT,NTRT)
      COMMON/SOILR2/ NH4,NO3
      INTEGER TRTNO
      REAL NH4,NO3
      CHARACTER FILE5*12
      DIMENSION DLAYR(10),SW(10),NH4(10),NO3(10),PH(10),SWINIT(10)
      IF (DSFILE .GT. 0) RETURN
      OPEN (15,FILE = FILE5,STATUS = 'OLD')
  100 READ (15,101,END = 500,ERR = 300) TRTNO
101   FORMAT(I2)
      I = 0
  200 I = I + 1
      READ (15,102,END = 500,ERR = 300) DLAYR(I),SW(I),NH4(I),
     + NO3(I),PH(I)
102   FORMAT(f6.0,1x,f6.3,3(1x,f4.1))
      IF (SW(I).EQ.0.) SW(I)=SWINIT(I)
      IF (DLAYR(I) .GE. 0) GO TO 200
      IF (TRTNO .NE. NTRT) GO TO 100
```

May 20 15:31 1987 cerice3.f Page 11

```
      CLOSE (15)
      RETURN
C
  300 WRITE (*,400) FILE5
  400 FORMAT(/10X,'Erorr! FORMAT DATA MISMATCH IN FILE: ',A12,/10X,
     +      'Fix the file. Program execution will terminate.')
      CLOSE (15)
      STOP
C
  500 WRITE (*,600) FILE5
  600 FORMAT(/10X,'Error! ENDOF DATA IN FILE: ',A12,/10X,
     +      'Fix the file. Program execution will terminate.')
      CLOSE (15)
      STOP
C
      END
```

May 20 16:54 1987 cerice4.f Page 1

```
$OPTION TRACE OFF
C ***********************************************************************
C ********** GENERATES HEADINGS FOR EACH OUTPUT FILE ********************
C ***********************************************************************
      SUBROUTINE OPSEAS (NREP,NTRT,VARTY,IIRR,IECHON,YEAR)
C
      COMMON/SOIL1/ IDUMSL,PEDON,TAXON
      COMMON/TITLE1/ INSTE,SITEE
      COMMON/TITLE2/ TITLEE,TITLET
      COMMON/TITLE3/ INSTS,SITES
      COMMON/TITLE4/ YR,EXPTNO
      COMMON/TITLE5/ INSTW,SITEW
      COMMON/TITLE6/ TITLEW,TITLER
      COMMON/TITLE7/ BDATE,EDATE,DWFILE
      COMMON/OPSEA1/ AMTMIN
      COMMON/IPFRE1/ KOUTGR,KOUTNU,KOUTWA
      COMMON/IPEXP6/ DSOIL,THETAC
C
      CHARACTER PEDON*12,TAXON*60,VARTY*16
      CHARACTER ANS*1,INSTS*2,SITES*2,YR*2,EXPTNO*2,TITLER*20
      CHARACTER INSTE*2,SITEE*2,TITLEE*40,TITLET*40
      CHARACTER INSTW*2,SITEW*2,TITLEW*40,BDATE*8,EDATE*8,DWFILE*12
C
      INTEGER TRTNO,YEAR
      LOGICAL IECHON
C
      WRITE (41,95) TITLER
      WRITE (41,100) NREP
      IF (IECHON) THEN
         WRITE (*,95) TITLER
         WRITE (*,100) NREP
      END IF
   95 FORMAT (//,1X,'RUN IDENTIFIER : ',A20,/)
  100 FORMAT (/1X,'RUN NO. ',I2,' INPUT AND OUTPUT SUMMARY',/)
C
      IF (KOUTGR.GT.0) THEN
         WRITE (42,200) NREP,TITLER
         WRITE (42,600) INSTE,SITEE,EXPTNO,YEAR,NTRT
         WRITE (42,400) TITLEE,TITLET
         WRITE (42,300) TITLEW
         WRITE (42,500) TAXON
         WRITE (42,700) VARTY
      END IF
      IF (KOUTWA.GT.0) THEN
         WRITE (43,200) NREP,TITLER
         WRITE (43,600) INSTE,SITEE,EXPTNO,YEAR,NTRT
         WRITE (43,400) TITLEE,TITLET
         WRITE (43,300) TITLEW
         WRITE (43,500) TAXON
         WRITE (43,700) VARTY
      END IF
      IF (KOUTNU.GT.0) THEN
         WRITE (44,200) NREP,TITLER
         WRITE (44,600) INSTE,SITEE,EXPTNO,YEAR,NTRT
         WRITE (44,400) TITLEE,TITLET
         WRITE (44,300) TITLEW
```

```
          WRITE (44,500) TAXON
          WRITE (44,700) VARTY
       END IF
   200 FORMAT(/1X,'RUN ',I2,' ',A20)
   300 FORMAT (1X,'WEATHER :',A40)
   400 FORMAT (1X,'EXP.     :',A40,
     +        /1X,'TRT.     :',A40)
   500 FORMAT (1X,'SOIL     :',A60)
   600 FORMAT (1X,'INST_ID :',A2,2X,'SITE_ID: ',A2,2X,'EXPT_NO: ',
     +A2,2X,'YEAR : 19',I2,2X,'TRT_NO: ',I2)
   700 FORMAT (1X,'VARIETY :  ',A16)
C
       GO TO (800,1000,1200,1400),IIRR
   800 IF (KOUTGR.GT.0) WRITE (42,900)
       IF (KOUTWA.GT.0) WRITE (43,900)
       IF (KOUTNU.GT.0) WRITE (44,900)
   900 FORMAT (1X,'IRRIG.  :NEVER IRRIGATED, RAINFED.')
       GO TO 1800
  1000 IF (KOUTGR.GT.0) WRITE (42,1100)
       IF (KOUTWA.GT.0) WRITE (43,1100)
       IF (KOUTNU.GT.0) WRITE (44,1100)
  1100 FORMAT(1X,'IRRIG.  :ACCORDING TO THE FIELD SCHEDULE.')
       GO TO 1800
  1200 IF (KOUTGR.GT.0) THEN
          WRITE (42,1300) DSOIL,THETAC
          WRITE (42,1700) AMTMIN
       END IF
       IF (KOUTWA.GT.0) THEN
          WRITE (43,1300) DSOIL,THETAC
          WRITE (43,1700) AMTMIN
       END IF
       IF (KOUTNU.GT.0) THEN
          WRITE (44,1300) DSOIL,THETAC
          WRITE (44,1700) AMTMIN
  1300 FORMAT(1X,'IRRIG.  :IRRIGATED TO F.C. IF AVAILABLE WATER IN ',
     +'TOP ',F4.2,'m DROPS BELOW ',F4.1,' %.',/,
     +' This function Disabled for now.')
  1700 FORMAT(10X,'NOTE: not irrigated if demand is less',
     +' than ',F5.2,'mm')
       END IF
       GO TO 1800
  1400 IF (KOUTGR.GT.0) WRITE (42,1500)
       IF (KOUTWA.GT.0) WRITE (43,1500)
       IF (KOUTNU.GT.0) WRITE (44,1500)
  1500 FORMAT(1X,'IRRIG.  :ASSUMED NO WATER STRESS.')
 1800  RETURN
       END
C ***********************************************************************
C ************* WRITES INPUT VALUES TO OUTPUT FILES *********************
C ***********************************************************************
       SUBROUTINE ECHO (IECHON,ISWNIT,YEAR,NTRT,VARTY,LAT,SDEPTH,IIRR,
     +    SALB,U,SWCON,CN2,NLAYR,DUL,DLAYR,LL,SW,SAT,ESW,WR,DEPMAX,
     +    TLL,PLANTS,IPLANT,JTRANSP)
C
       COMMON/SOIL1/ IDUMSL,PEDON,TAXON
       COMMON/TITLE1/ INSTE,SITEE
```

May 20 16:54 1987 cerice4.f Page 3

```
      COMMON/TITLE2/ TITLEE,TITLET
      COMMON/TITLE3/ INSTS,SITES
      COMMON/TITLE4/ YR,EXPTNO
      COMMON/TITLE5/ INSTW,SITEW
      COMMON/TITLE6/ TITLEW,TITLER
      COMMON/TITLE7/ BDATE,EDATE,DWFILE
      COMMON/IPTRT2/ P1,P2R,P5,P2O
      COMMON/IPTRT3/ G1,TR
      COMMON/IPTRT5/ NFERT,JFDAY,AFERT,DFERT,IFTYPE
      COMMON/IPTRT7/ NIRR,JDAY,AIRR
      COMMON/SOILR2/ NH4,NO3
      COMMON/SOILN4/ SNH4,SNO3
      CHARACTER FTYPE*40,VARTY*16,PEDON*12,TAXON*60,INSTE*2,SITEE*2,
     +   TITLEE*40,TITLET*40,INSTS*2,SITES*2,YR*2,EXPTNO*2,INSTW*2,
     +   SITEW*2,TITLEW*40,TITLER*20,BDATE*8,EDATE*8,DWFILE*12
      REAL LAT,LL,NO3,NH4
      INTEGER YEAR
      DIMENSION JDAY(26),AIRR(26),SNO3(10),SNH4(10),DUL(10),DLAYR(10),
     +   LL(10),SW(10),SAT(10),ESW(10),WR(10),NO3(10),NH4(10),
     +   JFDAY(10),AFERT(10),DFERT(10),FTYPE(6),IFTYPE(10)
      LOGICAL IECHON
C
      DATA FTYPE/'UREA','AMMONIUM NITRATE',
     +'ANHYDROUS AMMONIA OR AMMONIUM SULPHATE',
     +'CALCIUM AMMONIUM NITRATE','M NITRATE',' '/
C
      WRITE (41,600) INSTE,SITEE,EXPTNO,YEAR,NTRT
      WRITE (41,400) TITLEE,TITLET
      WRITE (41,300) TITLEW
      WRITE (41,500) TAXON
      WRITE (41,700) VARTY
  300 FORMAT (1X,'WEATHER :',A40)
  400 FORMAT (1X,'EXP.    :',A40,
     +       /1X,'TRT.    :',A40)
  500 FORMAT (1X,'SOIL    :',A60)
  600 FORMAT (1X,'INST_ID :',A2,2X,'SITE_ID: ',A2,2X,'EXPT_NO: ',
     +A2,2X,'YEAR : 19',I2,2X,'TRT_NO: ',I2)
  700 FORMAT(1X,'VARIETY :',A16,//)
      IF (IECHON) THEN
         WRITE (*,600) INSTE,SITEE,EXPTNO,YEAR,NTRT
         WRITE (*,400) TITLEE,TITLET
         WRITE (*,300) TITLEW
         WRITE (*,500) TAXON
         WRITE (*,700) VARTY
      END IF
      WRITE (41,105) LAT
      IF (IECHON) WRITE (*,105) LAT
      IF (IPLANT.EQ.0) THEN
         DPLANTS=PLANTS/(0.25*0.9)
         WRITE (41,750) DPLANTS
         IF (IECHON) WRITE (*,750) DPLANTS
 750     FORMAT (6X,'PLANT POPULATION = ',F8.2,' plants per sq.',
     +          ' meter')
      ELSE
         WRITE (41,760) PLANTS
         IF (IECHON) WRITE (*,760) PLANTS
```

May 20 16:54 1987 cerice4.f Page 4

```
 760      FORMAT (6X,'PLANT POPULATION = ',F8.2,' hills per sq. meter')
       END IF
       WRITE (41,110) SDEPTH
       WRITE (41,120) P1,P2R,P5,P2O,G1,TR
       WRITE (41,150)
C
       IF (IECHON) THEN
          WRITE (*,110) SDEPTH
          WRITE (*,120)  P1,P2R,P5,P2O,G1,TR
          WRITE (*,150)
       END IF
       IF (IIRR.EQ.1) THEN
          WRITE (41,250)
          IF (IECHON) WRITE (*,250)
250       FORMAT (20X,'(No irrigation applied.)')
       ELSE IF (IIRR.EQ.2) THEN
          DO 2 J = 1, NIRR
             WRITE (41,160) JDAY(J),AIRR(J)
             IF (IECHON) WRITE (*,160) JDAY(J),AIRR(J)
2         CONTINUE
       ELSE IF (IIRR.EQ.3) THEN
          WRITE (41,260)
          IF (IECHON) WRITE (*,260)
260       FORMAT (20X,'(Automatic irrigation.)')
       ELSE
          WRITE (41,270)
          IF (IECHON) WRITE (*,270)
270       FORMAT (20X,'(Water is assumed non-limiting.)')
       END IF
       DL1=0.0
       ANO3=0.0
       ANH4=0.0
       TDUL=0.0
       TSAT=0.0
       TSW=0.0
       TPESW=0.0
       IF (IECHON) THEN
          WRITE (*,130) PEDON
          WRITE (*,140) SALB,U,SWCON,CN2
          WRITE (*,170)
       END IF
       WRITE (41,130) PEDON
       WRITE (41,140) SALB,U,SWCON,CN2
       WRITE (41,170)
       DO 3 L = 1, NLAYR
          DL2=DL1+DLAYR(L)
          ANO3=ANO3+SNO3(L)
          ANH4=ANH4+SNH4(L)
          TDUL=TDUL+DUL(L)*DLAYR(L)
          TPESW=TPESW+(DUL(L)-LL(L))*DLAYR(L)
          TSW=TSW+SW(L)*DLAYR(L)
          TSAT=TSAT+SAT(L)*DLAYR(L)
          WRITE (41,180) DL1,DL2,LL(L),DUL(L),SAT(L),ESW(L),SW(L),
     +    WR(L),NO3(L),NH4(L)
          IF (IECHON) WRITE (*,180) DL1,DL2,LL(L),DUL(L),SAT(L),
     +      ESW(L),SW(L),WR(L),NO3(L),NH4(L)
```

```
          DL1=DL2
3      CONTINUE
       WRITE (41,190) DEPMAX,TLL,TDUL,TSAT,TPESW,TSW,ANO3,ANH4
       IF (IECHON) WRITE (*,190) DEPMAX,TLL,TDUL,TSAT,TPESW,TSW,
      + ANO3,ANH4
       WRITE (41,193)
       IF (IECHON) WRITE (*,193)
       IF (ISWNIT.NE.0) THEN
           WRITE (41,200)
           IF (IECHON) WRITE (*,200)
           DO 4 J = 1, NFERT
               IF (AFERT(J) .EQ. 0.) THEN
                  M = 6
               ELSE
                  M = IFTYPE (J)
                  If (M .EQ. 0) M = 1
               END IF
               WRITE (41,210) JFDAY(J),AFERT(J),DFERT(J),FTYPE(M)
               IF (IECHON) WRITE (*,210) JFDAY(J),AFERT(J),
      +           DFERT(J),FTYPE(M)
4          CONTINUE
       ELSE
           WRITE(41,220)
           IF (IECHON) WRITE(*,220)
        END IF
        RETURN
105    FORMAT (6X,'LATITUDE OF EXPT. SITE =',F6.1,' degrees',/)
110    FORMAT (/6X,'SOWING DEPTH = ',F4.1,' cm.')
120    FORMAT (/6X,'GENETIC SPECIFIC CONSTANTS',3X,'P1 =',F7.2,2X,
      +  'P2R =',F7.2,2X,'P5=',F7.2,/,35X,'P2O =',F6.1,2X,
      +  'G1 =',F6.3,4X,'TR =',F6.3,/)
140    FORMAT (6X,'SOIL ALBEDO = ',F4.2,/,
      +    6X,'UPPER LIMIT OF SOIL EVAPORATION = ',F5.1,/,
      +    6X,'SOIL WATER DRAINAGE CONSTANT = ',F6.2,/,
      +    6X,'SCS RUNOFF CURVE NO.= ',F6.1)
150    FORMAT (/1X,'IRRIGATION SCHEDULE'/,
      +    6X,'   JUL DAY     IRRIGATION (mm.)')
160    FORMAT (8X,I5,7X,F5.0)
130    FORMAT(//1X,'SOIL PROFILE DATA [ PEDON: ',A12,' ]')
170    FORMAT (/6X,'DEPTH OF',2X,'LOWER ',2X,'UPPER',2X,' SAT. ',
      +  1X,'EXTR.',2X,'WATER',3X,'ROOT',3X,'SOIL',3X,'SOIL',/,
      +  6X,'LAYER-cm',2X,'LIMIT ',2X,'LIMIT',1X,'CONTENT',1X,'WATER',
      +  1X,'CONTENT',1X,'FACTOR',2X,'NO3*',3X,'NH4*')
180    FORMAT (3X,F5.0,'-',F5.0,F7.3,1X,4(1X,F6.3),1X,F6.3,2F7.1)
190    FORMAT (/,'TOTAL',' 0.-',F5.0,F7.1,1X,4(1X,F6.1),F14.0,F7.0)
193    FORMAT (/,'  * NOTE: Units are in kg N / ha. ')
200    FORMAT (/1X,'FERTILIZER INPUTS',/,'    JUL DAY',5X,'KG/HA',5X,
      +  'DEPTH','    SOURCE',/)
210    FORMAT (I10,1X,2F10.2,3X,A40)
220    FORMAT (/,' NITROGEN NON-LIMITING',/)
       END
C ********************************************************************
C ******* MANAGES WRITING OF GROWTH AND WATER BALANCE COMPONENTS *******
C ********************************************************************
       SUBROUTINE WRITE (CRAIN,PRECIP,KOUTGR,KOUTWA,ISTAGE,SOLRAD,
      +    RUNOFF,DRAIN,JTRANSP,JDATE,SW,PESW,CUMDTT,CUMPH,LAI,BIOMAS,
```

```
     +   RTWT,STMWT,LFWT,PPAWT,TILNO,RTDEP,RLV,ITRANS)
C
      DIMENSION SW(10),RLV(10)
      REAL LAI,LFWT
      COMMON/WRIT1/ AES,AEP,AET,AEO
      COMMON/WRIT2/ ASOLR,ATEMX,ATEMN,ARUNOF,ADRAIN,APRECP
      COMMON/WRIT3/ ASWDF1,ASWDF2
      COMMON/WRIT4/ IOUTGR,IOUTWA,JHEAD,KHEAD
      COMMON/PROGR2/ SWDF1,SWDF2,SWDF3
      COMMON/SOILN5/ TEMPMN,TEMPMX
      COMMON/WATBA1/ EO,EP,ES,ET
C
      IF (JHEAD.EQ.0) THEN
         AES=0.
         AEP=0.
         AET=0.
         AEO=0.
         ASOLR=0.
         ATEMX=0.
         ATEMN=0.
         ARUNOF=0.
         ADRAIN=0.
         APRECP=0.
         ASWDF1=0.
         ASWDF2=0.
      END IF
C
      CRAIN=CRAIN+PRECIP
      IF (KOUTWA.NE.0) THEN
         IOUTWA=IOUTWA+1
         AES=AES+ES
         AEP=AEP+EP
         AET=AET+ET
         AEO=AEO+EO
         ASOLR=ASOLR+SOLRAD
         ATEMX=ATEMX+TEMPMX
         ATEMN=ATEMN+TEMPMN
         ARUNOF=ARUNOF+RUNOFF
         ADRAIN=ADRAIN+DRAIN
         APRECP=APRECP+PRECIP
          IF (IOUTWA.EQ.KOUTWA) CALL OUTWA (JHEAD,KOUTWA,IOUTWA,
     +        SW,PESW,JDATE)
      END IF
      IF (KOUTGR.EQ.0) RETURN
      IF (ISTAGE.GT.6) RETURN
      IF (JTRANSP.NE.0.AND.JDATE.EQ.JTRANSP) THEN
         CALL OUTGRO (KHEAD,KOUTGR,IOUTGR,JDATE,CUMDTT,CUMPH,LAI,
     +       BIOMAS,RTWT,STMWT,LFWT,PPAWT,TILNO,RTDEP,RLV)
         ITRANS=1
      ELSE
         ITRANS=1
      END IF
      IF (ITRANS.NE.1) RETURN
      IOUTGR=IOUTGR+1
      ASWDF1=ASWDF1+SWDF1
      ASWDF2=ASWDF2+SWDF2
```

May 20 16:54 1987 cerice4.f Page 7

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      IF (IOUTGR.EQ.KOUTGR) CALL OUTGRO (KHEAD,KOUTGR,IOUTGR,
     +   JDATE,CUMDTT,CUMPH,LAI,BIOMAS,RTWT,STMWT,LFWT,PPAWT,
     +   TILNO,RTDEP,RLV)
      RETURN
      END
C ***********************************************************************
C ************* WRITES WATER BALANCE COMPONENTS ***********************
C ***********************************************************************
      SUBROUTINE OUTWA (JHEAD,KOUTWA,IOUTWA,SW,PESW,JDATE)
C
      COMMON/WRIT1/ AES,AEP,AET,AEO
      COMMON/WRIT2/ ASOLR,ATEMX,ATEMN,ARUNOF,ADRAIN,APRECP
      DIMENSION SW(10)
C
      IF (JHEAD.EQ.0) THEN
         IF (KOUTWA.NE.0) WRITE (43,60)
         JHEAD=1
      ELSE
         DAWA=FLOAT(IOUTWA)
         AEP=AEP/DAWA
         AET=AET/DAWA
         AEO=AEO/DAWA
         ASOLR=ASOLR/DAWA
         ATEMX=ATEMX/DAWA
         ATEMN=ATEMN/DAWA
         APRECP=APRECP/DAWA
         WRITE (43,70) JDATE,AEP,AET,AEO,ASOLR,ATEMX,ATEMN,APRECP,
     +      SW(1),SW(2),SW(3),SW(4),SW(5),PESW
      END IF
      AES=0.
      AEP=0.
      AET=0.
      AEO=0.
      ASOLR=0.
      ATEMX=0.
      ATEMN=0.
      ARUNOF=0.
      ADRAIN=0.
      APRECP=0.
      IOUTWA=0
      RETURN
C
60    FORMAT (//,1X,'JUL',1X,10('-'),' AVERAGE ',9('-'),1X,
     +  'PERIOD',3X,'SW CONTENT W/DEPTH',7X,'TOTAL',/,
     +  ' DAY  EP    ET    EO  SR   MAX  MIN  PREC',
     +  4X,'SW1  SW2  SW3  SW4  SW5',3X,'PESW',/)
70    FORMAT (I4,F4.1,2F5.1,F5.0,2F5.1,1X,F6.2,1X,5(F5.2),2X,F5.1)
      END
C **********************************************************************
C **************** WRITES PLANT GROWTH COMPONENTS ********************
C **********************************************************************
      SUBROUTINE OUTGRO (KHEAD,KOUTGR,IOUTGR,JDATE,CUMDTT,CUMPH,
     +   LAI,BIOMAS,RTWT,STMWT,LFWT,PPAWT,TILNO,RTDEP,RLV)
C
      COMMON/WRIT3/ ASWDF1,ASWDF2
      DIMENSION RLV(10)
```

```
      REAL LAI,LFWT
C
      IF (KHEAD.EQ.0) THEN
         IF (KOUTGR.NE.0) WRITE (42,40)
         KHEAD=1
      ELSE
         DAGR=FLOAT(IOUTGR)
         ASWDF1=ASWDF1/DAGR
         ASWDF2=ASWDF2/DAGR
         WRITE (42,50) JDATE,CUMDTT,CUMPH,LAI,BIOMAS,RTWT,
     +     LFWT,STMWT,PPAWT,TILNO,RTDEP,RLV(1),RLV(3),RLV(5)
      END IF
      ASWDF1=0.
      ASWDF2=0.
      IOUTGR=0
      RETURN
C
40    FORMAT (//69X,'ROOT LENGTH',/,
     + 1X,'JUL',2X,'CUM.',2X,'LEAF',3X,'LAI',2X,'BIO-',
     + 3X,'ROOT',3X,'LEAF',3X,'STEM',3X,'PAN.',1X,'TILLER',1X,
     + 'ROOT',2X,' DENSITY ',/,
     + 1X,'DAY',2X,'DTT',3X,'NO.',9X,'MASS',4X,'WT.',4X,'WT.',4X,
     + 'WT.',4X,'WT.',3X,'NO.',1X,'DEPTH',2X,'L1  L3  L5',/,
     + 24X,'(- - - grams per sq. meter - - )',7X,'(cm.)')
50    FORMAT (1X,I3,2F6.0,F6.2,F6.0,F7.2,F7.2,F7.2,F7.2,F7.0,F5.0,
     + 3F4.1)
      END
C *******************************************************************
C *********** MANAGES WRITING OF NITROGEN BALANCE COMPONENTS ********
C *******************************************************************
      SUBROUTINE NWRITE (APTNUP,STOVN,PLANTS,NOUT,TMINF,TMINH,DTNOX,
     +   KOUTNU,ISTAGE,IOUTNU,TANC,NDEF2,NHDUP,APANN,PANN,NO3,NH4,
     +   JDATE,NLAYR)
      DIMENSION NH4(10),NO3(10),DTNOX(10),NOUT(10)
      COMMON/NWRIT/ ATLCH,ATMIN,ATNOX,ATANC,ANFAC

      REAL NDEF2,NH4,NO3,NOUT
C
      IF (NHDUP.EQ.0) THEN
         ATLCH=0.
         ATMIN=0.
         ATNOX=0.
         ATANC=0.
         ANFAC=0.
      END IF
C
      TNOX=0.
      TNLCH=0.
      DO 10 L=1,NLAYR
         TNOX=TNOX+DTNOX(L)
         TNLCH=TNLCH+NOUT(L)
   10 CONTINUE
      APTNUP=STOVN*10*PLANTS
      ATLCH=ATLCH+TNLCH
      ATMIN=ATMIN+TMINF+TMINH
      ATNOX=ATNOX+TNOX
```

```
      IF (KOUTNU .EQ. 0) RETURN
      IF (ISTAGE .GT. 6) RETURN
      IOUTNU=IOUTNU+1
      ATANC=ATANC+TANC
      ANFAC=ANFAC+NDEF2
      IF (IOUTNU .EQ. KOUTNU) CALL OUTNU (NHDUP,KOUTNU,IOUTNU,
     +   APANN,PANN,PLANTS,JDATE,APTNUP,NO3,NH4)
      RETURN
      END
C ***********************************************************************
C ********** WRITES SOIL & PLANT NITROGEN COMPONENTS ********************
C ***********************************************************************
      SUBROUTINE OUTNU (NHDUP,KOUTNU,IOUTNU,APANN,PANN,PLANTS,
     +   JDATE,APTNUP,NO3,NH4)
C
      COMMON/NWRIT/ ATLCH,ATMIN,ATNOX,ATANC,ANFAC
      REAL NO3,NH4
C
      DIMENSION NO3(10),NH4(10)
      IF (NHDUP .EQ. 0) THEN
         IF (KOUTNU .NE. 0) WRITE (44,50)(L,L=1,3),(L,L=1,2)
         NHDUP=1
      ELSE
         DAUP=FLOAT(IOUTNU)
         ATANC=(ATANC/DAUP)*100.0
         ANFAC=ANFAC/DAUP
         APANN=PANN*10.0
         WRITE (44,70)JDATE,ATANC,ANFAC,APTNUP,APANN,
     +    ATLCH,ATMIN,ATNOX,(NO3(l),l=1,3),(NH4(l),l=1,2)
      END IF
      ATANC=0.0
      ATMIN=0.
      ATLCH=0.
      ATNOX=0.
      IOUTNU=0
      ANFAC = 0.0
      RETURN
C
50    FORMAT (//,' JUL',2X,'TOPS',2X,'NFAC',1X,'TOP N',1X,'PAN N',
     + 1X,'LEACH',1X,'MINLN',1X,'DENIT',
     + 3(3X,'NO3'),2(3X,'NH4'),/,1X,'DAY',3X,'N %',8X,'UPTK',
     + 2X,'UPTK',18X,5I6)
70    FORMAT (I4,F6.2,F6.2,2F6.0,8F6.1)
      END
C ***********************************************************************
C ******** WRITES SIMULATED AND OBSERVED VALUES *************************
C ***********************************************************************
      SUBROUTINE OPHARV (IHVON,JPHEAD,JPMAT,YIELD,GRNWT,PNO,PPAWT,
     +   HLAI,BIOMAS,PSTRAW,APTNUP,ATANC,PSRATIO)
C
      COMMON/OBDATA/ XYIELD,XGRNWT,XPNO,XPPAWT,XLAI,XBIOMAS,
     +   XSTRAW,XPSRAT,JDHEAD,JDMAT,XAPTNUP,XATANC
      LOGICAL IHVON
C
      PBIOMS=BIOMAS*10.0
      STRAW=PSTRAW*10.0
```

```
      PPAWT=PPAWT*10.0
      IF (IHVON) THEN
         WRITE (*,1000)
         WRITE (*,1010) JPHEAD,JDHEAD,JPMAT,JDMAT,YIELD,XYIELD,GRNWT,
     +    XGRNWT,PNO,XPNO,PPAWT,XPPAWT,PSRATIO,XPSRAT,HLAI,XLAI,
     +    PBIOMS,XBIOMAS,STRAW,XSTRAW
      END IF
      WRITE(41,1000)
      WRITE (41,1010) JPHEAD,JDHEAD,JPMAT,JDMAT,YIELD,XYIELD,GRNWT,
     + XGRNWT,PNO,XPNO,PPAWT,XPPAWT,PSRATIO,XPSRAT,HLAI,XLAI,
     + PBIOMS,XBIOMAS,STRAW,XSTRAW
1000  FORMAT (/1X,'COMPARISON BETWEEN PREDICTED AND FIELD-MEASURED ',
     +    'DATA',/,31X,'PREDICTED',5X,'OBSERVED')
1010  FORMAT (1X, 'HEADING DATE (DAY OF YEAR)    ',5X,I3,10X,I3,/,
     +          1X, 'MATURITY DATE (DAY OF YEAR)  ',5X,I3,10X,I3,/,
     +          1X, 'GRAIN YIELD (MT/HA)          ',1X,F7.1,6X,F7.1,/,
     +          1X, '1,000 GRAIN WEIGHT (G)       ',1X,F7.2,6X,F7.2,/,
     +          1X, 'NO. PANICLES PER SQ. METER   ',1X,F7.0,6X,F7.0,/,
     +          1X, 'PANICLE WEIGHT (KG/HA)       ',1X,F7.0,6X,F7.0,/,
     +          1X, 'PANICLE-STRAW RATIO          ',1X,F7.2,6X,F7.2,/,
     +          1X, 'LAI AT HEADING               ',2X,F6.2,7X,F6.2,/,
     +          1X, 'BIOMASS (KG/HA)              ',1X,F7.1,6X,F7.1,/,
     +          1X, 'STRAW  (KG/HA)               ',1X,F7.1,6X,F7.1)
C
      RETURN
      END
```

May 20 16:54 1987 cerice5.f Page 1

```
$OPTION TRACE OFF
C ********************************************************************
C ****** WRITES GROWTH COMPONENTS FOR EACH PHASE AS PART OF SUMMARY****
C ********************************************************************
      SUBROUTINE OUTGR (BIOMAS,CUMDTT,CUMPH,GRAIN,GRNWT,IHVON,ISTAGE,
     +  IYR,JDATE,JTRANSP,LAI,LFWT,MO,ND,PDLWT,PNO,PPAWT,PSRATIO,
     +  PSTRAW,RTWT,STMWT,TILNO,YIELD)
C
      REAL LAI,LFWT
      LOGICAL IHVON
C
      IF (JTRANSP.NE.0.AND.JDATE.LE.JTRANSP) THEN
         GO TO (11,66,66,66,66,66,77,88,99) ISTAGE
      ELSE
         GO TO 66
      END IF
C
   77 WRITE (41,120)
      WRITE (41,105) MO,ND,IYR,JDATE
      IF (IHVON) THEN
         WRITE (*,120)
         WRITE (*,105) MO,ND,IYR,JDATE
      END IF
      RETURN
C
   88 RETURN
C
   99 RETURN
C
   11 WRITE (41,110) MO,ND,IYR,JDATE,TILNO,BIOMAS,RTWT,LFWT,STMWT,
     +    PPAWT,LAI
      IF (IHVON) WRITE (*,110) MO,ND,IYR,JDATE,TILNO,BIOMAS,RTWT,
     +   LFWT,STMWT,PPAWT,LAI
      RETURN
C
   66 GO TO (1,2,3,4,5,6,7,8,9) ISTAGE
    7 WRITE (41,120)
      WRITE (41,130) MO,ND,IYR,JDATE,TILNO
      IF (IHVON) THEN
         WRITE (*,120)
         WRITE (*,130) MO,ND,IYR,JDATE,TILNO
      END IF
      RETURN
C
    8 WRITE (41,140) MO,ND,IYR,JDATE,TILNO
      IF (IHVON) WRITE (*,140) MO,ND,IYR,JDATE,TILNO
      RETURN
C
    9 WRITE (41,150) MO,ND,IYR,JDATE,TILNO,BIOMAS,RTWT,LFWT,STMWT,
     +      PPAWT,LAI
      IF (IHVON) WRITE (*,150) MO,ND,IYR,JDATE,TILNO,BIOMAS,RTWT,
     +   LFWT,STMWT,PPAWT,LAI
      RETURN
C
    1 WRITE (41,160) MO,ND,IYR,JDATE,TILNO,BIOMAS,RTWT,LFWT,STMWT,
     +      PPAWT,LAI
```

```
      IF (IHVON) WRITE (*,160) MO,ND,IYR,JDATE,TILNO,BIOMAS,RTWT,
     +   LFWT,STMWT,PPAWT,LAI
      RETURN
C
    2 WRITE (41,170) MO,ND,IYR,JDATE,TILNO,BIOMAS,RTWT,LFWT,STMWT,
     +     PPAWT,LAI
      IF (IHVON) WRITE (*,170) MO,ND,IYR,JDATE,TILNO,BIOMAS,RTWT,
     +   LFWT,STMWT,PPAWT,LAI
      RETURN
C
    3 WRITE (41,180) MO,ND,IYR,JDATE,TILNO,BIOMAS,RTWT,LFWT,STMWT,
     +     PPAWT,LAI
      IF (IHVON) WRITE (*,180) MO,ND,IYR,JDATE,TILNO,BIOMAS,RTWT,
     +   LFWT,STMWT,PPAWT,LAI
      RETURN
C
    4 WRITE (41,190) MO,ND,IYR,JDATE,TILNO,BIOMAS,RTWT,LFWT,STMWT,
     +     PPAWT,LAI
      IF (IHVON) WRITE (*,190) MO,ND,IYR,JDATE,TILNO,BIOMAS,RTWT,
     +   LFWT,STMWT,PPAWT,LAI
      RETURN
C
    5 WRITE (41,200) MO,ND,IYR,JDATE,TILNO,BIOMAS,RTWT,LFWT,STMWT,
     +     PPAWT,LAI
      IF (IHVON) WRITE (*,200) MO,ND,IYR,JDATE,TILNO,BIOMAS,RTWT,
     +   LFWT,STMWT,PPAWT,LAI
      RETURN
C
    6 WRITE (41,210) MO,ND,IYR,JDATE,TILNO,BIOMAS,RTWT,LFWT,STMWT,
     + PPAWT,LAI
      IF (IHVON) THEN
         WRITE (*,210) MO,ND,IYR,JDATE,TILNO,BIOMAS,RTWT,
     +      LFWT,STMWT,PPAWT,LAI
      END IF
      RETURN
C
105   FORMAT (I2,'/',I2,'/',I2,1X,I3,3X,'SOWING IN SEEDBED')
110   FORMAT (I2,'/',I2,'/',I2,1X,I3,3X,'TRANSPLANTING',5X,F6.0,
     + 5F7.1,F5.1)
130   FORMAT (I2,'/',I2,'/',I2,1X,I3,3X,'SOWING',12X,F6.0)
140   FORMAT (I2,'/',I2,'/',I2,1X,I3,3X,'GERMINATION',7X,F6.0)
150   FORMAT (I2,'/',I2,'/',I2,1X,I3,3X,'EMERGENCE',9X,F6.0,5F7.1,
     +   F5.1)
160   FORMAT (I2,'/',I2,'/',I2,1X,I3,3X,'END JUVENILE STAGE',
     +   F6.0,5F7.1,F5.1)
170   FORMAT (I2,'/',I2,'/',I2,1X,I3,3X,
     + 'FLORAL INITIATION',1X,F6.0,5F7.1,F5.1)
180   FORMAT (I2,'/',I2,'/',I2,1X,I3,3X,'HEADING',11X,F6.0,5F7.1,
     +   F5.1)
190   FORMAT (I2,'/',I2,'/',I2,1X,I3,3X,'START GRAIN FILL',2X,F6.0,
     +   5F7.1,F5.1)
200   FORMAT (I2,'/',I2,'/',I2,1X,I3,3X,'END GRAIN FILL',4X,F6.0,
     +   5F7.1,F5.1)
210   FORMAT (I2,'/',I2,'/',I2,1X,I3,3X,
     +        'PHYSIOLOGICAL',5X,F6.0,5F7.1,F5.1/17X,'MATURITY')
120   FORMAT (3(/),1X,'OUTPUT SUMMARY',/,
```

May 20 16:54 1987 cerice5.f Page 3

```
     + 2X,'DATE',3X,'JUL',3X,'PHENOLOGICAL',6X,'TILLER',1X,'BIOMASS',
     + 2X,'ROOT',3X,'LEAF',3X,'STEM',1X,'PANICLE',1X,'LAI',/,
     + 9X,'DAY',7X,'STAGE',11X,'NO.'12X,'WT.',4X,'WT.',4X,'WT.',
     + 4X,'WT.',/,
     +40X,'(- - - grams per sq. meter - - - -)')
      END
```

May 28 16:03 1987 cerice6.f Page 1

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$OPTION TRACE OFF
C ***********************************************************************
C ************* SOIL INITIALIZATION **************************************
C ***********************************************************************
      SUBROUTINE SOILRI (AIRR,CN2,CRAIN,CUMDEP,DEPMAX,DLAYR,DUL,ESW,
     +   FLOW,FLUX,IDRSW,IIRR,INSOIL,JDAY,LL,NLAYR,RTDEP,RWU,RWUMX,
     +   SALB,SAT,SMX,SW,SWEF,SWCON,T,TLL,U,WF,WR)
C
      REAL INSOIL,LL,NH4,NO3
      DIMENSION AIRR(26),DLAYR(10),DUL(10),ESW(10),FLOW(10),FLUX(10),
     +   JCNT(10),JDAY(26),LL(10),NH4(10),NO3(10),RWU(10),SAT(10),
     +   SW(10),WF(10),WR(10)
      COMMON/SOILR1/ CEP,CES,CET
      COMMON/SOILR2/ NH4,NO3
      COMMON/SOILR3/ SUMES1,SUMES2
C
         DEPMAX=0.
         CUMDEP=0.
         DO 80 L=1,NLAYR
            IF(INSOIL.LE.1.0) THEN
               SW(L)=LL(L)+(DUL(L)-LL(L))*INSOIL
               CUMDEP=CUMDEP+DLAYR(L)
               IF (CUMDEP.GT.110.) THEN
               DLL=0.008*(CUMDEP-110.)*(DUL(L)-LL(L))+LL(L)
               IF (SW(L).LT.DLL) SW(L)=DLL
               END IF
            END IF
         DEPMAX=DEPMAX+DLAYR(L)
   80    CONTINUE
C
      SWR=(SW(1)-LL(1))/(DUL(1)-LL(1))
C
      IF (SWR.LT.0.) THEN
         SWR=0.
      ELSE IF (SWR.GE..9) THEN
           SUMES2=0.
           SUMES1=100-SWR*100
           T=0.
      ELSE
         SUMES2=25-27.8*SWR
         SUMES1=U
         T=(SUMES2/3.5)**2
      END IF
C
      XX=0.
      TSW=0.
      TPESW=0.
      TLL=0.
      CUMDEP=0.
      IDRSW=0
      DO 170 L=1,NLAYR
        ESW(L)=DUL(L)-LL(L)
        CUMDEP=CUMDEP+DLAYR(L)
        TLL=TLL+LL(L)*DLAYR(L)
        IF (SW(L).GT.DUL(L)) IDRSW=1
        WX=1.016*(1.-EXP(-4.16*CUMDEP/DEPMAX))
```

```
        WF(L)=WX-XX
        XX=WX
        RWU(L)=0.0
        FLUX(L)=0.0
        IF (L.LE.5) FLOW(L)=0.0
  170 CONTINUE
C
      RTDEP=DEPMAX
      CN1=-16.91+1.348*CN2-0.01379*CN2**2+0.0001172*CN2**3
      SMX=254.*(100./CN1-1.)
      SWEF=0.9-0.00038*(DLAYR(1)-30.)**2
      CET=0.
      CES=0.
      CEP=0.
      CRAIN=0.
      APESW=TPESW/DEPMAX
      RWUMX=0.03
C
      RETURN
      END
C ******************************************************************
C ********* CALCULATES WATER BALANCE ********************************
C ******************************************************************
      SUBROUTINE WATBAL (BD,CUMDEP,DEPMAX,DLAYR,DRAIN,DTNOX,DTT,DUL,
     +   ESW,FAC,FLOW,FLUX,GRORT,HUM,ICSDUR,IDRSW,IIRR,ISTAGE,ISWNIT,
     +   JDATE,LAI,LL,MU,NLAYR,NO3,NOUT,NUP,PESW,PRECIP,RAIN,RNFAC,
     +   RNLOSS,RLDF,RLV,RTDEP,RUNOFF,RWU,RWUMX,SALB,SAT,SMX,SOLRAD,
     +   ST,SW,SWCON,SWX,SWEF,T,TLL,TSW,TRWU,U,WF,WR)
C
      REAL LAI,LL,NO3,NOUT,NUP
      DIMENSION AIRR(26),BD(10),DLAYR(10),DTNOX(10),DUL(10),ESW(10),
     +   FAC(10),FLOW(10),FLUX(10),FOM(10),FON(10),HUM(10),JDAY(26),
     +   LL(10),NO3(10),NOUT(10),NUP(10),RLDF(10),RLV(10),RNFAC(10),
     +   RNLOSS(10),RWU(10),SAT(10),SNH4(10),SNO3(10),ST(10),SW(10),
     +   SWX(10),WF(10),WR(10)
      COMMON/IPTRT7/ NIRR,JDAY,AIRR
      COMMON/PROGR2/ SWDF1,SWDF2,SWDF3
      COMMON/SOILR1/ CEP,CES,CET
      COMMON/SOILR3/ SUMES1,SUMES2
      COMMON/SOILN1/ FOM,FON
      COMMON/SOILN4/ SNH4,SNO3
      COMMON/SOILN5/ TEMPMN,TEMPMX
      COMMON/WATBA1/ EO,EP,ES,ET
C
      ICSDUR=ICSDUR+1
      PRECIP=0.
      TAIR=0.
      IOFF=0
C
      IF (IIRR.EQ.2) THEN
         DO 10 J=1,NIRR
         IF (JDATE.EQ.JDAY(J)) PRECIP=AIRR(J)
   10    CONTINUE
         IOFF=1
      ELSE IF (IIRR.EQ.3.AND. SWDF3.LT.0.9) THEN
         DO 30 L=1,NLAYR
```

```
            TAIR=TAIR+(DUL(L)-SW(L))*DLAYR(L)*10
   30    CONTINUE
      ELSE
      END IF
C
      PRECIP=PRECIP+RAIN+TAIR
      DRAIN=0.
      PINF=0.
      RUNOFF=0.
C
C********** CALCULATES RUNOFF BY WILLIAMS -SCS CURVE NO. TECHNIQUE **
C
      IF (PRECIP.NE.0.) THEN
         SUM=0.
         DO 100 L=1,NLAYR
           SUM=SUM+WF(L)*(SW(L)-LL(L))/ESW(L)
  100    CONTINUE
         R2=SMX*(1.-SUM)
         IF (R2.LE.2.54) R2=2.54
         PB=PRECIP-0.2*R2
         IF (PB.GT.0.) THEN
            RUNOFF=PB*PB/(PRECIP+.8*R2)
            IF (IOFF.EQ.1) RUNOFF=0.
         END IF
C
C********** CALCULATES DRAINAGE AND SOIL WATER REDISTRIBUTION *******
C
         WINF=PINF
         FLUX(1)=PINF*0.1
         IDRSW=1
      END IF
         PINF=PRECIP-RUNOFF
         WINF=PINF
         FLUX(1)=PINF*0.1
C
      IF (IDRSW.NE.0) THEN
         IDRSW=0
         DO 240 L=1,NLAYR
            IF (FLUX(L).NE.0.) THEN
               HOLD=(SAT(L)-SW(L))*DLAYR(L)
               IF (FLUX(L).GT.HOLD) THEN
                  DRAIN=SWCON*(SAT(L)-DUL(L))*DLAYR(L)
                  SW(L)=SAT(L)-DRAIN/DLAYR(L)
                  FLUX(L)=FLUX(L)-HOLD+DRAIN
                  IDRSW=1
                  GO TO 230
               END IF
            END IF
         SW(L)=SW(L)+FLUX(L)/DLAYR(L)
         IF (SW(L).GE.(DUL(L)+0.003)) THEN
            DRAIN=(SW(L)-DUL(L))*SWCON*DLAYR(L)
            SW(L)=SW(L)-DRAIN/DLAYR(L)
            FLUX(L)=DRAIN
            IDRSW=1
         ELSE
            FLUX(L)=0.
```

May 28 16:03 1987 cerice6.f Page 4

```
         END IF
  230    IF (L.LT.NLAYR) FLUX(L+1)=FLUX(L)
  240    CONTINUE
         DRAIN=FLUX(L)*10.0
         IF (ISWNIT.NE.0.AND.IDRSW.EQ.1) THEN
            CALL NFLUX (0,DLAYR,FAC,FLOW,FLUX,MU,NLAYR,NOUT,
     +         NO3,NUP,SNO3,SW)
            CALL DNIT (BD,DLAYR,DTNOX,DUL,FAC,FOM,HUM,NLAYR,NO3,
     +         SAT,SNO3,ST,SW)
         END IF
         DO 250 L=1,NLAYR
            FLUX(L)=0.0
  250    CONTINUE
      END IF
C
C ********* POTENTIAL EVAPORATION ROUTINE ***************************
C
      TD=0.60*TEMPMX+0.40*TEMPMN
      ALBEDO=SALB
      IF (ISTAGE.LT.5.) ALBEDO=0.23-(0.23-SALB)*EXP(-0.75*LAI)
      EEQ=SOLRAD*(2.04E-4-1.83E-4*ALBEDO)*(TD+29.)
      EO=EEQ*1.1
C
      IF (TEMPMX.GT.35.) THEN
         EO=EEQ*((TEMPMX-35.)*0.05+1.1)
      ELSE IF (TEMPMX.LT.5.0) THEN
         EO=EEQ*0.01*EXP(0.18*(TEMPMX+20.))
      END IF
C
      EOS=EO*(1.-0.43*LAI)
      IF (LAI.GT.1.) EOS=EO/1.1*EXP(-0.4*LAI)
C
C ********** SOIL AND PLANT EVAPORATION ROUTINE *********************
C
      IF (SUMES1.GE.U.AND.WINF.GE.SUMES2) THEN
         WINF=WINF-SUMES2
         SUMES1=U-WINF
         T=0.
         IF (WINF.GT.U) SUMES1=0.
      ELSE IF (SUMES1.GE.U.AND.WINF.LT.SUMES2) THEN
         T=T+1.
         ES=3.5*T**0.5-SUMES2
         IF (WINF.GT.0.) THEN
            ESX=0.8*WINF
            IF (ESX.LE.ES) ESX=ES+WINF
            IF (ESX.GT.EOS) ESX=EOS
            ES=ESX
         ELSE
           IF (ES.GT.EOS) ES=EOS
         END IF
         SUMES2=SUMES2+ES-WINF
         T=(SUMES2/3.5)**2
         GO TO 470
      ELSE IF (WINF.GE.SUMES1) THEN
         SUMES1=0.
      ELSE IF (WINF.LT.SUMES1) THEN
```

```
         SUMES1=SUMES1-WINF
      END IF
C
      SUMES1=SUMES1+EOS
C
      IF (SUMES1.GT.U) THEN
         ES=EOS-0.4*(SUMES1-U)
         SUMES2=0.6*(SUMES1-U)
         T=(SUMES2/3.5)**2
      ELSE
         ES=EOS
      END IF
C
  470 SW(1)=SW(1)-ES*.1/DLAYR(1)
C
      IF (SW(1).LT.(LL(1)*SWEF)) THEN
         ES1=(LL(1)*SWEF-SW(1))*DLAYR(1)*10.
         SW(1)=LL(1)*SWEF
         ES=ES-ES1
      END IF
C
      NIND=NLAYR-1
      DO 490 L=1,NLAYR
         FLOW(L)=0.0
         SWX(L)=SW(L)
  490 CONTINUE
      IST=1
      IF (DLAYR(1).EQ.5.0) IST=2
      DO 500 L=IST,NIND
        MU=L+1
        THET1=SW(L)-LL(L)
        IF (THET1.LT.0.) THET1=0.
        THET2=SW(MU)-LL(MU)
        DBAR=0.88*EXP(35.4*(THET1+THET2)*0.5)
        IF (DBAR.GT.100.) DBAR=100.
        FLOW(L)=DBAR*(THET2-THET1)/((DLAYR(L)+DLAYR(MU))*0.5)
        WAT1=DUL(1)-SW(1)
        IF (FLOW(1).GT.WAT1) FLOW(1)=WAT1
        IF (WAT1.LT.0.0) FLOW(1)=0.0
        SWX(L)=SWX(L)+FLOW(L)/DLAYR(L)
        SWX(MU)=SWX(MU)-FLOW(L)/DLAYR(MU)
  500 CONTINUE
      IF (ISWNIT.NE.0) CALL NFLUX (1,DLAYR,FAC,FLOW,FLUX,MU,NLAYR,NOUT,
     +   NO3,NUP,SNO3,SW)
      DO 510 L=1,MU
        SW(L)=SWX(L)
  510 CONTINUE
      CES=CES+ES
      EP=0.
      IF (ISTAGE.GE.6) THEN
         ET=ES
         CET=CET+ET
         TSW=0.
         DO 530 L=1,NLAYR
            TSW=TSW+SW(L)*DLAYR(L)
  530    CONTINUE
```

```
          PESW=TSW-TLL
          RETURN
       ELSE
          IF (LAI.LE.3.0) EP=EO*(1.-EXP(-LAI))
          IF (LAI.GT.3.0) EP=EO
          IF (EP+ES.GT.EO) EP=EO-ES
       END IF
C
C ********** ROOT GROWTH AND DEPTH ROUTINE *************************
C
       IF (GRORT.NE.0.) THEN
          RLNEW=GRORT*0.80
          TRLDF=0.
          CUMDEP=0.
          SWDF3=0.0
          DO 620 L=1,NLAYR
             L1=L
             CUMDEP=CUMDEP+DLAYR(L)
             SWDF=1.
             IF ((SW(L)-LL(L)).LT.0.25*ESW(L)) SWDF=4.*(SW(L)-LL(L))/
     +         ESW(L)
             IF (SWDF.LT.0.) SWDF=0.
             RLDF(L)=AMIN1(SWDF,RNFAC(L))*WR(L)
             IF (CUMDEP.LT.RTDEP) THEN
                SWDF3=SWDF3+(SW(L)-LL(L))/(DUL(L)-LL(L))*DLAYR(L)
                TRLDF=TRLDF+RLDF(L)
             ELSE
                RTDEP=RTDEP+DTT*0.22*AMIN1((SWDF1*2.0),SWDF)
                IF (RTDEP.GT.DEPMAX) RTDEP=DEPMAX
                RLDF(L)=RLDF(L)*(1.-(CUMDEP-RTDEP)/DLAYR(L))
                TRLDF=TRLDF+RLDF(L)
                GO TO 630
             END IF
  620     CONTINUE
  630     SWDF3=SWDF3/CUMDEP
          IF (TRLDF.GE.(RLNEW*0.00001)) THEN
             RNLF=RLNEW/TRLDF
             DO 640 L=1,L1
                RLV(L)=RLV(L)+RLDF(L)*RNLF/DLAYR(L)-0.005*RLV(L)
                IF (RLV(L).LT.0) THEN
                   RLV(L)=0.
                ELSE IF (RLV(L).GT.5.0) THEN
                   RLV(L)=5.0
                END IF
                SNH4(L)=SNH4(L)+RNLOSS(L)*10.0
  640        CONTINUE
          END IF
       END IF
C
C ********* CALCULATES WATER UPTAKE AND SOIL DEFICIT FACTORS ********
C
       IF (EP.NE.0.) THEN
          EP1=EP*0.1
          TRWU=0.
          DO 710 L=1,NLAYR
               IF (RLV(L).EQ.0.0) GO TO 720
```

```
               RWU(L)=2.67E-3*EXP(62.*(SW(L)-LL(L)))/(6.68-ALOG(RLV(L)))
               IF (RWU(L).GT.RWUMX) RWU(L)=RWUMX
               IF (SW(L).LT.LL(L)) RWU(L)=0.
               RWU(L)=RWU(L)*DLAYR(L)*RLV(L)
               TRWU=TRWU+RWU(L)
  710     CONTINUE
  720     WUF=1.
          IF (EP1.LE.TRWU) WUF=EP1/TRWU
          TSW=0.
          DO 730 L=1,NLAYR
             RWU(L)=RWU(L)*WUF
             SW(L)=SW(L)-RWU(L)/DLAYR(L)
             TSW=TSW+SW(L)*DLAYR(L)
  730     CONTINUE
          PESW=TSW-TLL
          SWDF2=1.
          IF (TRWU/EP1.LT.1.5) SWDF2=0.67*TRWU/EP1
          SWDF1=1.
          IF (EP1.GE.TRWU) THEN
             SWDF1=TRWU/EP1
             EP=TRWU*10.
          END IF
       END IF
C
       ET=ES+EP
       CEP=CEP+EP
       CET=CET+ET
       CSD1=CSD1+1.0-SWDF1
       CSD2=CSD2+1.0-SWDF2
       RETURN
       END
C ******************************************************************
C ****** SUBROUTINE TO CONVERT JULIAN DAY TO CALENDAR DATE ********
C ******************************************************************
       SUBROUTINE CALDAT (IYR,JDATE,JDATEX,MO,ND)
C
       DIMENSION IDIM(12)
       SAVE IDIM
       IF (JDATE.LT.JDATEX) THEN
          DO 10 I=1,12
             IDIM(I)=31
   10     CONTINUE
          IDIM(4)=30
          IDIM(6)=30
          IDIM(9)=30
          IDIM(11)=30
          IDIM(2)=28
          IF (MOD(IYR,4).EQ.0) IDIM(2)=29
       END IF
       MO=1
       ND=31
   30  IF (ND .LT. JDATE) THEN
          MO=MO+1
          ND=ND+IDIM(MO)
          GO TO 30
       END IF
```

```
      ND=JDATE-ND+IDIM(MO)
      JDATEX=JDATE
      RETURN
      END
```

May 28 11:21 1987 cerice7.f Page 1

```
$OPTION TRACE OFF
C ********************************************************************
C ********* SUBROUTINE TO CALCULATE PHENOLOGICAL STAGE *************
C ********************************************************************
      SUBROUTINE PHENOL (ISWNIT,ISWSWB,IQUIT,JTRANSP,NCYCLE,PLANTS,
     +   SDEPTH,YIELD,SOLRAD,TMFAC,TEMPM,IVARTY,VARTY,CUMDTT,SUMDTT,
     +   DTT,ISTAGE,TBASE,CUMPH,SWSD,PLTWT,PPAWT,PERPAWT,PDLWT,WTLF,
     +   GRNWT,PLA,LAI,PDL,SEEDRV,GRN,PA,PAN,TILNO,GPP,GRORT,LFWT,
     +   RTWT,STMWT,CUMDEP,ESW,ICSDUR,RLV,CRAIN,RTDEP,TANC,TCNP,RCNP,
     +   RANC,TMNC,VANC,VMNC,XSTAGE,GNP,NFAC,DSTOVN,ROOTN,STOVN,PDWI,
     +   STOVWT,PGRORT,NDEM,PANN,RNFAC,RNLOSS,TNUP,KOUTGR,FAC,PNUP,
     +   DLAYR,LL,SW,NLAYR,RWU,IHVON,BIOMAS)
C
      REAL LAI,LFWT,LL,NDEM,NH4,NO3,NDEF1,NDEF2,NFAC
      CHARACTER *16 VARTY
      DIMENSION TMFAC(8),RNO3U(10),RNH4U(10),ESW(10),RLV(10),RNFAC(10),
     +  RNLOSS(10),SNH4(10),SNO3(10),NH4(10);NO3(10),FAC(10),PNUP(10),
     +  DLAYR(10),LL(10),SW(10),RWU(10)
C
      COMMON/IPTRT2/ P1,P2R,P5,P2O
      COMMON/IPTRT3/ G1,TR
      COMMON/IPWTH1/ S1,C1
      COMMON/PROGR1/ NDEF1,NDEF2
      COMMON/PROGR2/ SWDF1,SWDF2,SWDF3
      COMMON/SOILR1/ CEP,CES,CET
      COMMON/SOILR2/ NH4,NO3
      COMMON/SOILN4/ SNH4,SNO3
      COMMON/SOILN5/ TEMPMN,TEMPMX
      COMMON/CALDA1/ MO,ND,IYR,JDATE,JDATEX
      COMMON/PHENO2/ CSD1,CSD2
      COMMON/PHENO3/ RNO3U,RNH4U
      COMMON/PHENO4/ CNSD1,CNSD2
C *** THE SAVE COMMAND (COMMENTED SECTION BELOW) WOULD HAVE TO BE
C     ACTIVATED WHEN RUNNING THIS MODEL IN THE HP SYSTEM *****************
      SAVE FERTILE,L0,OUTDTT,SIND,P3,P9,NDAS,
     +   PFR,PFL,PFC,PFP,PAWT,JPHEAD,JPMAT,HLAI
C ------------------------------------------------------------------------
C
      TEMPM=(TEMPMX+TEMPMN)/2.
      DTT=TEMPM-TBASE
      IF (TEMPMN.LE.TBASE .OR. TEMPMX .GE. 33) THEN
         DTT=0.
         DO 10 I=1,8
            TTMP=TEMPMN+TMFAC(I)*(TEMPMX-TEMPMN)
            IF(TTMP.GE.TBASE.AND.TTMP.LE.33) DTT=DTT+(TTMP-TBASE)/8.
            IF(TTMP.GT.33.AND.TTMP.LT.42) DTT=DTT+(33.-TBASE)
     +   *(1.-(TTMP-33.)/9.)/8.
   10    CONTINUE
      END IF
      SUMDTT=SUMDTT+DTT
      CUMDTT=CUMDTT+DTT
      GO TO (1,2,3,4,5,6,7,8,9), ISTAGE
C
C ******************* SOWING STAGE **********************************
C
    7 CALL CALDAT (IYR,JDATE,JDATEX,MO,ND)
```

```
      IF (NCYCLE.EQ.1) CALL OUTGR (BIOMAS,CUMDTT,CUMPH,GRAIN,GRNWT,
     +  IHVON,ISTAGE,IYR,JDATE,JTRANSP,LAI,LFWT,MO,ND,PDLWT,PNO,PPAWT,
     +  PSRATIO,PSTRAW,RTWT,STMWT,TILNO,YIELD)
      CALL PHASEI (CEP,CES,CET,CNSD1,CNSD2,CRAIN,CSD1,CSD2,
     +   CUMDTT,CUMDEP,DLAYR,DTT,ICSDUR,ISTAGE,ISWNIT,ISWSWB,NDAS,
     +   NDEF1,NDEF2,NLAYR,OUTDTT,P3,P9,PFR,PFL,PFC,PFP,PA,PAN,PANN,
     +   PLANTS,RANC,RLV,RTDEP,RWU,SDEPTH,SIND,SUMDTT,SWSD,TANC,TMNC,
     +   TSTRESS,VANC,VMNC)
      IF (ISWSWB.EQ.0) RETURN
      CUMDEP=0.
      DO 30 L=1,NLAYR
         CUMDEP=CUMDEP+DLAYR(L)
         IF (SDEPTH.LT.CUMDEP) GO TO 40
   30 CONTINUE
   40 LO=L
      RETURN
C
C ***************** GERMINATION STAGE ****************************
C
    8 IF (ISWSWB.NE.0.OR.SW(LO).LE.LL(LO)) THEN
         SWSD=(SW(LO)-LL(LO))*0.65+(SW(LO+1)-LL(LO+1))*0.35
      END IF
      NDAS=NDAS+1
      IF(NDAS.LT.40) THEN
         IF (SWSD.LT.0.02) RETURN
         IF (TEMPM.LT.15 .OR. TEMPM .GT. 42) RETURN
         IF (SUMDTT .LT. 45) RETURN
         CALL CALDAT (IYR,JDATE,JDATEX,MO,ND)
         IF (NCYCLE.EQ.1) CALL OUTGR (BIOMAS,CUMDTT,CUMPH,GRAIN,
     +      GRNWT,IHVON,ISTAGE,IYR,JDATE,JTRANSP,LAI,LFWT,MO,ND,
     +      PDLWT,PNO,PPAWT,PSRATIO,PSTRAW,RTWT,STMWT,TILNO,YIELD)
         CALL PHASEI (CEP,CES,CET,CNSD1,CNSD2,CRAIN,CSD1,CSD2,
     +      CUMDTT,CUMDEP,DLAYR,DTT,ICSDUR,ISTAGE,ISWNIT,ISWSWB,NDAS,
     +      NDEF1,NDEF2,NLAYR,OUTDTT,P3,P9,PFR,PFL,PFC,PFP,PA,PAN,
     +      PANN,PLANTS,RANC,RLV,RTDEP,RWU,SDEPTH,SIND,SUMDTT,SWSD,
     +      TANC,TMNC,TSTRESS,VANC,VMNC)
      ELSE
         WRITE (41,105)
  105    FORMAT (1X,'CROP FAILURE BECAUSE OF LACK OF GERMINATION',
     + ' WITHIN 40 DAYS OF SOWING')
         STOP
      END IF
      RETURN
C
C ***************** SEEDLING EMERGENCE STAGE *******************
C
    9 RTDEP=RTDEP+0.15*DTT
      CALL GROWTH (BIOMAS,CNSD1,CNSD2,CUMDTT,CUMPH,DLAYR,
     +   DSTOVN,DTT,ESW,FAC,G1,GNP,GPP,GRN,GRNWT,GRORT,ICSDUR,IDAY,
     +   ISTAGE,ISWNIT,KOUTGR,LAI,LFWT,LL,NDEM,NDEF1,NDEF2,NFAC,NLAYR,
     +   NH4,NO3,PA,PANN,PAWT,PDL,PDLWT,PDWI,PFR,PFL,PFC,PFP,PGRORT,
     +   PLANTS,PLA,PLTWT,PERPAWT,PNUP,PPAWT,RANC,RCNP,RLV,RNFAC,
     +   RNLOSS,RNH4U,RNO3U,ROOTN,RTWT,RWU,SEEDRV,SNH4,SNO3,STMWT,
     +   STOVN,STOVWT,SW,SWDF1,SWDF2,SOLRAD,TANC,TCNP,TEMPM,TEMPMN,
     +   TEMPMX,TILNO,TMNC,TNUP,TR,TSTRESS,VANC,VMNC,XSTAGE)
      IF (SUMDTT .LT. P9) RETURN
```

```
      CALL CALDAT (IYR,JDATE,JDATEX,MO,ND)
      IF (NCYCLE.EQ.1) CALL OUTGR (BIOMAS,CUMDTT,CUMPH,GRAIN,GRNWT,
     +  IHVON,ISTAGE,IYR,JDATE,JTRANSP,LAI,LFWT,MO,ND,PDLWT,PNO,PPAWT,
     +  PSRATIO,PSTRAW,RTWT,STMWT,TILNO,YIELD)
      CALL PHASEI (CEP,CES,CET,CNSD1,CNSD2,CRAIN,CSD1,CSD2,
     +    CUMDTT,CUMDEP,DLAYR,DTT,ICSDUR,ISTAGE,ISWNIT,ISWSWB,NDAS,
     +    NDEF1,NDEF2,NLAYR,OUTDTT,P3,P9,PFR,PFL,PFC,PFP,PA,PAN,PANN,
     +    PLANTS,RANC,RLV,RTDEP,RWU,SDEPTH,SIND,SUMDTT,SWSD,TANC,TMNC,
     +    TSTRESS,VANC,VMNC)
      RETURN
C
C *************** JUVENILE STAGE ****************************************
C
    1 XSTAGE=SUMDTT/P1
      OUTDTT=OUTDTT+DTT
      CALL GROWTH (BIOMAS,CNSD1,CNSD2,CUMDTT,CUMPH,DLAYR,
     +    DSTOVN,DTT,ESW,FAC,G1,GNP,GPP,GRN,GRNWT,GRORT,ICSDUR,IDAY,
     +    ISTAGE,ISWNIT,KOUTGR,LAI,LFWT,LL,NDEM,NDEF1,NDEF2,NFAC,NLAYR,
     +    NH4,NO3,PA,PANN,PAWT,PDL,PDLWT,PDWI,PFR,PFL,PFC,PFP,PGRORT,
     +    PLANTS,PLA,PLTWT,PERPAWT,PNUP,PPAWT,RANC,RCNP,RLV,RNFAC,
     +    RNLOSS,RNH4U,RNO3U,ROOTN,RTWT,RWU,SEEDRV,SNH4,SNO3,STMWT,
     +    STOVN,STOVWT,SW,SWDF1,SWDF2,SOLRAD,TANC,TCNP,TEMPM,TEMPMN,
     +    TEMPMX,TILNO,TMNC,TNUP,TR,TSTRESS,VANC,VMNC,XSTAGE)
      IF (SUMDTT .LT. P1) RETURN
      CALL CALDAT (IYR,JDATE,JDATEX,MO,ND)
      IF (NCYCLE.EQ.1) CALL OUTGR (BIOMAS,CUMDTT,CUMPH,GRAIN,GRNWT,
     +  IHVON,ISTAGE,IYR,JDATE,JTRANSP,LAI,LFWT,MO,ND,PDLWT,PNO,PPAWT,
     +  PSRATIO,PSTRAW,RTWT,STMWT,TILNO,YIELD)
      CALL PHASEI (CEP,CES,CET,CNSD1,CNSD2,CRAIN,CSD1,CSD2,
     +    CUMDTT,CUMDEP,DLAYR,DTT,ICSDUR,ISTAGE,ISWNIT,ISWSWB,NDAS,
     +    NDEF1,NDEF2,NLAYR,OUTDTT,P3,P9,PFR,PFL,PFC,PFP,PA,PAN,PANN,
     +    PLANTS,RANC,RLV,RTDEP,RWU,SDEPTH,SIND,SUMDTT,SWSD,TANC,TMNC,
     +    TSTRESS,VANC,VMNC)
      RETURN
C
C ****************** FLORAL INITIATION STAGE ***************************
C
    2 XSTAGE=1.0+0.5*SIND
      DEC=0.4093*SIN(0.0172*(JDATE-82.2))
      DLV=(-S1*SIN(DEC)-0.1047)/(C1*COS(DEC))
      IF(DLV.LT.-.87) DLV=-.87
      HRLT=7.639*ACOS(DLV)
      RATEIN=1./136.
      IF(HRLT .GT. P2O) RATEIN=1./(136.+P2R*(HRLT-P2O))
      SIND=SIND+RATEIN*DTT
      CALL GROWTH (BIOMAS,CNSD1,CNSD2,CUMDTT,CUMPH,DLAYR,
     +    DSTOVN,DTT,ESW,FAC,G1,GNP,GPP,GRN,GRNWT,GRORT,ICSDUR,IDAY,
     +    ISTAGE,ISWNIT,KOUTGR,LAI,LFWT,LL,NDEM,NDEF1,NDEF2,NFAC,NLAYR,
     +    NH4,NO3,PA,PANN,PAWT,PDL,PDLWT,PDWI,PFR,PFL,PFC,PFP,PGRORT,
     +    PLANTS,PLA,PLTWT,PERPAWT,PNUP,PPAWT,RANC,RCNP,RLV,RNFAC,
     +    RNLOSS,RNH4U,RNO3U,ROOTN,RTWT,RWU,SEEDRV,SNH4,SNO3,STMWT,
     +    STOVN,STOVWT,SW,SWDF1,SWDF2,SOLRAD,TANC,TCNP,TEMPM,TEMPMN,
     +    TEMPMX,TILNO,TMNC,TNUP,TR,TSTRESS,VANC,VMNC,XSTAGE)
      IF (SIND.LT.1.0) RETURN
      CALL CALDAT (IYR,JDATE,JDATEX,MO,ND)
      IF (NCYCLE.EQ.1) CALL OUTGR (BIOMAS,CUMDTT,CUMPH,GRAIN,GRNWT,
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     +  IHVON,ISTAGE,IYR,JDATE,JTRANSP,LAI,LFWT,MO,ND,PDLWT,PNO,PPAWT,
     +  PSRATIO,PSTRAW,RTWT,STMWT,TILNO,YIELD)
      CALL PHASEI (CEP,CES,CET,CNSD1,CNSD2,CRAIN,CSD1,CSD2,
     +    CUMDTT,CUMDEP,DLAYR,DTT,ICSDUR,ISTAGE,ISWNIT,ISWSWB,NDAS,
     +    NDEF1,NDEF2,NLAYR,OUTDTT,P3,P9,PFR,PFL,PFC,PFP,PA,PAN,PANN,
     +    PLANTS,RANC,RLV,RTDEP,RWU,SDEPTH,SIND,SUMDTT,SWSD,TANC,TMNC,
     +    TSTRESS,VANC,VMNC)
      RETURN
C
C ************* HEADING AND END OF LEAF GROWTH STAGE ****************
C
    3 XSTAGE=1.5+3.0*SUMDTT/P3
      CALL GROWTH (BIOMAS,CNSD1,CNSD2,CUMDTT,CUMPH,DLAYR,
     +    DSTOVN,DTT,ESW,FAC,G1,GNP,GPP,GRN,GRNWT,GRORT,ICSDUR,IDAY,
     +    ISTAGE,ISWNIT,KOUTGR,LAI,LFWT,LL,NDEM,NDEF1,NDEF2,NFAC,NLAYR,
     +    NH4,NO3,PA,PANN,PAWT,PDL,PDLWT,PDWI,PFR,PFL,PFC,PFP,PGRORT,
     +    PLANTS,PLA,PLTWT,PERPAWT,PNUP,PPAWT,RANC,RCNP,RLV,RNFAC,
     +    RNLOSS,RNH4U,RNO3U,ROOTN,RTWT,RWU,SEEDRV,SNH4,SNO3,STMWT,
     +    STOVN,STOVWT,SW,SWDF1,SWDF2,SOLRAD,TANC,TCNP,TEMPM,TEMPMN,
     +    TEMPMX,TILNO,TMNC,TNUP,TR,TSTRESS,VANC,VMNC,XSTAGE)
      IF (SUMDTT .LT. P3) RETURN
      CALL CALDAT (IYR,JDATE,JDATEX,MO,ND)
      JPHEAD=JDATE
      HLAI=LAI
      IF (NCYCLE.EQ.1) CALL OUTGR (BIOMAS,CUMDTT,CUMPH,GRAIN,GRNWT,
     +  IHVON,ISTAGE,IYR,JDATE,JTRANSP,LAI,LFWT,MO,ND,PDLWT,PNO,PPAWT,
     +  PSRATIO,PSTRAW,RTWT,STMWT,TILNO,YIELD)
      CALL PHASEI (CEP,CES,CET,CNSD1,CNSD2,CRAIN,CSD1,CSD2,
     +    CUMDTT,CUMDEP,DLAYR,DTT,ICSDUR,ISTAGE,ISWNIT,ISWSWB,NDAS,
     +    NDEF1,NDEF2,NLAYR,OUTDTT,P3,P9,PFR,PFL,PFC,PFP,PA,PAN,PANN,
     +    PLANTS,RANC,RLV,RTDEP,RWU,SDEPTH,SIND,SUMDTT,SWSD,TANC,TMNC,
     +    TSTRESS,VANC,VMNC)
      RETURN
C
C ************* BEGINNING OF EFFECTIVE GRAIN FILLING STAGE **********
C
    4 XSTAGE=4.5+1.5*SUMDTT/(P5*0.95)
      CALL GROWTH (BIOMAS,CNSD1,CNSD2,CUMDTT,CUMPH,DLAYR,
     +    DSTOVN,DTT,ESW,FAC,G1,GNP,GPP,GRN,GRNWT,GRORT,ICSDUR,IDAY,
     +    ISTAGE,ISWNIT,KOUTGR,LAI,LFWT,LL,NDEM,NDEF1,NDEF2,NFAC,NLAYR,
     +    NH4,NO3,PA,PANN,PAWT,PDL,PDLWT,PDWI,PFR,PFL,PFC,PFP,PGRORT,
     +    PLANTS,PLA,PLTWT,PERPAWT,PNUP,PPAWT,RANC,RCNP,RLV,RNFAC,
     +    RNLOSS,RNH4U,RNO3U,ROOTN,RTWT,RWU,SEEDRV,SNH4,SNO3,STMWT,
     +    STOVN,STOVWT,SW,SWDF1,SWDF2,SOLRAD,TANC,TCNP,TEMPM,TEMPMN,
     +    TEMPMX,TILNO,TMNC,TNUP,TR,TSTRESS,VANC,VMNC,XSTAGE)
      IF (SUMDTT .LT. 170.) RETURN
      IF (TEMPM .GT. 17 .AND. TEMPM.LT.35) FERTILE=0.853-0.00028*PLANTS
      IF (TEMPM .GE. 35) FERTILE=0.75-0.1*(TEMPM-35)
      IF (TEMPM .LE. 17) FERTILE=0.75-0.1*(17-TEMPM)
      CALL CALDAT (IYR,JDATE,JDATEX,MO,ND)
      IF (NCYCLE.EQ.1) CALL OUTGR (BIOMAS,CUMDTT,CUMPH,GRAIN,GRNWT,
     +  IHVON,ISTAGE,IYR,JDATE,JTRANSP,LAI,LFWT,MO,ND,PDLWT,PNO,PPAWT,
     +  PSRATIO,PSTRAW,RTWT,STMWT,TILNO,YIELD)
      CALL PHASEI (CEP,CES,CET,CNSD1,CNSD2,CRAIN,CSD1,CSD2,
     +    CUMDTT,CUMDEP,DLAYR,DTT,ICSDUR,ISTAGE,ISWNIT,ISWSWB,NDAS,
     +    NDEF1,NDEF2,NLAYR,OUTDTT,P3,P9,PFR,PFL,PFC,PFP,PA,PAN,PANN,
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May 28 11:21 1987 cerice7.f Page 5

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     +   PLANTS,RANC,RLV,RTDEP,RWU,SDEPTH,SIND,SUMDTT,SWSD,TANC,TMNC,
     +   TSTRESS,VANC,VMNC)
      RETURN
C
C ***************** END OF GRAIN FILLING STAGE *********************
C
    5 XSTAGE=6.0+4.0*SUMDTT/P5
      CALL GROWTH (BIOMAS,CNSD1,CNSD2,CUMDTT,CUMPH,DLAYR,
     +   DSTOVN,DTT,ESW,FAC,G1,GNP,GPP,GRN,GRNWT,GRORT,ICSDUR,IDAY,
     +   ISTAGE,ISWNIT,KOUTGR,LAI,LFWT,LL,NDEM,NDEF1,NDEF2,NFAC,NLAYR,
     +   NH4,NO3,PA,PANN,PAWT,PDL,PDLWT,PDWI,PFR,PFL,PFC,PFP,PGRORT,
     +   PLANTS,PLA,PLTWT,PERPAWT,PNUP,PPAWT,RANC,RCNP,RLV,RNFAC,
     +   RNLOSS,RNH4U,RNO3U,ROOTN,RTWT,RWU,SEEDRV,SNH4,SNO3,STMWT,
     +   STOVN,STOVWT,SW,SWDF1,SWDF2,SOLRAD,TANC,TCNP,TEMPM,TEMPMN,
     +   TEMPMX,TILNO,TMNC,TNUP,TR,TSTRESS,VANC,VMNC,XSTAGE)
      IF (SUMDTT .LT. 0.95*P5) RETURN
      CALL CALDAT (IYR,JDATE,JDATEX,MO,ND)
      IF (NCYCLE.EQ.1) CALL OUTGR (BIOMAS,CUMDTT,CUMPH,GRAIN,GRNWT,
     +  IHVON,ISTAGE,IYR,JDATE,JTRANSP,LAI,LFWT,MO,ND,PDLWT,PNO,PPAWT,
     +  PSRATIO,PSTRAW,RTWT,STMWT,TILNO,YIELD)
      CALL PHASEI (CEP,CES,CET,CNSD1,CNSD2,CRAIN,CSD1,CSD2,
     +   CUMDTT,CUMDEP,DLAYR,DTT,ICSDUR,ISTAGE,ISWNIT,ISWSWB,NDAS,
     +   NDEF1,NDEF2,NLAYR,OUTDTT,P3,P9,PFR,PFL,PFC,PFP,PA,PAN,PANN,
     +   PLANTS,RANC,RLV,RTDEP,RWU,SDEPTH,SIND,SUMDTT,SWSD,TANC,TMNC,
     +   TSTRESS,VANC,VMNC)
      RETURN
C
C ******************** PHYSIOLOGICAL MATURITY STAGE ****************
C
    6 IF (DTT .LE. 0.0) SUMDTT=P5
      CALL GROWTH (BIOMAS,CNSD1,CNSD2,CUMDTT,CUMPH,DLAYR,
     +   DSTOVN,DTT,ESW,FAC,G1,GNP,GPP,GRN,GRNWT,GRORT,ICSDUR,IDAY,
     +   ISTAGE,ISWNIT,KOUTGR,LAI,LFWT,LL,NDEM,NDEF1,NDEF2,NFAC,NLAYR,
     +   NH4,NO3,PA,PANN,PAWT,PDL,PDLWT,PDWI,PFR,PFL,PFC,PFP,PGRORT,
     +   PLANTS,PLA,PLTWT,PERPAWT,PNUP,PPAWT,RANC,RCNP,RLV,RNFAC,
     +   RNLOSS,RNH4U,RNO3U,ROOTN,RTWT,RWU,SEEDRV,SNH4,SNO3,STMWT,
     +   STOVN,STOVWT,SW,SWDF1,SWDF2,SOLRAD,TANC,TCNP,TEMPM,TEMPMN,
     +   TEMPMX,TILNO,TMNC,TNUP,TR,TSTRESS,VANC,VMNC,XSTAGE)
      IF (SUMDTT .LT. P5) RETURN
      CALL CALDAT (IYR,JDATE,JDATEX,MO,ND)
      JPMAT=JDATE
      PNO=PPAWT/PERPAWT
      GRAIN=(PPAWT*0.9/GRNWT)*FERTILE
      PSTRAW=STOVWT+(PPAWT*0.1)
      PSRATIO=PPAWT/PSTRAW
      DYIELD=(GRAIN*GRNWT)/100
      YIELD=DYIELD/0.86
      GRNWT=GRNWT*1000
      IF (NCYCLE.EQ.1) CALL OUTGR (BIOMAS,CUMDTT,CUMPH,GRAIN,GRNWT,
     +  IHVON,ISTAGE,IYR,JDATE,JTRANSP,LAI,LFWT,MO,ND,PDLWT,PNO,PPAWT,
     +  PSRATIO,PSTRAW,RTWT,STMWT,TILNO,YIELD)
      CALL PHASEI (CEP,CES,CET,CNSD1,CNSD2,CRAIN,CSD1,CSD2,
     +   CUMDTT,CUMDEP,DLAYR,DTT,ICSDUR,ISTAGE,ISWNIT,ISWSWB,NDAS,
     +   NDEF1,NDEF2,NLAYR,OUTDTT,P3,P9,PFR,PFL,PFC,PFP,PA,PAN,PANN,
     +   PLANTS,RANC,RLV,RTDEP,RWU,SDEPTH,SIND,SUMDTT,SWSD,TANC,TMNC,
     +   TSTRESS,VANC,VMNC)
```

```
      TILNO=0.
      IQUIT=1
      IF (NCYCLE.EQ.1) CALL OPHARV (IHVON,JPHEAD,JPMAT,YIELD,GRNWT,
     +   PNO,PPAWT,HLAI,BIOMAS,PSTRAW,APTNUP,ATANC,PSRATIO)
      RETURN
      END
```

Jun 30 14:09 1987 cerice8.f Page 1

```
$OPTION TRACE OFF
C ***********************************************************************
C *********** PHASE INITIALIZATION ***************************************
C ***********************************************************************
      SUBROUTINE PHASEI (CEP,CES,CET,CNSD1,CNSD2,CRAIN,CSD1,CSD2,
     +   CUMDTT,CUMDEP,DLAYR,DTT,ICSDUR,ISTAGE,ISWNIT,ISWSWB,NDAS,
     +   NDEF1,NDEF2,NLAYR,OUTDTT,P3,P9,PFR,PFL,PFC,PFP,PA,PAN,PANN,
     +   PLANTS,RANC,RLV,RTDEP,RWU,SDEPTH,SIND,SUMDTT,SWSD,TANC,TMNC,
     +   TSTRESS,VANC,VMNC)
C
      DIMENSION DLAYR(10),RLV(10),RWU(10)
      REAL NDEF1,NDEF2,NDEF3
      SAVE NITSW
C
      CNSD1=0.0
      CNSD2=0.0
      CSD1=0.
      CSD2=0.
      ICSDUR=0
      GO TO (1,2,3,4,5,6,7,8,9), ISTAGE
    1 ISTAGE=2
      SIND=0.
      RETURN
    2 ISTAGE=3
      P3=450.+0.15*SUMDTT
      SUMDTT=0.
      PA=PAN
      RETURN
    3 ISTAGE=4
      SUMDTT=SUMDTT-P3
      PFL=0.
      RETURN
    4 ISTAGE=5
      PFR=0.
      PFL=-0.1
      PFC=0.
      PFP=1.1
      VANC=TANC
      VMNC=TMNC
      RETURN
    5 ISTAGE=6
      NITSW=ISWNIT
      ISWNIT=0
      RETURN
    6 ISTAGE=7
      ISWNIT=NITSW
      CUMDTT=0.
      DTT=0.
      CRAIN=0.
      CES=0.
      CEP=0.
      CET=0.
      RETURN
    7 ISTAGE=8
      CUMDTT=0.
      SUMDTT=0.
```

```
      SWSD=1.0
      RTDEP=SDEPTH
      NDAS=0
      RETURN
    8 ISTAGE=9
      P9=7.*SDEPTH
      SUMDTT=SUMDTT-45
      PFL=0.
      PFC=0.
      PFP=0.
      CET=0.
      CES=0.
      CEP=0.
      NDEF1=1.0
      NDEF2=1.0
      NDEF3=1.0
      CRAIN=0.
      RANC=0.022
      TANC=0.044
      RETURN
    9 ISTAGE=1
      SUMDTT=SUMDTT-P9
      OUTDTT=0.
      TSTRESS=0.
      CUMDEP=0.
      IF (ISWSWB.EQ.0) RETURN
      DO 30 L=1,NLAYR
        CUMDEP=CUMDEP+DLAYR(L)
        RLV(L)=0.20*PLANTS/DLAYR(L)
        IF (CUMDEP.GT.RTDEP) GO TO 40
   30 CONTINUE
   40 RLV(L)=RLV(L)*(1.-(CUMDEP-RTDEP)/DLAYR(L))
      L1=L+1
      DO 60 L=L1,10
        RLV(L)=0.
   60 CONTINUE
      DO 70 L=1,10
        RWU(L)=0.
   70 CONTINUE
      PANN=0.0
   80 RETURN
      END
C ***********************************************************************
C ************* GROWTH AND ASSIMILATE PARTITIONING ********************
C ***********************************************************************
      SUBROUTINE GROWTH (BIOMAS,CNSD1,CNSD2,CUMDTT,CUMPH,DLAYR,
     +   DSTOVN,DTT,ESW,FAC,G1,GNP,GPP,GRN,GRNWT,GRORT,ICSDUR,IDAY,
     +   ISTAGE,ISWNIT,KOUTGR,LAI,LFWT,LL,NDEM,NDEF1,NDEF2,NFAC,NLAYR,
     +   NH4,NO3,PA,PANN,PAWT,PDL,PDLWT,PDWI,PFR,PFL,PFC,PFP,PGRORT,
     +   PLANTS,PLA,PLTWT,PERPAWT,PNUP,PPAWT,RANC,RCNP,RLV,RNFAC,
     +   RNLOSS,RNH4U,RNO3U,ROOTN,RTWT,RWU,SEEDRV,SNH4,SNO3,STMWT,
     +   STOVN,STOVWT,SW,SWDF1,SWDF2,SOLRAD,TANC,TCNP,TEMPM,TEMPMN,
     +   TEMPMX,TILNO,TMNC,TNUP,TR,TSTRESS,VANC,VMNC,XSTAGE)
C
      DIMENSION DLAYR(10),ESW(10),FAC(10),LL(10),NH4(10),NO3(10),
     +    PNUP(10),RLV(10),RNFAC(10),RNLOSS(10),RNH4U(10),RNO3U(10),
```

```
     +   RWU(10),SNH4(10),SNO3(10),SW(10)
      REAL LAI,LFWT,LL,NDEM,NDEF1,NDEF2,NFAC,NH4,NO3,NPOOL,NPOOL1,
     +   NPOOL2,NSINK,NSDR
C
      SAVE PLF,RRATIO
C
      IF (PLANTS .EQ. 0.) RETURN
      RRATIO=0.21*EXP(-PLTWT/PLANTS)
      PRFT=1.-0.0025*((0.25*TEMPMN+0.75*TEMPMX)-26.)**2
      IF (PRFT.LT.0.) PRFT=0.
      IF (PRFT.GT.1.) PRFT=1.
      POPFAC=0.94+0.0006*PLANTS
      IF (POPFAC .GT. 1.) THEN
         IF (POPFAC .LT. 2.) THEN
            POPFAC=2.-POPFAC
         ELSE
            POPFAC=0.5
         END IF
      END IF
      TI=DTT/83.
      TNO=TILNO
      TLPOPF=TR*PFL*100/PLANTS
      TILNO=TILNO+TI*TLPOPF*G1*32
      IF (TEMPM.GT.6.0) THEN
         SLFT=1.
         IF (TEMPMN.LE.0.0) SLFT=0.0
      ELSE
         SLFT=1.-(6.0-TEMPM)/6.0
         IF (SLFT.LT.0.) SLFT=0.
      END IF
C
C ************* GROWTH FROM GERMINATION TO EMERGENCE *****************
C
      IF (ISTAGE .EQ. 9) THEN
         PCARB=0.00008265*PLANTS*DTT
         CARBO=PCARB*AMIN1(PRFT,SWDF1)
         PFR=RRATIO
         PFL=1-PFR
         ROOTN=RANC*RTWT
         STOVN=STOVWT*TANC
         PLF=PFL
         SENESR=0.
         SENESL=0.
         SENESC=0.
         GO TO 888
      END IF
      IF (PLTWT.GT.SEEDRV.AND.ISWNIT.NE.0) CALL NFACTO (CNSD1,CNSD2,
     +   NDEF1,NDEF2,NFAC,RCNP,TANC,TCNP,TMNC,XSTAGE)
C
      GO TO (1,2,3,4,5,6),ISTAGE
C
C *********** GROWTH FROM EMERGENCE TO END OF JUVENILE STAGE *******
C
    1 IF (PLTWT .LE. SEEDRV) THEN
         PCARB=0.001*PLANTS*LOG(DTT)
         CARBO=PCARB*AMIN1(PRFT,SWDF1)
```

```
            PFR=RRATIO
            PFL=1-PFR
            ROOTN=RANC*RTWT
            STOVN=STOVWT*TANC
         ELSE
            PFL=PLF+0.001*DTT
            IF (PFL.GE. 0.84) PFL=0.84
            PFC=PFC+0.00002*DTT
            PFR=1-PFL-PFC
            CALL CARB (CARBO,G1,LAI,NDEF1,PCARB,POPFAC,PRFT,
     +   SOLRAD,SWDF1)
         END IF
         PLF=PFL
         SENESR=0.
         SENESL=0.
         SENESC=0.
         GO TO 999
C
C ****** GROWTH FROM BEGINNING OF INDUCTION TO FLORAL INITIATION ****
C
    2 PFR=0.15
      PFL=PLF-0.001*DTT
      PFC=1-PFR-PFL
      PLF=PFL
      SENESR=0.0005
      SENESL=0.0003
      SENESC=0.
      CALL CARB (CARBO,G1,LAI,NDEF1,PCARB,POPFAC,PRFT,
     +   SOLRAD,SWDF1)
      GO TO 999
C
C ********* GROWTH FROM FLORAL INITIATION TO HEADING ********
C
    3 PFR=0.10
      PFL=PLF-0.0014*DTT
      IF (PFL .LE. 0.) PFL=0.
      PLF=PFL
      PFC=PFC+0.00072*DTT
      PFP=1-PFR-PFL-PFC
      SENESR=0.001
      SENESL=0.0006
      SENESC=0.0005
      CALL CARB (CARBO,G1,LAI,NDEF1,PCARB,POPFAC,PRFT,
     +   SOLRAD,SWDF1)
      GO TO 999
C
C *********** GROWTH FROM HEADING TO START OF GRAIN FILLING **********
C
    4 PFR=0.1
      PFL=PLF
      PFL=PLF-0.0006*DTT
      PLF=PFL
      PFC=PFC-0.00215*DTT
      IF (PFC .LE. 0.) PFC=0.
      PFP=1-PFR-PFL-PFC
      SENESR=0.003
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Jun 30 14:09 1987 cerice8.f Page 5

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      SENESL=0.0006
      SENESC=0.0008
      TI=0.
      CALL CARB (CARBO,G1,LAI,NDEF1,PCARB,POPFAC,PRFT,
     +   SOLRAD,SWDF1)
      GO TO 999
C
C *********** GROWTH DURING GRAIN FILLING *****************************
C
    5 PF=-0.0009*DTT
      PFL=PFL+(PF*.7)
      PFC=PFC+(PF*.3)
      PFP=PFP-PF
      SENESR=0.005
      SENESL=0.001
      SENESC=0.0015
      TI=0.
      CALL CARB (CARBO,G1,LAI,NDEF1,PCARB,POPFAC,PRFT,
     +   SOLRAD,SWDF1)
      GROGRN=GRN*DTT
      GRNWT=GRNWT+GROGRN
      IF (ISWNIT.NE.0) THEN
C ********* GRAIN N ALLOWED TO VARY BETWEEN .01 AND .018.
C ********* HIGH TEMP., LOW SOIL WATER, AND HIGH N INCREASE GRAIN N
         TFAC=0.69+.0125*TEMPM
         SFAC=1.125-.125*SWDF2
         GNP=(.007 +.010*NDEF2)*AMAX1(TFAC,SFAC)
         NSINK=PAWT*GNP
         IF (NSINK.NE.0.0) THEN
            RMNC=0.75*RCNP
            VANC=STOVN/STOVWT
            NPOOL1=STOVWT*(VANC-VMNC)
            NPOOL2=RTWT*(RANC-RMNC)
            NPOOL=NPOOL1+NPOOL2
            NSDR=NPOOL/NSINK
            IF (NSDR.LT.1.0) PAWT=PAWT*NSDR
            NSINK=PAWT*GNP
            IF (NSINK.LE.NPOOL1) THEN
               NPOOL1=NPOOL1-NSINK
               STOVN=NPOOL1+VMNC*STOVWT
               VANC=STOVN/STOVWT
            ELSE
               VANC=VMNC
               STOVN=STOVWT*VANC
               NPOOL2=NPOOL2-(NSINK-NPOOL1)
               NPOOL1=0.0
               ROOTN=RTWT*RMNC+NPOOL2
               RANC=ROOTN/RTWT
            END IF
         END IF
         PANN=PANN+NSINK
      END IF
C
C *********** CALCULATES LEAF AREA ************************************
C
999   IF (ISTAGE .LE. 3) THEN
```

```
         PLAG=0.037*TI*CARBO*PFL*TR*G1*AMIN1(SWDF2,NDEF2,SLFT)
      ELSE
         PLAG=0.004*CARBO*PFL*TR*G1*(2-AMIN1(SWDF2,NDEF2,SLFT))
      END IF
      PLA=PLA+PLAG
      LAI=PLA
C
C ******* REDISTRIBUTION TO ROOTS DURING STRESS *********************
C
      IF (ISTAGE.NE.5) THEN
         PFL=PFL*AMIN1(SWDF2,NDEF1)
         PFR=1-PFL-PFC-PFP
      END IF
C
C ********** ESTIMATES WEIGHT OF DEAD LEAVES ***********************
C
      IF (PLAG.LE.0.) PDL=-PLAG
      DLWT=PDL*POPFAC*90.
      PDLWT=PDLWT+DLWT
C
C **** PARTITIONS ASSIMILATES AND CALCULATES WEIGHT OF PLANT PARTS *********
C
888   GRORT=CARBO*PFR
      GROLF=CARBO*PFL
      GROSTM=CARBO*PFC
      PAWT=CARBO*PFP
      PNWT=PA*DTT
      TOPWT=GROLF+GROSTM+PAWT
      RTWT=RTWT+GRORT-(RTWT*SENESR)
      LFWT=LFWT+GROLF-(LFWT*SENESL)
      STMWT=STMWT+GROSTM-(STMWT*SENESC)
      PPAWT=PPAWT+PAWT
      PERPAWT=PERPAWT+PNWT
      STOVWT=LFWT+STMWT
      BIOMAS=LFWT+STMWT+PPAWT
      PLTWT=BIOMAS+RTWT
      CUMPH=CUMPH+TI
C
C ********** POTENTIAL GROWTH FOR N DEMAND *************************
C
      IF (ISWNIT.NE.0.AND.PLTWT.GT.SEEDRV) THEN
         PDWI=PCARB*(1.0-GRORT/(CARBO+1.E-10))
         PGRORT=PCARB*GRORT/(CARBO+1.E-10)
         CALL NUPTAK (DLAYR,DSTOVN,ESW,FAC,GRORT,LL,NDEM,
     +   NH4,NLAYR,NO3,PDWI,PGRORT,PNUP,RANC,RCNP,RLV,RNFAC,
     +   RNLOSS,RNH4U,RNO3U,ROOTN,RTWT,RWU,SNH4,SNO3,STOVN,
     +   STOVWT,SW,TANC,TCNP,TNUP,XSTAGE)
      END IF
      IF (ISTAGE.EQ.4.OR.ISTAGE.EQ.5) THEN
         TLNO=PPAWT/PERPAWT+1.E-10
         IF (TLNO.GT.TILNO) TILNO=TLNO
         IF (TILNO.GT.TNO) TILNO=TNO
      END IF
      RETURN
C
C *********** PHYSIOLOGICAL MATURITY ********************************
```

```
C
    6 TILNO=PPAWT/PERPAWT
      RETURN
      END
C
C ***********************************************************************
C ************ ASSIMILATE PRODUCTION *********************************
C ***********************************************************************
      SUBROUTINE CARB (CARBO,G1,LAI,NDEF1,PCARB,POPFAC,PRFT,
     +   SOLRAD,SWDF1)
C
      REAL LAI,K,NDEF1
      PAR=0.02092*SOLRAD
      IF (LAI .LE. 0.6) K=EXP(-LAI)
      IF (LAI .GT. 0.6 .AND. LAI .LE. 5) K=0.58-0.04*LAI
      IF (LAI .GT. 5) K=0.36
      SHINE=-K*LAI
      PCARB=G1*PAR*(1-EXP(SHINE))
      CARBO=PCARB*POPFAC*PRFT*AMIN1(SWDF1,NDEF1)
      RETURN
      END
```

May 18 16:37 1987 cerice9.f Page 1

```
C ************************************************************************
C ************** SOIL NITROGEN INITIALIZATION ****************************
C ************** SUBROUTINE INITIALIZES SOIL NITROGEN PARAMETERS ********
C ************** AND INPUTS RESIDUE PARAMETERS **************************
C ************************************************************************
      SUBROUTINE SOILNI (ABD,ALX,AMP,ANG,BD,CNI,CTNUP,CUMDEP,DD,
     +   DEPMAX,DLAYR,DMINR,DMOD,DT,DTNOX,DUL,HUM,JDATE,LL,NHUM,
     +   NLAYR,NNOM,NOUT,NUP,OC,PESW,PH,PNUP,RCN,RNLOSS,SALB,
     +   SAT,SOLRAD,ST,STO,SW,TO,TA,TAV,TFY,TMN,TPESW,WFY,WRN,Z)
C
      REAL IFOM,IFON,LL,NH4,NO3,NNOM,NHUM,NOUT,NUP
      DIMENSION AFERT(10),BD(10),CNI(10),DFERT(10),DLAYR(10),
     +   DTNOX(10),DUL(10),FOM(10),FON(10),HUM(10),
     +   IFOM(10),IFON(10),IFTYPE(10),JFDAY(10),
     +   LL(10),NH4(10),NHUM(10),NNOM(10),NO3(10),NOUT(10),NUP(10),
     +   OC(10),PH(10),PNUP(10),RNLOSS(10),SAT(10),SNH4(10),SNO3(10),
     +   ST(10),SW(10),TO(5),TFY(10),WFY(10),WRN(10)
      COMMON/IPTRT4/ STRAW,SDEP,SCN,ROOT
      COMMON/IPTRT5/ NFERT,JFDAY,AFERT,DFERT,IFTYPE
      COMMON/SOILR2/ NH4,NO3
      COMMON/SOILN1/ FOM,FON
      COMMON/SOILN2/ IFOM,IFON
      COMMON/SOILN3/ RDCARB,RDCELL,RDLIGN
      COMMON/SOILN4/ SNH4,SNO3
      COMMON/SOILN5/ TEMPMN,TEMPMX
      COMMON/SOILN6/ TIFOM,TIFON
C
      IF (DMOD.EQ.0.) DMOD=1.
      CTNUP=0.0
      ABD=0
      DO 20 I=1,NLAYR
        ABD=ABD+BD(I)*DLAYR(I)
   20 CONTINUE
      ABD=ABD/CUMDEP
C
C ********** CALCULATES INITIAL SOIL TEMPERATURE *********************
C
      PESW=TPESW
      ANG=0.017214
      DO 50 I=1,5
        TMN=(TEMPMX+TEMPMN)/2.
        TO(I)=TMN
   50 CONTINUE
      STO=5.*TO(1)
      CALL SOLT (ABD,ALX,AMP,ANG,CUMDEP,DD,DLAYR,DT,JDATE,
     +   NLAYR,PESW,SOLRAD,ST,STO,SALB,TA,TAV,TMN,TO,TEMPMX,Z)
C
C ********** INPUTS FERTILIZER DATA ***********************************
C
      DO 80 J=1,NFERT
         M=IFTYPE(J)
         IF (M.EQ.0) M=1
         IF (AFERT(J).EQ.0.) M=6
   80 CONTINUE
C
C ********** CALCULATES N CONTRIBUTIONS ******************************
```

May 18 16:37 1987 cerice9.f Page 2

```
C
   99 SNKG=STRAW*0.40/SCN
      RCN=45.
      RNKG=ROOT*0.40/RCN
C
C ********** DISTRIBUTES ROOT MASS ***********************************
C
      WSUM=0.0
      DEPTH=0.0
      DO 100 I=1,NLAYR
        DEPTH=DEPTH+DLAYR(I)
        WRN(I)=EXP(-3.0*DEPTH/DEPMAX)
        WSUM=WSUM+WRN(I)
        NOUT(I)=0.0
        NUP(I)=0.0
        PNUP(I)=0.0
        NNOM(I)=0.0
  100 CONTINUE
      DO 110 I=1,NLAYR
        FACTOR=WRN(I)/WSUM
        FOM(I)=ROOT*FACTOR
        FON(I)=RNKG*FACTOR
  110 CONTINUE
      DEPTH=0.0
      FRSUM=0.0
      IOUT=1
      DO 150 I=1,NLAYR
        DEPTH=DEPTH+DLAYR(I)
        FR=DLAYR(I)/SDEP
        IF (I.EQ.1.AND.SDEP.LE.DEPTH) THEN
           FR=1
           IOUT=2
        END IF
        IF (SDEP.GT.DEPTH) THEN
           FRSUM=FRSUM+FR
        ELSE
           FR=1-FRSUM
           IOUT=2
        END IF
        ADD=STRAW*FR
        FOM(I)=FOM(I)+ADD
        FON(I)=FON(I)+ADD*0.40/SCN
        GO TO (150,160), IOUT
  150 CONTINUE
  160 TIFOM=0.0
      TIFON=0.0
      DO 170 I=1,NLAYR
        RNLOSS(I)=0.0
        HUM(I)=OC(I)*1.E03*BD(I)*DLAYR(I)/0.4
        IFOM(I)=FOM(I)
        IFON(I)=FON(I)
        TIFOM=TIFOM+IFOM(I)
        TIFON=TIFON+IFON(I)
  170 CONTINUE
      RDCARB=0.8
      RDCELL=0.05
```

May 18 16:37 1987 cerice9.f Page 3

```
      RDLIGN=0.0095
      DMINR=8.3E-05*DMOD
C
      DL1=0.0
      DO 190 L=1,NLAYR
        DL2=DL1+DLAYR(L)
        SNO3(L)=NO3(L)*BD(L)*DLAYR(L)*1.E-01
        SNH4(L)=NH4(L)*BD(L)*DLAYR(L)*1.E-01
        NHUM(L)=OC(L)*DLAYR(L)*BD(L)*1.E02-(SNO3(L)+SNH4(L))
        DL1=DL2
  190 CONTINUE
      DL1=0.0
      DO 200 L=1,NLAYR
        DL2=DL1+DLAYR(L)
        DL1=DL2
  200 CONTINUE
C
C ********** INITIALIZES NITRIFICATION ROUTINE ***********************
C
  210 DO 220 L=1,NLAYR
        CNI(L)=0.1
        WFY(L)=(SW(L)-LL(L))/DUL(L)
        IF (SW(L).GT.DUL(L)) WFY(L)=1.0-((SW(L)-DUL(L))
     +    /(SAT(L)-DUL(L)))
        IF (WFY(L).LT.0.0) WFY(L)=0.0
        TFY(L)=0.0009766*ST(L)*ST(L)
        IF (ST(L).LT.5.0) TFY(L)=0.0
  220 CONTINUE
      RETURN
C
      END
```

May 18 16:38 1987 cerice10.f Page 1

```
C ***********************************************************************
C ********* MINERALIZATION AND IMMOBILIZATION ROUTINE *****************
C ***********************************************************************
      SUBROUTINE MINIMO (ABD,ALX,AMP,ANG,BD,CNI,CNR,CUMDEP,DD,DECR,
     +   DLAYR,DMINR,DT,DUL,FAC,FOCNR,HUM,IFOM,JDATE,LL,NHUM,NLAYR,
     +   NNOM,PESW,POMR,PONR,RNTRF,SALB,SAT,SCNR,ST,STO,SOLRAD,SW,
     +   TA,TAV,TMN,TO,TFY,WFY,Z)
C
      REAL IFOM,LL,MF,NH4,NO3,NNOM,NHUM
      DIMENSION AFERT(10),BD(10),CNI(10),CNR(10),DECR(10),DLAYR(10),
     +   DFERT(10),DUL(10),FAC(10),FOCNR(10),FOM(10),FON(10),HUM(10),
     +   IFOM(10),IFTYPE(10),JFDAY(10),LL(10),NH4(10),NHUM(10),
     +   NNOM(10),NO3(10),RNTRF(10),SAT(10),SCNR(10),SNH4(10),
     +   SNO3(10),ST(10),SW(10),TO(5),TFY(10),WFY(10)
      COMMON/IPTRT5/ NFERT,JFDAY,AFERT,DFERT,IFTYPE
      COMMON/SOILR2/ NH4,NO3
      COMMON/SOILN1/ FOM,FON
      COMMON/SOILN3/ RDCARB,RDCELL,RDLIGN
      COMMON/SOILN4/ SNH4,SNO3
      COMMON/SOILN5/ TEMPMN,TEMPMX
      COMMON/SOILN6/ TIFOM,TIFON
      COMMON/MINIM1/ TIMOB,TMINF,TMINH,TNNOM
C
         DEPTH=0.0
         DO 10 K=1,NFERT
            J=K
            IF (JDATE.EQ.JFDAY(J)) THEN
               DO 60 L=1,NLAYR
                  DEPTH=DEPTH+DLAYR(L)
                  IF (DFERT(J).LE.DEPTH) THEN
                     M=IFTYPE(J)
                     GO TO (30,40,30,40,50), M
C ****************** FERTILIZER TYPES ********************************
C                    0,1 =UREA (HYDROLYSIS TO BE ADDED LATER)
C                    2   =AMMONIUM NITRATE
C                    3   =ANHYDROUS AMMONIA
C                    4   =CALCIUM AMMONIUM NITRATE
C                    5   =M NITRATE
C ---------------------------------------------------------------------
   30                SNH4(L)=SNH4(L)+AFERT(J)
                     GO TO 70
   40                SNH4(L)=SNH4(L)+0.5*AFERT(J)
                     SNO3(L)=SNO3(L)+0.5*AFERT(J)
                     GO TO 70
   50                SNO3(L)=SNO3(L)+AFERT(J)
                     GO TO 70
                  END IF
   60          CONTINUE
            END IF
   10    CONTINUE
C
   70 TMN=(TEMPMX+TEMPMN)*0.5
      CALL SURSOL (SALB,SOLRAD,STO,TEMPMX,TMN,TO)
      CALL SOLT (ABD,ALX,AMP,ANG,CUMDEP,DD,DLAYR,DT,JDATE,
     +   NLAYR,PESW,SOLRAD,ST,STO,SALB,TA,TAV,TMN,TO,TEMPMX,Z)
      TIMOB=0.0
```

```
      TMINF=0.0
      TMINH=0.0
      TNNOM=0.0
      TOM=0.0
      TON=0.0
C
      DO 90 I=1,NLAYR
        MF=(SW(I)-LL(I)*0.5)/(DUL(I)-LL(I)*0.5)
        IF (MF.LE.0.) MF=0.
        FAC(I)=1.0/(BD(I)*1.E-01*DLAYR(I))
        NO3(I)=SNO3(I)*FAC(I)
        NH4(I)=SNH4(I)*FAC(I)
        TFAC=0.00097666*ST(I)*ST(I)
        IF (TFAC.GE.1.0) TFAC=1.0
        IF (ST(I).LE.0.0) TFAC=0.0
        RATIO=FOM(I)/IFOM(I)
C
        IF (RATIO.GT.0.8) THEN
           RDECR=RDCARB
        ELSE IF (RATIO.LE.0.8.AND.RATIO.GT.0.1) THEN
           RDECR=RDCELL
        ELSE
           RDECR=RDLIGN
        END IF
        TOTN=SNO3(I)+SNH4(I)-2.0/FAC(I)
        IF (TOTN.LT.0.0) TOTN=0.0
        CNR(I)=(0.4*FOM(I))/(FON(I)+TOTN)
        CNRF=EXP(-0.693*(CNR(I)-25)/25.0)
        IF (CNRF.GT.1.0) CNRF=1.0
        DECR(I)=RDECR*TFAC*MF*CNRF
        GRNOM=DECR(I)*FON(I)
        RHMIN=NHUM(I)*DMINR*TFAC*MF
        HUM(I)=HUM(I)-RHMIN*10.0+0.2*GRNOM/0.04
        NHUM(I)=NHUM(I)-RHMIN+0.2*GRNOM
        RNAC=AMIN1(TOTN,DECR(I)*FOM(I)*(0.02-FON(I)/FOM(I)))
        FOM(I)=FOM(I)-DECR(I)*FOM(I)
        FON(I)=FON(I)+RNAC-GRNOM
        NNOM(I)=0.8*GRNOM+RHMIN-RNAC
        TNNOM=TNNOM+NNOM(I)
        TON=TON+FON(I)
        TOM=TOM+FOM(I)
        SNH4(I)=SNH4(I)+NNOM(I)
        IF (SNH4(I).LE.1.0) THEN
           DEF=1.0-SNH4(I)
           IF (DEF.GT.SNO3(I)) DEF=SNO3(I)
           SNO3(I)=SNO3(I)-DEF
           SNH4(I)=1.0
        END IF
        SCNR(I)=0.4*(FOM(I)+HUM(I))/(FON(I)+NHUM(I)+SNO3(I)+SNH4(I))
        FOCNR(I)=0.4*FOM(I)/FON(I)
        TIMOB=TIMOB+RNAC
        TMINF=TMINF+GRNOM*0.8
        TMINH=TMINH+RHMIN
   90 CONTINUE
      POMR=TOM/TIFOM
      PONR=TON/TIFON
```

```
      CALL NITRIF (CNI,DUL,LL,NLAYR,RNTRF,SAT,SNH4,SNO3,ST,
     +   SW,TFY,WFY)
C
      RETURN
      END
C ***********************************************************************
C ********** NITROGEN UPTAKE ROUTINE ***********************************
C ***********************************************************************
      SUBROUTINE NUPTAK (DLAYR,DSTOVN,ESW,FAC,GRORT,LL,NDEM,
     +   NH4,NLAYR,NO3,PDWI,PGRORT,PNUP,RANC,RCNP,RLV,RNFAC,
     +   RNLOSS,RNH4U,RNO3U,ROOTN,RTWT,RWU,SNH4,SNO3,STOVN,
     +   STOVWT,SW,TANC,TCNP,TNUP,XSTAGE)
C
      DIMENSION DLAYR(10),ESW(10),FAC(10),LL(10),NH4(10),NO3(10),
     +   PNUP(10),RLV(10),RNFAC(10),RNLOSS(10),RNH4U(10),RNO3U(10),
     +   RWU(10),SNH4(10),SNO3(10),SW(10)
      REAL LL,NDEM,NH4,NO3,NUF
C
      TNUP=0.0
      TRNLOS=0.0
      DO 10 L=1,NLAYR
        NO3(L)=SNO3(L)*FAC(L)
        NH4(L)=SNH4(L)*FAC(L)
        TOTN=NO3(L)+NH4(L)
        RNFAC(L)=1.0-(1.17*EXP(-0.15*TOTN))
        IF (RNFAC(L).LE.0.01) RNFAC(L)=0.01
        PNUP(L)=0.0
   10 CONTINUE
      IF (PDWI.EQ.0.) PDWI=1.
      DNG=PDWI*TCNP
      IF (XSTAGE.LE.1.2) DNG=0.0
      TNDEM=STOVWT*(TCNP-TANC)+DNG
      RNDEM=RTWT*(RCNP-RANC)+PGRORT*RCNP
      NDEM=TNDEM+RNDEM
      ANDEM=NDEM*10.0
      DROOTN=0.0
      DSTOVN=0.0
      TRNU=0.0
      TNUP=0.0
      IF (ANDEM.GT.0.0) THEN
            DO 20 L=1,NLAYR
               IF (RLV(L).EQ.0.0) GO TO 30
               L1=L
               FNH4=1.0-EXP(-0.030*NH4(L))
               FNO3=1.0-EXP(-0.030*NO3(L))
               IF (FNO3.LT.0.03) THEN
                  FNO3=0.0
               ELSE IF (FNO3.GT.1.0) THEN
                  FNO3=1.0
               END IF
               IF (FNH4.LT.0.03) THEN
                  FNH4=0.0
               ELSE IF (FNH4.GT.1.0) THEN
                  FNH4=1.0
               END IF
            SMDFR=(SW(L)-LL(L))/ESW(L)
```

```
            RFAC=RLV(L)*SMDFR*SMDFR*DLAYR(L)*100
            RNO3U(L)=(RWU(L)/(SW(L)*DLAYR(L)))*SNO3(L)
            IF (SMDFR.LT.0.30) RNO3U(L)=RFAC*FNO3*0.008
            UP1=SNO3(L)-RNO3U(L)
            SMIN=1.5/FAC(L)
            IF (UP1.LT.SMIN) RNO3U(L)=SNO3(L)-SMIN
            IF (RNO3U(L).LE.0.0) RNO3U(L)=0.
            RNH4U(L)=RFAC*FNH4*0.008
            UP2=SNH4(L)-RNH4U(L)
            IF (UP2.LT.SMIN) RNH4U(L)=SNH4(L)-SMIN
            IF (RNH4U(L).LE.0.0) RNH4U(L)=0.
            TRNU=TRNU+RNO3U(L)+RNH4U(L)
   20    CONTINUE
   30    IF (ANDEM.GT.TRNU) ANDEM=TRNU
         IF (TRNU.NE.0.0) THEN
            NUF=ANDEM/TRNU
            TRNU=ANDEM
            TRNS=0.0
            DO 40 L=1,L1
               UNO3=RNO3U(L)*NUF
               UNH4=RNH4U(L)*NUF
               SNO3(L)=SNO3(L)-UNO3
               SNH4(L)=SNH4(L)-UNH4
               PNUP(L)=UNO3+UNH4
               RNLOSS(L)=RANC*RLV(L)*0.006665
               TRNLOS=TRNLOS+RNLOSS(L)
               TNUP=TNUP+PNUP(L)
               TRNS=TRNS+SNO3(L)+SNH4(L)
   40       CONTINUE
            TRNU=TRNU/10.0
            DSTOVN=TNDEM/NDEM*TRNU
            DROOTN=RNDEM/NDEM*TRNU
            STOVN=STOVN+DSTOVN
         ELSE
            RETURN
         END IF
      END IF
C
      TANC=STOVN/STOVWT
      DROOTN=DROOTN-TRNLOS
      ROOTN=ROOTN+DROOTN
      RANC=ROOTN/(RTWT+0.5*GRORT-0.005*RTWT)
   60 RETURN
      END
```

May 18 16:38 1987 ceric ell.f Page 1

```
C ************************************************************************
C ********** DRAINAGE AND LEACHING ROUTINE *****************************
C ************************************************************************
      SUBROUTINE NFLUX (ICODE,DLAYR,FAC,FLOW,FLUX,MU,NLAYR,NOUT,
     +   NO3,NUP,SNO3,SW)
C
      DIMENSION DLAYR(10),FAC(10),FLOW(10),FLUX(10),NOUT(10),NO3(10),
     +   NUP(10),SNO3(10),SW(10)
      REAL NO3,NOUT,NUP
C
      IF (ICODE.NE.1) THEN
         DO 10 L=1,NLAYR
            NOUT(L)=0.0
   10    CONTINUE
         OUTN=0.0
         DO 30 L=1,NLAYR
            SNO3(L)=SNO3(L)+OUTN
            NO3(L)=SNO3(L)*FAC(L)
            IF (NO3(L).GT.1.0) THEN
               NOUT(L)=SNO3(L)*FLUX(L)/(SW(L)*DLAYR(L)+FLUX(L))
               SMIN=1.0/FAC(L)
               IF ((SNO3(L)-NOUT(L)).LT.SMIN) NOUT(L)=SNO3(L)-SMIN
               OUTN=NOUT(L)
               SNO3(L)=SNO3(L)-OUTN
               NO3(L)=SNO3(L)*FAC(L)
            ELSE
               OUTN=0.0
            END IF
   30    CONTINUE
         RETURN
      END IF
C
      DO 50 L=1,NLAYR
        NUP(L)=0.0
   50 CONTINUE
      OUTN=0.0
      DO 60 J=1,MU
        K=MU+1-J
        SNO3(K)=SNO3(K)+OUTN
        IF (FLOW(K).GE.0.) THEN
           NUP(K)=SNO3(K)*FLOW(K)/(SW(K)*DLAYR(K)+FLOW(K))*0.5
           OUTN=NUP(K)
           IF (K.NE.1) SNO3(K)=SNO3(K)-OUTN
        END IF
   60 CONTINUE
      OUTN=0.0
      DO 70 J=1,MU
        SNO3(J)=SNO3(J)-OUTN
        IF (FLOW(J).LE.0.) THEN
           NUP(J)=SNO3(J)*FLOW(J)/(SW(J)*DLAYR(J)+FLOW(J))*0.5
           OUTN=NUP(J)
           SNO3(J)=SNO3(J)+OUTN
        END IF
   70 CONTINUE
      RETURN
      END
```

```
C ************************************************************************
C ********** NITROGEN DEFICIENCY FACTOR ROUTINE ***************************
C ************************************************************************
      SUBROUTINE NFACTO (CNSD1,CNSD2,NDEF1,NDEF2,NFAC,RCNP,TANC,
     +   TCNP,TMNC,XSTAGE)
C
      REAL NFAC,NDEF1,NDEF2
      TCNP=EXP(1.52-.160*XSTAGE)/100.0
      TMNC=0.0045
      IF (XSTAGE.LT.4.) TMNC=(1.25-0.20*XSTAGE)/100.0
      RCNP=1.06/100.0
      NFAC=1.0-(TCNP-TANC)/(TCNP-TMNC)
      IF (NFAC.GT.1.0) THEN
         NFAC=1.0
      ELSE IF (NFAC.LT.0.) THEN
         NFAC=0.
      END IF
      NDEF1=1.0
      NDEF2=1.0
      IF (NFAC.LT.0.8) NDEF1=1.25*NFAC
      NDEF2=NFAC
      CNSD1=CNSD1+1.0-NDEF1
      CNSD2=CNSD2+1.0-NDEF2
      RETURN
      END
C ************************************************************************
C ********** DENITRIFICATION SUBROUTINE **********************************
C ************************************************************************
      SUBROUTINE DNIT (BD,DLAYR,DTNOX,DUL,FAC,FOM,HUM,NLAYR,NO3,
     +   SAT,SNO3,ST,SW)
C
      DIMENSION BD(10),DLAYR(10),DTNOX(10),DUL(10),FAC(10),FOM(10),
     +   HUM(10),NO3(10),SAT(10),SNO3(10),ST(10),SW(10)
      REAL NO3
C
      DO 10 L=1,NLAYR
         IF (NO3(L).GE.1.0) THEN
            FW=0.0
            IF (SW(L).GT.DUL(L)) THEN
               SOILC=0.40*FOM(L)+0.58*HUM(L)
               CW=(SOILC*FAC(L))*0.0031+24.5
               FW=(SAT(L)-SW(L))/(SAT(L)-DUL(L))
               FT=0.1*EXP(0.046*ST(L))
               DNRATE=6.0*1.E-05*CW*NO3(L)*BD(L)*FW*FT*DLAYR(L)
               SMIN=1.0/FAC(L)
               SNO3(L)=SNO3(L)-DNRATE
               X=0
               IF (SNO3(L).LT.SMIN) X=SMIN-SNO3(L)
               SNO3(L)=SNO3(L)+X
               DNRATE=DNRATE-X
               DTNOX(L)=DNRATE
               NO3(L)=SNO3(L)*FAC(L)
            END IF
         END IF
   10 CONTINUE
      RETURN
```

```
      END
C **********************************************************************
C ************** NITRIFICATION  SUBROUTINE ******************************
C **********************************************************************
      SUBROUTINE NITRIF (CNI,DUL,LL,NLAYR,RNTRF,SAT,SNH4,SNO3,ST,
     +   SW,TFY,WFY)
C
      DIMENSION CNI(10),DUL(10),LL(10),RNTRF(10),SAT(10),SNH4(10),
     +   SNO3(10),ST(10),SW(10),TFY(10),WFY(10)
      REAL LL
C
      DO 10 L=1,NLAYR
        SANC=1.0-EXP(-0.01363*SNH4(L))
        XL=(DUL(L)-LL(L))*0.25
        WFD=(SW(L)-LL(L))/XL
        IF (SW(L).GT.XL) WFD=1.0
        IF (SW(L).GT.DUL(L)) WFD=1.0-((SW(L)-DUL(L))/(SAT(L)-DUL(L)))
        IF (WFD.LT.0.0) WFD=0.0
        TF=(ST(L)-5.0)/30.0
        IF (ST(L).LT.5.0) TF=0.0
        ELNC=AMIN1(TF,WFD,SANC)
        RP2=CNI(L)*EXP(2.302*ELNC)
C
        IF (RP2.LT.0.01) THEN
           RP2=0.01
        ELSE IF (RP2.GT.1.0) THEN
           RP2=1.0
        END IF
C
        CNI(L)=RP2
        A=AMIN1(RP2,WFD,TF)
        RNTRF(L)=A*40.0*SNH4(L)/(SNH4(L)+90.0)
        SNH4(L)=SNH4(L)-RNTRF(L)
        SNO3(L)=SNO3(L)+RNTRF(L)
        SARNC=1.0-EXP(-0.1363*SNH4(L))
        XW=AMAX1(WFD,WFY(L))
        XT=AMAX1(TF,TFY(L))
        CNI(L)=CNI(L)*AMIN1(XW,XT,SARNC)
        IF (CNI(L).LE.0.01) CNI(L)=0.01
        WFY(L)=WFD
        TFY(L)=TF
   10 CONTINUE
      RETURN
      END
```

May 18 16:38 1987 cerice12.f Page 1

```
C ***********************************************************************
C ********* SOIL TEMPERATURE ROUTINE ************************************
C ***********************************************************************
      SUBROUTINE SOLT (ABD,ALX,AMP,ANG,CUMDEP,DD,DLAYR,DT,JDATE,
     +   NLAYR,PESW,SOLRAD,ST,STO,SALB,TA,TAV,TMN,TO,TEMPMX,Z)
C
      DIMENSION ST(10),TO(5),DLAYR(10)
C
      ALX=ANG*(JDATE-200.)
      STO=STO-TO(5)
      K=5
    1 TO(K)=TO(K-1)
      K=K-1
      IF (K.GT.1) GO TO 1
      TO(1)=(1.-SALB)*(TMN+(TEMPMX-TMN)*SQRT(SOLRAD/800.))+SALB
     + *TO(1)
      STO=STO+TO(1)
      F=ABD/(ABD+686.*EXP(-5.63*ABD))
      DP=1000.0+2500.*F
      WW=0.356-0.144*ABD
      B=ALOG(500./DP)
      AW=PESW
      WC=AW/(WW*CUMDEP)
      F=EXP(B*((1.-WC)/(1.+WC))**2)
      DD=F*DP
      TA=TAV+AMP*COS(ALX)/2.
      DT=STO/5.-TA
      Z=0.
      DO 10 L=1,NLAYR
         Z1=DLAYR(L)*10.0
         Z=Z+Z1
         ZD=-Z/DD
         ST(L)=TAV+(AMP/2.*COS(ALX+ZD)+DT)*EXP(ZD)
   10 CONTINUE
      RETURN
      END
C ***********************************************************************
C ************* PART OF SOIL TEMPERATURE ROUTINE ************************
C ***********************************************************************
      SUBROUTINE SURSOL (SALB,SOLRAD,STO,TEMPMX,TMN,TO)
C
      DIMENSION TO(5)
C
      STO=STO-TO(5)
      K=5
    1 TO(K)=TO(K-1)
      K=K-1
      IF (K.GT.1) GO TO 1
      TO(1)=(1.-SALB)*(TMN+(TEMPMX-TMN)*SQRT(SOLRAD/800.))+SALB
     + *TO(1)
      STO=STO+TO(1)
      RETURN
      END
```

APPENDIX C

USER DOCUMENTATION OF THE RICE SIMULATION MODEL

B.1. General Description

The CERES-Rice model, Version 1.10, is a growth and development simulation model of the rice crop under upland condition. It is a daily time-step model that simulates grain yield and growth components of different varieties in any agroclimatic condition for one cropping season. The model represents the transformation of seeds, water, and fertilizers into grain and straw through the use of land, energy (solar, chemical and biological), and management practices, subject to environmental factors such as solar radiation, maximum and minimum air temperatures, precipitation, daylength variation, soil properties, and soil water conditions. It has the flexibility of running with irrigation and nitrogen fertilization.

The main features of the model are:

1. Phasic development or duration of growth stages as influenced by plant genetics, weather and other environmental factors
2. Biomass production and partitioning
3. Root system dynamics
4. Effect of soil water deficit and nitrogen deficiency on the photosynthesis and photosynthate partitioning in the plant

system.

The rice simulation model was developed in Fortran 77 language and compiled in Microsoft FORTRAN77 V3.20 02/84.

The user of the model is expected to have at least an idea of rice production and a general working knowledge of operating a microcomputer system.

Accompanying this documentation is a 5 1/4 in. 2S/2D model diskette that contains the compiled program.

B.2. Hardware Requirements

1. Any IBM-compatible microcomputer with at least one disk drive
2. Requires at least 256 K bytes of RAM (random access memory)
3. Requires about 250 K bytes of storage disk space
4. Any compatible printer to generate a hard copy of the outputs.

B.3. Software Requirements

1. MS-DOS (Version 2.1 or later) as operating system

B.4. Limitations Of The Model

Weeds, diseases, and insects, although important in the crop production process, are not considered as limiting factors in the model. The simulation model is for upland rice production where the field is not bunded, hence, runoff is allowed to occur. Method of planting is direct-seeding and fertilizer application is basal, to be applied once at the beginning of the planting season. Except for nitrogen, all other nutrients required for plant growth are assumed non-limiting, that is, sufficient to support normal growth. The simulation model will not account for highly problematic soils such as soils with high salinity and acidity, heavily compacted soils, and soils that are highly deficient in trace elements. In the same manner, the model will not account for the destructive effects of typhoons.

B.5. Input Files

There are three types of input files: directory files, parameter, coefficient and treatment files, and field-measured data files.

The directory files are: RIEXP.DIR, WTH.DIR, and SIM.DIR.

There are 9 parameter, coefficient and treatment files. The filenames are user-supplied with at most 12 character strings defined in RIEXP.DIR file. For this demonstration, these are files with RI+Number extensions. Examples are:

(a) IRPI8301.RI1 is a 1983 weather file of IRRI, Phil. (FILE1).

(b) IRPI8001.RI7 is a fertilizer application file for a 1980 experiment (FILE7).

The field-measured data files are FILEA and FILEB. These are files with RIA and RIB extensions, respectively. This version of the model does not make use of FILEB. An example is:

IRPI8301.RIA is a field-measured data for a 1983 experiment (FILEA).

For naming and detailed description of the input files, refer to the "Documentation for IBSNAT Crop Model Input and Output Files, Version 1.0" which is attached to this User Documentation.

B.6. Steps To Run The CERES-Rice Model

B.6.1. Start-up instructions

1. Make sure computer is on.
2. For multiple-disk drive systems, set the default drive to where the model diskette will be inserted. For single-disk drive systems, drive A is automatically the default drive.
3. Insert model diskette into the default disk drive.
4. Type "RICE"
5. The following message should come up on the screen:

C E R E S   R I C E   M O D E L
Version 1.10 - Upland Condition
Pause.
Please press <return> to continue.

B.6.2. Screen prompts, options, and screen inputs

1. The first prompt is for user to press the <return> key to continue. At this stage, press the <return> key.
2. The second prompt is a list of experiments to be simulated. The screen display will vary depending on the list of experiments defined in RIEXP.DIR file. For this entry, the screen would display the following experiments:

```
                                                INST.  SITE  EXPT.
    LIST OF EXPERIMENTS TO BE SIMULATED          ID     ID    NO    YEAR
    -------------------------------------       ----   ----  ----   ----
 1)  IRRI, LOS BANOS, PHENOLOGY STUDY, 1983      IR     PI    01    1983
 2)  IRRI, LOS BANOS, IRRIG. & N STUDY, 1980     IR     PI    01    1980

 1]  <--- CURRENT EXPERIMENT SELECTION.
     <--- NEW SELECTION?
```

3. Press the number corresponding to the experiment selection.

4. The third prompt is a list of treatments under the experiment chosen in step 3. The screen display will depend upon the treatments of the experiment defined in FILE8. For experiment no. 2 of step 2, the following list of treatments would be displayed on the screen:

```
TRT                                             INST.  SITE  EXPT.
NO.  IRRI, LOS BANOS, IRRIG. & N STUDY, 1980     ID     ID    NO    YEAR
---  -------------------------------------------       ----  ----   ----
 1)  IR36, 120 Kg N/Ha, W1 irrig. level          IR     PI    01    1980
 2)  IR36,   0 Kg N/Ha, W2 irrig. level          IR     PI    01    1980
 3)  IR36,  30 Kg N/Ha, W2 irrig. level          IR     PI    01    1980
 4)  IR36,  60 Kg N/Ha, W2 irrig. level          IR     PI    01    1980
 5)  IR36, 120 Kg N/Ha, W2 irrig. level          IR     PI    01    1980

 1]  <--- CURRENT TREATMENT SELECTION
     <--- NEW SELECTION?
```

5. Press the number corresponding to the treatment selection.

6. The fourth prompt is the run-time options. The user could proceed to run the simulation (0), select the simulation output frequency (1), or modify selected inputs interactively (2). The screen should display the following:

```
RUN-TIME OPTIONS?

0)  RUN SIMULATION

1)  SELECT SIMULATION OUTPUT FREQUENCY
```

2) MODIFY SELECTED MODEL INPUTS INTERACTIVELY

<—— CHOICE ? [DEFAULT = 0]

7. Press the number corresponding to the run-time option.

8. If choice is 0, proceed to step 11.

9. If choice is 1, the user has the option to change the frequency of writing the simulation output to the output files. These are the choices on the screen:

" 7 Days <——OUTPUT FREQUENCY FOR WATER BALANCE COMPONENTS.
<--- NEW VALUE? "

Press the frequency of output according to choice.

" 7 Days <——OUTPUT FREQUENCY FOR GROWTH COMPONENTS.
<--- NEW VALUE? "

Press the frequency of output according to choice.

" 7 Days <——OUTPUT FREQUENCY FOR NITROGEN COMPONENTS.
<--- NEW VALUE? "

Press the frequency of output according to choice.

10. If choice is 2, the user has the option to change selected inputs interactively from the screen.

11. The next prompt is for the user to enter a run identifier to label the simulation run. A character string of at most 20 is acceptable as input. This is optional.

" <—— ENTER RUN IDENTIFIER, HIT <CR> FOR NONE. "

Enter run identifier and/or press the <return> key to continue.

12. The next prompt is a querry if the user is interested to

write on the screen selected inputs and summary outputs.

"Do you want input data echoed to screen (Y/N)?"

Press "Y" for "yes" or "N" for "no".

13. The next prompt is a querry if the user is interested to display on the screen post harvest comparison with field-measured data.

"Do you want post harvest comparison with observed data displayed on the screen (Y/N) ?"

Press "Y" for "yes" or "N" for "no".

14. If the choice for steps 12 or 13 is "Y" , some information will be displayed on the screen during the simulation.

15. When the simulation is done, a querry if the user is interested to simulate another treatment is displayed on the screen.

"Simulation complete for this treatment.
Do you want to simulate another treatment (Y/N) ?"

Press "Y" for "yes" or "N" for "no".

16. A choice of "Y" will re-initialize the simulation. In this case, go back to step 2.

17. A choice of "N" will end the simulation.

"END OF SIMULATION RUN."

B.7. Output Files

There are four output files. The filenames are user-supplied with at most 7 character strings defined in RIEXP.DIR file. For this demonstration, the output files are OUT80.1, OUT80.2, OUT80.3, and OUT80.4.

OUTPUT FILE NO. 1 - contains some selected inputs and the summary output. The following codes are part of output no. 1:

RUN IDENTIFIER - identifies the simulation run for the user; any character string of 20 or less is valid.

RUN NO. - A counter on the number of simulation runs

INST_ID - Institute identification code

SITE_ID - Site or Location identification code

EXPT_NO - Experiment number

YEAR - Calendar year of the experiment

TRT_NO - Treatment number

EXP. - Title of experiment

TRT. - Title of treatment

WEATHER - Title of weather file used in the simulation

SOIL - Soil type where experiment was conducted

VARIETY - Name of the rice variety used in the simulation

LATITUDE OF EXPT. SITE - Latitude of the experimental site

PLANT POPULATION - Number of plants/m^2

SOWING DEPTH - Depth of sowing, in cm

P1 - Degree-days required from emergence to end of juvenile stage

P2R - Rate of photo-induction, degree-days/hr

P5 - Degree-days required for grain filling

P2O - Optimum photoperiod, in hr

G1 - Conversion efficiency from intercepted PAR (photoynthetically active radiation) to dry matter production, g/MJ PAR

TR - Tillering factor, unitless

JUL DAY - Day of the year

IRRIGATION (MM) - Amount of irrigation, in mm

PEDON - SCS pedon number

SOIL ALBEDO - Bare soil albedo, unitless

UPPER LIMIT OF SOIL EVAPORATION - Upper limit of stage 1 soil evaporation, in mm

SOIL WATER DRAINAGE CONSTANT - Soil water drainage constant, fraction drained/day

SCS RUNOFF CURVE NO. - SCS curve number used to calculate daily runoff

DEPTH OF LAYER-cm - Thickness of the soil layers, in cm

LOWER LIMIT - Lower limit of plant-extractable soil water of the soil layer, cm^3/cm^3

UPPER LIMIT - Drained upper limit soil water content of the soil layer, cm^3/cm^3

SAT. CONTENT - Saturated water content of the soil layer, cm^3/cm^3

EXTR. WATER - Extractable soil water content of the soil layer, the difference between UPPER LIMIT and LOWER LIMIT

WATER CONTENT - Soil water content of the soil layer, cm^3/cm^3

ROOT FACTOR - Weighting factor of the soil layer to determine new root growth distribution, unitless

SOIL NO3 - Initial soil nitrate in the soil layer, mg elemental N/Kg soil

SOIL NH4 - Initial soil ammonium in the soil layer, mg elemental N/Kg soil

KG/HA - Amount of nitrogen fertilizer applied, in Kg N/Ha

DEPTH - Depth of application, in cm

SOURCE - Type of fertilizer

DATE - Date of the event according to the calendar year

PHENOLOGICAL STAGE - Phenological stages of the rice crop

TILLER NO. - Number of tillers/m^2

BIOMASS - Biomass of the crop, in g/m^2

ROOT WT. - Weight of roots, in g/m^2

LEAF WT. - Weight of leaves, in g/m^2

STEM WT. - Weight of stem, in g/m^2

PANICLE WT. - Weight of the panicles, in g/m^2

LAI - Leaf are index

PREDICTED - Output of the simulation

OBSERVED - Field-measured data

OUTPUT FILE NO. 2 - contains the simulation outputs on the growth components, output frequency varying with user option. The following codes are part of output no. 2:

RUN - Run number and run identifier, as defined in output no. 1

INST_ID, SITE_ID, EXPT_NO, YEAR, TRT_NO, EXP., TRT., WEATHER, SOIL, VARIETY - as defined in output no. 1

IRRIG. - Type of irrigation strategy

JUL DAY - Day of the year

CUM. DTT - Cumulative thermal time, in degree-days

LEAF NO. - Number of leaf tips that have emerged

LAI, BIOMASS, ROOT WT., LEAF WT., STEM WT., PANICLE WT., TILLER NO. - as defined in output no. 1

ROOT DEPTH - Depth of rooting, in cm

ROOT LENGTH DENSITY, L1, L3, L5 - Root length density of the soil layers 1, 3, and 5, in cm root/cm^3 soil

OUTPUT FILE NO. 3 - contains the simulation output on the water balance components, frequency of output varying with user option. The following codes are in output no. 3:

RUN - Run number and run identifier, as defined in output no. 1

INST_ID, SITE_ID, EXPT_NO, YEAR, TRT_NO, EXP., TRT., WEATHER, SOIL, VARIETY - as defined in output no. 1

IRRIG., JUL DAY - as defined in output no. 2

AVERAGE EP - Average plant evaporation, in mm/day

AVERAGE ET - Average plant transpiration, in mm/day

AVERAGE EO - Average potential evapotranspiration, in mm/day

AVERAGE SR - Average solar radiation, MJ/day

AVERAGE MAX - Average maximum temperature, in ^{o}C

AVERAGE MIN - Average minimum temperature, in ^{o}C

PERIOD PREC - Total precipitation for the period, in mm

SW CONTENT W/ DEPTH, SW1, SW2, SW3, SW4, SW5 - Soil water content of the soil layers 1, 2, 3, 4, and 5

TOTAL PESW - Total plant extractable soil water in the profile, in cm

OUTPUT FILE NO. 4 - contains the simulation output on the nitrogen components, frequency of output varying with user option. The following codes are part of output no. 4:

RUN - Run number and run identifier, as defined in output no. 1

INST_ID, SITE_ID, EXPT_NO, YEAR, TRT_NO, EXP., TRT., WEATHER, SOIL, VARIETY - as defined in output no. 1

IRRIG., JUL DAY - as defined in output no. 2

TOPS N% - Actual nitrogen concentration in plant tops, percent

NFAC - Average nitrogen stress factor affecting leaf area expansion, 0-1 unitless

TOP N UPTK - Total nitrogen in the stover, in g/m^2

PAN N UPTK - Total nitrogen in the panicle, in g/m^2

LEACH - Total amount of nitrogen leached from all soil layers, in Kg N/Ha

MINLN - Total amount of nitrogen released by mineralization, in Kg N/Ha

DENIT - Total amount of nitrogen lost from all soil layers by denitrification, in Kg N/Ha

NO3 1, 2, 3 - Amount of soil nitrate in layers 1, 2 and 3, in Kg N/Ha

NH4 1, 2 - Amount of soil ammonium in layers 1 and 2, in Kg N/Ha

A sample of each output files follows. The output filenames are OUT80.1, OUT80.2, OUT80.3, and OUT80.4.

Jun 30 14:51 1987 OUT80.1 Page 1

RUN IDENTIFIER : vangie

RUN NO. 1 INPUT AND OUTPUT SUMMARY

INST_ID :IR SITE_ID: PI EXPT_NO: 01 YEAR : 1980 TRT_NO: 1
EXP. :IRRI, LOS BANOS, IRRIG. & N STUDY, 1980
TRT. :IR36, 120 kg N/ha, W1 irrig. level
WEATHER :IRRI 1980 UPLAND DATA
SOIL :Typic Eutrandept
VARIETY :IR 36

LATITUDE OF EXPT. SITE = 15.0 degrees

PLANT POPULATION = 368.00 plants per sq. meter

SOWING DEPTH = 2.5 cm.

GENETIC SPECIFIC CONSTANTS P1 = 550.00 P2R = 149.00 P5= 550.00
P2O = 11.7 G1 = 4.000 TR = .730

IRRIGATION SCHEDULE

JUL DAY	IRRIGATION (mm.)
35	150.
59	165.
68	45.
78	55.
98	245.
115	115.
116	35.

SOIL PROFILE DATA [PEDON: IRRI PEDON]
SOIL ALBEDO = .14
UPPER LIMIT OF SOIL EVAPORATION = 5.0
SOIL WATER DRAINAGE CONSTANT = .60
SCS RUNOFF CURVE NO.= 60.0

DEPTH OF LAYER-cm	LOWER LIMIT	UPPER LIMIT	SAT. CONTENT	EXTR. WATER	WATER CONTENT	ROOT FACTOR	SOIL NO3*	SOIL NH4*
0.- 15.	.120	.260	.430	.140	.260	1.000	4.7	2.0
15.- 30.	.220	.350	.400	.130	.350	.900	3.1	2.0
30.- 45.	.210	.330	.390	.120	.330	.500	3.8	2.0
45.- 60.	.210	.330	.390	.120	.330	.100	3.5	2.0
60.- 75.	.210	.330	.390	.120	.330	.050	3.5	2.0
TOTAL 0.- 75.	14.5	24.0	30.0	9.5	24.0		30.	16.

* NOTE: Units are in kg N / ha.

FERTILIZER INPUTS

JUL DAY	KG/HA	DEPTH	SOURCE
8	120.00	10.00	UREA

Jun 30 14:51 1987 OUT80.1 Page 2

OUTPUT SUMMARY

DATE	JUL DAY	PHENOLOGICAL STAGE	TILLER NO.	BIOMASS	ROOT WT.	LEAF WT.	STEM WT.	PANICLE WT.	LAI
				(- - - grams per sq. meter - - - -)					
1/ 9/80	9	SOWING	0.						
1/12/80	12	GERMINATION	0.						
1/13/80	13	EMERGENCE	0.	.1	.0	.1	.0	.0	.0
2/13/80	44	END JUVENILE STAGE	555.	117.8	48.1	116.9	.9	.0	2.2
2/27/80	58	FLORAL INITIATION	726.	282.0	153.7	239.9	42.1	.0	4.6
3/29/80	89	HEADING	830.	781.4	256.2	312.5	332.2	136.7	6.1
4/ 7/80	98	START GRAIN FILL	822.	985.7	267.9	301.7	436.6	247.4	5.9
4/25/80	116	END GRAIN FILL	722.	1385.0	244.8	216.1	408.2	760.7	4.6
4/26/80	117	PHYSIOLOGICAL MATURITY	722.	1385.0	244.8	216.1	408.2	760.7	4.6

COMPARISON BETWEEN PREDICTED AND FIELD-MEASURED DATA

	PREDICTED	OBSERVED
HEADING DATE (DAY OF YEAR)	89	90
MATURITY DATE (DAY OF YEAR)	117	118
GRAIN YIELD (MT/HA)	6.6	6.7
1,000 GRAIN WEIGHT (G)	29.65	23.00
NO. PANICLES PER SQ. METER	722.	522.
PANICLE WEIGHT (KG/HA)	7607.	0.
PANICLE-STRAW RATIO	1.09	.00
LAI AT HEADING	6.12	.00
BIOMASS (KG/HA)	13850.1	.0
STRAW (KG/HA)	7003.5	6830.0

Jun 30 14:20 1987 OUT80.2 Page 1

RUN 1 vangie
INST_ID :IR SITE_ID: PI EXPT_NO: 01 YEAR : 1980 TRT_NO: 1
EXP. :IRRI, LOS BANOS, IRRIG. & N STUDY, 1980
TRT. :IR36, 120 kg N/ha, W1 irrig. level
WEATHER :IRRI 1980 UPLAND DATA
SOIL :Typic Eutrandept
VARIETY : IR 36
IRRIG. :ACCORDING TO THE FIELD SCHEDULE.

JUL DAY	CUM. DTT	LEAF NO.	LAI	BIO-MASS	ROOT WT.	LEAF WT.	STEM WT.	PAN. WT.	TILLER NO.	ROOT DEPTH (cm.)	ROOT LENGTH DENSITY L1	L3	L5
				(- - - grams	per sq.	meter	- -)						
26	296.	4.	.10	5.	1.39	5.27	.01	.00	244.	55.	.4	.0	.0
33	423.	5.	.58	29.	12.50	29.09	.13	.00	378.	75.	.6	.1	.0
40	546.	7.	1.66	87.	32.80	86.00	.57	.00	493.	75.	1.0	.3	.0
47	666.	8.	2.67	145.	61.68	142.17	2.86	.00	599.	75.	1.5	.5	.0
54	794.	10.	4.08	239.	117.88	215.20	23.33	.00	689.	75.	2.3	1.2	.1
61	924.	11.	4.93	318.	170.87	256.42	57.79	4.11	747.	75.	2.6	2.0	.2
68	1053.	13.	5.61	423.	205.71	290.89	108.53	24.03	794.	75.	3.0	2.5	.3
75	1187.	14.	6.04	548.	230.87	310.88	177.55	59.39	823.	75.	3.2	2.8	.3
82	1318.	16.	6.12	693.	247.83	313.83	267.80	110.88	830.	75.	3.3	3.0	.3
89	1443.	18.	6.12	781.	256.22	312.51	332.17	136.72	830.	75.	3.4	3.1	.4
96	1578.	18.	5.99	940.	265.97	305.56	420.86	213.32	826.	75.	3.5	3.1	.4
103	1716.	18.	5.56	1171.	261.28	274.61	430.48	465.98	806.	75.	3.6	3.1	.4
110	1853.	18.	5.08	1298.	252.27	244.31	419.52	634.28	769.	75.	3.6	3.1	.4

Jun 30 14:20 1987 OUT80.3 Page 1

RUN 1 vangie
INST_ID :IR SITE_ID: PI EXPT_NO: 01 YEAR : 1980 TRT_NO: 1
EXP. :IRRI, LOS BANOS, IRRIG. & N STUDY, 1980
TRT. :IR36, 120 kg N/ha, W1 irrig. level
WEATHER :IRRI 1980 UPLAND DATA
SOIL :Typic Eutrandept
VARIETY : IR 36
IRRIG. :ACCORDING TO THE FIELD SCHEDULE.

JUL	----------	AVERAGE	---------				PERIOD	SW CONTENT W/DEPTH					TOTAL
DAY	EP	ET	EO	SR	MAX	MIN	PREC	SW1	SW2	SW3	SW4	SW5	PESW
14	.0	.7	4.2	390.	29.7	20.9	.00	.19	.32	.32	.33	.33	7.9
21	.1	1.2	3.7	337.	29.5	21.7	1.60	.21	.33	.32	.32	.32	8.1
28	.2	.9	2.7	254.	28.7	21.9	.24	.20	.32	.32	.32	.32	7.6
35	1.3	2.2	4.6	425.	31.4	21.7	21.57	.30	.37	.36	.35	.35	11.4
42	1.9	3.5	3.5	347.	29.6	20.6	.39	.18	.32	.32	.33	.33	7.7
49	2.2	3.3	3.3	330.	29.4	21.3	1.96	.17	.30	.31	.32	.32	6.7
56	4.2	5.2	5.5	539.	32.4	20.5	.00	.11	.24	.24	.28	.30	3.0
63	3.9	4.5	4.9	480.	33.3	19.9	23.57	.22	.32	.32	.33	.33	8.4
70	4.4	4.9	4.9	479.	33.5	20.2	7.09	.26	.34	.34	.34	.34	9.6
77	4.6	5.0	5.0	489.	32.7	21.5	.00	.17	.27	.29	.31	.32	6.0
84	3.7	4.1	4.1	402.	31.2	21.1	23.14	.33	.37	.36	.35	.35	11.8
91	3.5	3.8	3.8	377.	30.3	22.6	1.53	.22	.32	.31	.33	.33	8.1
98	4.8	5.3	5.3	511.	32.8	22.3	35.30	.32	.35	.35	.35	.35	11.3
105	5.2	5.8	5.8	510.	33.0	22.5	1.77	.24	.30	.30	.32	.32	7.6
112	4.3	4.8	4.8	421.	32.2	23.8	12.13	.20	.30	.30	.32	.33	7.3

Jun 30 14:20 1987 OUT80.4 Page 1

RUN 1 vangie
INST_ID :IR SITE_ID: PI EXPT_NO: 01 YEAR : 1980 TRT_NO: 1
EXP. :IRRI, LOS BANOS, IRRIG. & N STUDY, 1980
TRT. :IR36, 120 kg N/ha, W1 irrig. level
WEATHER :IRRI 1980 UPLAND DATA
SOIL :Typic Eutrandept
VARIETY : IR 36
IRRIG. :ACCORDING TO THE FIELD SCHEDULE.

JUL DAY	TOPS N %	NFAC	TOP N UPTK	PAN N UPTK	LEACH	MINLN	DENIT	NO3 1	NO3 2	NO3 3	NH4 1	NH4 2
26	3.72	.84	156.	0.	10.6	4.6	16.2	68.2	4.9	4.7	2.2	3.6
33	3.44	.75	893.	0.	10.6	4.6	16.2	64.2	4.9	4.8	2.6	3.9
40	3.10	.72	2082.	0.	270.8	5.1	12.4	13.5	16.0	12.9	1.8	3.1
47	2.80	.62	3227.	0.	.6	4.2	12.9	11.0	15.0	12.6	1.6	1.9
54	2.45	.55	4507.	0.	.6	4.1	12.9	9.4	12.0	10.1	1.7	1.6
61	2.14	.47	5427.	0.	104.2	4.0	9.7	2.0	5.6	7.4	1.6	1.6
68	1.98	.50	6277.	0.	5.0	4.9	6.6	1.1	4.1	6.6	1.6	1.6
75	1.80	.52	6932.	0.	4.8	5.4	5.0	1.0	2.9	5.1	1.6	1.6
82	1.63	.54	7483.	0.	7.1	4.9	4.1	1.0	1.6	3.9	1.6	1.6
89	1.51	.58	7801.	0.	28.7	4.6	1.6	1.0	1.0	1.3	1.6	1.6
96	1.38	.56	8108.	0.	.8	4.6	1.6	1.0	1.1	1.4	1.6	1.6
103	1.19	.78	5628.	33.	13.3	5.1	.4	1.0	1.1	1.0	1.6	1.6
110	.83	.58	4063.	55.	2.4	5.1	.1	1.0	1.0	1.0	1.6	1.6

APPENDIX D

SAMPLE OUTPUT OF THE SIMULATION-MULTICRITERIA OPTIMIZATION TECHNIQUE

FARM PRODUCTION MULTICRITERIA OPTIMIZATION
****

OBJECTIVE FUNCTIONS:
1) MAXIMIZE PROFIT, F(1) ($/Ha)
2) MINIMIZE FARM PRODUCTION RISK, F(2) (std. deviation from the mean yield)

DECISION VARIABLES:
1) SOWING DATE, U(1), (Julian day)
2) AMOUNT OF N FERTILIZER APPLIED, U(2), (Kg N/Ha)
3) PLANT POPULATION, U(3), (plants/sq.meter)

NO. OF U(1)-POINT SEARCH : 1
NO. OF U(2),U(3)-POINT SEARCH : 200
NO. OF SIMULATION CYCLES TO GET AVE.YIELD (MT/Ha): 25

SET NO. 1

THE SET OF FEASIBLE SOLUTIONS ARE :

U(1) : 171
(SOWING DATE)

RUN NO.	U(2) (N FERT.)	U(3) (POPULATION)	AVE. YIELD	F(1) (PROFIT)	F(2) (RISK)
1	0.	400.	3.16	61.42	.302
2	873.	698.	7.55	2628.23	1.025
3	676.	717.	7.51	2872.54	1.023
4	783.	316.	7.88	3055.13	1.085
5	711.	344.	7.89	3137.58	1.085
6	647.	549.	7.78	3177.19	1.063
7	805.	352.	7.91	3008.46	1.084
8	751.	236.	7.81	2997.68	1.087
9	463.	541.	7.69	3313.68	1.091
10	604.	152.	7.69	3104.52	1.106
11	316.	513.	7.41	3280.54	1.105
12	841.	868.	7.27	2456.04	.987

13	313.	454.	7.48	3334.01	1.114
14	469.	216.	7.67	3294.24	1.123
15	157.	690.	5.89	2162.90	.884
16	769.	490.	7.89	3063.91	1.074
17	211.	110.	6.47	2593.60	1.031
18	872.	655.	7.62	2689.77	1.035
19	399.	434.	7.74	3494.49	1.134
20	458.	340.	7.77	3377.00	1.118
21	195.	574.	6.46	2662.32	.966
22	544.	333.	7.84	3367.96	1.098
23	269.	242.	7.11	3084.62	1.106
24	329.	578.	7.38	3250.21	1.095
25	261.	393.	7.17	3138.44	1.095
26	523.	249.	7.75	3296.16	1.105
27	802.	632.	7.66	2791.42	1.041
28	868.	740.	7.48	2568.26	1.016
29	111.	530.	5.24	1666.77	.749
30	100.	761.	4.94	1473.72	.708
31	860.	331.	7.89	2926.60	1.084
32	120.	256.	5.38	1787.71	.781
33	876.	164.	7.74	2798.36	1.093
34	643.	550.	7.78	3175.04	1.063
35	852.	593.	7.72	2778.35	1.049
36	153.	480.	5.96	2225.57	.882
37	283.	591.	7.16	3132.74	1.071
38	768.	569.	7.76	2950.49	1.056
39	759.	722.	7.51	2731.46	1.020
40	62.	436.	4.37	971.67	.574
41	806.	571.	7.76	2878.96	1.055
42	424.	524.	7.67	3363.72	1.106
43	845.	784.	7.41	2575.32	1.006
44	611.	402.	7.91	3294.32	1.090
45	137.	508.	5.69	2058.25	.834
46	625.	553.	7.77	3167.26	1.063
47	136.	744.	5.54	1928.86	.824
48	420.	539.	7.64	3338.71	1.103
49	82.	579.	4.70	1266.92	.645
50	697.	305.	7.86	3181.17	1.086
51	508.	160.	7.65	3203.96	1.121
52	335.	541.	7.45	3312.00	1.106
53	866.	745.	7.47	2561.12	1.015
54	155.	722.	5.84	2118.56	.878
55	102.	639.	5.04	1487.94	.717
56	23.	164.	3.49	282.49	.407
57	226.	726.	6.64	2743.41	1.004
58	395.	567.	7.56	3336.98	1.102
59	498.	154.	7.63	3259.98	1.124
60	378.	829.	7.14	2970.46	1.040
61	621.	847.	7.29	2751.00	.996
62	348.	832.	7.08	2986.74	1.044
63	12.	770.	3.25	68.09	.356
64	816.	820.	7.35	2523.65	.998
65	215.	365.	6.76	2848.23	1.026
66	752.	124.	7.69	2889.12	1.102

67	594.	652.	7.60	3090.10	1.042
68	179.	888.	6.01	2266.04	.905
69	108.	777.	5.07	1515.21	.734
70	897.	390.	7.93	2962.41	1.083
71	181.	857.	6.06	2309.18	.911
72	780.	642.	7.64	2846.43	1.039
73	232.	462.	6.95	3018.30	1.048
74	354.	323.	7.56	3334.40	1.140
75	123.	344.	5.46	1858.83	.794
76	536.	765.	7.39	2982.71	1.021
77	564.	316.	7.83	3296.04	1.096
78	883.	461.	7.94	2968.39	1.080
79	790.	260.	7.84	3017.21	1.086
80	267.	887.	6.71	2738.57	1.006
81	203.	500.	6.62	2726.58	.991
82	869.	334.	7.89	2928.63	1.084
83	59.	705.	4.22	845.24	.558
84	849.	781.	7.41	2579.63	1.007
85	553.	115.	7.61	3104.38	1.121
86	522.	342.	7.83	3361.00	1.101
87	539.	795.	7.35	2942.21	1.013
88	735.	162.	7.74	3000.98	1.096
89	103.	893.	4.92	1385.04	.710
90	822.	542.	7.81	2920.96	1.062
91	82.	561.	4.71	1269.66	.645
92	571.	595.	7.68	3163.56	1.058
93	4.	462.	3.20	22.41	.317
94	604.	863.	7.26	2725.41	.993
95	613.	499.	7.85	3241.00	1.077
96	772.	627.	7.66	2867.58	1.042
97	203.	443.	6.66	2763.21	.997
98	483.	387.	7.83	3429.27	1.111
99	288.	649.	7.12	3090.62	1.060
100	213.	295.	6.69	2792.81	1.026
101	293.	708.	7.07	3047.88	1.058
102	563.	829.	7.30	2832.90	1.003
103	758.	775.	7.42	2656.01	1.009
104	438.	357.	7.75	3435.03	1.124
105	490.	394.	7.84	3439.37	1.109
106	273.	512.	7.20	3166.13	1.084
107	319.	496.	7.45	3310.57	1.109
108	697.	254.	7.82	3145.56	1.088
109	162.	378.	6.10	2340.84	.911
110	415.	607.	7.53	3243.11	1.087
111	592.	288.	7.82	3287.54	1.093
112	441.	761.	7.33	3066.80	1.040
113	491.	769.	7.36	3023.54	1.028
114	93.	173.	4.87	1408.66	.694
115	550.	779.	7.38	2968.53	1.016
116	529.	810.	7.32	2917.11	1.012
117	30.	268.	3.68	442.14	.442
118	866.	799.	7.38	2484.15	1.003
119	526.	611.	7.63	3191.91	1.060
120	518.	660.	7.55	3119.84	1.049

121	13.	728.	3.28	92.30	.360
122	523.	435.	7.89	3416.33	1.102
123	256.	846.	6.71	2732.27	1.004
124	29.	738.	3.60	370.97	.434
125	442.	713.	7.41	3132.38	1.052
126	165.	254.	6.08	2325.14	.912
127	459.	356.	7.78	3388.51	1.118
128	297.	179.	7.19	3154.18	1.128
129	558.	760.	7.41	2928.00	1.019
130	337.	753.	7.17	3063.90	1.062
131	472.	736.	7.40	3056.69	1.039
132	45.	217.	3.98	703.75	.510
133	383.	290.	7.60	3374.19	1.143
134	527.	402.	7.87	3399.84	1.100
135	891.	537.	7.81	2859.10	1.062
136	325.	298.	7.43	3297.34	1.133
137	209.	234.	6.60	2714.27	1.016
138	821.	871.	7.27	2451.49	.987
139	517.	716.	7.46	3041.77	1.035
140	404.	708.	7.36	3096.31	1.063
141	463.	298.	7.74	3353.23	1.120
142	764.	791.	7.39	2633.30	1.005
143	484.	463.	7.84	3437.63	1.106
144	788.	233.	7.81	2997.15	1.087
145	107.	268.	5.16	1597.54	.736
146	174.	313.	6.23	2460.17	.938
147	764.	657.	7.61	2824.36	1.035
148	485.	872.	7.19	2878.69	1.005
149	843.	850.	7.30	2481.53	.991
150	172.	665.	6.11	2352.64	.910
151	464.	682.	7.48	3123.75	1.054
152	657.	762.	7.43	2806.52	1.013
153	350.	809.	7.12	3019.85	1.049
154	732.	821.	7.34	2659.20	.998
155	75.	407.	4.62	1189.65	.622
156	498.	792.	7.33	2996.08	1.021
157	186.	461.	6.44	2640.77	.960
158	759.	898.	7.22	2481.80	.981
159	355.	413.	7.62	3393.90	1.135
160	714.	286.	7.85	3100.53	1.086
161	227.	436.	6.92	2989.20	1.041
162	221.	655.	6.67	2768.19	1.000
163	852.	451.	7.96	2982.29	1.083
164	101.	674.	5.00	1454.58	.711
165	263.	332.	7.14	3114.73	1.096
166	101.	149.	4.99	1442.06	.723
167	319.	560.	7.37	3239.02	1.097
168	231.	386.	6.93	2993.83	1.054
169	753.	737.	7.48	2709.76	1.017
170	222.	351.	6.82	2904.22	1.040
171	589.	185.	7.73	3203.04	1.102
172	672.	514.	7.84	3161.15	1.070
173	341.	593.	7.40	3268.19	1.097
174	255.	221.	7.00	2986.03	1.097

175	318.	703.	7.17	3070.71	1.068
176	308.	316.	7.38	3248.25	1.124
177	487.	751.	7.39	3046.25	1.033
178	10.	694.	3.23	54.83	.347
179	315.	432.	7.49	3347.07	1.119
180	310.	360.	7.42	3284.88	1.121
181	765.	239.	7.82	3000.73	1.087
182	348.	705.	7.26	3148.31	1.075
183	49.	517.	4.08	793.04	.520
184	575.	211.	7.75	3221.30	1.100
185	67.	258.	4.43	1025.08	.598
186	463.	346.	7.78	3386.06	1.117
187	192.	508.	6.48	2676.35	.967
188	125.	297.	5.48	1874.90	.799
189	200.	190.	6.47	2662.70	.998
190	609.	135.	7.67	3085.92	1.108
191	150.	583.	5.86	2201.54	.869
192	104.	311.	5.12	1563.28	.729
193	486.	787.	7.33	2995.81	1.024
194	262.	112.	6.89	2893.44	1.117
195	417.	617.	7.52	3232.40	1.084
196	631.	411.	7.92	3304.15	1.089
197	17.	586.	3.39	187.69	.379
198	425.	393.	7.76	3439.28	1.128
199	848.	383.	7.93	3027.56	1.084
200	574.	617.	7.65	3133.53	1.052

THE IDEAL VECTOR OF OBJECTIVE FUNCTIONS ARE:

FO(1)= 3494.49 FO(2)= .302

THE SET OF PARETO OPTIMAL SOLUTIONS ARE:

POINT NO.	U(1)	U(2)	U(3)	YIELD	F(1)	F(2)
1	171	0.	400.	3.16	61.42	.302
2	171	498.	792.	7.33	2996.08	1.021
3	171	526.	611.	7.63	3191.91	1.060
4	171	526.	611.	7.63	3191.91	1.060
5	171	463.	541.	7.69	3313.68	1.091
6	171	195.	574.	6.46	2662.32	.966
7	171	544.	333.	7.84	3367.96	1.098
8	171	153.	480.	5.96	2225.57	.882
9	171	399.	434.	7.74	3494.49	1.134
10	171	490.	394.	7.84	3439.37	1.109
11	171	195.	574.	6.46	2662.32	.966
12	171	544.	333.	7.84	3367.96	1.098
13	171	111.	530.	5.24	1666.77	.749
14	171	100.	761.	4.94	1473.72	.708
15	171	120.	256.	5.38	1787.71	.781
16	171	526.	611.	7.63	3191.91	1.060

17	171	153.	480.	5.96	2225.57	.882
18	171	498.	792.	7.33	2996.08	1.021
19	171	621.	847.	7.29	2751.00	.996
20	171	62.	436.	4.37	971.67	.574
21	171	498.	792.	7.33	2996.08	1.021
22	171	631.	411.	7.92	3304.15	1.089
23	171	137.	508.	5.69	2058.25	.834
24	171	136.	744.	5.54	1928.86	.824
25	171	82.	561.	4.71	1269.66	.645
26	171	613.	499.	7.85	3241.00	1.077
27	171	150.	583.	5.86	2201.54	.869
28	171	102.	639.	5.04	1487.94	.717
29	171	23.	164.	3.49	282.49	.407
30	171	621.	847.	7.29	2751.00	.996
31	171	498.	792.	7.33	2996.08	1.021
32	171	621.	847.	7.29	2751.00	.996
33	171	594.	652.	7.60	3090.10	1.042
34	171	12.	770.	3.25	68.09	.356
35	171	594.	652.	7.60	3090.10	1.042
36	171	179.	888.	6.01	2266.04	.905
37	171	104.	311.	5.12	1563.28	.729
38	171	172.	665.	6.11	2352.64	.910
39	171	123.	344.	5.46	1858.83	.794
40	171	498.	792.	7.33	2996.08	1.021
41	171	203.	500.	6.62	2726.58	.991
42	171	59.	705.	4.22	845.24	.558
43	171	539.	795.	7.35	2942.21	1.013
44	171	82.	561.	4.71	1269.66	.645
45	171	571.	595.	7.68	3163.56	1.058
46	171	613.	499.	7.85	3241.00	1.077
47	171	203.	443.	6.66	2763.21	.997
48	171	490.	394.	7.84	3439.37	1.109
49	171	563.	829.	7.30	2832.90	1.003
50	171	490.	394.	7.84	3439.37	1.109
51	171	172.	665.	6.11	2352.64	.910
52	171	415.	607.	7.53	3243.11	1.087
53	171	441.	761.	7.33	3066.80	1.040
54	171	491.	769.	7.36	3023.54	1.028
55	171	93.	173.	4.87	1408.66	.694
56	171	550.	779.	7.38	2968.53	1.016
57	171	529.	810.	7.32	2917.11	1.012
58	171	30.	268.	3.68	442.14	.442
59	171	526.	611.	7.63	3191.91	1.060
60	171	518.	660.	7.55	3119.84	1.049
61	171	13.	728.	3.28	92.30	.360
62	171	523.	435.	7.89	3416.33	1.102
63	171	29.	738.	3.60	370.97	.434
64	171	442.	713.	7.41	3132.38	1.052
65	171	472.	736.	7.40	3056.69	1.039
66	171	45.	217.	3.98	703.75	.510
67	171	527.	402.	7.87	3399.84	1.100
68	171	487.	751.	7.39	3046.25	1.033
69	171	484.	463.	7.84	3437.63	1.106
70	171	107.	268.	5.16	1597.54	.736

71	171	174.	313.	6.23	2460.17	.938
72	171	485.	872.	7.19	2878.69	1.005
73	171	172.	665.	6.11	2352.64	.910
74	171	75.	407.	4.62	1189.65	.622
75	171	498.	792.	7.33	2996.08	1.021
76	171	186.	461.	6.44	2640.77	.960
77	171	221.	655.	6.67	2768.19	1.000
78	171	487.	751.	7.39	3046.25	1.033
79	171	49.	517.	4.08	793.04	.520
80	171	67.	258.	4.43	1025.08	.598
81	171	192.	508.	6.48	2676.35	.967
82	171	125.	297.	5.48	1874.90	.799
83	171	150.	583.	5.86	2201.54	.869
84	171	104.	311.	5.12	1563.28	.729
85	171	631.	411.	7.92	3304.15	1.089
86	171	17.	586.	3.39	187.69	.379
87	171	574.	617.	7.65	3133.53	1.052

THE SET OF OPTIMAL SOLUTION IN THE MIN-MAX SENSE:

L* = 200   Z* =   1.37

A) OPTIMAL VALUES OF DECISION VARIABLES:

U*(1)= 171   U*(2)= 100.   U*(3)= 761.   YIELD* = 4.94

B) OPTIMAL VALUES OF OBJECTIVE FUNCTIONS:

F*(1)= 1473.72   F*(2)= .708

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